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THE ATLANTIC GEOSCIENCE CENTRE SEDIMENT TRANSPORT NUMERIC MODELS

by

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The Atlantic Geoscience Centre sediment transport numeric model has been developed over the last 5 years. It can be used interactively, or in batch mode to predict sediment transport under currents, or combined (wave/current) flows. It can provide solutions of bed stress using methods of Grant and Madsen (1979) or Smith (1977) together with the sediment transport algorithms of Engelund and Hansen (1967), Einstein and Brown (1950), Bagnold (1963) and Yalin (1963). The model is available in Fortran 5 executable code on the Bedford Institute cyber, or is available for use on IBM compatible microcomputers. The source code, theories, model structure and operators guide are given in a series of contract reports. These reports are provided in this open file document and are as follows:

Martec Ltd., 1983. A 2-D sediment transport model for continental shelves. Consultant final report to Geol. Surv. Canada (DSS file # 10SC.23420-M777).

Davidson, S., 1984. SED1D: a sediment transport model for the continental shelf. Consultant final report to Geol. Surv. Canada (DSS file # 10SC.23420-3-M753).

Davidson, S. and Amos, C.L. 1985. A re-evaluation of SED1D and SED2D: sediment transport models for the continental shelf. Internal Report, 54p.

Davidson, S., 1986. SED1D: a microcomputer version. Final consultant report (DSS contract # 10SC.23420-6-M736/01-SC)

Martec Ltd., 1986. The comparison between observed and predicted sediment transport for the radio-active sand tracer study and SED1D model upgrade. Consultant final report to Geol. Surv. Canada (DSS file # 10SC.23420-6-M625/01-OAE).

Watanabe, R. and Han, R. 1987. Upgrading of AGC sediment transport model. Consultant final report to Geol. Surv. Canada (DSS file # 10SC.23420-6-M887/01-OAE).

REPORT

A 2-D SEDIMENT TRANSPORT MODEL FOR CONTINENTAL SHELVES

For:

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Dartmouth, N.S.
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1. Introduction

The objective of the present study is to produce a working model to simulate sediment transport over a given area of ocean bottom, during a storm. In an earlier study (Martec, 1982), a computer model had been developed to compute the mean, instantaneous sediment transport for an idealized simple environment, consisting of a sediment of uniform size and a monochromatic wave field interacting with a steady current. This earlier work founded on Grant and Madsen's (1979) approach will be used as a basis in the present study. Extensions over the earlier model will include:

- Simulation of a complex environment defined as consisting of bottom sediments with a range of size and waves with a full spectra of heights, periods and directions, interacting with a steady current.
- Sediment transport rates, as well as, accretion or depletion rates will be calculated at each point of a grid representing a geographical area.
- The sediment transport over the model grid will be time-stepped over the duration of a storm, to give a better representation of the impact of atmospheric events.

The methods used are applicable over the major part of continental shelves where waves do not normally break and where bottom slopes do not significantly affect sediment transport. In the present study the model is specifically applied to the Sable Island Bank and Banquereau region of the Eastern Canadian Shelf, for which field data is available for verification of results.

The task of developing the 2-D sediment transport model can be divided in two main components, namely:

- The creation of an algorithm to compute sediment transport under complex environmental conditions, varying with space and time.

- The development of a method to assess the driving component of the environment (steady current and wave climate) at each grid point and time step, during a storm.

The following two chapters of this report will consider each of these topics in turn. A third chapter will discuss model testing, error analysis, sample results and instructions to the model users.

Much of the software developed during this project is peripheral to the 2-D sediment transport model. Such programs were used to generate basic data needed by the 2-D sediment transport algorithm, such as lookup tables and refraction analyses. Because these programs are unlikely to be used again they are not conceived for user operation or servicability. The present document, however, provides the theoretical basis for all programs. This report and the documentation imbeded in the program coding itself, should enable a competent scientist and programmer to repeat all necessary steps, if required. Figure 1.1 presents cross-reference chart for all the developed programs giving a brief description of their purpose and referring to the appropriate sections or appendices in this report.

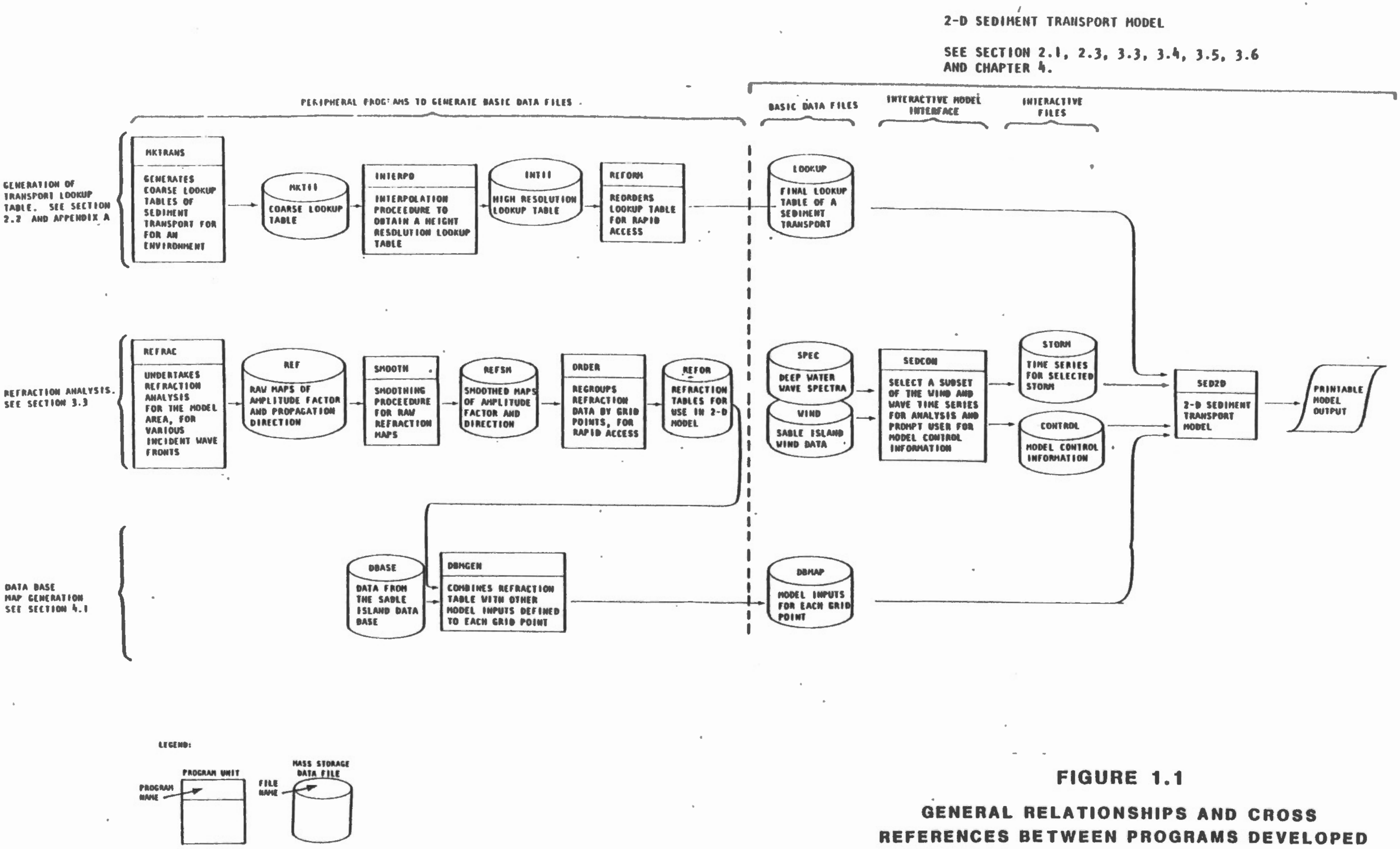


FIGURE 1.1

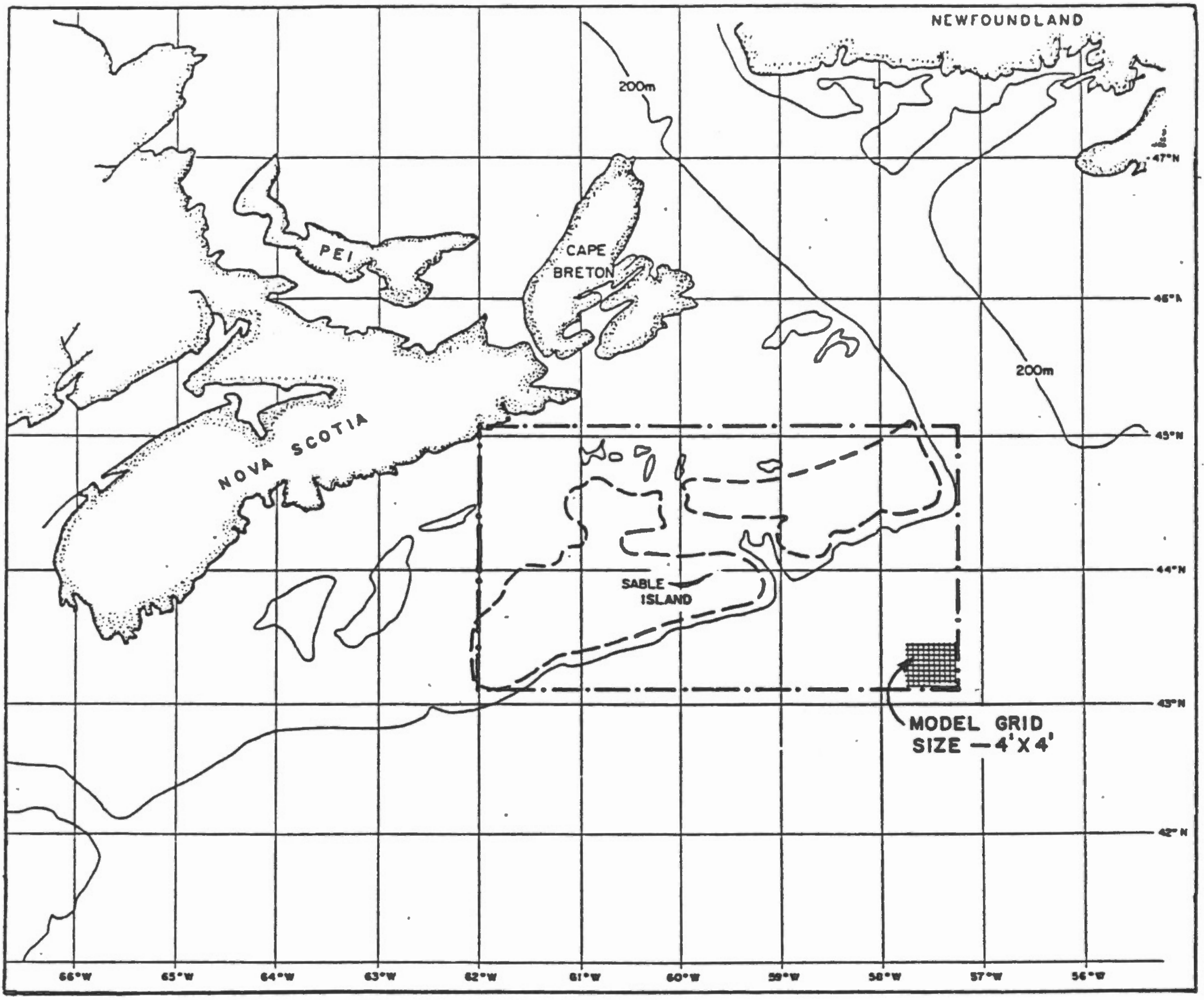
GENERAL RELATIONSHIPS AND CROSS REFERENCES BETWEEN PROGRAMS DEVELOPED FOR THE 2-D SEDIMENT TRANSPORT MODEL

2. 2-D Sediment Transport

Several theories and empirical formulae are available to relate the instantaneous transport of sediment to the motion of a fluid. Some of these have been reviewed and implemented in a computer code during a previous study (Martec, 1982). All of the formulae used earlier, however, considered a very simple environment consisting of a sediment of uniform size, under the influence of a monochromatic wave field and a steady current. The present research has two basic objectives, first to devise a scheme to assess sediment transport in a more realistic complex environment, and second to use this scheme to compute the space and time distribution of sediment transport. As will be seen the implementation of these two objectives is closely related since the approach is to segment the complex environment into a series of simpler discrete components in a manner analogous to the discretization of space and time into a grid system.

The study area consisting of Sable Island Bank and Banquereau (Figure 2.1) is divided into a grid of 4' in longitude and 4' in latitude. Within each of these grid elements we will consider that the depth, wave climate, steady current and sediment grain size distribution is uniform. The size of the spacial elements (approximately 7.4 km by 5.2 km) is dictated by the availability of data and by the observed scale of changes.

The time step is also chosen according to data availability and scales of change. Wind, which is the primary atmospheric variable driving the ocean climate near Sable Island, is measured hourly, however, the time scale for energetic atmospheric events is of two to five days suggesting that longer time steps may be used. Three hours was chosen, since it will adequately describe the variation of atmospheric parameters during a storm, and because it is the interval used in a wave hindcasting study we wish to use. Within each time step, the wave climate and steady current are assumed to be constant. Depth and sediment distribution are considered time invariant, it is therefore assumed implicitly that these will



LEGEND:

— · — · — OVERALL AREA CONSIDERED IN THE SEDIMENT TRANSPORT MODEL

— — — — — 100 m CONTOUR WITHIN WHICH SEDIMENT TRANSPORT IS ACTUALLY COMPUTED

FIGURE 2.1

BOUNDARIES FOR THE SEDIMENT TRANSPORT MODEL not change significantly in response to a single storm. Although this may not hold in shallow regions where bars rapidly form and dissappear, it is reasonable over the largest part of the study area.

The method for determining the steady current and wave property distribution (broadly termed ocean climate) at each geographical grid location and time step, will be explained in chapter three. The following pages will describe a method of computing the sediment transport for a complex environment, given the ocean climate.

2.1 Sediment Transport for a Complex Environment

On continental shelves where bottom slopes are small and where waves do not break, the rate of sediment transport depends on:

- Wave period (T), direction (Dir), and bottom orbital velocity (U);
- Sediment grain size (Φ)
- Steady current velocity (V);

Several formulations are available to compute sediment transport for a simple environment, with a single grain size and a monochromatic wave field. In the natural environment, however, the bottom material will have a range of size and wave of several periods, directions and orbital velocities will be present at the same time. Fortunately, most of the variability in steady currents occurs on time scales of several hours to days so that at least the variability in this aspect of the environment is considered to be included in the time stepping procedure of the present model.

The approach used here to compute sediment transport under a chaotic sea state has been suggested by Smith (1977) and consists of computing sediment transport for a series of discrete monochromatic wave components. If the sum of each monochromatic wave component adequately represents the chaotic seastate, then to a first approximation the net sediment transport can be calculated by adding the contribution of each component. For example, the wave climate may be adequately specified by:

- 30% of waves with T=10s, D=120°, and U=30 cm/sec;
- 20% of waves with T=10s, D=120°, and U=40 cm/sec;
- 20% of waves with T=12s, D=120°, and U=50 cm/sec;
- 15% of waves with T=10s, D=80°, and U=15 cm/sec;
- 15% of waves with T=10s, D=160°, and U=15 cm/sec;

which is equivalent to saying that during 30% of the time waves have T=10s, D=120°, and U=30 cm/sec, etc... Denoting the sediment transport for a single wave component by the vector $\vec{G}(T,D,U)$, the transport during 30% of the time can then be expressed as $\vec{G}(10s,120°,30\ cm/sec)$, and by extension:

$$\begin{aligned}\vec{G}_{Total} = {} & .3\ \vec{G}(10s,120^\circ,30\ \text{cm/sec}) + .2\ \vec{G}(10s,120^\circ,40\ \text{cm/sec}) \\ & + .2\ \vec{G}(12s,120^\circ,50\ \text{cm/sec}) + .15\ \vec{G}(10s,80^\circ,15\ \text{cm/sec}) \\ & + .15\ \vec{G}(10s,160^\circ,50\ \text{cm/sec})\end{aligned}$$

The number of individual components needed to specify the wave environment will generally depend on the particular conditions. Since in the present application no specific sea state is considered, we will define a large set of basic components which can adequately describe any wave field. These components were chosen with wave orbital velocities between 2.5 to 152.5 cm/sec at 5 cm/sec intervals, direction between 0° and 180° at 22.5° intervals (Note that because of the symmetry of monochromatic waves only half of the full range of directions needs to be considered), and 20 periods given in Table 2.1. The selection of the intervals for each wave characteristic reflects the accuracy with which these may be measured or estimated, and also the present availability of data. The total number of basic wave components is (30 velocity values x 8 directions x 20 periods) 4,800. To compute the sediment transport at one location, in response to an arbitrary seastate will therefore require assessing transport for 4,800

TABLE 2.1

PERIODS FOR BASIC WAVE COMPONENTS

Component Number	Period (sec)
1	30
2	25
3	22.2
4	20.0
5	18.2
6	16.7
7	15.4
8	14.2
9	13.3
10	12.5
11	11.8
12	11.1
13	10.5
14	10.0
15	9.5
16	9.1
17	8.3
18	7.7
19	6.9
20	6.25

individual wave components, each with different parameters. The method used to estimate the relative weight of each component relies on the sea state spectra and will be explained in Chapter 3.

In order to calculate sediment transport for natural bottom materials with a range of grain size, a component approach can also be adopted. This method is used in several sediment transport formulae (Vanoni, 1975) and can be formulated as follows:

$$\vec{G}_{Total} = \Sigma s_i \vec{G}_i$$

where $\vec{G}_{Total}$ is the total transport vector;
s_i is the fraction of sediment with a size Φ_i; and
$\vec{G}_i$ is the transport rate for a sediment of uniform size Φ_i.

Extending the example for the wave components to a situation where there are 60% of grains of size $\Phi=1$ and 40% of size $\Phi=2$, the net total transport would be calculated as:

$$\begin{aligned}
\vec{G}_{Total} = {} & .6\ [.3\ \vec{G}_1(10s,120°,30\ cm/sec) + .2\ \vec{G}_1(10s,120°,40\ cm/sec) \\
& + .2\ \vec{G}_1(12s,120°,50\ cm/sec) + .15\ \vec{G}_1(10s,80°,15\ cm/sec) \\
& + .15\ \vec{G}_1(10s,160°,15\ cm/sec)] + \\
& .4\ [.3\ \vec{G}_2(10s,120°,30\ cm/sec) + .2\ \vec{G}_2(10s,120°,40\ cm/sec) \\
& + .2\ \vec{G}_2(12s,120°,50\ cm/sec) + .15\ \vec{G}_2(10s,80°,15\ cm/sec) \\
& + .15\ \vec{G}_2(10s,160°,15\ cm/sec)]
\end{aligned}$$

where $\vec{G}_1$ is the transport for $\Phi=1$ and $\vec{G}_2$ for $\Phi=2$.

Examining sediment grain size distribution for Sable Island Bank, it was found that 10 standard grain size components with Φ from -.75 to 3.75 at .5 intervals would be sufficient to represent the mode and spread of the distribution for most sites. The relative weight of each component (s_i) is computed by imposing a normal distribution with a mean and standard deviation equal to observed or estimated mean Φ and sorting, at each grid point of the model area.

Combining the number of grain size components with the number of basic wave components we find that 48,000 estimates will be needed to compute the sediment transport for a complex environment, at each time step and grid location. Anticipating the high cost and the repetitiveness of this calculation it would seem preferable to somehow compute ahead of time the sediment transport for each simple component, then access this information and perform the necessary summation to obtain total transport. For this, however, we would have to know the steady current velocity. Since this velocity will vary between grid locations and time steps, preliminary transport calculation will be done for 30 steady currents from 2.5 to 152.5 cm/sec at 5 cm/sec intervals, and values nearest to the local steady current velocity will be used for transport computation. The general formula for the transport calculation for a complex environment with steady current equal to V_m is:

$$\vec{G}_{Total} = \Sigma\, s_i (\Sigma\, w_{jkl}\, \vec{G}_{ijklm})$$

where s_i is the fraction of grains with size Φ_i;

w_{jkl} is the fraction of time during which waves have a period T_j, direction Dir_k and bottom orbital velocity V_l; and

$\vec{G}_{ijklm}$ is the sediment transport vector for a simple environment with parameters equal to Φ_i, T_j, Dir_k, V_l and V_m.

The transport vector $\vec{G}_{ijklm}$ will be computed in a preliminary step, for every discretized environment components. In order to avoid having to do preliminary calculations for a range of steady current directions, $\vec{G}_{Total}$ and $\vec{G}_{ijklm}$ are referenced to the current direction. Once $\vec{G}_{Total}$ is calculated as above, knowing the direction of the steady current, we can easily recover the transport vector in standard geographical coordinates as follows:

- The transport magnitude will remain the same whether measured with respect to the current direction or from true north.

- The transport direction with respect to true north is equal to the current direction with respect to true north plus the relative angle of $\overrightarrow{G}_{ijklm}$.

The total number of preliminary transport calculations can be halved, if we consider that the transport for waves with directions between 90° and 180° can easily be derived for the transport from 0° to 90°. Taking this into account and the 30 steady velocity intervals, 720,000 estimates of sediment transport for a simple environment (single grain size, current velocity, and wave characteristics) will be required before the 2-D modelling is undertaken. For each time step and grid location the 2-D model will then access the values nearest to the local current velocity and apply the appropriate weighing and summation to obtain total transport. The next section will give more detail on the procedure used for the generation of the lookup table of sediment transport for 720,000 sets of simple environmental conditions. Another section will describe in more detail the control algorithm of the 2-D sediment model.

2.2 Sediment Transport of a Simple Environment

In a previous study, a computer program was developed to compute the rate of transport for sediments of uniform grain size, under the action of a steady current and superimposed on a monochromatic wave field. The basic approach consisted of first computing the instantaneous bottom shear stress as a function of time, for a given steady and oscillatory velocities. It was then possible to compute the instantaneous transport rate using any of several empirical or semi-empirical formulae for sediment transport as a function of bottom stress. The mean transport could then be computed by performing integration and averaging over one wave period. Although several formulations were used, it was concluded that the most appropriate method of assessing bottom stress was that of Grant and Madsen (1979), while the best transport formula was that of Brown (1950) as modified by Madsen and Grant (1976).

In the present study the same general algorithm was used to compute sediment transport for a simple environment. Minor modifications included stripping the program of all codes related to formulae other than those mentioned above. Also in the original study, graphical approximations were used for Grant and Madsen's stress formulation while the present program iteratively solves their analytical equations. In the earlier model errors of up to 5% were allowed in the graphical fit of bottom friction velocity, while in the present study a convergence to within 1% is specified in the iterative procedures. In the earlier version this could result in inaccuracies of up to 30% in the final transport estimates, while now this has been reduced to approximately 6%. The new sediment transport algorithm has been implemented in a FORTRAN subroutine called TRANSPO.

It should be mentioned that a coding error was uncovered and has now been corrected in the original "SEDMO" program. This consisted of a missing multiplicative factor to preserve C.G.S. units in the final transport calculation and as a result, transport rates given in cm^2/sec should have been multiplied by 100. Also, in Grant and Madsen (1979), the exponent of α on the right hand sied of equation (54) should be 3/2 instead of 3/4. In the earlier report, section 3.2.4, an estimated boundary layer thickness of 20 m was used to compute the friction factor due to Jonsson (1967); reexamination indicated that the logarithmic layer thickness should have been used instead. This last discrepancy is of no consequence in the present work, but the original "SEDMO" has been corrected to use a logarithmic boundary layer thickness equal to 2 m.

The new program to compute sediment transport for a simple environment requires an average of .2 seconds to execute. Repeating this calculation 720,000 for each element of the lookup table needed by the 2-D model would require 40 hours of full time attention from the BIO computer. In order to reduce the computational burden, a two step approach is used to generate the lookup table:

- First, a smaller table of 2,800 elements, with coarser intervals is generated, using the sediment transport algorithm; and

- Secondly, an interpolation procedure is used to find transport rates for each of the 720,000 elements of the final, high resolution lookup table.

The coarse lookup table is presented in Appendix A, in a format appropriate for use as a reference for manual calculations of sediment transport. To find transport rates for intermediate values not given in this table the following interpolation procedure was found to yield errors below 10%, as long as entries are not near the threshold of no motion:

- Logarithmic interpolation between values of steady and orbital velocities;

- Linear interpolation between values of grain size; and

- Linear interpolation between values of wave frequency (inverse of period).

For regions near the threshold of no motion the transport function is discontinuous and the use of SEDMO or TRANSPO is recommended.

A 10% error in the final lookup table was judged acceptable, and the above interpolation procedure was adopted to determine the value of its 720,000 elements. In regions near the threshold of motion the TRANSPO subroutine. A set of three programs were written to generate the final high resolution lookup table:

- MKTRANS implements the new TRANSPO and repeats the calculations for the 2,880 elements of the coarse lookup table;

- INTERPO uses the interpolation procedure and TRANSPO to generate the fine lookup table (720,000 elements); and

- REFORM organizes the high resolution lookup table in blocks corresponding to a single steady current amplitude and wave direction, for efficient access by the 2-D transport model.

The listings of these three programs are included in Appendix B and the reader may refer to the earlier report (Martec, 1982) for an overall description and flowchart of SEDMO and TRANSPO.

2.3 2-D Sediment Transport Algorithm

To enhance the flexibility of the present model, it was decided to allow the user to specify computations on a subset of the model area and at selected time steps during a storm. The user may also specify summation for a subset of the basic 48,000 wave and sediment size components. Although the present grid size and the number of components have been chosen to give a reasonable representation of nature, it may be found that some applications, adequate accuracy for sediment transports may be obtained with coarser divisions.

Two programs are needed to actually run the 2-D sediment transport model. The first one, called SEDCON, is designed for interactive use and prompts the user for such information as run identifier and desired spatial, temporal and component resolution. It also informs the user of the computational requirement for the model run. This program is a straightforward code which sequentially require various information from the user. It is self-documented in the sense that all prompts are in clear English and no instruction manual is needed to run it. Its listing is included in Appendix C.

SED2D, is a second program which forms the core of the sediment transport model. The overall structure of SED2D is given in Figure 2.2,

```
DETERMINE SPACIAL DISTRIBUTION OF ACCRETION OR EROSION
    CALCULATE NET SEDIMENT TRANSPORT FOR SELECTED GRID POINTS
    For columns from IF to IL by increment of II, and
        rows from JF to JL by increments of JI:
    -> Read grid point data (DEPTH, D50, SORT, WREF(3,20,16), TCON(2,4);
    -> Compute grain size distribution SD(10), subroutine SDIST;
    -> Initialize net transports to zero, TNETX = TNETY = 0;
    -> CALCULATE THE NET TRANSPORT AT EACH TIME STEP DURING A STORM
       For times from ITF to ITL by increments of ITI times three hours:
       -> Read storm conditions (WINDSP, WINDIR, WSPEC(20,16));
       -> Compute tidal currents UT and VT, subroutine TIDE;
       -> Compute wind-driven currents UWI and VWI, subroutine WIND;
       -> Compute wave induced currents UWA and VWA, subroutine WAVE;
       -> Add all currents, U = UT + UWI + UWA and V = VT + VWI + VWA;
       -> Compute direction and magnitude of total current,
          CDIR = arctan (V/U);
          $CMAG = \sqrt{U^2 + V^2}$;
       -> Compute wave height/period/direction distribution WD(30,20,8),
          subroutine WDIST;
       -> Initialize instantaneous transports to zero, TINSTC = TINSTT = 0;
       -> CUMULATE INSTANTANEOUS TRANSPORT FOR EACH WAVE AND SEDIMENT COMPONENT
          For wave directions D from 11.25° to 78.75° by increments of 22.5°:
          Read the sediment transport look-up table corresponding to the current
          magnitude CMAG, and wave direction (TRANS(2,10,30,20,4);
          For grain sizes S from SMIN to SMAX by increments of NS,
              wave orbital velocities O from OMIN to OMAX by increments of NO,
              wave periods P from PMIN to PMAX by increments of NP, and
          -> Cumulate instantaneous transport from each component,
             $TINSTC = TINSTC + SD(S)*(WD(O,P,D) + WD(O,P,-D+\frac{\pi}{2}))*TRANS(1,S,O,P,D)$.
             $TINSTT = TINSTT + SD(S)*(WD(O,P,D) - WD(O,P,-D+\frac{\pi}{2}))*TRANS(2,S,O,P,D)$.
       -> Compute direction and magnitude of instantaneous transport,
          TDIR = CDIR + arctan (TINSTT/TINSTC);
          $TMAG = \sqrt{TINSTC^2 + TINSTT^2}$;
       -> Convert transport to North and East components,
          TINSTX = TMAG * sin (TDIR),
          TINSTY = TMAG * cos (TDIR);
       -> Write instantaneous transports rate TINSTX and TINSTY;
       -> Cumulate net transports,
          TNETX = TNETX + TINSTX * 3 hours,
          TNETY = TNETY + TINSTY * 3 hours.
    -> Write net transports for this location TNETX, TNETY.
-> Determine accretion or erosion between each grid point by taking the difference in net
   transport at adjacent locations.
```

FIGURE 2.2

STUCTURE OF THE
2-D SEDIMENT MODEL

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and its variable definition is in Table 2.2. In the diagram each heavy vertical line identifies a global process comprising the various elements identified by horizontal arrows. The primary functions of SED2D are to:

- Orchestrate the repetition of sediment transport calculations for every selected grid location and time step;
- Estimate the ocean climate regime;
- Estimate the weighing factors for each wave and sediment size components;
- Perform the summation over all desired components to obtain total net transport; and
- Finally, to consider accretion and depletion rates by considering how much material enters and leaves each model grid element during a storm.

Internally, SED2D uses subroutines TIDE, WIND, and WAVE for computing the local tidal, wind-driven, and wave induced currents, as explained in Sections 3.6, 3.7 and 3.5, respectively. Subroutine WDIST computes the weighing factors for each wave component, depending on wave spectra and refraction information, as described in Section 3.2. Subroutine SDIST computes the weighting factors for grain size components by simply imposing a normal distribution with mean Φ and sorting corresponding to observed characteristics.

TABLE 2.2

DEFINITION OF VARIABLES

Name	Dimension If Applicable	Description	Units (SI)
DEPTH		Local depth at a grid point	m
D50		Median grain size at a grid point	m
SORT		Grain sorting at a grid point	units
WREF	(2,20,16)	Wave refraction parameters at each grid point	
		- first index corresponds to two parameters:	
		HCOEF, height coefficient	dimensionless
		WDIR, local wave direction	degrees
		- second index corresponds to 20 wave periods	
		- third index corresponds to 16 wave direction	
TCON	(2,4)	Tidal constants	
		- first index corresponds to two tidal constituents	
		- second index corresponds to	
		U_T, easterly current amplitude	m/sec
		V_T, northerly current amplitude	m/sec
		P_{UT} phase lag for U_T	sec
		P_{VT} phase lag for V_T	sec
		Presently only the constant (Z0) and the lunar semi-dirunal (M_2) constituents are included	
SD	(10)	Sediment grain size distribution, or proportion of sediments in each of 10 grain size class ($\sum_I SD(I) = 1.0$)	
WINDSP		Wind speed at a given time step	m/sec
WINDIR		Wind direction at a given time step	degrees
WSPEC	(20,16)	Wave energy spectra at a given time step	m^2sec
		- first index corresponds to 20 wave periods	
		- second index corresponds to 16 wave directions	
UT		Easterly tidal current at a given time step	m/sec
VT		Northerly tidal current at a given time step	m/sec
UWI		Easterly wind-driven current at a given time step	m/sec
VWI		Northerly wind-driven current at a given time step	m/sec
UWA		Easterly wave induced current at a given time step	m/sec
VWA		Northerly wave induced current at a given time step	m/sec

TABLE 2.2 (Continued)

DEFINITION OF VARIABLES

Name	Dimension If Applicable	Description	Units (SI)
U		Total easterly current at a given time step	m/sec
V		Total northerly current at a given time step	m/sec
WD	(30,20,8)	Wave property distribution at a given time step - first index corresponds to 30 bottom orbital velocities - second index corresponds to 20 wave periods - third index corresponds to eight wave directions Each element stores the proportion of waves with given properties ($\sum_{I,J,K} WD(I,J,K) = 1.0$)	dimensionle
TRANS	(2,10,30,20,4)	Transport rate look-up table for a given current and wave direction - first index correspond to colinear and transverse transports, with respect to the current direction - second index corresponds to 10 grain sizes - third index corresponds to 30 orbital velocities - fourth index corresponds to 20 wave periods - fifth index corresponds to four directions between waves and currents	m^2/sec
TINSTC		Colinear transport rate for a given time step and grid point	m^2/sec
TINSTT		Transverse transport rate for a given time step and grid point	m^2/sec
TINSTX		Easterly transport rate for a given time step and grid point	m^2/sec
TINSTY		Northerly transport rate for a given time step and grid point	m^2/sec
TNETX		Easterly net transport during a storm, for a given grid point	m^2
TNETY		Northerly net transport during a storm, for a given grid point	m^2

3. Ocean Climate

3.1 Hindcast Information Source

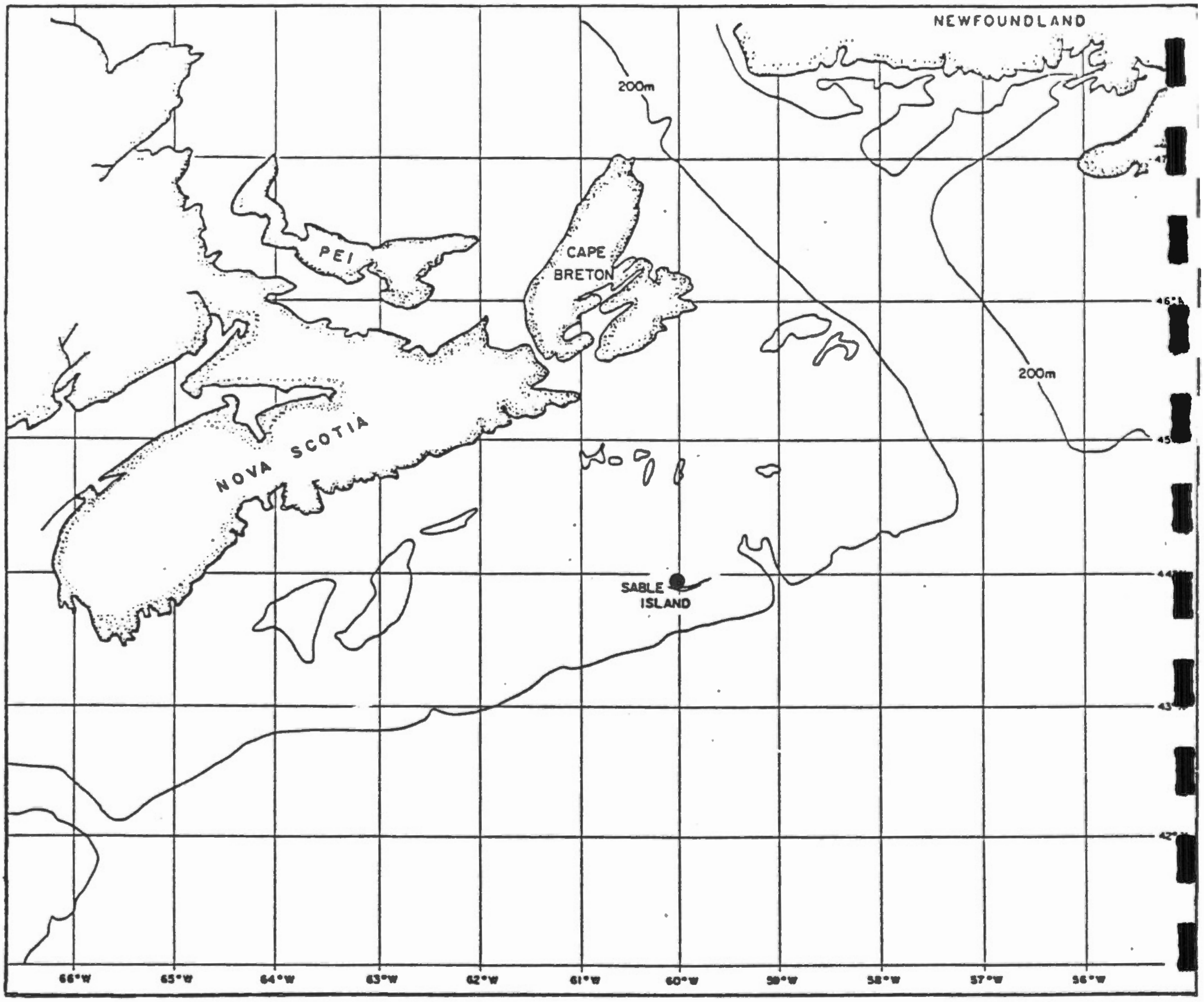
In an effort to obtain realistic wave information to compute sediment transport on and around Sable Island Bank, it was decided to design a sediment transport model which could interface with state-of-the-art wave hindcasting programs. Two methods are presently widely used for wave modelling:

- Parametric models, in which the wave spectra are assumed to have a characteristic shape determined by a few parameters dependent upon wind history; and

- Discrete spectral models, in which the wave spectra are divided into discrete "slices" which exchange energy among themselves and with the atmosphere.

Here we will take advantage of a hindcasted data set developed for the North Atlantic using a discrete spectral model covering the 20 year period from 1956 to 1975. This data set was developed for the Wave Information Study of the U.S. Army Corp of Engineers (Resio _et al_., 1981) and has the advantage over most parametric models, of providing the directional distribution of wave energy. One of the grid points used in the WES work is about 4 km off of Sable Island (Figure 3.1) and is thus ideally suited for the present study.

The WES data set was primarily developed for use on the U.S. East Coast and its applicability to the Canadian East Coast has recently been investigated (Baird, 1981 and Resio, 1982). It has been shown that in most cases, where shallow water effects were not present, the hindcast data tracked observations reasonably well. The irregularities which did



LEGEND:

● LOCATION OF WIND AND WAVE HINDCASTING POINT

FIGURE 3.1

WES WIND /WAVE HINDCASTING POINT

exist were linked to difficulties in interpreting the pressure charts for wind computations, rather than in the wave model itself. Examination of the wind data used to force the model has shown that on occasions wind spikes were either missing or created. Before using the wave hindcast data to simulate sediment transport due to a given storm, it is therefore advisable to compare the input wind data with Sable Island observations, for consistency.

Resio (1982) points out the fact that the WIS hindcast data set is obtained from a coarse grid deep water model and is not directly applicable to shallow banks or coastal regions. He suggests two approaches to resolve this, either by rehindcasting the wave for specific locations with shallow water effects taken into consideration, or by applying correction factors to the existing data. Here the later approach is adopted and outlined in Section 3.3.

The present sediment transport model requires wave spectra for input, with no regard to their sources which may be from any type of hindcasting or from observations. A pre-processor program is used to transform specific wave data for use by the sediment transport model. The main program for sediment transport is therefore independent of wave data origin and simple modifications to the pre-processor will suffice to adapt the model for an alternate data source.

3.2 Discretization of Wave Spectra

Solutions to the problem of sediment transport under the joint influence of currents and waves have been obtained for monochromatic wave fields (Grant and Madsen, 1979). We now wish to use these solutions to investigate the response to a more realistic wave field, described by its energy spectra.

The simplest approach to this problem is to treat the chaotic wave field as being composed of a series of monochromatic wave components.

Because sediment transport depends nonlinearly on wave height and frequency, it is important that our set of wave components represent the distribution of heights as well as frequencies.

In the frequency domain, we require that our components reproduce the shape of the energy spectra $\left[\mathbb{E}(\omega) = \frac{dE}{d\omega}\right]$ derived from hindcasting or observations. In the height domain we will impose the Rayleigh distribution, which observed wave heights generally follow. The Rayleigh distribution is given in terms of cumulative probability by:

$$R(\hat{H}) = P(H > \hat{H}) = e^{-\left(\frac{\hat{H}}{H_{RMS}}\right)^2} \qquad 3.1$$

and in terms of probability density by:

$$r(H) = -\frac{dR}{d\hat{H}}\bigg|_{\hat{H}=H} = \frac{H}{2\,H_{RMS}^2}\, e^{-\left(\frac{H}{H_{RMS}}\right)^2} \qquad 3.2$$

where H_{RMS} is related to wave energy by:

$$H_{RMS} = 2\sqrt{2\frac{E}{\rho g}} \quad , \quad E = \int_0^\infty \mathbb{E}\, d\omega$$

A simple bivariate distribution function which will satisfy the above requirements is:

$$p(H\,\omega) = r(H) \cdot \frac{\mathbb{E}(\omega)}{E} \qquad 3.4$$

It can easily be verified by integrating over frequency for a fixed height, that we recover the Rayleigh distribution,

$$\int_0^\infty p\, d\omega = r(H) \qquad 3.5$$

and that integrating the energy $\left(E = \frac{\rho g H^2}{8}\right)$ over height for a fixed frequency we recover the energy spectrum:

$$\int_0^\infty \text{ENERGY DENSITY}\, dH = \int_0^\infty \frac{\rho g H^2}{8}\, p\, dH = \mathbb{E}(\omega) \qquad 3.6$$

For numerical computations the distribution function $p(H,\omega)$ is discretized and the relative proportion of waves with a height between $H-\frac{\Delta H}{2}$ and $H+\frac{\Delta H}{2}$ and frequency between $\omega-\frac{\Delta\omega}{2}$ and $\omega+\frac{\Delta\omega}{2}$ is given by:

$$W(h,\omega)=\int_{\omega-\frac{\Delta\omega}{2}}^{\omega+\frac{\Delta\omega}{2}}\int_{H-\frac{\Delta H}{2}}^{H+\frac{\Delta H}{2}} p \, dH \, d\omega = \frac{\Delta E}{E}\left[e^{-\left(\frac{H+\frac{\Delta H}{2}}{H_{RMS}}\right)^2} - e^{-\left(\frac{H-\frac{\Delta H}{2}}{H_{RMS}}\right)^2}\right] \qquad 3.7$$

where $\Delta E=\int_{\omega-\frac{\Delta\omega}{2}}^{\omega+\frac{\Delta\omega}{2}} E \, d\omega$ is the energy in the frequency band.

Sediment transport (G) is therefore computed for each of a series of waves with varying height (H) and frequency (ω), ΔH and $\Delta\omega$ apart. The total transport rate is then computed, using W as a weighing function, such that:

$$G=\sum_j \sum_i W(H_i,\omega_j)\, G(H_i,\omega_j) \qquad 3.8$$

The interval $\Delta\omega$ and the summation range of j can be varied, but in the case where a discrete spectral model is used for hindcasting, it is easiest to keep the same discretization for ω. For wave height, Δh can be varied according to the desired precision; however, care must be taken not to include waves higher than physically possible. This occurs because the tail of the Rayleigh distribution extends to infinity while waves reach a finite maximum height. Since the hindcasting results to be used here are for deep water we will use the deep water relation for maximum height (U.S. Army Corp of Engineers, 1976):

$$H_{MAX}=\frac{8.75}{\omega^2}\ \frac{m}{sec^2} \qquad 3.9$$

and consider the effect of shallow water breaking separately (see section 3.3). The summation for wave heights is therefore truncated at H_{MAX}. To preserve the total energy in the wave spectrum, the small amount of energy which lies in the Rayleigh distribution beyond H_{MAX}, is added to the largest wave height element, just below H_{MAX}.

The procedure described above can be directly extended for use with directional energy wave spectra in which case the only change is that the joint probability density function becomes

$$p(H, \omega, \theta) = r(H)\,E(\omega, \theta) \tag{3.10}$$

and the direction θ is discretized into elements $\Delta\theta$. In the present study we preserve the discretization interval used for the directional energy spectra in the WIS model. This gives us 20 frequency elements by 16 direction elements whose central values are given in Table 3.1.

The overall procedure presented here in computing sediment transport using wave spectra assumes that a chaotic sea state can be simulated by considering a series of short time periods within which waves can be regarded as unidirectional, monochromatic and of uniform amplitude. The wave spectrum is effectively simulated by varying the proportion of time during which waves of various frequency, height and direction act on the sediment (Smith, 1977). The procedure to compute the weighing factor for each wave component is implemented in subroutine WDIST, which is used by the 2-D sediment transport model TRANSP.

3.3 Shallow Water Effects

As seen earlier the wave hindcast data to be used in the present study is derived for deep water. Following is a description of the method used to compute the modification of deep water waves by topography, at each of the sediment model grid point.

The principal effects of topography on waves are refraction, shoaling, dissipation, reflection and diffraction. The latter two occur only in areas of abrupt changes in depth, such as at the edge of breakwaters (U.S. Army Corps of Engineers, 1976), and will not be considered here. The other three processes, depending on circumstances, may all be very important in modifying the deep water wave field.

TABLE 3.1

Discretization intervals for the directional spectra of the WIS hindcasting model

Frequency Domain

Interval #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Central frequency (sec^{-1})	.033	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100	.105	.110	.120	.130	.145	.160
Central period (sec)	30.	25.	22.2	20.0	18.2	16.7	15.4	14.2	13.3	12.5	11.8	11.1	10.5	10.0	9.5	9.1	8.3	7.7	6.9	6.25

Direction Domain

Interval #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction	E	ENE	NE	NNE	N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE

Refraction is basically a bending of wave crests due to changes in the water depth in a direction parallel to the wave fronts. In other words the wave crests tend to align themselves with bottom contours. In addition, the change in direction of wave fronts can produce convergence or divergence of wave energy which will modify the wave height.

Shoaling is caused by changes in the water depth in the direction of travel of the waves. Since the rate of energy propagation by a wave must remain constant, the change in celerity which occurs with decreasing depth induces a corresponding change in wave height.

Dissipation results primarily from internal viscous dissipation, bottom friction and turbulent dissipation during wave breaking. Internal viscous dissipation is extremely small (Phillips, 1966) and at any rate is already included in deep water wave modelling. In shallow water, dissipation by bottom friction occurs principally in a turbulent boundary layer. Smith (1976) has estimated the thickness of this boundary layer (δ) to be typically 1 cm during storms on continental shelves. Assuming that this boundary layer is dissipated and regenerated with each passing wave, and that the kinetic energy in the layer is lost from the wave motion, we can determine a time scale for the damping of waves as:

$$T_{\text{DAMPING}} = \frac{DT}{\delta} \qquad 3.11$$

taking the depth (D) as 10 m and the wave period (T) as 10 sec we obtain a damping time constant of 10^4 seconds. In this time a wave would travel a large distance compared to the typical size of shallow banks, and the effect of bottom friction on the waves may be neglected.

Wave breaking occurs when the wave profile becomes unstable and results in intense turbulent dissipation. The height at which waves become unstable and break can be given by (U.S. Army Corps of Engineers, 1976);

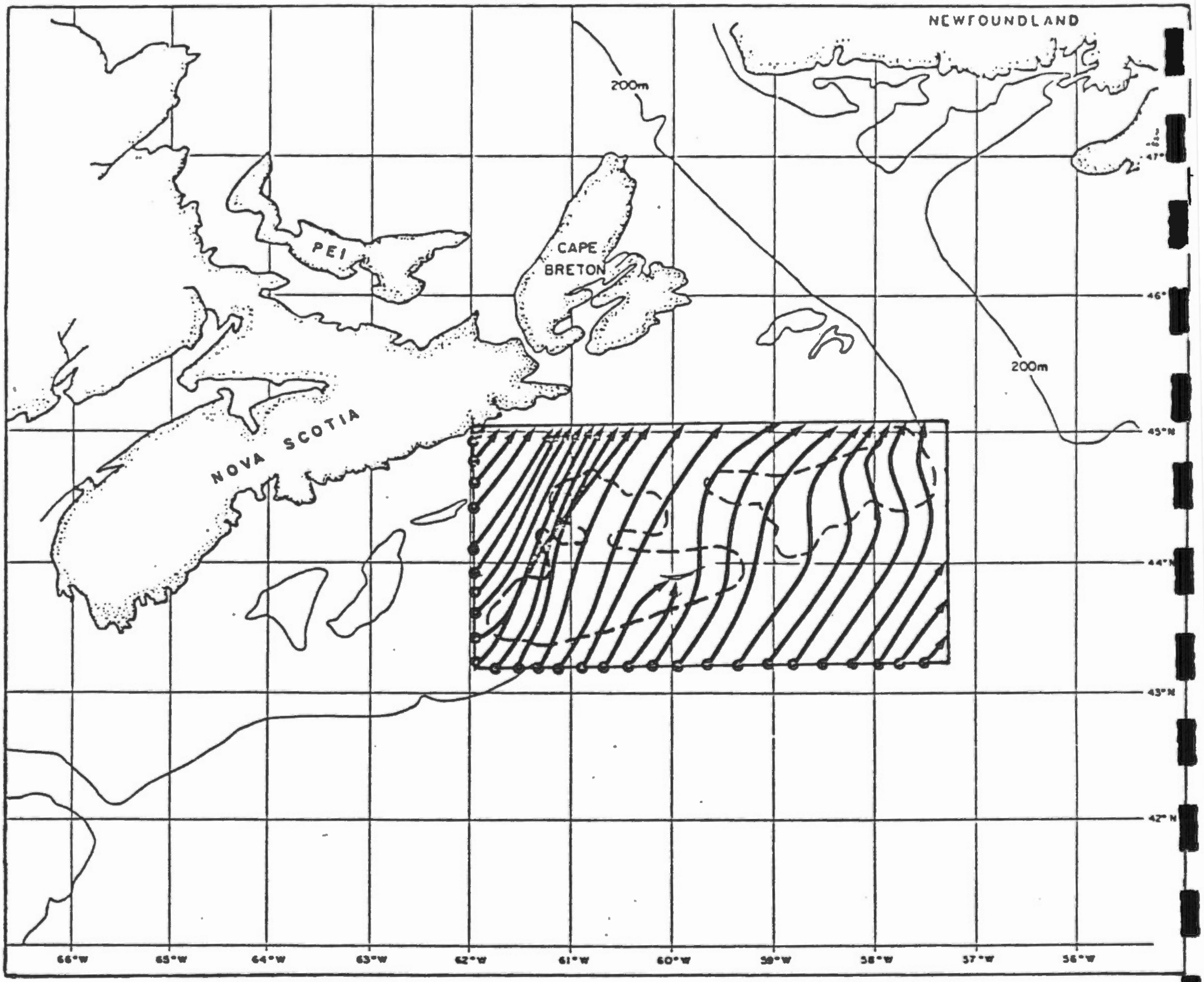
$$H_{MAX} = .142 \; L \tanh \frac{2\pi D}{L} \qquad 3.12$$

where L is the wave length and D is the water depth. Since energy dissipation is very intense during breaking, we assume that all the excess energy is dissipated locally. Then the breaking process is simply simulated by limiting the wave heights to the value given above.

The program used to compute the shallow water effect is a modification of the one developed at the Hydraulics Laboratory of the National Research Council of Canada. The reader may consult Crookshank (1976) for details of computational procedures. The NRC model was striped of plotting and output presentation routine and an alternate method of computing wave height coefficient was used.

The shallow water effect program was run for a series of wave fronts with periods and directions corresponding to the spectral estimates of the WIS hindcasting model. A series of 320 refraction diagrams were obtained for the Sable Island region by initiating a series of wave orthogonal along the edge of a rectangular area totally enclosing the sediment model (Figure 3.2). From these diagrams, lookup tables with 320 elements were generated for each grid point in the sediment model. The lookup tables contain the amount of rotation in the wave propagation direction, and the relative amplification factor (due to refraction and shoaling). Since this information is constant for any grid point, it is included in the data base for the Sable Island Bank, this data is then accessed by the program as are other grid specific quantities like sediment grain size or depth.

A set of three programs has been written to generate the refraction lookup tables. The first, REFRAC, performs the actual refraction analysis for each orthogonal and generates a series of maps showing wave direction and relative energy intensity for each model grid locations. Because of computational constraints the density of orthogonals origines used in REFRAC was limited to one for every 2.6 km along the model boundary. This resulted in some interior model grid point with no or very few



LEGEND:

——— BOUNDARY OF AREA USED FOR REFRACTION CALCULATIONS

FINISH— —START WAVE ORTHOGONAL (THESE ARE FOR ILLUSTRATIVE PURPOSES AND DO NOT CORRESPOND TO REAL CALCULATIONS)

NOTE: 320 REFRACTION DIAGRAMS WERE COMPUTED FOR INPUT INTO THE SEDIMENT TRANSPORT MODEL

THE SPACING OF ORTHOGONALS FOR ACTUAL COMPUTATIONS IS ABOUT 10 TIMES AS SHOWN

FIGURE 3.2

REFRACTION DIAGRAM

orthogonal passing through them and in order to improve the quality of estimates for the refraction parameters, a smoothing program (SMOOTH) was developed. The modified maps produced by SMOOTH were then used by program ORDER which grouped the data by grid point, for inclusion in the basic model data base.

This information is used to adjust the deep water energy spectra data to a local energy spectra for each grid point, taking into account wave direction, period and height. It assumes that no generation occurs in the shallow waters themselves, which is a good approximation since in most cases the wind fetch is much greater than the size of banks.

3.4 General Current Regime

Numerical circulation modelling is the most promising tool for hindcasting and forecasting the current regime on Sable Island Bank. Due to heavy computational requirements it is not presently feasible to run a circulation model for each storm for which we want to compute sediment transport. The approach used here will be to linearily combine solutions already derived from numerical modelling experiments. In the present work we will use results of a numerical model currently under development at BIO (Martec Limited, 1983), and which encloses our study area (Figure 3.3).

The assumption of linearity will be made to allow us to consider various components of motion separately and then simply add them to obtain the total circulation pattern. The overall circulation on the Scotian Shelf can be divided into three broad categories or components:

- Tidal motion;
- Wind-driven motion; and
- Motion forced by interaction with the rest of the ocean.

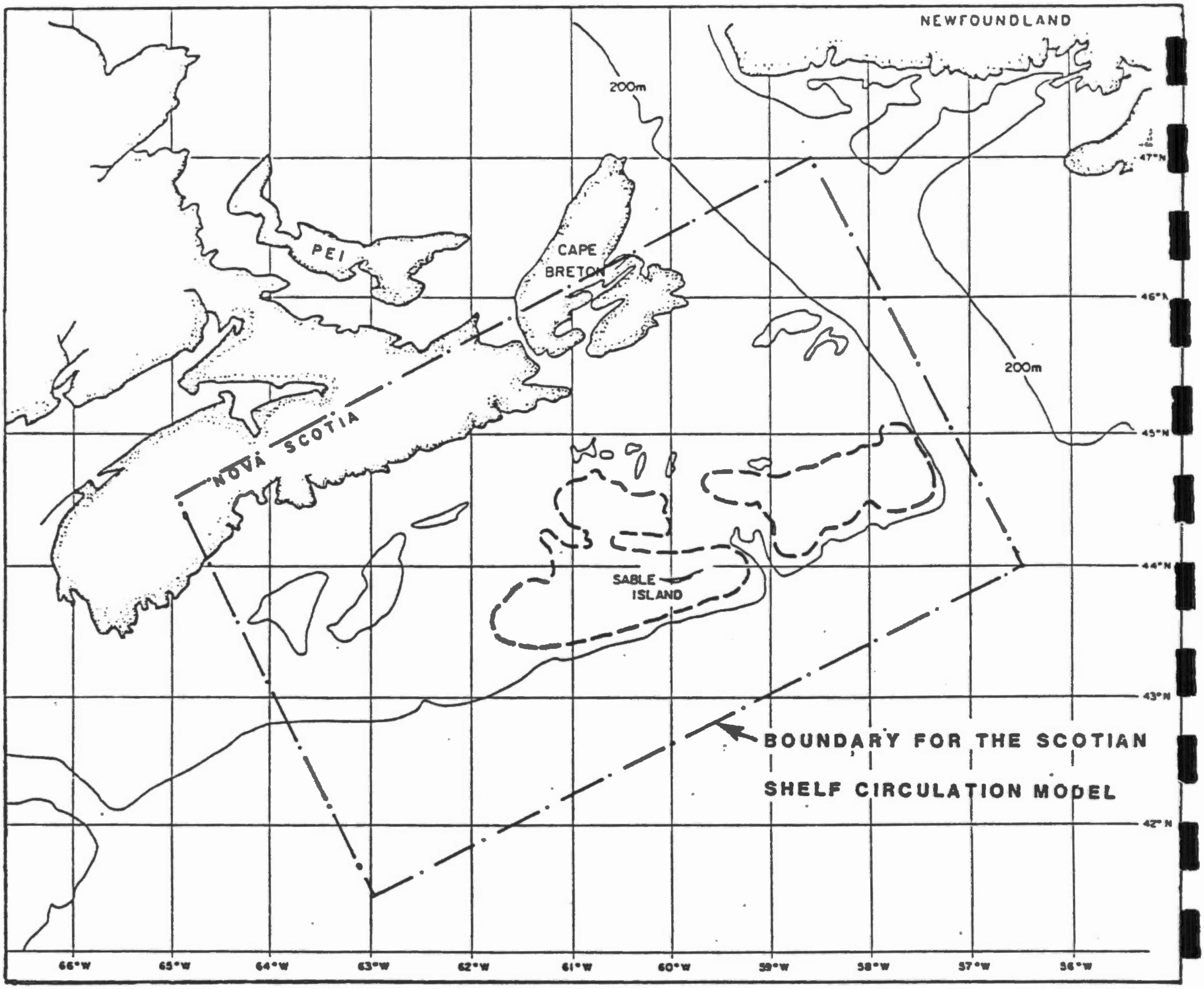


FIGURE 3.3

MODEL BOUNDARY FOR THE SCOTIAN SHELF CIRCULATION MODEL

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As shown by Petrie and Smith (1977) and Smith and Petrie (1982), tidal and wind-driven motions account for the major part of the current variance on the Scotian Shelf. Ocean forcing through interaction with Gulf Stream eddies and meanders is most important along the Scotian Slope and Shelf Edge. These interactions will not be considered here as they are not yet predictable. One aspect of externally forced circulation which could be included is the effect of run off from the St. Lawrence. However, this is of appreciable magnitude only on the inner half of the Shelf (Drinkwater et al., 1979) and is negligibly small compared to other currents on Sable Island Bank.

Our linearity assumption does not preclude the use of nonlinear theory within tidal flow calculations, but it does imply that wind conditions will not influence the tides. Furthermore we will wish to obtain the response to complex wind patterns by superposition so that the equations used in modelling the wind-driven circulation should be linear. The use of linearized equations of motion for Sable Island Bank is hard to justify, especially in regions of abrupt topographical change. However, in the present study, the neglect of stratification and the simple parameterization of continuity are likely to be more serious. The burden of showing the effects and importance of nonlinear wind forcing, will therefore be left to future numerical experiments.

Circulation modelling for the Scotian Shelf is still in its infancy and to reduce the chance of the present work becoming obsolete in a short time, we will try to anticipate future development and create an easily upgradable sediment transport model. In addition, circulation results are subject to several simplifying assumptions, the consequence of which must be clearly identified. The next sections will discuss the present status and evolution of numerical circulation modelling on the Scotian Shelf, and describe the exact methods used to compute tidal and wind-driven flows.

3.5 Wave Induced Current

As discussed earlier, the sediment transport equations to be used herein are for sinusoidal waves and therefore use first order wave theory. It is outside of the scope of the present work to derive transport and bottom stress equations for non-sinusoidal wave profiles. However one major consequence of higher order wave theory is net transport, which may be simulated by adding a wave induced net drift to the steady background flow, before transport calculations are undertaken.

For waves of finite height in inviscid flow, Longuet-Higins (1953) have derived the net bottom velocity in the direction of wave propagation as:

$$U_w = \frac{5}{4}\left(\frac{\pi H}{L}\right)^2 c \qquad \frac{1}{\sinh\left(2\pi D/L\right)}$$

where c is the phase velocity of the wave.

Using the relationship between wave energy and height, the net bottom velocity in a given direction can be expressed in terms of the directional spectra as:

$$U_w = 10\left(\frac{\pi}{L}\frac{E}{\rho g}\right)^2 c \qquad \frac{1}{\sinh\left(2\pi D/L\right)}$$

To obtain net velocity from all directions, the above is vectorialy summed over all angles . This procedure is implemented in subroutine WAVE used by the 2-D sediment transport model.

3.6 Tidal Circulation

The circulation model being developed at BIO is barotropic, fully nonlinear, and at present considers only tidal forcing. Examination of temperature, salinity and density data for the Scotian Shelf (de la Ronde 1972, and Dobson 1975) shows that the upper layer of the ocean is almost unstratified to about 20 m in summer and 80 m in winter. Therefore baroclinic flows which are not considered here may be important beyond the 20 m depth contour in summer and the 80 m contour in winter (see Figure 3.4).

Tides are cyclic phenomenae and the barotropic flows they engender can be calculated for any given time, given that we know the frequency, phase and amplitude of the tidal current constituents (globally referred to as tidal constants). Since these quantities are time invariant, but change in space, they can be considered fixed characteristics of the ocean at a given location. It is then logical to treat them as basic input into the sediment transport model, together with depth and grain size distribution, which are defined at each grid point. The tidal constants are therefore best included in the permanent data base for the sediment transport model. Presently only the semi-diurnal M_2 tide has been analyzed with the circulation model, so that only M_2 tidal constants and their associated residual current are available. The data base therefore contains the following six tidal constants for each grid location:

U_z - residual flow in the easterly direction
V_z - residual flow in the northerly direction
U_{M2} - amplitude of the M_2 currents in an easterly direction
P_{UM2} - the phase of U_{M2}
V_{M2} - amplitude of the M_2 currents in a northerly direction
P_{VM2} - the phase of V_{M2}

The tidal flows for a given grid location are computed as:

$$u_t = U_z + U_{M2} \sin(\omega_{M2} t + P_{UM2})$$
$$v_t = V_z + V_{M2} \sin(\omega_{M2} t + P_{VM2}) \qquad 4.1$$

where

u_T and v_T denote the easterly and northerly components of tidal velocity;

ω_{M2} is the angular frequency of the M_2 constituent; and
t denotes time.

It can be noted that U_z and V_z can include steady current of non-tidal origin, and the compounded residual flow due to several tidal constituents. As numerical experiments for the Scotian Shelf are extended, the four last constants should be repeated for each new constituent, and the residual currents updated to include their effect. On the Scotian Shelf the M_2 tidal constituent account for about 80% of the variance of tidal currents, and it can be expected that five or six additional constituents will be required to accurately describe the whole tidal regime (D. Greenberg, pers. comm.).

Tidal analysis results were not yet available for inclusion in the model test runs. The above formulae, however, are implemented in subroutine TIDE, used by the 2-D sediment transport model. Tidal constituent amplitudes are presently all set to zero.

As shown in Figure 3.4, the influence of stratification is important over most of our study area in summer. Although baroclinic tides are now being investigated it is still not possible to predict them with any accuracy. One of the problems which arises is that the stratification, on which internal tides depend, will change with seasons and the passage of storms. Another complication is strong nonlinear effects which may have important implications for sediment transport since they are associated with strong intermittent current surges (solitons). At least for the foreseeable future, therefore, deterministic modelling of bottom currents over the largest part of the Sable Island Bank is only possible for the winter season, and thus sediment transport calculations using modelled currents are subject to the same limitations.

3.7 Wind-Driven Currents

As mentioned previously, only the M_2 tides have until now been modelled for the Scotian Shelf. A natural extension of this modelling effort is to consider wind forcing. The circulation model under development has the capability of including wind forcing, with nonlinear effect, however, the nonlinear effects will have to be neglected if superposition of solutions is to be used in sediment transport calculations. For the moment a simpler approach is taken to estimate currents on Sable Island Bank.

Using a typical depth of 100 m for the Scotian Shelf we can calculate the Rosby radius ($R = \sqrt{gh}/f$, where h is depth, g is gravity and f is the coriolis parameter) as approximately 300 km. Since the width of the Shelf is only about 200 km this means that the shore constraint will dominate the equations of motion for the entire width of the Shelf. To a first approximation we may therefore neglect the coriolis term in the momentum equations and impose the condition that there be no flow in a direction normal to the coast. The equation for the longshore wind-driven current is then

$$h(dV_{longshore}/dt) = U_*{}^2{}_{longshore} - KV^2{}_{longshore} \qquad 4.2$$

where V denotes the current velocity;

h the water depth;

t is time;

K is at the bottom drag coefficient; and

U_* is the surface friction velocity related to the wind speed W by:

$$U_* = \sqrt{(C_D\, \rho_{air}/\rho_{water})}\ W = 1.4 \times 10^{-3}\ W$$

Substituting a value of $K = 3 \times 10^{-3}$ and integrating the above equation we obtain:

$$V_{longshore} = .025\ W_{longshore} \tanh\left(7.7 \times 10^{-5}\ t\ W_{longshore}/h\right) \qquad 4.3$$

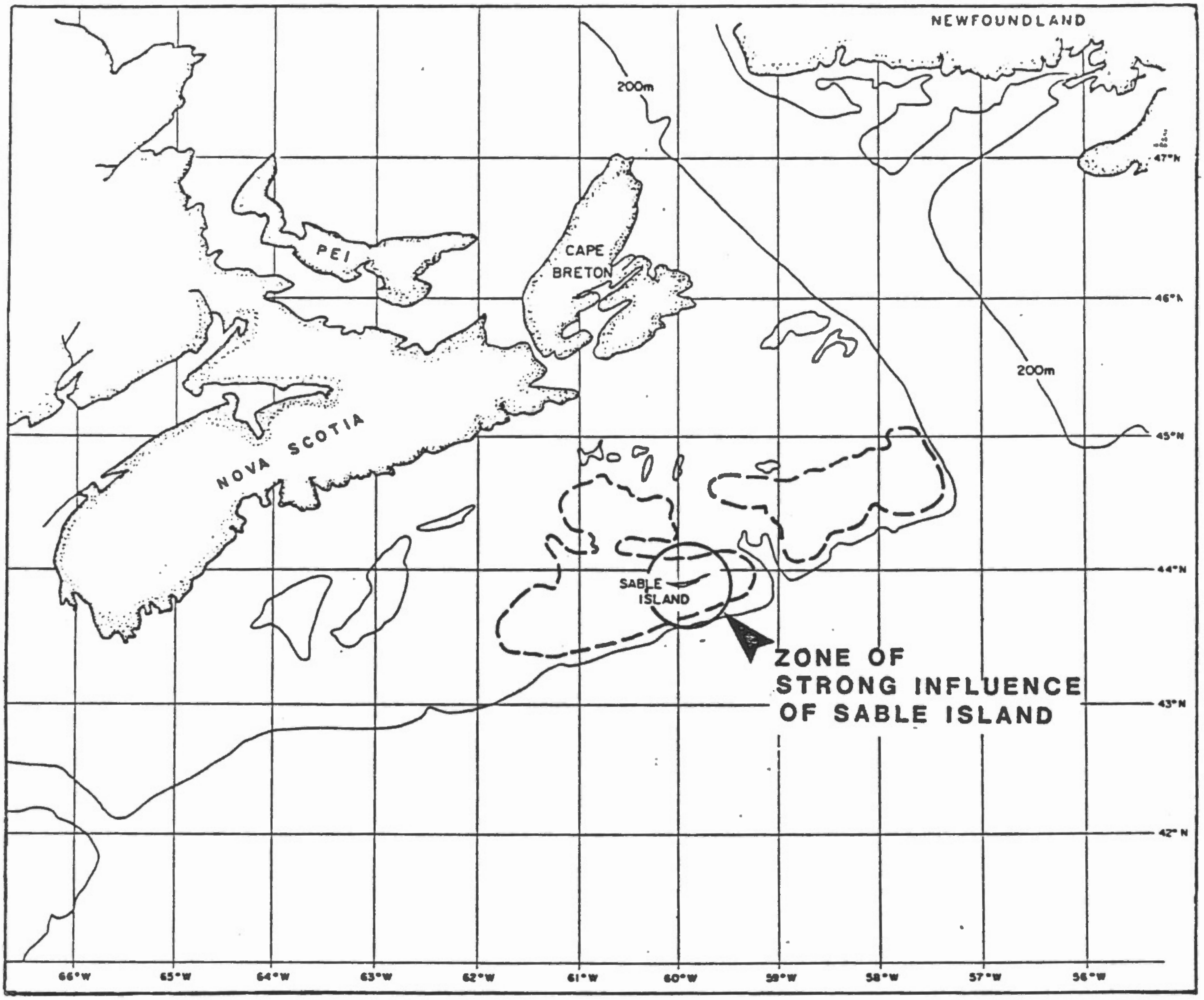
With the Nova Scotia coast oriented at 60° with respect to North we can cast the above equation in terms of the more usual easterly and northerly component of current, as

$$u_w = .50\ V_{longshore}$$

$$v_w = .87\ V_{longhsore} \qquad 4.4$$

Using the local depth at each grid point as h in equation 4.4, the wind-driven component of current u_w and v_w can be calculated for any time during a storm, and added to the tidal currents and wave drift currents u_t, v_t, u_d and v_d. These equations are implemented in subroutine WIND used by the 2-D sediment transport model.

In the above relations we have neglected the effect of Sable Island. Because of the small size of Sable Island we can expect it to have a more localized effect. In the idealized case of inviscid flow around a circular obstacle, the disturbance decreases with distance at a rate of (r^2/d^2), where r is the radius of the obstacle and d is distance from it. By analogy, taking half the length of Sable Island as r, we can estimate that the blocking effect will change the currents by less than 25% at a distance of 30 km from the center of the Island (Figure 3.5). Since the wind-driven currents flow almost parallel to the Island, its effective radius is probably smaller than the 15 km used above, so that the area shown in Figure 3.5 represents the maximum region where Sable Island is expected to have a substantial effect.



ZONE OF STRONG INFLUENCE OF SABLE ISLAND

FIGURE 3.5

AREA WITHIN WHICH OUR WIND DRIVEN CURRENT CALCULATIONS ARE NOT APPLICABLE

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STORAGE REQUIREMENTS OF INPUT FILES FOR THE 2-D SEDIMENT TRANSPORT MODEL

Data Name	File Contents	Organization	Size	Storage Media
DBMAP Sable Island Bank Data Base	For each of 1200 grid points - DEPTH - D50 - SORT - WREF(3,20,16) - TCONST(2,4)	Sequential, column by column	972 words/grid point 15.2 pru/grid point Total: 1.17 M words 18.2 k pru	Magnetic tape or disk
LOOKUP Sediment Transport Lookup Table	Colinear and transverse transport rates, TRANS(2,10,30,20,4,30), for: - 10 grain sizes - 30 wave orbital velocities - 20 wave periods - 4 angles between currents and waves - 30 current magnitudes	Random access with 120 blocks each containing the section corresponding to one current magnitude, and wave direction	12 k words/section 750 pru/section Total: 1.44 M words 22.5 k pru	Disk
STORM Storm Data	Meteorological data at 3 hour intervals: - WINDSP wind speed - WINDIR wind direction - WSPEC (20,16) directional wave spectra	Sequential, time step after time step	322 words/time step 6 pru/time step Total for 5 day storm: 13 k words 240 pru	Disk

STORAGE REQUIREMENTS OF INPUT FILES FOR THE 2-D SEDIMENT TRANSPORT MODEL (Continued)

Data Name	File Contents	Organization	Size	Storage Media
CONTROL Control Data	Range and increments for looping of: - X grid location - Y grid location - grain size - wave orbital velocity - wave period - angle between current and wave - current velocity - time	Sequential	24 words 1 pru	Disk

APPENDIX A

SEDIMENT TRANSPORT LOOKUP TABLES

Direction of Wave Propagation / Grain Size	11.25°	33.75°	66.25°	88.75°
$\phi = -.75$ $d = .6$ mm	transport direction	transport direction	transport direction	transport direction
$\phi = .75$ $d = 1.7$ mm	transport direction	transport direction	transport direction	transport direction
$\phi = 2.25$ $d = 4.8$ mm	transport direction	transport direction	transport direction	transport direction
$\phi = 3.75$ $d = 13.5$ mm	transport direction	transport direction	transport direction	transport direction

Key to Reference Tables

The following six tables contain sediment transport rates and directions for steady currents of 2.5 cm/sec, 32.5 cm/sec, 62.5 cm/sec, 92.5 cm/sec, 122.5 cm/sec and 152.5 cm/sec.

Each table is divided into 30 subgroups corresponding to six different wave orbital velocities and five wave periods. As shown above, within each subgroup, transport rates and directions are given for four different angles between wave propagation and steady current, and for four different grain sizes.

* Example from Table A2:

For a steady current of 32.5 cm/sec;
For a wave orbital velocity of 62.5 cm/sec;
For a wave period of 9.1 sec;
For an angle of 33.75° for wave propagation; and
For a grain size of $\phi = 2.25$;

the transport rate is .02298 cm^2/sec at 24.55° to current direction.

PERIOD (SEC.)

WAVE ORBITAL VELOCITY (CM/S)	30.0				16.7				11.8				9.1				5.5			
2.5	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
32.5	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00002 5.6326	.00001 15.4761	.00001 19.7796	.00001 10.7038	.00003 5.8033	.00002 15.9968	.00002 20.6178	.00001 11.3081	.00003 5.9211	.00003 16.3584	.00002 21.2081	.00002 11.7544	.00005 6.1257	.00004 16.9901	.00003 22.2554	.00002 12.5710
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
62.5	.00060 6.6558	.00053 18.6469	.00040 25.1037	.00027 14.9770	.00066 6.7073	.00057 18.8081	.00043 25.3853	.00029 15.2441	.00070 6.7351	.00061 18.8955	.00046 25.5391	.00031 15.3692	.00073 6.7546	.00064 18.9570	.00048 25.6478	.00032 15.4683	.00082 6.7697	.00072 19.0676	.00054 25.8437	.00036 15.6483
	.00035 6.1536	.00031 17.0748	.00023 22.3955	.00017 12.6812	.00041 6.3015	.00036 17.5342	.00027 23.1719	.00019 13.3131	.00045 6.3799	.00039 17.7788	.00030 23.5900	.00021 13.6615	.00049 6.4342	.00043 17.9487	.00032 23.8821	.00022 13.9085	.00057 6.5294	.00050 18.2469	.00038 24.3986	.00026 14.3527
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00014 5.7010	.00012 15.6763	.00010 20.0858	.00007 10.9102	.00026 5.9536	.00023 16.4535	.00018 21.3556	.00013 11.8640
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
92.5	.00355 6.8392	.00309 19.2251	.00230 26.1272	.00152 15.9130	.00360 6.8620	.00314 19.2965	.00234 26.2532	.00155 16.0452	.00369 6.8745	.00321 19.3361	.00240 26.3236	.00158 16.0967	.00377 6.8835	.00329 19.3643	.00245 26.3740	.00162 16.1441	.00403 6.8999	.00351 19.4161	.00262 26.4665	.00173 16.2316
	.00235 6.6171	.00206 18.5237	.00154 24.8843	.00105 14.7799	.00243 6.6783	.00213 18.7160	.00160 25.2209	.00108 15.0803	.00252 6.7111	.00220 18.8192	.00165 25.4029	.00111 15.2445	.00261 6.7341	.00228 18.8916	.00171 25.5307	.00115 15.3607	.00285 6.7749	.00249 19.0204	.00187 25.7590	.00125 15.5698
	.00107 6.0731	.00094 16.8240	.00072 21.9728	.00052 12.3446	.00122 6.2467	.00107 17.3628	.00082 22.8792	.00058 13.0721	.00132 6.3379	.00116 17.6471	.00089 23.3634	.00062 13.4715	.00141 6.4006	.00124 17.8432	.00094 23.6996	.00066 13.7536	.00163 6.5094	.00143 18.1840	.00109 24.2889	.00075 14.2572
	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00034 5.6693	.00030 15.5784	.00023 19.9277	.00017 10.7946	.00070 5.9484	.00062 16.4372	.00048 21.3285	.00035 11.8432
122	.01281 6.9077	.01117 19.4415	.00829 26.5143	.00545 16.2780	.01236 6.9211	.01078 19.4839	.00802 26.5892	.00526 16.3633	.01230 6.9287	.01072 19.5077	.00797 26.6316	.00524 16.3891	.01235 6.9341	.01076 19.5248	.00801 26.6624	.00526 16.4184	.01273 6.9442	.01109 19.5567	.00825 26.7196	.00541 16.4731
	.00870 6.7781	.00759 19.0308	.00567 25.7794	.00378 15.5893	.00844 6.8116	.00737 19.1366	.00551 25.9666	.00367 15.7764	.00845 6.8299	.00738 19.1943	.00551 26.0693	.00367 15.8576	.00855 6.8428	.00746 19.2352	.00557 26.1422	.00370 15.9257	.00898 6.8661	.00783 19.3091	.00585 26.2742	.00387 16.0495
	.00467 6.4753	.00410 18.0776	.00310 24.1057	.00214 14.0997	.00464 6.5678	.00407 18.3677	.00307 24.6092	.00210 14.5366	.00472 6.6167	.00413 18.5213	.00312 24.8777	.00213 14.7733	.00484 6.6505	.00423 18.6277	.00319 25.0645	.00217 14.9395	.00524 6.7097	.00458 18.8143	.00345 25.3934	.00233 15.2355
	.00141 5.7508	.00124 15.8295	.00096 20.3344	.00071 11.0931	.00195 6.0054	.00172 16.6134	.00133 21.6206	.00097 12.0689	.00218 6.1381	.00192 17.0244	.00148 22.3075	.00106 12.6101	.00236 6.2286	.00208 17.3062	.00159 22.7826	.00114 12.9932	.00278 6.3837	.00244 17.7902	.00186 23.6082	.00131 13.6763
152	.03549 6.9425	.03095 19.5516	.02293 26.7121	.01501 16.4667	.03280 6.9517	.02859 19.5807	.02124 26.7635	.01387 16.5303	.03186 6.9569	.02776 19.5973	.02063 26.7931	.01351 16.5439	.03146 6.9607	.02741 19.6093	.02038 26.8146	.01334 16.5646	.03150 6.9679	.02745 19.6318	.02041 26.8551	.01335 16.6035
	.02437 6.8542	.02127 19.2713	.01582 26.2082	.01047 15.9881	.02249 6.8758	.01962 19.3399	.01462 26.3300	.00966 16.1168	.02190 6.8878	.01910 19.3778	.01424 26.3978	.00941 16.1663	.02173 6.8964	.01895 19.4049	.01413 26.4463	.00932 16.2122	.02207 6.9120	.01925 19.4544	.01434 26.5351	.00945 16.2966
	.01368 6.6591	.01197 18.6549	.00897 25.1136	.00608 14.9839	.01267 6.7160	.01107 18.8345	.00831 25.4295	.00561 15.2826	.01242 6.7465	.01086 18.9305	.00814 25.5994	.00547 15.4233	.01242 6.7677	.01085 18.9976	.00813 25.7184	.00545 15.5323	.01288 6.8054	.01126 19.1166	.00843 25.9300	.00563 15.7277
	.00650 6.1971	.00572 17.2081	.00438 22.6176	.00311 12.8594	.00636 6.3553	.00559 17.7016	.00426 23.4566	.00299 13.5492	.00641 6.4377	.00562 17.9590	.00428 23.8991	.00298 13.9227	.00639 6.4940	.00574 18.1352	.00435 24.2039	.00301 14.1839	.00708 6.5905	.00620 18.4387	.00469 24.7327	.00321 14.6448

SAMPLE DATA GROUP

ANGLE BETWEEN CURRENT AND WAVE DIRECTION

		11.25°	33.75°	66.25°	88.75°
φ	-0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A1

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 2.5 CM/SEC

PERIOD (SECONDS)

30.0				16.7				11.8				9.1				5.5				WAVE ORBITAL VELOCITY (CM/S)
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	2.5
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.00334 2.7091	.00277 11.7369	.00183 24.4907	.00096 10.3426	.00392 3.1705	.00334 13.0727	.00226 26.4978	.00120 11.3689	.00448 3.5363	.00379 14.0023	.00265 27.9552	.00140 11.9538	.00496 3.8626	.00426 14.9413	.00275 19.5247	.00158 12.3878	.00612 4.5600	.00527 16.3827	.00351 20.8099	.00203 13.3706	32.5
.00100 3.3925	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00185 3.9130	.00128 15.1026	0.00000 0.0000	0.00000 0.0000	.00251 4.2746	.00189 16.0763	.00058 31.4057	0.00000 0.0000	.00303 4.6246	.00237 16.7621	.00120 32.2615	0.00000 0.0000	.00426 5.3747	.00355 18.3734	.00230 34.4167	.00079 53.3816	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.03211 5.1938	.02698 15.9506	.01845 23.7655	.01052 15.2833	.03983 5.5987	.03374 16.8334	.02327 24.4360	.01338 15.6414	.04571 5.8138	.03877 17.2585	.02684 24.8207	.01580 15.8533	.05094 5.9570	.04327 17.5451	.03009 25.0882	.01782 16.1312	.06366 6.1985	.05426 18.0312	.03853 25.6356	.02289 16.2250	62.5
.02362 6.0852	.02042 19.9365	.01236 21.9398	.00709 13.2741	.02803 5.4253	.02366 16.1013	.01626 22.7898	.00956 13.9567	.03290 5.6603	.02786 16.5995	.01932 23.3344	.01158 14.4816	.03732 5.8194	.03168 16.9406	.02214 23.7010	.01344 15.2363	.04839 6.0877	.04087 17.5331	.02915 24.3829	.01798 14.9279	
.00861 6.5560	.00581 21.2317	0.00000 0.0000	0.00000 0.0000	.01546 7.2290	.01288 22.8464	.00810 40.6298	0.00000 0.0000	.02088 7.6223	.01807 23.8189	.01304 41.9020	.00703 62.1230	.02604 7.9110	.02298 24.5487	*.01768 42.8533	.00596 11.7163	.04031 8.4506	.02341 16.0722	.01668 21.8692	.01028 12.4188	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.15205 6.1354	.12770 17.9203	.08829 25.5056	.05155 16.3452	.18747 6.3515	.15791 18.3592	.11113 25.9474	.06519 16.5619	.21402 6.4583	.18092 18.5826	.12820 26.2838	.07645 16.7449	.23722 6.5286	.20221 18.7517	.14300 26.2734	.08595 16.6537	.29269 6.6445	.24955 18.9682	.17687 26.4888	.10879 16.6074	92.5
.10522 6.0033	.08804 17.4200	.06147 24.5010	.03636 15.2384	.13334 6.2464	.11242 17.9495	.07902 24.9514	.04795 15.6041	.15495 6.3660	.13154 18.2726	.09343 25.3385	.05684 15.7435	.17424 6.4452	.14875 18.4126	.10591 25.5211	.06493 15.7437	.22150 6.5748	.18996 18.6990	.13618 25.8230	.08468 15.8842	
.07113 7.7261	.04694 16.0506	.03242 21.9805	.01935 13.0118	.07534 5.9106	.06340 16.8332	.04491 23.1089	.02766 13.5859	.09024 6.0739	.07693 17.2564	.05474 23.4935	.03420 13.9068	.10385 6.1829	.08842 17.5045	.06290 23.8568	.04011 14.1398	.13819 6.3639	.11887 17.9795	.08603 24.4283	.05505 14.5301	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.03160 8.6429	.02209 26.5296	0.00000 0.0000	0.00000 0.0000	.05808 8.9552	.05039 27.3436	.03622 46.8419	.01374 67.8652	.08168 9.1799	.07368 27.9435	.05917 47.7221	.01441 11.1868	.07192 5.8521	.06084 16.3406	.04461 21.5543	.02906 12.0711	
.48727 6.4923	.40963 18.7010	.28478 26.0624	.16959 16.7259	.59376 6.6272	.50170 18.9544	.35620 26.6500	.21161 16.7874	.67225 6.6926	.57037 19.0927	.40624 26.6887	.24632 16.8058	.74014 6.7353	.62989 19.1820	.45009 26.7332	.27484 16.7434	.90032 6.8042	.77294 19.3333	.54677 26.7992	.34207 16.7179	122
.33707 6.4015	.28332 18.3497	.19729 25.3473	.11933 15.9904	.42090 6.5545	.35613 18.6829	.25358 26.0298	.15444 16.1898	.48408 6.6283	.41154 18.8477	.29435 26.1407	.18125 16.1616	.53980 6.6763	.46046 18.9585	.33046 26.2185	.20481 16.1914	.67427 6.7536	.58011 19.1342	.41821 26.3501	.26209 16.3347	
.18892 6.1522	.15849 17.5292	.11242 24.3179	.06847 14.5333	.24424 6.3544	.20692 18.0159	.14807 24.7432	.09237 14.9299	.28713 6.4534	.24471 18.2676	.17607 24.9968	.11097 15.0542	.32579 6.5183	.27971 18.4314	.20311 25.1498	.12769 15.1703	.42123 6.6181	.36389 18.6915	.26478 25.4905	.16932 15.4815	
.12656 8.5822	.11213 26.3663	.08934 45.5254	.02658 11.6268	.12045 5.8443	.10151 16.4013	.07229 21.9028	.04572 12.4380	.14970 6.0167	.12745 16.8711	.09373 22.4843	.05964 12.8875	.17646 6.1318	.15165 17.1910	.10996 22.9529	.07201 13.1929	.24417 6.3171	.20921 17.7245	.15587 23.7642	.10267 13.8922	
1.23659 6.6642	1.03939 19.0537	.73927 26.9520	.43911 16.8658	1.48721 6.7594	1.26093 19.2512	.89893 26.8621	.53955 16.8565	1.67025 6.8045	1.42202 19.3373	1.01797 26.8860	.62352 16.8109	1.82789 6.8336	1.56065 19.3981	1.12072 26.9082	.69011 16.7758	2.19294 6.8738	1.88902 19.4985	1.34163 26.9429	.84519 16.8745	152
.85333 6.5958	.71809 18.8179	.51165 26.4759	.30713 16.3276	1.04931 6.7039	.89068 19.0431	.63733 26.4298	.39135 16.3619	1.19576 6.7550	1.01985 19.1544	.73264 26.4832	.45396 16.3789	1.32393 6.7878	1.13238 19.2286	.81553 26.5240	.50693 16.4940	1.62678 6.8343	1.40421 19.3492	1.01601 26.6344	.63948 16.5225	
.48289 6.4270	.40651 18.2690	.29015 25.3866	.17758 15.3168	.61133 6.5678	.51985 18.5895	.37354 25.5420	.23369 15.5078	.71001 6.6350	.60678 18.7528	.43832 25.7023	.27673 15.7053	.79856 6.6781	.68634 18.8663	.49595 25.8115	.31379 15.7843	1.01116 6.7437	.86583 19.0453	.63855 26.0331	.40693 15.8813	
.24284 6.0030	.20374 16.9341	.14525 22.9962	.09084 13.2335	.32497 6.2354	.27655 17.5267	.19997 23.6366	.12869 13.7902	.39032 6.3490	.33389 17.8387	.24315 24.0442	.15737 14.1935	.44836 6.4187	.38718 18.0488	.27996 24.3206	.18391 14.4154	.59623 6.5437	.51193 18.3757	.38157 24.8447	.24959 14.7950	

SAMPLE DATA GROUP

	ANGLE BETWEEN CURRENT AND WAVE DIRECTION 11.25°	33.75°	66.25°	88.75°
φ -0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A2

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 32.5 CM/S

PERIOD (SECONDS)																				
30.0				16.7				11.8				9.1				5.5				
.00454 .0304	.00443 .0540	.00427 .0561	.00406 .0264	.00453 .0263	.00444 .0645	.00428 .0671	.00407 .0318	.00454 .0294	.00445 .0721	.00429 .0752	.00408 .0359	.00455 .0321	.00446 .0788	.00430 .0822	.00408 .0394	.00457 .0384	.00448 .0944	.00431 .0987	.00409 .0479	2.5
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.03004 1.7468	.02512 5.2053	.01781 7.9769	.01114 5.7256	.03295 1.9099	.02927 5.6646	.01969 9.0050	.01206 6.7024	.03498 2.0044	.02927 6.4214	.02068 9.8265	.01276 7.3762	.03689 2.0765	.03032 6.8633	.02174 10.5216	.01397 7.9791	.04166 2.2053	.03490 7.4706	.02434 12.2934	.01538 9.2063	32.5
.01916 2.0483	.01559 6.7301	.01012 13.2241	.00394 24.5408	.02166 2.1799	.01798 7.2409	.01145 14.3657	.00487 26.5215	.02357 2.2622	.01899 7.7689	.01258 15.2719	.00759 5.3635	.02537 2.3218	.02075 8.0092	.01360 16.1930	.00820 5.9438	.02971 2.2437	.02485 8.5742	.01629 17.6471	.00942 7.2638	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00160 2.9826	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.00999 2.9836	.00430 11.1897	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.14913 2.4202	.12050 9.8184	.08240 18.1211	.04495 13.6210	.16946 2.5518	.14154 10.5518	.09569 19.4644	.05418 14.5598	.18543 2.7907	.15622 11.2938	.10602 20.3070	.06048 15.2745	.19910 3.0306	.16929 11.8886	.11586 21.1272	.06611 15.8022	.23920 3.5976	.20137 13.1058	.14125 22.8501	.07956 16.8020	62.5
.10199 2.4958	.08315 10.5466	.05593 16.0276	.03161 10.4127	.11886 2.7199	.09951 11.7829	.06665 17.3983	.03834 11.6377	.13198 3.0439	.11215 12.7124	.07560 18.5090	.04304 12.3843	.14837 3.3871	.12379 13.4841	.08486 19.4860	.04810 12.8857	.18114 4.0537	.15121 13.4976	.10397 21.0819	.06131 13.8021	
.05405 2.7717	.04318 11.6493	.02624 24.5435	.00883 41.6440	.06636 3.0939	.05503 12.9790	.03555 26.6124	.01592 44.3737	.07844 3.5313	.06457 13.9861	.04388 28.1703	.02078 10.8211	.08753 3.8513	.07354 14.8498	.05009 29.4790	.02518 11.3383	.11387 4.6845	.09793 16.6973	.07017 31.9722	.03598 12.4208	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	.04237 5.6372	.02692 19.1040	0.00000 0.0000	0.00000 0.0000	
.50327 3.6556	.42647 13.8351	.29112 23.1532	.15817 17.3050	.60555 4.2459	.51769 15.1011	.35516 24.5423	.19695 17.8302	.68217 4.5908	.58435 15.1572	.39234 25.5128	.22529 18.2986	.75245 4.8485	.63998 15.6465	.43663 26.0087	.24760 18.5509	.91872 5.3055	.77733 16.5539	.54945 26.8420	.31263 19.0151	92.5
.36026 3.8219	.29308 13.3708	.19985 21.0352	.11123 14.2815	.42923 4.3565	.36576 14.4784	.24536 22.5140	.14183 14.8449	.49231 4.7216	.41889 15.2317	.28099 23.2672	.16320 15.2283	.55059 4.9945	.46418 15.7980	.31785 23.7139	.18517 15.4937	.69292 5.4599	.58634 16.6747	.40846 24.5180	.23977 16.0119	
.19659 4.1445	.16975 15.3443	.11041 19.6526	.06081 12.4723	.25828 4.9226	.22444 17.1706	.14002 21.3112	.08155 13.2486	.30711 5.4459	.24701 14.9624	.16811 22.0777	.09805 13.8516	.35318 5.8403	.28180 15.5004	.19423 22.6171	.11494 14.1950	.43804 5.4957	.37043 16.4588	.25868 23.6253	.15558 15.2572	
.08464 4.5721	.06490 16.6677	.02696 32.3632	0.00000 0.0000	.12872 5.4103	.10686 18.5101	.06576 34.8960	.01613 54.2035	.16489 5.9470	.13943 19.7529	.09597 36.3498	.04825 55.6390	.19984 6.3512	.17171 20.6387	.12399 37.5523	.05073 11.9821	.29775 7.1248	.26233 22.5562	.14459 21.3897	.08648 12.6764	
1.40301 4.8969	1.20530 16.3517	.82843 26.0007	.45094 18.8344	1.72540 5.3500	1.46962 17.3167	1.01832 26.9839	.56366 19.0805	1.95401 5.5973	1.64309 17.0677	1.16921 27.3105	.65339 19.2399	2.15489 5.7669	1.83167 17.4266	1.30096 27.7190	.72970 19.4089	2.63625 6.0563	2.24343 17.9761	1.61161 28.2870	.92098 19.6833	122
.96898 4.9154	.82224 15.5575	.56225 23.7759	.31537 15.9502	1.22060 5.3990	1.02409 16.5225	.70639 24.7341	.40613 16.0530	1.40510 5.6536	1.19298 17.0667	.82002 24.9161	.47567 16.2953	1.57018 5.8309	1.33320 17.4115	.92309 25.2907	.53629 16.4436	1.97552 6.1234	1.68187 17.9850	1.17534 25.7788	.69307 16.5457	
.57166 5.4563	.46340 15.0436	.31748 22.6399	.17959 14.4709	.71537 5.3529	.59899 16.1904	.41548 23.5200	.24123 14.9220	.84059 5.6282	.71251 16.7931	.49235 24.1306	.28829 15.2597	.95503 5.8128	.81069 17.1677	.56351 24.5028	.33734 15.4818	1.24474 6.1185	1.06106 17.7929	.75486 25.2114	.45175 15.8155	
.30405 5.6596	.25663 18.9405	.18309 35.4300	.07936 11.9855	.42652 6.5009	.37325 20.9847	.21506 21.2861	.12256 12.8262	.53399 6.9924	.38971 15.8211	.26796 22.1499	.16036 13.3424	.53934 5.5844	.45655 16.2942	.31728 22.6867	.19122 13.7682	.74173 5.9454	.62599 17.1047	.44713 23.6461	.27806 14.2768	
3.35535 5.5824	2.84393 17.8148	1.95728 27.5266	1.08219 19.4412	4.07396 5.9233	3.43927 17.7347	2.44825 28.0811	1.35686 19.4513	4.60996 6.0971	3.87658 18.0325	2.79406 28.3005	1.57266 19.6427	5.07767 6.2138	4.27990 18.2565	3.10061 28.5323	1.75581 19.7325	6.18725 6.4092	5.27269 18.6613	3.85035 28.9413	2.19891 20.0149	152
2.30876 5.5762	1.91926 16.8291	1.31627 25.2426	.75355 19.4300	2.86992 5.9380	2.40756 17.5989	1.67127 25.4757	.96444 16.6193	3.29832 6.1196	2.77388 17.9575	1.94028 25.8366	1.13440 16.7548	3.67851 6.2402	3.10240 18.2007	2.17828 26.0430	1.27817 16.8274	4.60223 6.4383	3.92441 18.6257	2.75330 26.2788	1.65209 15.9200	
1.31212 5.4922	1.08746 16.4695	.74730 24.1804	.43064 15.4237	1.67849 5.8865	1.40641 17.3158	.97651 24.6906	.57611 15.7349	1.96640 6.0822	1.65514 17.7241	1.16100 25.1869	.66507 15.9439	2.22714 6.2110	1.89430 18.0257	1.32947 25.4462	.79418 16.1573	2.87873 6.4200	2.45877 18.4574	1.72852 25.8017	1.05997 16.2318	
.75838 6.4721	.56637 15.4716	.39621 22.2393	.22295 13.5171	.91551 5.6608	.76557 16.5114	.53394 23.1839	.31355 14.1526	1.10208 5.8930	.92739 17.0297	.65239 23.7504	.39911 14.5244	1.27535 6.0460	1.08475 17.4056	.76557 24.1732	.46601 14.6873	1.72324 6.2735	1.47498 17.9615	1.04513 24.7113	.65770 15.0564	

SAMPLE DATA GROUP

		ANGLE BETWEEN CURRENT AND WAVE DIRECTION			
		11.25°	33.75°	66.25°	88.75°
φ	-0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
	3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A3

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 62.5 CM/S

PERIOD (SECONDS)

30.0				16.7				11.8				9.1				5.5				WAVE ORBITAL VELOCITY (CM/S)
.04518 .0090	.04455 .0220	.04339 .0226	.04200 .0103	.04526 .0107	.04463 .0262	.04349 .0269	.04202 .0122	.04531 .0119	.04468 .0291	.04353 .0299	.04204 .0137	.04535 .0130	.04471 .0316	.04356 .0325	.04206 .0149	.04544 .0153	.04480 .0375	.04363 .0386	.04211 .0178	2.5
.02901 .0097	.02859 .0237	.02784 .0244	.02690 .0111	.02906 .0118	.02865 .0288	.02790 .0296	.02692 .0135	.02910 .0133	.02869 .0325	.02793 .0335	.02695 .0154	.02914 .0146	.02872 .0358	.02796 .0369	.02696 .0170	.02922 .0178	.02879 .0436	.02802 .0451	.02700 .0210	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.15781 1.2951	.13658 2.8206	.10433 3.7977	.07361 2.5191	.16568 1.1327	.14351 3.2407	.10949 4.4450	.07671 2.9992	.17171 1.2218	.14888 3.5264	.11639 4.8348	.07897 3.3427	.17861 1.2919	.15361 3.7606	.11416 5.3492	.07989 3.6020	.19086 1.4450	.16477 4.2475	.12417 6.1794	.08480 4.2997	32.5
.10482 1.3713	.09024 2.9580	.06882 4.0147	.04827 2.6926	.10976 1.2461	.09591 3.4516	.07586 4.6966	.05076 3.2767	.11545 1.3725	.10046 3.7911	.07374 5.4452	.05196 3.6679	.11957 1.4678	.10449 4.0561	.07881 5.8492	.05351 4.0535	.12894 1.6555	.11749 4.7607	.08511 6.9378	.05717 4.9181	
.04522 1.6902	.03605 5.4249	.01958 10.5434	0.00000 0.0000	.05136 1.8179	.04147 5.8536	.02373 11.4247	0.00000 0.0000	.05526 1.9081	.04554 6.1267	.02613 12.1439	0.00000 0.0000	.05883 1.9751	.05302 6.1608	.03035 12.4434	.00535 23.2091	.06804 2.1165	.05911 6.7870	.03638 13.5746	.01176 25.0105	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.51899 1.9938	.42738 6.4257	.29586 10.4842	.17015 7.7922	.58605 2.1276	.47571 7.0732	.32370 12.0250	.18909 8.9016	.61949 2.1350	.54208 7.2497	.34541 12.9904	.21139 9.7260	.66123 2.0947	.53977 7.8854	.37158 13.1439	.22282 10.3240	.74712 2.2951	.61088 8.6631	.41806 14.7994	.25065 11.5643	62.5
.34988 2.0673	.28757 6.7604	.19664 10.3426	.11461 8.1408	.39601 2.2139	.34412 7.2856	.22106 12.6552	.13532 9.5072	.43666 2.2798	.35355 8.0727	.24412 13.1506	.14611 10.3733	.46433 2.2528	.37724 8.5182	.26039 14.0615	.15588 11.0610	.53628 2.3784	.44019 9.4609	.30806 16.8226	.17736 12.5505	
.19146 2.2472	.15513 7.6951	.09904 15.3424	.05547 5.6828	.22523 2.3491	.19640 8.0858	.11903 16.9954	.06995 7.0531	.24913 2.3509	.20074 8.9874	.13254 18.2899	.07835 7.9183	.27062 2.4170	.21809 9.4419	.14489 19.3575	.08415 8.6639	.31649 2.4576	.27051 10.3033	.17999 21.9557	.10496 10.0051	
.05197 2.8383	.00699 9.8630	0.00000 0.0000	0.00000 0.0000	.08438 2.7883	.05314 10.4515	0.00000 0.0000	0.00000 0.0000	.10563 2.8422	.08841 10.4003	.01134 22.5789	0.00000 0.0000	.12366 2.8607	.09144 11.3349	.03885 23.7253	0.00000 0.0000	.16434 2.9725	.13390 12.4357	.07834 25.8705	0.00000 0.0000	
1.44424 2.3426	1.14475 9.2412	.76974 15.8462	.42682 12.8603	1.63621 2.4549	1.34046 10.1726	.90452 18.4525	.50885 13.7521	1.76110 2.5225	1.46959 10.8024	1.00257 19.6820	.56184 14.4674	1.88248 2.6854	1.58077 11.3473	1.06888 19.9142	.60882 15.0033	2.17657 3.1169	1.84939 12.5424	1.26759 21.4879	.71373 16.0755	92.5
.98074 2.3746	.81956 8.9474	.53609 17.3699	.29202 13.1646	1.12158 2.4423	.93238 10.1584	.62862 18.9451	.35550 14.1936	1.23735 2.6549	1.03525 10.9124	.70083 19.8231	.39924 14.9754	1.33549 2.8795	1.12686 11.5366	.76838 20.6828	.43883 15.5547	1.60648 3.4658	1.35579 12.8318	.95038 22.5573	.53491 16.6558	
.55088 2.4465	.44824 10.0617	.30054 15.4731	.16796 9.9086	.64838 2.5756	.53658 11.3078	.36152 17.0007	.20607 11.2460	.72554 2.8663	.61097 12.2502	.41060 17.9633	.23320 12.0706	.79557 3.1706	.67878 13.0743	.45874 18.9079	.26269 12.6270	1.00704 3.9095	.85231 13.2575	.57753 20.8185	.34112 13.6470	
.27283 2.7159	.21351 11.1229	.12975 23.8462	.03578 40.6449	.34035 2.8998	.27887 12.4293	.17712 25.8025	.07693 43.3256	.39377 3.2752	.33076 13.4751	.21916 27.3848	.10406 10.5921	.45222 3.6367	.37966 14.3578	.26127 28.7539	.12869 11.1628	.60981 4.5106	.51620 16.3617	.36858 31.4684	.18994 12.3429	
3.34671 2.8129	2.76351 11.8205	1.84452 20.8451	1.00170 15.8376	3.84262 3.3225	3.24145 13.0552	2.19704 22.2203	1.20711 16.7345	4.34932 3.6548	3.60574 13.8525	2.46474 23.1222	1.37703 17.0291	4.64698 3.9607	3.93507 14.4470	2.70370 23.7999	1.51367 17.4179	5.55511 4.4990	4.78512 15.5534	3.23819 25.1640	1.82787 18.1228	122
2.28274 2.8895	1.88901 12.0310	1.27020 21.2620	.68944 16.0401	2.67339 3.5227	2.26642 13.4234	1.54251 22.6566	.86216 16.7817	3.02323 3.8665	2.55056 13.8218	1.76183 23.6513	.98804 17.3563	3.33839 4.1626	2.82006 14.3874	1.97198 24.4236	1.10205 17.7764	4.10349 4.7501	3.47905 15.4971	2.43343 25.7313	1.38282 18.4543	
1.29198 2.9887	1.07115 12.6746	.72049 19.3622	.39654 12.9337	1.64338 3.6295	1.31069 13.0552	.89159 20.5915	.50937 13.7499	1.81146 4.2251	1.50266 13.2768	1.04422 21.6532	.59560 14.3335	2.01150 4.3353	1.71353 14.4854	1.15564 22.3981	.66995 14.7090	2.56177 4.9581	2.17241 15.6993	1.50653 23.3957	.87952 15.3911	
.68288 3.1788	.56320 13.2808	.37445 27.1670	.18915 11.1378	.86429 4.0189	.73317 15.1840	.51081 29.8516	.26406 12.2499	1.03244 4.5701	.89020 16.4008	.56427 20.5185	.32262 12.8817	1.18882 5.0225	1.02462 17.4838	.65829 21.2511	.38280 13.3372	1.62731 5.9129	1.29901 15.5153	.90232 22.5786	.53818 14.5317	
6.96024 3.8009	5.86458 14.1272	3.96994 23.5058	2.14852 17.5535	8.25169 4.3800	7.00419 15.3439	4.79851 24.8229	2.63391 18.2073	9.25357 4.7052	7.88626 15.8747	5.61350 25.3347	2.99758 18.4729	10.12778 4.9414	8.65857 16.4234	6.08984 25.9329	3.34816 18.6675	12.30144 5.3760	10.61537 17.4373	7.30223 26.9569	4.09181 19.0612	152
4.75154 3.8582	4.01287 14.2968	2.73542 23.7110	1.48006 17.6773	5.76988 4.4805	4.92968 15.6171	3.38240 25.2173	1.86184 18.3329	6.56626 4.8301	5.54960 15.5478	4.00932 25.6881	2.17375 18.5907	7.32176 5.0844	6.20282 16.1059	4.36348 26.3691	2.43683 18.7515	9.07966 5.5299	7.72088 16.9618	5.48855 27.2755	3.09715 19.2497	
2.71903 4.0291	2.25772 13.7068	1.53324 21.5268	.85182 14.6733	3.35746 4.5468	2.84024 14.8533	1.82227 23.2756	1.10896 15.1719	3.91578 4.9251	3.30488 15.5745	2.30064 23.5690	1.30646 15.4513	4.40760 5.1914	3.74400 16.1561	2.56664 24.1391	1.47858 15.7807	5.64925 5.6465	4.77060 17.0608	3.33737 24.9149	1.96334 16.2371	
1.49556 4.1013	1.23231 15.5162	.79741 20.1733	.44014 13.0300	1.90547 5.0674	1.54991 14.3246	1.09081 21.6369	.60837 13.8462	2.30556 5.6216	1.87166 15.3187	1.28041 22.5243	.73578 14.2785	2.53300 5.1904	2.14554 15.8907	1.43710 23.1309	.86877 14.6151	3.38703 5.6740	2.86167 16.3691	2.00595 24.1411	1.21224 15.7549	

SAMPLE DATA GROUP

ANGLE BETWEEN CURRENT AND WAVE DIRECTION

φ	11.25°	33.75°	66.25°	88.75°
-0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A4

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 92.5 CM/S

PERIOD (SECONDS)

30.0				WAVE ORBITAL VELOCITY (CM/S)
.23789 .0048	.23533 .0116	.23064 .0118	.22445 .0053	2.5
.15264 .0051	.15096 .0123	.14789 .0126	.14396 .0056	
.08066 .0054	.07976 .0132	.07809 .0135	.07596 .0061	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.59892 .7722	.53304 1.6756	.42726 2.1065	.33244 1.2991	32.5
.39360 .8160	.34858 1.7557	.27828 2.2227	.21362 1.3895	
.20433 1.0310	.18083 2.2793	.14986 2.3631	.11303 1.5024	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
1.50998 1.4905	1.25592 4.4733	.92429 6.5146	.57247 4.6593	62.5
1.00604 1.5272	.83463 4.6115	.59863 6.8787	.37825 4.8839	
.54746 1.6868	.45140 5.2624	.31936 7.3280	.20712 5.1496	
.24655 2.1195	.18926 7.0446	.09999 14.0637	0.00000 0.0000	
3.46379 2.0875	2.82988 6.8824	1.81045 11.8203	1.09397 8.5490	92.5
2.33385 2.1226	1.90147 7.0173	1.28502 11.0910	.73693 9.1983	
1.30462 2.1805	1.05342 7.4760	.72564 11.6945	.41100 9.5166	
.66340 2.3887	.52984 8.3779	.33053 17.0986	.14113 31.2570	
7.37163 2.2850	5.68289 8.9265	3.91790 15.8408	2.15340 12.3274	122
4.97164 2.3092	3.86490 9.0464	2.63808 16.1602	1.45892 12.5755	
2.77962 2.3466	2.17911 9.4021	1.47561 16.4861	.82119 12.8388	
1.46431 2.4458	1.15151 9.8892	.74431 20.4358	.41927 9.3119	
13.98004 2.4556	11.44516 10.6745	7.68371 19.5900	4.06557 14.7798	152
9.47312 2.4886	7.74356 10.8206	5.16704 19.7856	2.77994 14.9643	
5.32045 2.5272	4.34208 10.6115	2.89228 19.8633	1.57111 15.1540	
2.83188 2.6016	2.30817 11.5523	1.51032 17.2763	.82659 11.6602	

16.7				WAVE ORBITAL VELOCITY (CM/S)
.23805 .0056	.23547 .0137	.23077 .0140	.22499 .0062	2.5
.15274 .0061	.15106 .0149	.14801 .0153	.14411 .0068	
.08072 .0068	.07981 .0165	.07816 .0169	.07603 .0075	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.62108 .9186	.54965 1.9417	.43898 2.4783	.32854 1.5766	32.5
.41101 .9903	.36169 2.0704	.29835 2.6607	.21368 1.7175	
.21486 1.2703	.18717 2.8429	.15689 2.8945	.11499 1.8993	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
1.62871 1.6415	1.35537 5.0171	.96620 7.5887	.60881 5.4214	62.5
1.09955 1.6969	.91607 5.2062	.64974 8.0158	.40700 5.7809	
.61064 1.8647	.50630 5.9293	.36780 8.4997	.22633 6.2217	
.29135 2.2584	.24745 7.3201	.13197 15.1375	0.00000 0.0000	
3.90671 2.1352	3.15368 7.5387	2.13030 12.5603	1.22602 10.0259	92.5
2.67263 2.2507	2.15764 7.7618	1.44929 13.5200	.86886 10.2120	
1.51471 2.1900	1.22184 8.3118	.83428 13.4534	.49309 10.7309	
.80400 2.3725	.64201 9.1819	.41057 18.8962	.22418 7.9068	
8.30082 2.3968	6.88156 9.6144	4.56858 17.8668	2.48958 13.4505	122
5.68755 2.4303	4.62007 10.0065	3.15591 18.4046	1.76014 13.5634	
3.24483 2.4792	2.65985 10.5142	1.78948 18.4785	1.01469 13.9896	
1.75142 2.5212	1.44642 11.1148	.97248 23.6045	.53485 10.6826	
15.90112 2.8035	13.20018 11.7877	8.94690 21.0929	4.84200 15.7549	152
10.94573 2.9159	9.11127 12.0799	6.13786 21.0389	3.37258 16.0233	
6.27569 3.0460	5.22838 11.9793	3.54398 21.4639	1.98708 16.0602	
3.43583 3.2179	2.88420 13.2740	1.91796 19.0367	1.08963 12.6453	

11.8				WAVE ORBITAL VELOCITY (CM/S)
.23819 .0063	.23566 .0153	.23101 .0156	.22503 .0069	2.5
.15286 .0069	.15119 .0168	.14812 .0172	.14417 .0077	
.08082 .0078	.07991 .0189	.07824 .0193	.07608 .0087	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.63684 1.0220	.56149 2.1270	.44841 2.7345	.33164 1.7651	32.5
.42368 1.1156	.37125 2.2935	.29576 2.9775	.21635 1.9522	
.22330 1.4349	.19311 3.1950	.16184 3.2955	.11679 2.2015	
.01704 2.3419	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
1.71537 1.7365	1.43133 5.3394	1.02879 8.2721	.63530 5.9493	62.5
1.16417 1.8052	.97616 5.5905	.68946 8.3960	.42852 6.4104	
.65651 1.9748	.56421 6.2594	.39021 9.2526	.24125 6.9855	
.32696 2.3419	.25814 7.9666	.15526 16.0055	.04074 29.4823	
4.19036 2.1400	3.39213 7.9726	2.30311 13.2725	1.36617 10.5005	92.5
2.89378 2.2191	2.34427 8.2629	1.59008 13.9491	.94150 11.0494	
1.66749 2.3045	1.49739 8.4334	.91868 14.7515	.54348 11.6888	
.90596 2.4747	.72668 9.8133	.47118 20.3340	.25772 8.8352	
8.96089 2.4703	7.35834 10.2822	4.94444 18.4986	2.79567 13.8884	122
6.16723 2.4717	5.13042 10.6315	3.49394 19.4416	1.95912 14.3432	
3.58480 2.5915	2.98396 11.3388	2.03129 19.7678	1.15130 14.8491	
1.98706 2.7967	1.66283 12.0833	1.10600 17.3323	.62007 11.5424	
17.27856 3.1007	14.52041 12.5328	9.81355 21.5631	5.48685 16.0783	152
12.04735 3.2544	10.17081 12.9138	6.89861 22.0447	3.87548 16.4127	
7.04828 3.4839	5.93549 12.8556	4.07210 22.5920	2.29459 16.7737	
3.90899 3.7769	3.36286 14.4901	2.25762 20.2145	1.29349 13.3443	

9.1				WAVE ORBITAL VELOCITY (CM/S)
.23834 .0068	.23579 .0165	.23110 .0169	.22508 .0075	2.5
.15299 .0076	.15130 .0184	.14821 .0188	.14423 .0084	
.08091 .0086	.07999 .0210	.07831 .0216	.07612 .0097	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.65023 1.1089	.57156 2.2815	.45613 2.9535	.33431 1.9271	32.5
.43462 1.2222	.37967 2.4813	.30196 3.2517	.21847 2.1583	
.23095 1.5722	.19916 3.4720	.17397 3.5651	.11817 2.4738	
.04049 2.3985	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
1.78231 1.8115	1.49501 5.6086	1.05670 8.4159	.65817 6.3866	62.5
1.22589 1.8866	1.05831 5.8071	.72216 9.2437	.44755 6.9360	
.69992 2.0562	.57466 6.8000	.41358 10.0482	.26587 7.6754	
.35729 2.4045	.28249 8.3387	.17540 16.7727	.05821 30.6464	
4.43383 2.2248	3.59410 8.3227	2.43642 14.0507	1.44438 11.0810	92.5
3.09035 2.2913	2.53437 8.6389	1.69963 14.8451	1.00667 11.7079	
1.80240 2.3666	1.46579 9.4061	.99509 15.7774	.58984 12.4377	
.99655 2.5278	.80298 10.4246	.53810 21.8134	.29530 9.5049	
9.44982 2.5105	7.88274 10.7607	5.38045 19.6473	3.01196 14.4239	122
6.63668 2.6353	5.55342 11.2091	3.75333 19.7534	2.13795 14.9280	
3.89812 2.8190	3.27413 11.3340	2.23415 20.5130	1.27701 15.4866	
2.19807 3.1075	1.86711 12.9541	1.25182 18.3507	.71142 12.1423	
18.43834 3.3659	15.68901 13.1139	10.65806 22.2573	5.98211 16.5141	152
13.66613 3.4812	11.12547 13.5835	7.60777 22.8248	4.28159 16.8781	
7.80965 3.7547	6.58262 13.5489	4.61090 23.5204	2.57741 17.2721	
4.50788 4.1644	3.84303 13.8180	2.59167 21.1623	1.47389 13.8349	

5.5				WAVE ORBITAL VELOCITY (CM/S)
.23866 .0080	.23607 .0194	.23133 .0199	.22521 .0089	2.5
.15326 .0091	.15155 .0222	.14842 .0228	.14436 .0103	
.08109 .0108	.08017 .0263	.07846 .0270	.07620 .0123	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
.68103 1.3050	.59588 2.6248	.50743 3.3363	.33963 2.3075	32.5
.46042 1.4665	.40110 2.9006	.32160 3.8623	.23169 2.6093	
.24980 1.6826	.23595 3.8141	.16149 5.9340	.12790 3.0725	
.07205 2.3512	.04581 6.8107	0.00000 0.0000	0.00000 0.0000	
1.95749 1.9564	1.62056 6.2460	1.15041 9.8034	.71230 7.3492	62.5
1.36379 2.0579	1.12358 6.7138	.80228 10.6951	.51587 8.1457	
.80543 2.2132	.66717 7.5625	.47223 12.0554	.29844 9.1300	
.44188 2.5122	.35997 8.9327	.22891 18.4878	.09198 33.4558	
4.99580 2.3405	4.06267 9.1229	2.75236 15.6759	1.63283 12.2691	92.5
3.55069 2.4033	2.89083 9.7017	2.01282 17.4477	1.14645 13.1299	
2.09110 2.4435	1.80404 10.5133	1.21099 18.3233	.70206 13.9807	
1.21059 2.7289	1.02662 11.7312	.69643 24.3721	.39375 10.8554	
10.77365 2.8569	9.11488 11.8554	6.19258 20.5876	3.53434 15.4591	122
7.72696 3.1196	6.59055 12.5006	4.52046 21.4639	2.55132 16.0859	
4.75525 3.4524	4.01288 12.7322	2.81935 22.5662	1.59348 16.6841	
2.84598 3.9101	2.45064 14.9014	1.62471 20.4317	.96126 13.2573	
21.92398 3.9024	18.54341 14.3081	12.87231 23.6987	7.17837 17.3248	152
15.92966 4.1553	13.63654 14.3000	9.41953 24.3643	5.23829 17.7377	
9.77989 4.4117	8.24128 14.8416	5.77061 25.1063	3.29482 18.1289	
5.78672 4.6340	4.91144 15.0093	3.41678 22.6353	1.98707 14.7134	

SAMPLE DATA GROUP

ANGLE BETWEEN CURRENT AND WAVE DIRECTION

ϕ	11.25°	33.75°	66.25°	88.75°
-0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A5

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 122 CM/S

PERIOD (SECONDS)

30.0				16.7				11.8				9.1				5.5				WAVE ORBITAL VELOCITY (CM/S)
.87270 .0029	.86512 .0070	.85123 .0071	.83341 .0031	.87310 .0034	.86544 .0083	.85140 .0084	.83343 .0037	.87330 .0038	.86562 .0092	.85154 .0093	.83409 .0041	.87350 .0041	.86586 .0100	.85201 .0101	.83418 .0045	.87435 .0048	.86668 .0117	.85258 .0119	.83446 .0052	2.5
.55984 .0030	.55489 .0074	.54579 .0075	.53407 .0033	.56004 .0037	.55503 .0089	.54582 .0091	.53405 .0040	.56012 .0041	.55511 .0101	.54595 .0102	.53429 .0045	.56036 .0045	.55537 .0110	.54620 .0112	.53441 .0049	.56109 .0054	.55603 .0132	.54672 .0134	.53472 .0060	
.29579 .0032	.29311 .0079	.28818 .0080	.28180 .0035	.29581 .0040	.29310 .0098	.28811 .0100	.28175 .0044	.29589 .0046	.29320 .0112	.28825 .0114	.28187 .0050	.29613 .0051	.29341 .0124	.28842 .0126	.28197 .0056	.29663 .0063	.29388 .0154	.28880 .0157	.28221 .0070	
0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	
1.81765 .5018	1.84144 1.0206	1.36741 1.2969	1.16715 .7451	1.85577 .5982	1.91241 1.1745	1.38967 1.5269	1.14600 .9025	1.88842 .6667	1.95439 1.2834	1.40550 1.6897	1.13926 1.0154	1.91584 .7246	1.72079 1.4829	1.42052 1.8276	1.13507 1.1123	1.97797 .8563	1.76733 1.7151	1.45749 2.1368	1.15080 1.3241	32.5
1.18185 .5287	1.17006 1.0749	.88634 1.3617	.74434 .7934	1.21815 .6434	1.22854 1.2559	.90360 1.6371	.73428 .9824	1.24407 .7265	1.11398 1.4846	.91750 1.8355	.73198 1.1207	1.26616 .7977	1.13041 1.6116	.93107 2.0018	.73784 1.2356	1.31730 .9623	1.16969 1.8999	.96099 2.3954	.75059 1.5102	
.63826 .5606	.62083 1.1332	.47423 1.4396	.39186 .8519	.66205 .6996	.59143 1.4339	.48574 1.7758	.38786 1.0853	.67944 .8027	.60440 1.6180	.49660 2.0178	.39256 1.2527	.69453 .8923	.61565 1.7777	.50561 2.2325	.39647 1.4027	.73041 1.1035	.64544 2.1406	.56091 2.6658	.40522 1.7723	
.23773 1.1663	.21599 3.1190	.11008 6.3159	0.00000 0.0000	.25969 1.3310	.21106 3.6207	.12920 6.8637	0.00000 0.0000	.27548 1.4520	.22428 3.8529	.14247 7.2470	0.00000 0.0000	.28906 1.5568	.23640 4.0406	.17771 7.1707	0.00000 0.0000	.32101 1.6491	.29306 4.2696	.18538 8.2121	.03933 15.9161	
3.74631 1.1126	3.24110 3.1735	2.41427 4.3750	1.64238 2.9644	3.99763 1.2411	3.41191 3.6022	2.54079 5.0572	1.72199 3.4860	4.14771 1.3280	3.53447 3.8912	2.71183 5.4464	1.74966 3.8484	4.30845 1.3956	3.65002 4.1239	2.67341 5.9822	1.79443 4.1477	4.61531 1.5402	3.91898 4.6030	2.79003 7.0273	1.91769 4.8417	62.5
2.49731 1.1385	2.13517 3.2745	1.58838 4.5419	1.06461 3.0878	2.66055 1.2896	2.26803 3.7683	1.77304 5.1986	1.13059 3.7212	2.80309 1.3877	2.37276 4.1027	1.73949 5.9533	1.16521 4.1529	2.91044 1.4674	2.46706 4.3693	1.81197 6.3990	1.19796 4.5200	3.16137 1.6343	2.89056 4.7398	1.95939 7.1651	1.29469 5.3297	
1.36291 1.1721	1.16438 3.3885	.86476 4.7361	.57617 3.2608	1.48241 1.3445	1.25304 3.9639	.94105 5.6546	.62140 4.0101	1.56542 1.4604	1.32670 4.3495	.97318 6.3875	.64136 4.5411	1.63425 1.5750	1.39200 4.6538	1.02563 6.9787	.67448 5.0134	1.79909 1.7924	1.57788 5.2825	1.11904 8.0396	.72883 6.0252	
.65198 1.5534	.54083 4.9042	.36352 9.0891	.15652 17.3700	.73381 1.7166	.60553 5.4848	.39132 10.4698	.18712 19.1566	.79117 1.8262	.65843 5.8479	.44808 11.0831	.20930 20.4674	.84068 1.9146	.74711 5.9835	.47425 11.5313	.31498 2.8489	.98023 2.0839	.82540 6.8220	.55103 13.2960	.37344 4.1519	
7.54972 1.7163	6.29251 5.2947	4.40669 8.1521	2.64827 5.8735	8.23416 1.8617	6.88760 5.8267	4.76551 9.2812	2.85825 6.7738	8.73974 1.9499	7.30746 6.1738	5.03912 9.4634	3.01119 7.3706	9.17194 2.0162	7.97033 6.3029	5.25968 10.4084	3.14336 7.8571	10.17358 2.1467	8.57386 7.0269	5.78694 12.0616	3.61658 8.9677	92.5
5.03485 1.7438	4.19183 5.4090	2.92262 8.3860	1.75268 6.1093	5.57060 1.9047	4.65377 5.9977	3.25644 9.6437	1.91797 7.1258	5.97052 2.0018	5.20626 6.2304	3.41923 10.2543	2.04082 7.8221	6.31843 2.0742	5.36614 6.6611	3.61323 11.2476	2.26166 8.4429	7.16096 2.1094	6.11263 7.3225	4.04704 12.9358	2.50240 9.7067	
2.77790 1.7961	2.31479 5.5328	1.60853 8.6455	.96217 6.3553	3.12831 1.9807	2.61452 6.2008	1.80047 9.6741	1.07053 7.5442	3.39634 2.0858	2.90037 6.5829	1.94235 11.1479	1.21353 8.4187	3.63687 2.1640	3.06286 7.0207	2.06576 12.1206	1.28218 9.1149	4.22683 2.1774	3.69998 7.7105	2.41682 13.4647	1.45921 10.6033	
1.42845 1.9743	1.17225 6.4678	.77257 12.3313	.49632 3.5110	1.65625 2.1402	1.42217 6.9863	.89663 13.9240	.60840 4.8493	1.83476 2.2383	1.52368 7.6130	.99230 15.4516	.65492 5.8918	1.99647 2.2456	1.68849 7.9334	1.08131 16.5069	.70072 6.7241	2.39432 2.3662	1.95137 9.1037	1.31599 18.5058	.81420 8.4974	
14.48898 2.1270	11.82684 7.0385	7.46463 12.2451	4.48990 9.2646	16.36862 2.2314	13.29699 7.5747	8.82065 12.9449	5.01899 10.3570	17.47838 2.1765	14.24122 8.0188	9.50518 13.6123	5.59256 10.8003	18.47041 2.2480	14.96380 8.4686	10.03929 14.3745	5.91513 11.3642	20.73858 2.3567	16.57495 9.3093	11.34174 15.9597	6.68731 12.5120	122
9.66033 2.1471	7.91726 7.1438	5.04131 12.4746	3.00287 9.4981	11.14836 2.2521	9.03407 7.7708	5.99766 13.8194	3.41654 10.7266	11.99995 2.2330	9.71049 8.3745	6.51825 14.1974	3.83665 11.2776	12.79225 2.2986	10.26833 8.8192	6.96274 15.0629	4.10106 11.9131	14.62677 2.4099	11.72183 9.8215	8.24729 17.6717	4.75148 13.1992	
5.33365 2.1850	4.39397 7.2540	2.92232 12.5408	1.66599 9.7522	6.26291 2.1837	5.10755 7.9925	3.40417 13.6245	1.99804 10.9039	6.87036 2.2926	5.61257 8.6458	3.73368 14.8757	2.19972 11.8262	7.40140 2.3567	5.87203 9.2513	4.04509 15.8792	2.38389 12.5457	8.53734 2.4280	7.05034 10.4165	4.92224 18.5365	2.81438 14.0431	
2.87000 2.2604	2.28557 7.8705	1.49626 15.3481	.88005 10.0204	3.36693 2.2842	2.70971 8.7697	1.84361 11.6030	1.07954 11.3964	3.75918 2.3790	3.03058 9.4537	2.06138 13.1670	1.21329 12.4503	4.10608 2.4419	3.31286 10.0953	2.31078 15.2214	1.33976 10.0653	4.92097 2.6341	4.17071 11.3966	2.84459 17.1341	1.67975 11.6099	
26.35107 2.2387	21.47250 8.4078	13.82988 15.0416	7.63072 11.9212	29.51138 2.3564	23.47774 9.3630	15.60327 16.0643	8.75611 13.0256	31.76406 2.4210	25.77804 9.9576	17.58301 18.2563	9.80978 13.4396	33.66809 2.4806	27.68301 10.3525	18.56521 18.5542	10.52503 13.9724	37.83545 2.6841	31.77516 11.3552	21.48627 19.9244	12.23932 15.0106	152
17.67188 2.2531	14.40835 8.5176	9.31037 15.2153	5.13421 12.1261	20.09696 2.3835	16.60226 9.5381	11.02372 17.6543	6.00978 13.3465	21.85063 2.4595	17.90761 10.2078	12.06035 18.4540	6.80778 13.8506	23.22264 2.4930	19.32863 10.7176	13.19505 19.6193	7.38981 14.4351	26.85099 2.8790	22.67602 11.9144	15.44988 20.6951	8.82370 15.5626	
9.82154 2.2802	8.01586 8.6277	5.14728 15.8932	2.86538 12.3405	11.38157 2.4158	9.22864 9.7730	6.28806 18.1476	3.51078 13.4495	12.45915 2.4435	10.34408 10.5365	7.00698 19.1742	3.95099 14.3068	13.52248 2.6160	11.29462 11.1622	7.63817 19.7209	4.35333 14.9497	16.05170 3.1481	13.68488 12.6009	9.40262 21.6125	5.32694 16.2001	
5.17902 2.3296	3.99013 9.2920	2.79423 13.4260	1.52232 12.5543	6.14777 2.4707	4.99532 10.4346	3.40495 16.0672	1.91750 13.8522	6.87573 2.5616	5.71431 11.2734	3.87801 17.3407	2.20650 14.8058	7.55347 2.8008	6.34823 12.0647	4.30297 18.1538	2.44624 15.5620	9.45145 3.5012	7.94189 12.6981	5.53719 20.3573	3.22053 13.6508	

SAMPLE DATA GROUP

ANGLE BETWEEN CURRENT AND WAVE DIRECTION

φ	11.25°	33.75°	66.25°	88.75°
-0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
0.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
2.25	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000
3.75	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000	0.00000 0.0000

TABLE A6

TRANSPORT LOOKUP TABLE FOR STEADY CURRENT VELOCITY OF 152.5 CM/S

Contract Report

SEDID: A SEDIMENT TRANSPORT MODEL FOR THE CONTINENTAL SHELF

by
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ABSTRACT

Modelling of sediment transport under the combined influence of waves and a current has continued with the development of a new one-dimensional model, SED1D. This model was produced after a review and evaluation of the existing one-dimensional model, SEDMO. The new model uses more accurate and efficient numerical methods for solving transcendental equations and for calculating integrals. As well, theoretical modifications include the partition of the bottom stress into form drag and skin friction components, the inclusion of a subroutine to predict the type of bedform likely to be encountered under the given flow and seabed conditions, and changes in the calculation of the bottom friction factor under steady flow conditions to reflect the field measurements of Sternberg (1972). SED1D has been checked for validity of the computer coding by comparison with both published results and hand calculations, but the basic theoretical formulation cannot be verified until an adequate set of field measurements becomes available.

1. INTRODUCTION

The recent increase in the exploration and development of offshore resources, in particular hydrocarbon resources, has highlighted several topics in need of further investigation. One such topic is seabed sediment mobility. Although many researchers have extensively considered sediment transport both in rivers under steady flow conditions and in the coastal zone as a result of wave action, little effort has been devoted to the study of sediment motion on continental shelves, where the combined influence of waves and currents may be significant.

Previous contracts awarded to Martec Limited in 1980 and 1982 have had as their respective goals development of one-dimensional and two-dimensional numerical models for the estimation of sediment transport on a continental shelf under the influence of both waves and currents (Martec, 1982 and 1983). The one-dimensional model, SEDMO, computes the instantaneous sediment transport resulting from a chosen set of wave, current and seabed conditions. The user is provided with a choice of methods for calculating bottom friction, threshold conditions and net sediment transport. The two-dimensional model, SED2D, simulates sediment transport over a given area of the seafloor throughout the duration of a storm. SED2D was specifically developed for the Sable Island Bank and Banquereau regions.

The original objectives of the present study were

- to recall all computer files required for the two-dimensional model, SED2D, such that the model is operational on the BIO Cyber computer;
- to run the various components of SED2D using the existing data base to evaluate sediment transport for the Sable Island and Banquereau banks under storm conditions;

- to review the structure, composition and coding of both SEDMO and SED2D in order to evaluate their suitability for the purposes of the Geological Survey of Canada;
- to conduct a sensitivity analysis of the physical factors controlling shelf sediment transport using SEDMO.

Due to the research nature of this study, these objectives were modified during the course of this project. In conjunction with the scientific authority, it was determined that a thorough review of the one-dimensional model was required before proceeding with the two-dimensional case. Three major tasks were emphasized during this project:

- a review and evaluation of the theoretical considerations involved in the calculation of sediment transport under the combined influence of waves and currents;
- a detailed verification of the computer coding in SEDMO2, the shortened version of SEDMO (SEDMO2 employs the same numerical methods for calculation of sediment transport as does the two-dimensional model, SED2D);
- modification of SEDMO to reflect the results of the first two tasks. The upgraded one-dimensional model has been renamed SED1D.

The results of these tasks can best be summarized by reviewing both the present structure of SED1D and the differences between SEDMO and SED1D. Chapters 2 and 3 of this report will address each of these topics in turn.

Appendix A contains a summary, as implemented in SED1D, of Grant and Madsen's (1979) method for calculating bottom shear stress when both waves and currents are present. Model verification is described in Appendix B. A brief description of SED1D is contained in Appendix C, along with a sample terminal session. Appendix D contains a program listing for SED1D.

2. MODEL STRUCTURE

SED1D is a user-interactive computer model written in FORTRAN V. The program structure is such that the process of computing sediment transport from a given set of wave, current and seabed conditions is broken down into component form and each component is contained in a separate subroutine. This modular approach allows each component of the computational process to be separately modified without rewriting the entire program. There are ten components to the model SED1D:

1. MAIN PROGRAM - controls passage of information between various subroutines where calculations are performed;
2. SUBROUTINE READIN - interactive user input of data required to run SED1D;
3. SUBROUTINE INOUT - echoes the input data from subroutine READIN to user;
4. SUBROUTINE OSCIL - calculates necessary waves parameters from input data;
5. SUBROUTINE FRICFAC - calculates bottom friction factor and other parameters required for bottom stress calculation;
6. SUBROUTINE THRESH - calculates the threshold fluid velocity for initiation of both bedload and suspended load transport;
7. SUBROUTINE TIMING - calculates times during a wave cycle when the respective critical velocities for bedload and suspended load transport are exceeded;
8. SUBROUTINE TRANSPO - calculates the time-averaged net sediment transport by one of several available methods;
9. SUBROUTINE OUTOUT - prints the values of the output parameters from all subroutines;

10. SUBROUTINE BEDFORM - prints out the expected type of bedform for the given flow conditions.

The various subroutines and the various theories and calculations involved will be described in the next section of this report.

2.1 SED1D Subroutines

In order to calculate sediment transport resulting from a given set of wave, current and seabed conditions, it is necessary to first make some estimate of the instantaneous bottom shear stress. This step is contained in subroutines OSCIL and FRICFAC. Once the bottom stress is known, the threshold conditions for sediment motion are determined in subroutine THRESH. Next, the instantaneous sediment transport must be integrated over those parts of the wave cycle where threshold conditions are exceeded; these steps are contained in TIMING and TRANSPO. Subroutine BEDFORM gives an indication of what types of bedforms are likely to be encountered under the existing flow conditions. These subroutines will now be described in more detail.

2.1.1 Subroutine OSCIL

It is common practice to describe the characteristics of wind-induced surface waves in terms of three variables: water depth (d), wave height (H) and wave period (T). However, the parameters required for bottom stress calculations are the maximum wave orbital velocity (U_b) and the maximum bottom particle displacement (A_b) at the seabed; these are given by

$$U_b = \frac{\pi H}{T} \frac{1}{\sinh (kd)} \tag{1}$$

and $$A_b = \frac{H}{2} \frac{1}{\sinh (kd)} \tag{2}$$

where k, the wave number, is determined from the linear wave theory dispersion equation

$$\omega^2 = gk \tanh (kd) \tag{3}$$

ω, the wave angular frequency, is given by

$$\omega = \frac{2\pi}{T} \tag{4}$$

and g is the acceleration due to gravity. Due to the transcendental nature of the dispersion equation it is necessary to solve for k using an iterative procedure; a Newton-Raphson root-finding scheme was chosen. The use of linear wave theory limits the range of validity of the above equations to cases where $H/L < 1/20$, i.e. to small amplitude waves.

A check for breaking waves is also made using the Miche (1944) criterion, where the height at which a wave breaks, H_b, is given by

$$H_b = 0.142 \; L \tanh (kd) \tag{5}$$

and L is the wavelength. If the wave height H exceeds H_b a warning message is sent to the user while execution continues.

2.1.2 Subroutine FRICFAC

A quadratic drag law was chosen to represent bottom stress as in the previous models:

$$\vec{\tau}_b = \frac{\rho}{2} f \, \vec{u} \, |\vec{u}| \tag{6}$$

where $\vec{\tau}_b$ is the instantaneous bottom stress vector, f is a friction factor and $\vec{u}$ is the instantaneous velocity vector. This subroutine is subdivided into three cases: (i) the pure wave case with no current, (ii) the pure current case with no waves, and (iii) mixed wave and current conditions.

(i) Pure wave case

The friction factor for the pure wave case is calculated using the method of Jonsson (1966) as modified by Nielsen (1979):

$$f = \exp\left[\, 5.213 \left(\frac{k_b}{A_b}\right)^{0.194} - 5.977\right] \quad \text{for } \frac{A_b}{k_b} > 1.7 \tag{7}$$

$$f = 0.28 \qquad\qquad \text{for } \frac{A_b}{k_b} \leq 1.7 \tag{8}$$

where k_b is the bottom roughness height usually related to the bedform height or, in the absence of bedforms, the grain diameter.

Bottom stress is considered to be the product of two main components: that due to form drag associated with individual bedform elements and that due to skin friction evaluated at the granular level at the fluid-solid interface. Recent work (Grant and Madsen, 1976) has indicated that sediment transport is related to the skin friction component of total bottom stress only. Thus the sediment grain diameter (D) is used to determine bottom roughness height irrespective of the actual bedforms present on the seabed.

The instantaneous velocity vector for the pure wave case is given by

$$\vec{u} = \vec{u}_b \cos \omega t \tag{9}$$

where $\vec{u}_b$ and ω are calculated using linear wave theory in subroutine OSCIL.

(ii) Pure current case

Based on the field experiments of Sternberg (1972), the friction factor (as used in equation 6) is assumed to have a constant value of 6.0×10^{-3} for the pure current case. This value relates bottom stress to the square of the velocity when the current velocity is measured 100 cm above the seabed; a minor programming change must be made in subroutine FRICFAC if the velocity is measured at any other level.

(iii) Mixed wave and current conditions

The method described by Grant and Madsen (1979) is used to calculate both the friction factor and the appropriate velocity for use in calculating bottom stress under mixed wave and current conditions. It is assumed that the presence of the wave motion acts to increase the bottom roughness affecting the velocity profile and therefore the bottom stress. This method is an iterative procedure based on four non-dimensional input parameters: k_b/A_b (as previously defined); ϕ_c, the angle between the wave and current directions outside the wave boundary layer; $|\vec{u}_{cr}|/|\vec{u}_b|$ where $\vec{u}_{cr}$ is the steady current velocity measured at a height Z_r above the seabed; and Z_r/k_b. Grant and Madsen's method is outlined in detail in Appendix A.

Although Grant and Madsen's method is used over the entire range of mixed wave and current conditions, its range of validity is limited to the case where current velocities are of the same order of magnitude as the bottom wave orbital velocity maximum. Outside this range the solutions may be less valid and a warning message is sent to the user while execution continues. In addition, if the friction factor calculated using ths method is less than 6.0×10^{-3}, the friction factor defaults to the pure current value. This ensures that the frictional dissipation of fluid momentum under mixed flow conditions is never less than that for the pure current condition.

2.1.3 Subroutine THRESH

In this subroutine the critical conditions for initiation of both bedload and suspended load transport are determined. The critical stress for initiation of bedload transport (τ_{cb}) is determined from a modified Shields curve (see Miller *et al.* 1977) as follows:

$$\tau_{cb} = 0.04\ \Delta\rho g D \qquad \text{for } Re_* > 10 \tag{10}$$

$$\tau_{cb} = 0.096\ \Delta\rho g D\ Re_*^{-1/3} \qquad \text{for } Re_* \leq 10 \tag{11}$$

where $\Delta\rho = \rho_s - \rho_f$,

and ρ_s is the sediment density, ρ_f is the fluid density, g is the acceleration due to gravity, D is the sediment grain diameter and Re_* is the grain Reynolds Number given by

$$Re_* = \frac{D}{\nu} \sqrt{\frac{\tau_b}{\rho}} \tag{12}$$

where ν is the kinematic viscosity of the fluid.

The critical stress for initiation of suspended load transport (τ_{cs}) is from Bagnold (1966):

$$\tau_{cs} = 0.64\ \rho W^2 \tag{13}$$

where W, the fall velocity of the sediment grains, is given by Gibbs *et al.* (1971) as:

$$W = \frac{-3\mu + [9\mu^2 + gD^2/4\ \rho\Delta\rho\ (0.015476 + 0.099205\ D)]^{1/2}}{\rho(0.011607 + 0.074405\ D)} \tag{14}$$

where μ is the dynamic viscosity of the fluid. These critical stresses for transport are transformed to critical velocities using the quadratic stress law and the appropriate friction factor.

2.1.4 Subroutine TIMING

Once the critical velocities for transport are known, the next step is to determine when during a wave cycle these critical velocities are exceeded. For the pure wave case, this involves the solution of the following simple equations for t:

$$\left|\vec{u}_b \cos \omega t\right| = V_{cb} \tag{15}$$

$$\left|\vec{u}_b \cos \omega t\right| = V_{cs} \tag{16}$$

where V_{cb} and V_{cs} are the critical velocities for initiation of bedload and suspended load transport, respectively. Two roots to each equation are possible, one occurring during the passage of the wave crest and the other during the wave trough.

The combined wave and current case is somewhat more complex. Taking the magnitude of the instantaneous velocity vector and equating to the respective critical velocities results in these quadratic equations:

$$\cos \omega t = \frac{-1}{\left|\vec{u}_b\right|} \left[\left|\vec{u}_a\right| \cos \phi_b \pm \left(V_{cb}{}^2 - \left|\vec{u}_a\right|^2 \sin^2 \phi_b\right)^{1/2}\right] \tag{17}$$

$$\cos \omega t = \frac{-1}{\left|\vec{u}_b\right|} \left[\left|\vec{u}_a\right| \cos \phi_b \pm \left(V_{cs}{}^2 - \left|\vec{u}_a\right|^2 \sin^2 \phi_b\right)^{1/2}\right] \tag{18}$$

$\vec{u}_a$ is the steady current velocity used in bottom stress calculations and ϕ_b is the angle between the wave and current directions inside the wave boundary layer.

The percent time spent in each transport phase (no transport, bedload transport, suspended load transport) is also calculated in this subroutine.

2.1.5 Subroutine TRANSPO

In this subroutine the instantaneous sediment transport is numerically integrated over the course of a wave cycle. For the pure current case no integration is required since the conditions are constant. No net sediment transport occurs for the pure wave case due to the symmetry resulting from the use of linear wave theory (Higher order wave theories include a wave-induced drift current).

The user must choose during each computer run one of four methods for calculating sediment transport. The options are:

(i) The Engelund-Hansen (1967) total load equation, where

$$g_s = 0.05V^2 \frac{(|\tau_b|^3 \rho)^{1/2}}{gD\Delta\rho^2} \tag{19}$$

and g_s is the volume rate of sediment transport per unit width of bed (cm^2/sec). This formula was originally based on flume experiments where V represented the mean flow velocity (discharge/cross-sectional area). For the present application it has been assumed that $V = |\vec{u}_{100}|$, the steady current velocity 1 m above the seabed; however, this assumption has not been verified.

(ii) The Einstein-Brown (1950) bedload equation, where

$$g_s = 40\ WD\ \left(\frac{|\vec{\tau}_b|}{\Delta\rho g D}\right)^3 \tag{20}$$

Grant and Madsen (1976) tested this equation for the instantaneous transport under waves alone and found that it agreed well with available data provided that $\vec{\tau}_b$, the bottom shear stress, was evaluated as the skin friction component only.

(iii) The Yalin (1963) bedload equation, where

$$g_s = 0.635\ D\ u_* s\ [\ 1 - \frac{1}{as}\ \ln\ (1 + as)] \tag{21}$$

$$s = \frac{|\vec{u}|^2}{V_{cb}^2} - 1 \tag{22}$$

$$a = 2.45\ [\ \frac{\tau_{cb}}{g\,\Delta\rho D}\ ]^{1/2}\ (\frac{\rho}{\rho_s})^{0.4} \tag{23}$$

and $$u_* = \sqrt{\frac{\tau_b}{\rho}} \tag{24}$$

The instantaneous velocity vector, $\vec{u}$, is taken as $\vec{u}_{100}$ for the pure current case and as the vector sum $\vec{u}_a + \vec{u}_b \cos \omega t$ for mixed flow conditions.

(iv) The Bagnold (1963) total load equation for mixed flow conditions, where

$$g_s = K\ \tau_{bw}\ \vec{u}_{100} \tag{25}$$

The shear stress on the bottom due to the waves alone, τ_{bw}, is determined

from $$\tau_{bw} = \frac{\rho}{2}\ f\,|\vec{u}_b|^2 \tag{26}$$

where f is calculated using the method of Jonsson (1966). K, a coefficient of proportionality, ranges between 0 and 1.0 and is chosen by the user.

Alternatively, for the pure current case, Bagnold's bedload equation as modified by Gadd et al. (1978) is used. This method states that

$$g_s = \frac{\beta}{\rho_s} (u_{100} - V_{cb})^3 \qquad (27)$$

where β is a coefficient whose value depends on the sediment grain size. Based on numerous flume tests Gadd et al. report values of β for grain sizes of 0.18 mm and 0.45 mm; for intermediate grain sizes the present program interpolates linearly between the reported values. This method has been tested with moderate success in a marine environment by Heathershaw (1981).

Where numerical integration is required, an IMSL (International Mathematical and Statistical Library) routine, DCADRE, is used. This routine uses cautious adaptive Romberg extrapolation to estimate the value of the given integral. The IMSL library must be accessible in order to run SED1D for the mixed wave and current case.

2.1.6 Subroutine BEDFORM

In this subroutine, an estimate is made of the type of bedform likely to be encountered under the given flow conditions. This estimate is based only on near-bed flow velocities (u_{30} for currents, u_b for waves) so it is approximate. At the present time, only the pure wave and pure current cases are considered. Expected bedform type is determined from table 2.1, after Amos (in prep.).

Non Cohesive Sediment

BEDFORM	BOUNDS	SAND			
		Fine	Medium	Coarse	V. Coarse
Current	Upper Lower	60 cm/s 13 cm/s	50 cm/s 20 cm/s	35 cm/s 25 cm/s	no ripples
Flat Bed (Lower)	Upper Lower	no flat bed	no flat bed	45 cm/s 35 cm/s	50 cm/s 45 cm/s
2-D Megaripples	Upper Lower	no 2-D megaripples	60 cm/s 50 cm/s	60 cm/s 40 cm/s	60 cm/s 40 cm/s
Sand Waves	Upper Lower	no sand waves	100 cm/s 60 cm/s	100 cm/s 50 cm/s	100 cm/s 40 cm/s
3-D Megaripples	Upper Lower	no 3-D megaripples	150 cm/s 60 cm/s	150 cm/s 60 cm/s	no 3-D mega's
Flat Bed (Upper) and Sand Ribbons	Upper Lower	85 cm/s 60 cm/s	170 cm/s 150 cm/s	240 cm/s 150 cm/s	295 cm/s 100 cm/s
Wave Ripples	Upper Lower	70 cm/s 10 cm/s	100 cm/s 13 cm/s	125 cm/s 20 cm/s	200 cm/s 30 cm/s
Wave Induced Flat Bed	Upper Lower	- 70 cm/s	- 80 cm/s	- 90 cm/s	- 100 cm/s

Table 2.1 Near-bed flow velocities for formation of various bedform types (after C.L. Amos, in prep.)

3.0 IMPROVEMENTS OVER PREVIOUS MODEL

This chapter will briefly review the differences between the one-dimensional models SEDMO and SED1D. For a more detailed description of the original one-dimensional model, SEDMO, the user is referred to Martec (1982). The structure and interactive nature of the present model are very similar to that of SEDMO; most of the changes are theoretical in nature. They include:

- SED1D is programmed in FORTRAN V rather than the FORTRAN IV used in SEDMO. This reflects a change in the industry-standard language and, for this particular application, has its main impact in the format statements.
- The option for computing wave and current characteristics directly from wind parameters has been dropped; it was felt that this option added unnecessary complication to a sediment transport model. In addition, the current calculation is rather simple and the wave characteristics can easily be determined from a nomograph such as that in the Shore Protection Manual (1977).

Subroutine OSCIL:

- The method used to calculate wavelength, L, from the linear wave theory dispersion equation has been changed to a more efficient version.
- The maximum wave-induced bottom particle velocities and displacements are now calculated right at the seafloor (assuming inviscid flow) instead of 1 m above the seabed as in SEDMO.
- SED1D includes a check for breaking waves using the Miche (1944) criterion.

Subroutine FRICFAC:

- SEDMO offers the user a choice of methods for calculating the bottom friction factor; however, this choice was eliminated in SED1D due to the exclusive range of validity of each method.
- The method for calculating bottom friction factor in the absence of wave motion was changed from that of Jonsson (1966) to that of Sternberg (1972). In light of Sternberg's experimental measurements it was felt that Jonsson's method gave friction factors as much as an order of magnitude too high.
- SEDMO uses graphical approximations to Grant and Madsen's method for calculating bottom stress, while SED2D uses the actual analytical formulation presented in their 1979 paper. The equations used in SED2D have been incorporated into SED1D. SED1D is structured such that the bottom roughness associated with the presence of bedforms is used to determine the velocity profile characteristics while only the bottom roughness associated with the sediment grain size is used to determine the skin friction component of total bottom shear stress.
- Both Jonsson's and Grant and Madsen's methods for calculating bottom stress depend on the bottom roughness as parameterized by the equivalent Nikuradse sand grain roughness, k_b. Unfortunately, the relationship between bedform height, h_b, and k_b is not simple and many different formulations have been proposed. SEDMO uses the relationship

  $$k_b = D + 3h_b \tag{28}$$

  for all bed configurations, based on the conclusions of Jonsson 1966). SED1D requires direct input of bottom roughness height, k_b, rather than bedform height, h_b; thus it is up to the user to determine the appropriate relationship for the particular bed characteristics under consideration. The calculation of k_b cannot be further clarified until more experimental data becomes available.

Subroutine THRESH:

- The user option in calculating the threshold stress for bedload transport has been deleted. The method now used is that attributed to Miller et al. (1977) in Martec (1982).
- In calculation of the grain Reynolds Number, the wave and current velocities are added vectorally in SED1D rather than by summing the absolute values as in SEDMO. This change is significant for small grain Reynolds numbers only ($Re_* < 10$).

Subroutine TRANSPO:

- The integration routine in SEDMO has been changed to a more efficient and accurate version in SED1D.
- Bagnold's equation for sediment transport has been changed to a version thought to be more applicable under continental shelf conditions (Gadd et al., 1978). Yalin's (1963) bedload equation has been added to the list of user options.

Subroutine BEDFORM:

- This routine is not present in SEDMO.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The existing one-dimensional model for sediment transport on a continental shelf (SEDMO) has been thoroughly reviewed with respect to both theoretical assumptions and numerical formulation. The shortened version of SEDMO, SEDMO2, has been verified as to accuracy of the computer coding. Details of the model verification procedures are contained in Appendix B. These processes have resulted in the development of a new one-dimensional model, SED1D, whose structure is reviewed in Chapter 2 of this report.

Several areas remain for possible improvement of the one-dimensional model. These include

- the use of some higher order wave theory. The present model uses linear wave theory, however, this theory is not accurate for large waves or shallow water conditions. The use of a non-linear wave theory would include a wave-induced drift current which may significantly affect the net sediment transport.
- the use of an instantaneous friction factor rather than some time-averaged value as in the methods of Jonsson (1966) and Grant and Madsen (1979). This possibility was briefly investigated during this study; unfortunately the mathematics involved proved to be beyond the scope of this project.
- consideration of input and output parameters in a probabilistic sense. Due to the inherent uncertainty in estimating wave, current and seabed characteristics at a given site, it may be wise to characterize both the input and output variables by probability distributions rather than discrete values.
- consideration of the effects of sediment transport on bottom roughness height, k_b. The present model assumes that the

bottom roughness is fixed at the input value regardless of the predicted sediment transport. This is unrealistic since sediment transport may significantly alter the seabed configuration and thus the bottom roughness. However, it was felt that the relationship between sediment transport and bottom roughness is not well enough understood to warrant inclusion in the model at the present time.

- the inclusion of wave-current interaction effects. Wave characteristics may be significantly altered in the presence of a current from those measured with no current present. Grant and Masden's bottom stress formulation as used in the present model ignores these effects; future work should determine the relative importance of wave-current interactions.
- bedforms resulting from the combined influences of waves and currents have not been included in the present model due to a lack of information available on their characteristics.

Regardless of possible improvements to the model, further progress is severely constrained by the lack of an appropriate data set for calibration of the existing model. Although there is a good supply of sediment transport measurements for both unidirectional and purely oscillatory flows, there is very little information available for sediment transport under the combined influence of waves and currents. It is recommended that future efforts be focussed on the acquisition and analysis of a data set consisting of coincident measurements of wave and current velocities, seabed characteristics (bedforms, grain size distribution), bottom stress and resultant sediment transport.

REFERENCES

AMOS, C.L. (In prep). Bedforms. Modern Sedimentation Processes, Ch. 5, EG-1, DNAG Series.

BAGNOLD, R.A. 1963. Mechanics of marine sedimentation. In: The Sea, M.N. Hill (ed.) Publ. Wiley-Interscience, New York, N.Y.: 507-582.

BAGNOLD, R.A. 1966. An approach to the sediment transport problem from general physics. U.S. Geol. Surv. Prof. paper 4421, 37 pp.

BROWN, C.B. 1950. In Rouse H., ed., Engineering Hydraulics, John Wiley and Sons, N.Y. 1039 pp.

ENGELUND, F. and HANSEN, E. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen, Denmark.

GADD, P.E., J.W. LAVELLE and D.J.P. SWIFT. 1978. Estimates of sand transport on the New York shelf using near-bottom current-meter observations, J. Sedim. Petrol., 48: 239-252.

GIBBS, R.J., M.D. MATHEWS and D.A. LINK. 1971. The relationship between sphere size and settling velocity. J. Sedim. Petrol., 41(1): 7-18.

GRANT, W.D. and O.S. MADSEN. 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res., 84(4): 1797-1808.

GRANT, W.D. and S.M. GLENN. 1983. Continental shelf bottom boundary layer model, Vol. I-III. Report to Pipeline Research Committee, American Gas Association, Project No. PR-153-126.

HEATHERSHAW, A.D. 1981. Comparisons of measured and predicted sediment transport rates in tidal currents. Mar. Geol., 42: 75-104.

JONSSON, E.G. 1966. Wave boundary layers and friction factors. Proc. Coastal Eng. Conf. 10th, I: 127-148.

MADSEN, O.S. and W.D. GRANT. 1976. Quantitative description of sediment transport by waves, Proc. Coastal Eng. Conf. 15th, II: 1093-1112.

MARTEC LIMITED. 1982. Sediment transport on a continental shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-1-M571, 91 pp.

MARTEC LIMITED. 1983. A 2-D sediment transport model for continental shelves. Unpublished report submitted to the Geological Survey of Canada. Dss Contract 10SC.23420-2-M777, 63 pp.

MICHE, R. 1944. Mouvements ondulatoires des mers en profondeur constante on décroissante. Annales des Ponts et Chaussées, p. 25-78: 131-164, 270-292, 369-406.

MILLER, M.C., J.N. McCAVE and P.D. KOMAR. 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24: 507-527.

NIELSON, P. 1979. Some basic concepts of wave sediment transport: Inst. Hydrodynamics and Hydraulic Eng., Tech. Univ. of Denmark, Sed. Paper 20.

SMITH, J.D. 1977. Modelling of sediment transport on continental shelves. The Sea, 6, Publ. Wiley-Interscience, New York.

STERNBERG, R.W. 1972. "Predicting Initial Motion and Bedload Transport of Sediment Particles in the Shallow Marine Environment". In: Shelf Sediment Transport, Process and Pattern, D.J.P. Swift, D.B. Duane and O.H. Pilkey (editors), Dowden, Hutchinson & Ross, Inc. 61-83.

U.S. ARMY CORPS. OF ENGINEERS. 1977. Shore Protection Manual, Publ. Coastal Engineering Research Center. 3 Vols.

YALIN, M.S. 1963. An expression for bed-load transportation. Proc. A.S.C.E. 89, HY 3.

APPENDIX A

Grant and Madsen's (1979) method for calculating stress under the combined influence of waves and currents.

The mathematical formulation of this method for calculating bottom stress, as used in SED1D, will be reviewed here. For a theoretical justification of the following, see Grant and Madsen (1979).

The input variables to this routine are:

u_{100} = current speed 1 m above the seabed (cm/sec);

ϕ_{100} = angle between the wave and current directions 1 m above the seabed (radians);

u_b = maximum wave-induced bottom particle velocity from potential flow theory (cm/sec);

A_b = maximum wave-induced bottom particle displacement (cm);

k_b = bottom roughness (cm).

The output variables are:

f_{cw} = bottom friction factor for the combined wave and current case;

u_a = current speed to be used in bottom stress calculations (cm/sec);

ϕ_b = angle between wave and current directions within the wave boundary layer (radians)

The instantaneous bottom stress is calculated from the output vaiables using

$$\left|\vec{\tau}_b\right| = \frac{\rho}{2} f_{cw} \left|\vec{u}_a + \vec{u}_b \cos \omega t\right|^2 \qquad \text{(A-1)}$$

where the current and wave velocities are added vectorally and the instantaneous stress is assumed to act colinearly with the instantaneous velocity vector. The procedure for calculating the output values is an iterative process and involves these steps:

1. Estimate u_a, ϕ_b and, initially, f_{cw}. The initial estimates are

$$\phi_{bo} = \phi_{100} \tag{A-2}$$

$$f_{cwo} = \exp\left[5.213 \left(\frac{k_b}{A_b}\right)^{0.194} - 5.977\right] \quad \text{for } \frac{A_b}{k_b} > 1.7 \tag{A-3}$$

$$= 0.28 \quad \text{for } \frac{A_b}{K_b} \leq 1.7 \tag{A-4}$$

$$u_{ao} = u_{100} \frac{\log\left(\frac{30a_2}{k_b}\right)}{\log\left(\frac{3000}{k_b}\right)} \tag{A-5}$$

where a_2, the thickness of the wave boundary layer (Smith, 1977), is given by

$$a_2 = 0.4\, A_b \left(\frac{f_{cw}}{2}\right)^{1/2} \tag{A-6}$$

All subsequent estimates of u_a and ϕ_b are obtained using the error in the previous estimate.

2. Calculate magnitude and direction of time-averaged shear stress. It is assumed that the time-averaged shear stress acts in the same direction as the steady current outside the wave boundary layer. ϕ_c, the angle between the wave and current directions outside the wave boundary layer, is given by

$$\phi_c = \tan^{-1}(\frac{B}{A}) \qquad \text{(A-7)}$$

where $$A = 2 \int_{-\pi/2}^{\pi/2} g_x(g_x{}^2 + g_y{}^2)^{1/2} d\theta \qquad \text{(A-8)}$$

$$B = 2 \int_{-\pi/2}^{\pi/2} g_y\ (g_x{}^2 + g_y{}^2)^{1/2} d\theta \qquad \text{(A-9)}$$

$$g_x = \sin\ \theta + \frac{u_a}{u_b} \cos\phi_b \qquad \text{(A-10)}$$

$$g_y = \frac{u_a}{u_b} \sin\ \phi_b \qquad \text{(A-11)}$$

The magnitude of the time-averaged shear stress, $\vec{\tau}_c$, is given by

$$|\vec{\tau}_c| = \frac{\rho}{2} f_{cw}\ V_2\ |\vec{u}_b|^2 \qquad \text{(A-12)}$$

where $$V_2 = \frac{(A^2 + B^2)^{1/2}}{2\pi} \qquad \text{(A-13)}$$

3. Next, calculate the bottom friction factor. This in itself is an iterative procedure, however, three iterations have been found to be sufficient for convergence (Martec, 1983).

$$f_{cw} = \left| \frac{0.097\ K\ (\frac{k_b}{A_b})^{1/2}}{(\frac{\alpha^{3/2}}{4} - C^2 \sin^2\ \phi_{100})^{1/2} - C \cos\phi_{100}} \right|^{4/3} \qquad \text{(A-14)}$$

where $$\alpha = 1 + (\frac{u_a}{u_b})^2 + 2(\frac{u_a}{u_b})\ \cos\phi_b \qquad \text{(A-15)}$$

$$C = \frac{V_2}{2\alpha^{1/4}} \qquad \text{(A-16)}$$

$$K = \frac{1}{2\zeta_0^{1/2}\,[\mathrm{Ker}^2(2\zeta_0^{1/2}) + \mathrm{Kei}^2\,(2\zeta_0^{1/2})]^{1/2}} \tag{A-17}$$

$$\zeta_0 = \frac{k_b}{30\ell} \tag{A-18}$$

$$\ell = 0.4\ A_b\left(\frac{f_{cw}\alpha}{2}\right)^{1/2} \tag{Aa-19}$$

Ker and Kei are Kelvin functions of order zero.

4. The apparent bottom roughness, k_{bc}, is next calculated using

$$k_{bc} = k_b\left[24\left(\frac{A_b}{k_b}\right)\left(\frac{f_{cw}\alpha}{2}\right)^{1/2}\right]^{\beta} \tag{A-20}$$

where $\beta = 1 - \left(\frac{V_2}{\alpha}\right)^{1/2}$ (A-21)

5. The variables calculated in steps 2, 3 and 4 define a velocity profile for which the steady current velocity at 1 m above the seabed, u_{100}, can be determined.

$$u_c = 2.5\ \left(\frac{f_{cw}V_2}{2}\right)^{1/2} u_b\ \log\ \left(\frac{3000}{k_b}\right) \tag{A-22}$$

6. Convergence is checked by comparing the calculated values u_c and ϕ_c to the input values u_{100} and ϕ_{100}, respectively. The allowable error has been set to 1.0%; steps 1-6 are repeated until this error level is achieved.

APPENDIX B

Model Verification:

The present model can be roughly divided into two major components: subroutines OSCIL and FRICFAC determine the velocity profile structure for the near-bed flow and the associated bottom stress; subroutines THRESH, TIMING and TRANSPO calculate the sediment transport resulting from the predetermined bottom stress and near-bed fluid kinematics. Accuracy of the computer coding was determined separately for each of these two components.

Grant and Glenn (1983) present results from their neutral near bottom flow model for both normal and storm conditions; these results were compared with output from the first component of the present model run for the same input conditions. As can be seen from Table B.1, the maximum difference between the two models was approximately 1%. This can likely be attributed to different allowable error limits used within each model, and, regardless of source, is insignificant when compared with the errors associated with the input variables.

The second components of the present model, the calculation of sediment transport, was verified by comparison with hand calculations. Hand calculations were performed for two cases: current and wave directions parallel and perpendicular. For the parallel case, the integrals involved in calculating the net transport over a wave period can be solved analytically; it was found that the hand calculations agreed exactly with the computer model. For the perpendicular case, these integrals computed using Simpson's rule, and agreement with the computer model was excellent (less than 0.1% difference).

INPUT VARIABLES	OUTPUT VARIABLES	
	GRANT & GLENN	SEDID
Normal conditions:		
u_b = 10 cm/sec	u_{*c} = 0.937665	u_{*c} = 0.938742
A_b = 25 cm	u_{*cw} = 2.41595	u_{*cw} = 2.415117
u_{100} = 10 cm/sec	z_{oc} = 1.40385	z_{oc} = 1.400967
ϕ_{100} = 0°	f_{cw} = 0.0870562	f_{cw} = 0.0868974
k_b = 6 cm	$\frac{u_a}{u_b}$ = 0.157985	$\frac{u_a}{u_b}$ = 0.158643
D = 0.01 mm		
ρ_s = 2.65 g/cm^3		
Storm conditions:		
u_b = 50 cm/sec	u_{*c} = 4.69051	u_{*c} = 4.665712
A_b = 120 cm	u_{*cw} = 8.77578	u_{*cw} = 8.75322
u_{100} = 50 cm/sec	z_{oc} = 1.40719	z_{oc} = 1.41503
ϕ_{100} = 0°	f_{cw} = 0.028742	f_{cw} = 0.028820
k_b = 4.857 cm	$\frac{u_a}{u_b}$ = 0.464117	$\frac{u_a}{u_b}$ = 0.458369
D = 0.01 mm		
ρ_s = 2.65 g/cm^3		

where $$|u_{*c}| = \left(\frac{f_{cw}}{2} V_2\right)^{1/2} |u_b|$$

$$|u_{*cw}| = \left(\frac{f_{cw}}{2} \alpha\right)^{1/2} |u_b|$$

$$z_{oc} = \frac{k_{bc}}{30}$$

Table B.1 Comparison of results presented by Grant and Glenn (1983) and those from SEDID for the same input conditions.

APPENDIX C

Description of SED1D:

SED1D is a user-interactive computer model written in FORTRAN V. Although the user instructions contained in this appendix are specific to the CDC Cyber system at BIO, the model can readily be adapted for use on another system.

The required program input data is entered directly from the terminal following the appropriate user prompts. Once data entry is complete, all input data is echoed to the screen for verification. All output parameters from each subroutine are also printed on the screen for immediate examination. A backup copy of input and output data is stored on the local file TAPE7; this file can be sent to the line printer or made permanent if future reference is required.

In order to retrieve SED1D from the user catalogue and produce a compiled version, two commands are required:

```
GET, SED1D
FTN5, I=SED1D, L=0, ANSI=0, B=SED1DB
```

The compiled version of SED1D is here given the name SED1DB (or any admissible name of the user's choice). The compiled version can be made permanent so that this step does not have to be repeated in future terminal sessions. The command is

```
SAVE, SED1DB
```

Two commands are needed to access the IMSL library:

```
ATTACH, IMSLIB/UN=LIBRARY
LIBRARY, IMSLIB/A
```

Program execution is initiated simply by repeating the name of the file containing the compiled version.

The above procedures are illustrated in the sample terminal session on the following pages. Entries made by the user are preceded by either a / or a ?

At the end of a terminal session, results may be sent to the line printer by typing

```
REWIND, TAPE7
COPYSBF, TAPE7, OUT
ROUTE, OUT, DC=LP
```

The file TAPE7 can also be added to the user's permanent catalogue by using the SAVE command,

```
SAVE, TAPE7
```

```
/GET,SED1D
/FTN5,I=SED1D,L=0,ANSI=0,B=SED1DB
     7.113 CP SECONDS COMPILATION TIME.


/ATTACH,IMSLIB/UN=LIBRARY
/LIBRARY,IMSLIB/A
LIBRARY,IMSLIB/A.
/SAVE,SED1DB
/SED1DB

          SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
                   SHELF CONDITIONS

          VERSION I   MARCH 31,1984   SUSAN DAVIDSON, MARTEC LTD.



          THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
          AND THEIR LIMITATIONS


IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE
          TO ANY OF THE FOLLOWING QUESTIONS


 ENTER RUN NUMBER (1 - 9999)
? 1


 ENTER WATER DEPTH (M)
? 50


 ENTER CURRENT SPEED AND DIRECTION 1 M. ABOVE SEABED
 (CM/SEC, DEGREES TRUE)
? 50,90


 ENTER WAVE HEIGHT, PERIOD AND DIRECTION
 (METRES,SECONDS,DEGREES TRUE)
? 10,10,0


 ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY
 (MM, GRAMS/CUBIC CM)
? 1.00,2.65


 ENTER BOTTOM ROUGHNESS HEIGHT (CM)
? 10


 ENTER FLUID DENSITY (GRAMS/CUBIC CM)
? 1.003
```

```
                 RUN NUMBER    1


   INPUT DATA:


          WATER DEPTH =  50.00 M
          CURRENT SPEED =  50.00 CM/SEC
          CURRENT DIRECTION =  90.00 DEGREES TRUE

          WAVE HEIGHT =  10.00 M
          WAVE PERIOD = 10.00 SEC
          WAVE DIRECTION =   0.00 DEGREES TRUE

          SEDIMENT GRAIN SIZE =  1.00 MM
          SEDIMENT DENSITY = 2.65 GRAMS/CUBIC CM

          BOTTOM ROUGHNESS HEIGHT =  10.00 CM


          FLUID DENSITY = 1.00 GRAMS/CUBIC CM




 PERCENT TIME SPENT AS BEDLOAD =  73.70
 PERCENT TIME SPENT IN SUSPENSION =   0.00


 CHOOSE BETWEEN:
   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
   3 - BAGNOLD (1963) TOTAL LOAD EQUATION
   4 - YALIN (1963) BEDLOAD EQUATION
 ENTER 1,2,3 OR 4
? 2
```

```
 RESULTS:

          MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
          VELOCITY, FROM LINEAR WAVE THEORY            =  80.04 CM/SEC
          MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
          DISPLACEMENT, FROM LINEAR WAVE THEORY        =  127.38 CM
          WAVELENGTH, FROM LWT DISPERSION EQUATION = 151.30 M

          BOTTOM FRICTION FACTOR =  .0082
          (GRANT AND MADSEN, 1979)
          CURRENT SPEED TO BE USED IN BOTTOM STRESS
          CALCULATIONS                               =  23.42 CM/SEC
          ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
          WITHIN WAVE BOUNDARY LAYER                 =  90.00 DEGREES
          NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

          CRITICAL FLUID VELOCITY FOR INITIATION OF
          BEDLOAD TRANSPORT                          =  39.76 CM/SEC
          CRITICAL FLUID VELOCITY FOR INITIATION OF

          SUSPENDED LOAD TRANSPORT                   = 186.35 CM/SEC

          TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
          SUSPENDED LOAD TRANSPORT CEASES             =  0.00 SEC
          TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
          BEDLOAD TRANSPORT CEASES                    =  1.84 SEC
          TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
          SUSPENDED LOAD TRANSPORT RECOMMENCES        =  0.00 SEC
          TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
          BEDLOAD TRANSPORT RECOMMENCES               =  3.16 SEC

          PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =  73.70
          PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =   0.00

          DIRECTION OF NET SEDIMENT TRANSPORT =  90.00 DEGREES TRUE
          TIME-AVERAGED NET SEDIMENT TRANSPORT =   .3241E-01 CM**2/SEC
          (EINSTEIN-BROWN (1950) BEDLOAD EQUATION)
          NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER  THAN
                 SOIL VOLUME TRANSPORT RATE


          EXPECTED BEDFORMS ARE (C. L. AMOS):

                    BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS


 ENTER 1 TO DO ANOTHER RUN, 0 TO STOP
? 0
     0.681 CP SECONDS EXECUTION TIME.
/
```

APPENDIX D

Program Listing

```
      PROGRAM SED1D(INPUT,OUTPUT,TAPE7)
      REAL KB
      INTEGER OPT
C
C  THIS PROGRAM CALCULATES SEDIMENT TRANSPORT UNDER A VARIETY OF WAVE
C  AND CURRENT CONDITIONS FOR HORIZONTAL BEDS ONLY.  A CHOICE OF
C  TRANSPORT FORMULAE IS AVAILABLE TO THE USER, HOWEVER, IT MUST BE
C  REMEMBERED THAT NONE OF THESE FORMULAE HAVE BEEN CALIBRATED FOR
C  COMBINED WAVE AND CURRENT CONDITIONS.
C
      PRINT 5
      WRITE(7,5)
    5 FORMAT(/,T11,'SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL',
     @/,'                          SHELF CONDITIONS',//,
     @T11,'VERSION I   MARCH 31,1984   SUSAN DAVIDSON, MARTEC LTD.',////,
     @T11,'THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED',/,
     @T11,'AND THEIR LIMITATIONS',//)
    1 CALL READIN(IRUN,D,U100,CDIR,HT,PER,WDIR,GD,KB,RHOS,RHOW,QI)
      IF (QI .EQ. 1.0) GO TO 10
      CALL INOUT(IRUN,D,U100,CDIR,HT,PER,WDIR,GD,KB,RHOS,RHOW)
C
C  CHANGE GRAIN SIZE FROM MM TO CM
C
      GD=GD*0.10
C
C  DO CALCULATIONS AND PRINT RESULTS
C
      CALL OSCIL(HT,PER,D,UB,AB,WL)
      CALL FRICFAC(U100,CDIR,WDIR,UB,AB,PER,GD,KB,FCW,UA,PHIB,PHI100)
      CALL THRESH(UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
      CALL TIMING(UA,PHIB,UB,PER,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP)
      CALL TRANSPO(UA,PHIB,U100,PHI100,UB,PER,WL,GD,KB,FCW,RHOS,RHOW,
     @VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,OPT)
      CALL OUTOUT(UB,AB,WL,FCW,UA,PHIB,VCB,VCS,TS1,TB1,TS2,TB2,PERBED,
     @PERSUSP,SED,SEDDIR,OPT)
      CALL BEDFORM(U100,UB,GD,KB)
C
C  GIVE USER THE OPTION OF DOING ANOTHER RUN
C
   10 PRINT 15
   15 FORMAT(///,' ENTER 1 TO DO ANOTHER RUN, 0 TO STOP')
      READ*, IND
      IF (IND .EQ. 1) GO TO 1
      STOP
      END
C*********************************************************************
C*********************************************************************
C*********************************************************************
C*********************************************************************
      SUBROUTINE READIN(IRUN,D,U100,CDIR,HT,PER,WDIR,GD,KB,RHOS,RHOW,QI)
      REAL KB
```

```
C
C  THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING
C  SED1D.
C
C  OUTPUT VARIABLES:
C
C         IRUN = RUN NUMBER
C         D = WATER DEPTH (M)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH, DEG.)
C         HT = WAVE HEIGHT (M)
C         PER = WAVE PERIOD (SEC)
C         WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C         GD = SEDIMENT GRAIN SIZE (MM)
C         KB = BOTTOM ROUGHNESS (CM)
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY ( GRAMS/CM**3)
C         QI = QUIT INDEX
C
      PRINT 15
  15  FORMAT('IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE',/,
     @T11,'TO ANY OF THE FOLLOWING QUESTIONS')
C
C  INITIALIZE QUIT INDEX TO 0
C
      QI=0.0
C
C  ENTER DATA
C
      PRINT 25
  25  FORMAT(//,' ENTER RUN NUMBER (1 - 9999)')
      READ*, IRUN
C
      PRINT 35
  35  FORMAT(//,' ENTER WATER DEPTH (M)')
      READ*, D
      IF ( D .EQ. -99.) GO TO 998
C
      PRINT 45
  45  FORMAT(//,' ENTER CURRENT SPEED AND DIRECTION 1 M. ABOVE SEABED',
     @/,' (CM/SEC, DEGREES TRUE)')
      READ*, U100,CDIR
      IF (U100 .EQ. -99. .OR. CDIR .EQ. -99.) GO TO 998
C
      PRINT 55
  55  FORMAT(//,' ENTER WAVE HEIGHT, PERIOD AND DIRECTION',/,
     @' (METRES,SECONDS,DEGREES TRUE)')
      READ*, HT,PER,WDIR
      IF (HT .EQ. -99. .OR. PER .EQ. -99. .OR. WDIR .EQ. -99.) GO TO 998
C
      PRINT 65
```

```
  65  FORMAT(//,' ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY',/,
     @' (MM, GRAMS/CUBIC CM)')
      READ*, GD,RHOS
      IF (GD .EQ. -99. .OR. RHOS .EQ. -99.) GO TO 998
C
      PRINT 75
  75  FORMAT(//,' ENTER BOTTOM ROUGHNESS HEIGHT (CM)')
      READ*, KB
      IF (KB .EQ. -99.) GO TO 998
C
      PRINT 85
  85  FORMAT(//,' ENTER FLUID DENSITY (GRAMS/CUBIC CM)')
      READ*, RHOW
      IF (RHOW .EQ. -99) GO TO 998
C
      GO TO 999
 998  QI=1.0
 999  RETURN
      END
C
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE INOUT(IRUN,D,U100,CDIR,HT,PER,WDIR,GD,KB,RHOS,RHOW)
      REAL KB
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE INPUT PARAMETERS FROM
C  SUBROUTINE READIN
C
      PRINT 15, IRUN
      WRITE(7,15) IRUN
  15  FORMAT(////,T21,'RUN NUMBER ',I4,////,T4,'INPUT DATA:',//)
C
      PRINT 25, D,U100,CDIR
      WRITE(7,25) D,U100,CDIR
  25  FORMAT(T11,'WATER DEPTH =',F7.2,' M',/,T11,'CURRENT SPEED =',F7.2,
     @' CM/SEC',/,T11,'CURRENT DIRECTION =',F7.2,' DEGREES TRUE',/)
C
      PRINT 35, HT,PER,WDIR
      WRITE(7,35) HT,PER,WDIR
  35  FORMAT(T11,'WAVE HEIGHT =',F7.2,' M',/,T11,'WAVE PERIOD =',F6.2,
     @' SEC',/,T11,'WAVE DIRECTION =',F7.2,' DEGREES TRUE',/)
C
      PRINT 45, GD,RHOS
      WRITE(7,45) GD,RHOS
  45  FORMAT(T11,'SEDIMENT GRAIN SIZE =',F6.2,' MM',/,T11,
     @'SEDIMENT DENSITY =',F5.2,' GRAMS/CUBIC CM',/)
C
      PRINT 55, KB,RHOW
      WRITE(7,55) KB,RHOW
```

```
  55  FORMAT(T11,'BOTTOM ROUGHNESS HEIGHT =',F7.2,' CM',//,T11,
     @'FLUID DENSITY =',F5.2,' GRAMS/CUBIC CM',///)
C
      RETURN
      END
C**********************************************************************
C**********************************************************************
C**********************************************************************
C**********************************************************************
      SUBROUTINE OSCIL(HT,PER,D,UB,AB,WL)
      REAL KD,KDO,K
C
C  THIS SUBROUTINE CALCULATES WAVE-INDUCED BOTTOM PARTICLE VELOCITY
C  AND DISPLACEMENT USING LINEAR WAVE THEORY.  A CHECK IS ALSO MADE
C  FOR WAVE BREAKING.
C
C  INPUT VARIABLES:
C         HT = WAVE HEIGHT (M)
C         PER = WAVE PERIOD (SEC)
C         D = WATER DEPTH (M)
C
C  OUTPUT VARIABLES:
C
C         UB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE VELOCITY (CM/SEC)
C         AB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE DISPLACEMENT(CM)
C         WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C
C  INTERMEDIATE VARIABLES:
C
C         G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C         C = CONVERSION FACTOR TO CGS UNITS
C         W = WAVE ANGULAR FREQUENCY (RAD/SEC)
C         K = WAVE NUMBER (RAD/CM)
C         KD = K*D
C         HB = BREAKING WAVE HT. FOR GIVEN WAVE PERIOD, WATER DEPTH (CM)
C
      IF (HT .EQ. 0.0) THEN
        UB=0.0
        AB=0.0
        WL=0.0
C
C  CALCULATE WAVELENGTH BY NEWTON-RAPHSON SOLUTION OF LWT DISPERSION
C  EQUATION.
C
      ELSE
      G=981.
      PI=2.*ASIN(1.)
      C=100.
      HT=HT*C
      D=D*C
      W=2.*PI/PER
```

```
      KDO=W**2*D/G
      KD=KDO
   20 CONTINUE
      DKD=(1./TANH(KD)-KD/KDO)/(1./KDO+1./SINH(KD)**2)
      KD=KD+DKD
      IF (ABS(DKD) .GE. 1.0E-4) GO TO 20
      WL=2.*PI*D/KD
C
C  NEXT CHECK FOR BREAKING WAVES USING THE MICHE (1944) CRITERION
C
      HB=0.142*WL*TANH(KD)
      IF (HT .GE. HB) THEN
      PRINT 25
      WRITE(7,25)
   25 FORMAT(///,' ***WARNING***',/,' THIS CASE CORRESPONDS TO BREAKING',
     @' WAVE CONDITIONS WHERE',/,' LINEAR WAVE THEORY IS NOT VALID')
      ENDIF
C
C  CALCULATE WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND DISPLACEMENT
C
      UB=PI*HT/(PER*SINH(KD))
      AB=UB/W
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRICFAC(U100,CDIR,WDIR,UB,AB,PER,GD,KB,FCW,UA,PHIB,
     @PHI100)
      REAL KB
C
C  THIS SUBROUTINE CONTROLS THE CALCUATION OF THE BOTTOM FRICTION
C  FACTOR FOR VARIOUS WAVE AND CURRENT CONDITIONS.  ALTHOUGH THERE
C  IS NO NET SEDIMENT TRANSPORT IN THE ABSENCE OF A CURRENT, BED
C  MOBILITY AND BEDFORM GENERATION MUST STILL BE CONSIDERED.
C
C  INPUT VARIABLES:
C
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH)
C         WDIR = WAVE DIRECTION (AZIMUTH)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
```

```
C
C         FCW= BOTTOM FRICTION FACTOR
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)
C
C  INTERMEDIATE VARIABLES:
C
C         FBAD = BOTTOM FRICTION FACTOR INCLUDING FORM DRAG
C         UBAD = CURRENT SPEED NEGLECTING FORM DRAG (CM/SEC)
C         PHIBAD = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS, WITHIN
C                  WAVE B.L. AND NEGLECTING FORM DRAG (RADIANS)
C         RATIO = UA/UB;  DETERMINES VALIDITY OF EQUATION OF MOTION
C                 USED BY GRANT AND MADSEN (1979)
C
C  PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        CALL FRIC1(U100,GD,KB,FCW,UA)
        PHIB=0.0
        PHI100=0.0
C
C  WAVES AND CURRENT CASE (CHECK FOR VALIDITY OF METHOD)
C
      ELSE IF (U100 .NE. 0.0) THEN
        PHI100=AMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
     @  360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
        IF (KB .EQ. 0.0) THEN
          CALL FRIC2(U100,PHI100,UB,AB,PER,GD,FCW,UA,PHIB)
        ELSE
          CALL FRIC2(U100,PHI100,UB,AB,PER,KB,FBAD,UA,PHIB)
          CALL FRIC2(U100,PHI100,UB,AB,PER,GD,FCW,UBAD,PHIBAD)
        ENDIF
        RATIO=UA/UB
        IF (RATIO .GT. 1.0) PRINT 15
        IF (RATIO .GT. 1.0) WRITE(7,15)
   15   FORMAT(///,' ***WARNING*** ',/,' UA/UB > 1.0',5X,'GRANT AND',
     @ ' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
C
        IF (FCW .LT. 6.0E-3) THEN
          FCW=6.0E-3
          PRINT 25
          WRITE(7,25)
   25     FORMAT(//,' ***WARNING***',/,' THE FRICTION FACTOR HAS ',
     @    'DEFAULTED TO THE PURE CURRENT VALUE ',/,' OF 6.0E-3')
        ENDIF
C
C  PURE WAVES CASE
C
```

```
      ELSE
        CALL FRIC3(UB,AB,PER,GD,KB,FCW)
        UA=0.0
        PHIB=0.0
        PHI100=0.0
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC1(U100,GD,KB,FCW,UA)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  CURRENT CASE.  A CONSTANT FRICTION FACTOR IS ASSUMED, BASED ON THE
C  WORK OF STERNBERG (1971).  THIS IS MOST LIKELY INADEQUATE AND WILL
C  BE REVISED IN THE FUTURE.
C
C  INPUT VARIABLES:
C
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        GD = SEDIMENT GRAIN SIZE (CM)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        FCW = BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C
      FCW=6.0E-3
      UA=U100
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC2(U100,PHI100,UB,AB,PER,KB,FCW,UA,PHIB)
      REAL K,KB,KBC,L
      EXTERNAL FUN1,FUN2
      COMMON /FUNCTS/U,GY
C
C  THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND
C  CURRENT CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1979).  THIS
C  METHOD IS NOT VALID FOR UA/UB > 1.0 (APPROXIMATELY) DUE TO THE REL-
C  ATIVE IMPORTANCE OF THE CONVECTIVE ACCELERATION TERMS IN THE EQUATION
C  OF MOTION.
C
```

```
C  INPUT VARIABLES:
C
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                 ABOVE SEABED (RADIANS)
C        UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C        AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C        PER = WAVE PERIOD (SEC)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        FCW = BOTTOM FRICTION FACTOR FOR THE COMBINED CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C        PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C               WAVE BOUNDARY LAYER (RADIANS)
C
C  INTERMEDIATE VARIABLES:
C
C        PHIC = CALCULATED ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
C               AT 1 M. ABOVE SEABED (RADIANS) - SHOULD CONVERGE TO
C               PHI100.
C        UC = CALCULATED CURRENT VELOCITY AT 1 M. ABOVE SEABED (CM/SEC)
C        A2 = INITIAL ESTIMATE OF WAVE BOUNDARY LAYER THICKNESS, AFTER
C             SMITH (1977) (CM)
C        ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2
C        KBC = APPARENT BOTTOM ROUGHNESS (CM)
C        K = FACTOR USED IN COMPUTATION OF BOTTOM SHEAR STRESS
C        A = FACTOR RELATING MEAN SHEAR STRESS COMPONENT IN WAVE
C            DIRECTION TO RHO*UB**2*FRW/2
C        B = FACTOR RELATING MEAN SHEAR STRESS COMPONENT NORMAL TO WAVE
C            DIRECTION TO RHO*UB**2*FCW/2
C        V2 = FACTOR RELATING MAGNITUDE OF MEAN SHEAR STRESS TO
C             RHO*UB**2*FCW/2
C        L = WAVE BOUNDARY LAYER LENGTH SCALE (CM)
C        U = RATIO OF CURRENT TO WAVE VELOCITIES IN WAVE DIRECTION
C        V = RATIO OF CURRENT TO WAVE VELOCITIES NORMAL TO WAVE
C             DIRECTION
C        IT = ITERATION COUNTER
C        UA0,UC0,UA1,UDIF,DIF ARE VARIABLES USED TO ESTIMATE A NEW
C        VALUE FOR UA
C        PHIB0,PHIC0,PHIB1,PHIDIF,DIF ARE VARIABLES USED TO ESTIMATE A
C        NEW VALUE FOR PHIB
C
C  INITIALIZE ITERATION PARAMETERS
C
      UA0=0.0
      UC0=0.0
      UDIF=U100/4.
      PHIB0=0.0
      PHIC0=0.0
```

```
      PHIDIF=PHI100/4.
      BEST=2.0
      IT=1
C
C  INITIAL ESTIMATE OF FCW (JONSSON,1966), A2 (SMITH, 1977), UA AND PHIB
C
      PI=2.*ASIN(1.)
      FCW1=EXP(5.213*(KB/AB)**0.194-5.977)
      FCW=AMIN1(FCW1,0.28)
      A2=0.4*AB*SQRT(FCW/2.)
      UA=U100*ALOG(30.*A2/KB)/ALOG(3000./KB)
      PHIB=PHI100
C
C  ITERATION LOOP:  FIRST, DETERMINE MAGNITUDE AND DIRECTION OF MEAN
C  SHEAR STRESS FOR ESTIMATED UA AND PHIB.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
  100 ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      U=UA*COS(PHIB)/UB
      GY=UA*SIN(PHIB)/UB
C
      A=2.*DCADRE(FUN1,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) PRINT 5,IER
      IF (IER .GT. 0) WRITE(7,5) IER
    5 FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN1')
      B=2.*DCADRE(FUN2,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) PRINT 15,IER
      IF (IER .GT. 0) WRITE(7,15) IER
   15 FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN2')
C
      V2=SQRT(A*A+B*B)/(2.*PI)
      PHIC=ATAN2(B,A)
C
C  THE EQUATION FOR THE BOTTOM FRICTION FACTOR IS TRANSCENDENTAL AND
C  THUS MUST BE SOLVED ITERATIVELY.  THREE ITERATIONS WERE FOUND
C  SUFFICIENT TO OBTAIN A REASONABLE VALUE (MARTEC, 1983).
C  NOTE:  MMKELO IS AN IMSL SUBROUTINE TO COMPUTE KELVIN FUNCTIONS OF
C  ORDER ZERO.  THE IMSL LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS
C  PROGRAM.
C
      DO 30 I=1,3
      L=0.4*AB*SQRT(FCW*ALPHA/2.)
      ZETA0=KB/(30.*L)
      CALL MMKEL0(2.*SQRT(ZETA0),DUMMY1,DUMMY2,XKER,XKEI,IER)
      IF (IER .GT. 0) PRINT 25,IER
      IF (IER .GT. 0) WRITE(7,25) IER
   25 FORMAT(///,' ***MMKEL0 ERROR*** ',I3)
      K=1./(2.*SQRT(ZETA0)*SQRT(XKER**2+XKEI**2))
      C=V2/(2.*ALPHA**0.25)
      FCW=ABS(0.097*K*SQRT(KB/AB)/(SQRT(ALPHA**1.5/4.-(C*SIN(PHI100))
```

```
     @**2)-C*COS(PHI100)))**(4./3.)
  30  CONTINUE
C
C  CALCULATE APPARENT BOTTOM ROUGHNESS AND RESULTING CURRENT VELOCITY
C  AT 1 M. ABOVE SEABED
C
      KBC=KB*(24.*(AB/KB)*SQRT(ALPHA*FCW/2.))**(1.-SQRT(V2/ALPHA))
      UC=UB*SQRT(V2*FCW/2.)*ALOG(3000./KBC)/0.4
C
C  CHECK CONVERGENCE OF UC TO U100 AND PHIC TO PHI100.  THE ERROR LIMIT
C  HAS BEEN SET TO 0.01 (OR 1.0 PERCENT).
C
      IF (PHI100 .NE. 0.0) THEN
        ERR=AMAX1(ABS(1.0-UC/U100),ABS(1.0-PHIC/PHI100))
      ELSE
        ERR=AMAX1(ABS(1.0-UC/U100),ABS(PHIC-PHI100))
      ENDIF
      IF (ERR .LT. BEST) THEN
        BEST=ERR
        IF (BEST .LT. 0.01) GO TO 999
        BFCW=FCW
        BUA=UA
        BPHIB=PHIB
      ELSE IF (IT .EQ. 50) THEN
        FCW=BFCW
        UA=BUA
        PHIB=BPHIB
        PRINT 35,U100,PHI100,UB,PER,KB,BEST
        WRITE(7,35) U100,PHI100,UB,PER,KB,BEST
  35    FORMAT(///,' ***WARNING*** ',/,' FOR U100=',F8.2,', PHI100=',
     @  F7.4,', UB=',F8.2,', PER=',F6.2,/,' AND KB=',F7.3,', THE BEST',
     @  ' ESTIMATE AFTER 50 ITERATIONS HAS',/,' AN ERROR OF',F5.2)
        GO TO 999
      ENDIF
C
C  INCREMENT ITERATION COUNTER AND MAKE NEW ESTIMATE OF UA AND PHIB.
C
      IT=IT+1
      UA1=UA
      DIF=(U100-UC)*(UA-UA0)/(UC-UC0)
      IF (DIF .LT. -UA) DIF=UA*UA/DIF
      DIF=SIGN(AMIN1(ABS(DIF),ABS(UDIF)),DIF)
      UDIF=DIF*2.
      UA=UA+DIF
      UA0=UA1
      UC0=UC
C
      IF (PHIC .NE. 0.0) THEN
        PHIB1=PHIB
        IF (PHIC .NE. PHIC0) THEN
          DIF=(PHI100-PHIC)*(PHIB-PHIB0)/(PHIC-PHIC0)
```

```
          DIF=SIGN(AMIN1(ABS(DIF),ABS(PHIDIF)),DIF)
          PHIDIF=DIF*2.
          PHIB=PHIB+DIF
        ELSE
          PHIB=PHI100
        ENDIF
        PHIB0=PHIB1
        PHIC0=PHIC
      ELSE
        PHIB=0.
      ENDIF
C
C  REPEAT ITERATION; RETURN TO MAIN PROGRAM WHEN ERROR LIMIT OR
C  ITERATION COUNT IS SATISFIED.
C
      GO TO 100
 999  RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN1(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN1=GX*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN2(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN2=GY*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC3(UB,AB,PER,GD,KB,FCW)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  WAVE CONDITION USING THE METHOD OF JONSSON (1966) AS MODIFIED BY
C  NIELSEN (197?).  THE BOTTOM ROUGHNESS IS TAKEN AS THE GRAIN DIAMETER
C  AS IN GRANT AND MADSEN (1976).
C
C  INPUT VARIABLES:
C
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
```

```
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         FCW = BOTTOM FRICTION FACTOR FOR THE PURE WAVE CASE
C
      FCW=AMIN1(EXP(5.213*(GD/AB)**0.194-5.977),0.28)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE THRESH(UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
C
C  THIS SUBROUTINE CALCULATES THE THRESHOLD FLUID VELOCITY FOR SEDIMENT
C  TRANSPORT FOR BOTH BEDLOAD AND SUSPENDED LOAD.  THE CRITICAL STRESSES
C  ARE FROM MARTEC (1982).  THE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS
C  BASED ON THE WORK OF MILLER ET AL. (1977); THE CRITICAL STRESS FOR
C  SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966), WHERE THE
C  PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971).
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         FCW = BOTTOM FRICTION FACTOR
C         GD = SEDIMENT GRAIN SIZE (CM)
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY (GRAMS/CM**3)
C
C  OUTPUT VARIABLES:
C
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C
C  INTERMEDIATE VARIABLES:
C
C         ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2.
C         DRHO = SEDIMENT DENSITY - FLUID DENSITY (GRAMS/CM**3)
C         VISC = DYNAMIC VISCOSITY OF THE FLUID (GRAMS/CM*SEC)
C         G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C         RE = GRAIN REYNOLDS NUMBER
C         FALL = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS
C                ET AL. (1971) (CM/SEC)
C         TCB = CRITICAL BOTTOM STRESS FOR INITIATION OF BEDLOAD
```

```
C                 TRANSPORT (DYNES/CM**2)
C          TCS = CRITICAL BOTTOM STRESS FOR INITIATION OF SUSPENDED LOAD
C                 TRANSPORT (DYNES/CM**2)
C
C  INITIALIZE CONSTANTS
C
      G= 981.
      VISC=13.E-3
      DRHO=RHOS-RHOW
C
C  CALCULATE THRESHOLD VELOCITY FOR BEDLOAD TRANSPORT, VCB
C
      IF (UB .EQ. 0.0) THEN
        RE=GD*UA*SQRT(FCW/2.)*RHOW/VISC
      ELSE
        ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
        RE=GD*UB*SQRT(FCW*ALPHA/2.)*RHOW/VISC
      ENDIF
      TCB=0.04*DRHO*G*GD
      IF (RE .LT. 10.0) TCB=TCB*2.4/RE**0.33
      VCB=SQRT(2.*TCB/(RHOW*FCW))
C
C  CALCULATE THRESHOLD VELOCITY FOR SUSPENDED LOAD TRANSPORT, VCS
C
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TCS=0.64*RHOW*FALL**2
      VCS=SQRT(2.*TCS/(RHOW*FCW))
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TIMING(UA,PHIB,UB,PER,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,
     @PERSUSP)
C
C  THIS SUBROUTINE CALCULATES THE DURATION OF SEDIMENT TRANSPORT PHASES
C  (NO TRANSPORT, BEDLOAD TRANSPORT, SUSPENDED LOAD TRANSPORT) BY
C  CALCULATING WHEN THE RESPECTIVE CRITICAL VELOCITIES ARE EXCEEDED.
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         PER = WAVE PERIOD (SEC)
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C                TRANSPORT (CM/SEC)
```

```
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C
C  OUTPUT VARIABLES:
C
C         TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT CEASES (SEC)
C         TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT CEASES (SEC)
C         TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT RECOMMENCES (SEC)
C         TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT RECOMMENCES (SEC)
C         PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C         PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                   PHASE
C
C  INTERMEDIATE VARIABLES:
C
C         XS1 = COS(W*TS1), WHERE W IS THE WAVE ANGULAR FREQUENCY
C         XB1 = COS(W*TB1),            "                 "
C         XS2 = COS(W*TS2),            "                 "
C         XB2 = COS(W*TB2),            "                 "
C         B = -B/2A, AS IN EQ'N. FOR ROOTS OF A QUADRATIC EQUATION
C         B24AC = (B**2-4*A*C)/(2*A)**2, AS IN QUADRATIC EQ'N. SOLUTION
C
C  FIRST, SET DEFAULT VALUES TO ZERO
C
      PI=2.*ASIN(1.)
      TS1=0.0
      TB1=0.0
      TS2=0.0
      TB2=0.0
      PERSUSP=0.0
      PERBED=0.0
C
C  CONSIDER PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        IF (UA .GE. VCS) PERSUSP=100.
        IF (UA .GE. VCB .AND. UA .LT. VCS) PERBED=100.
        RETURN
C
C  CONSIDER PURE WAVE CASE
C
      ELSE IF (UA .EQ. 0.0) THEN
        IF (VCS .LT. UB) TS1=PER/(2.*PI)*ACOS(VCS/UB)
        IF (VCB .LT. UB) TB1=PER/(2.*PI)*ACOS(VCB/UB)
        TS2 = PER/2.-TS1
        TB2 = PER/2.-TB1
        PERSUSP=400.*TS1/PER
```

```
         PERBED=400.*(TB1-TS1)/PER
         RETURN
C
C  CONSIDER COMBINATION OF WAVES AND A CURRENT.  FIRST CALCULATE TIMES
C  FOR SUSPENDED LOAD, THEN BEDLOAD (SEE FLOWCHART IN USER'S GUIDE)
C
        ELSE
         B24ACS=(VCS**2-(UA*SIN(PHIB))**2)/(UB**2)
         IF (B24ACS .LE. 0.0) THEN
           TS1=PER/2.
           PERSUSP=100.0
           PERBED=0.0
           RETURN
         ELSE
           B=-UA*COS(PHIB)/UB
           XS1=B+SQRT(B24ACS)
C
           IF (XS1 .GE. 1.0) THEN
             PERSUSP=0.0
             GO TO 50
           ELSE IF (XS1 .LE. -1.0) THEN
             TS1=PER/2.
             PERSUSP=100.0
             PERBED=0.0
             RETURN
           ELSE
             TS1=PER/(2.*PI)*ACOS(XS1)
           ENDIF
C
           XS2=B-SQRT(B24ACS)
C
           IF (XS2 .LE. -1.0) THEN
             PERSUSP=200.*TS1/PER
           ELSE
             TS2=PER/(2.*PI)*ACOS(XS2)
             PERSUSP=(2.*(TS1-TS2)+PER)/PER*100.
           ENDIF
C
         ENDIF
C
C  CALCULATE TIMES FOR BEDLOAD
C
  50     B24ACB=(VCB**2-(UA*SIN(PHIB))**2)/(UB**2)
C
        IF (B24ACB .LE. 0.0) THEN
           TB1=PER/2.
           PERBED=100.-PERSUSP
           RETURN
         ELSE
           B=-UA*COS(PHIB)/UB
           XB1=B+SQRT(B24ACB)
```

```
C
          IF (XB1 .GE. 1.0) THEN
            PERBED=0.0
            RETURN
          ELSE IF (XB1 .LE. -1.0) THEN
            TB1=PER/2.
            PERBED=100.-PERSUSP
            RETURN
          ELSE
          TB1=PER/(2.*PI)*ACOS(XB1)
          ENDIF
C
          XB2=B-SQRT(B24ACB)
C
          IF (XB2 .LE. -1.0) THEN
            PERBED=200.*TB1/PER-PERSUSP
          ELSE
            TB2=PER/(2.*PI)*ACOS(XB2)
            PERBED=(2.*(TB1-TB2)+PER)/PER*100.-PERSUSP
          ENDIF
C
        ENDIF
C
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TRANSPO(UA,PHIB,U100,PHI100,UB,PER,WL,GD,KB,FCW,RHOS,
     @RHOW,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,
     @OPT)
      REAL K,KB
      INTEGER OPT
      EXTERNAL F1,F2,F3,F4,F5,F6
      COMMON UAX,UAY,UBB,W,A,VCBB
C
C  THIS SUBROUTINE CALCULATES THE TIME-AVERAGED NET SEDIMENT TRANSPORT

C  BY A CHOICE OF METHODS.  FOR THE PURE WAVE CASE THERE IS NO NET
C  TRANSPORT SINCE TRANSPORT DURING THE WAVE CREST IS EQUAL AND OPPOSITE
C  TO THAT DURING THE WAVE TROUGH (DUE TO THE USE OF LWT).  FOR THE PURE
C  CURRENT AND MIXED CONDITIONS, THE USER MAKES A CHOICE BETWEEN TRANS-
C  PORT FORMULAE, HOWEVER IF SUSPENDED LOAD TRANSPORT IS SIGNIFICANT IT
C  IS RECOMMENDED THAT A TOTAL LOAD FORMULA BE USED.
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
```

```
C                 WAVE BOUNDARY LAYER (RADIANS)
C          U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C          PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                   ABOVE SEABED (RADIANS)
C          UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C          PER = WAVE PERIOD (SEC)
C          WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C          GD = SEDIMENT GRAIN SIZE (CM)
C          KB = BOTTOM ROUGHNESS (CM)
C          FCW = BOTTOM FRICTION FACTOR
C          RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C          RHOW = FLUID DENSITY (GRAMS/CM**3)
C          VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C                TRANSPORT (CM/SEC)
C          VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C                LOAD TRANSPORT (CM/SEC)
C          TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C                TRANSPORT CEASES (SEC)
C          TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C                TRANSPORT RECOMMENCES (SEC)
C          TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C                LOAD TRANSPORT CEASES (SEC)
C          TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C                LOAD TRANSPORT RECOMMENCES (SEC)
C          PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C          PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                    PHASE
C          WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C          CDIR = CURRENT DIRECTION (AZIMUTH, DEGREES)
C
C  OUTPUT VARIABLES:
C
C          SED = TIME-AVERAGED NET SEDIMENT TRANSPORT AS VOLUME OF SEDIMENT
C                TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME (CM**2/SEC)
C                NOTE:  THIS IS NOT THE SAME AS VOLUME OF SOIL TRANSPORTED!
C          SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH, DEGREES)
C
      G=981.
      VISC=13.E-3
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TAUCRB=RHOW*FCW/2.*VCB**2
      TAUCRS=RHOW*FCW/2.*VCS**2
      UAX=UA*COS(PHIB)
      UAY=UA*SIN(PHIB)
      W=2.*PI/PER
      VCBB=VCB
      UBB=UB
```

```
C
C
      PRINT 15,PERBED,PERSUSP
      WRITE(7,15) PERBED,PERSUSP
  15  FORMAT(///,' PERCENT TIME SPENT AS BEDLOAD =',F7.2,/,
     @' PERCENT TIME SPENT IN SUSPENSION =',F7.2)
C
C  FOR THE PURE WAVE CASE NO NET TRANSPORT OCCURS
C
      IF (UA .EQ. 0.0) THEN
        SED=0.0
        SEDDIR=0.0
C
C  NO INTEGRATION IS REQUIRED FOR THE PURE CURRENT CASE.  WHEN TRANSPORT
C  IS AS SUSPENDED LOAD, THE TOTAL TRANSPORT FORMULA OF ENGELUND AND
C  HANSEN (1967) IS USED.  WHEN TRANSPORT IS AS BEDLOAD, THE USER HAS
C  A CHOICE OF FORMULAE.
C
      ELSE IF (UB .EQ. 0.0) THEN
        TAUO=RHOW*FCW/2.*UA**2
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
        ELSE IF (PERBED .EQ. 0.0) THEN
          PRINT 25
          WRITE (7,25)
  25      FORMAT(/,' SEDIMENT TRANSPORT WILL BE CALCULATED USING THE',/,
     @    ' ENGELUND-HANSEN TOTAL LOAD FORMULA')
          V=U100
          SED=0.05*V**2*SQRT(TAUO**3*RHOW)/(GD*DGAMMA**2)
          SEDDIR=CDIR
        ELSE
  30      PRINT 35
  35      FORMAT(//,' CHOOSE BETWEEN:',/,
     @    '   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
     @    '   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
     @    '   3 - MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION',/,
     @    '   4 - YALIN (1963) BEDLOAD EQUATION',/,
     @    ' ENTER 1,2,3 OR 4')
          READ*, OPT
          IF (OPT .EQ. 1) THEN
            V=U100
            SED=0.05*V**2*SQRT(TAUO**3*RHOW)/(GD*DGAMMA**2)
          ELSE IF (OPT .EQ. 2) THEN
            SED=40.0*FALL*GD*(TAUO/(DGAMMA*GD))**3
          ELSE IF (OPT .EQ. 3) THEN
            BETA=-2.033E-3*GD+1.088E-4
            SED=BETA/RHOS*(U100-VCB)**3
          ELSE IF (OPT .EQ. 4) THEN
            USTAR=SQRT(FCW/2.)*UA
            S=(UA/VCB)**2-1.0
```

```
            A=2.45*(RHOW/RHOS)**0.4*SQRT(TAUCRB/(G*DRHO*GD))
            SED=0.635*GD*USTAR*S*(1.0-ALOG(1.0+A*S)/(A*S))
          ELSE
            GO TO 30
          ENDIF
C
         SEDDIR=CDIR
        ENDIF
C
C  THE COMBINED WAVE AND CURRENT CASE REQUIRES INTEGRATION OF THE
C  INSTANTANEOUS TRANSPORT OVER THE WAVE PERIOD.  THE USE OF LWT ALLOWS
C  INTEGRATION TO BE DONE OVER ONLY HALF A WAVE CYCLE.  BAGNOLD'S METHOD
C  DOES NOT REQUIRE INTEGRATION.
C  THE X- AND Y- COMPONENTS OF TRANSPORT ARE CONSIDERED SEPARATELY,
C  WHERE THE X-COMPONENT IS PARALLEL TO THE WAVE DIRECTION AND THE
C  Y-COMPONENT IS NORMAL TO THE WAVE DIRECTION.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
      ELSE
        IF (TB1 .EQ. 0.0 .AND. TS1 .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
          GO TO 999
        ENDIF
        SEDXC=0.0
        SEDXT=0.0
        SEDYC=0.0
        SEDYT=0.0
 50     PRINT 55
 55     FORMAT (//,' CHOOSE BETWEEN:',/,
     @  '   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
     @  '   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
     @  '   3 - BAGNOLD (1963) TOTAL LOAD EQUATION',/,
     @  '   4 - YALIN (1963) BEDLOAD EQUATION',/,
     @  ' ENTER 1,2,3 OR 4')
        READ*,OPT
        IF (OPT .EQ. 1) THEN
          V=U100
          CONST=0.0177*(V*RHOW/DGAMMA)**2/GD
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F1,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 65,IER
            IF (IER .GT. 0) WRITE(7,65) IER
 65         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F1')
            SEDYC=2.*CONST*DCADRE(F2,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 75,IER
            IF (IER .GT. 0) WRITE(7,75) IER
 75         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F2')
          ELSE
            SEDXC=2.*CONST*DCADRE(F1,0.0,PER/2.,0.01,0.0,ER,IER)
```

```
          IF (IER .GT. 0) PRINT 65,IER
          IF (IER .GT. 0) WRITE(7,65) IER
          SEDYC=2.*CONST*DCADRE(F2,0.0,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 75,IER
          IF (IER .GT. 0) WRITE(7,75) IER
        ENDIF
        IF (TB2 .NE. 0.0) THEN
          SEDXT=2.*CONST*DCADRE(F1,TB2,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 65,IER
          IF (IER .GT. 0) WRITE(7,65) IER
          SEDYT=2.*CONST*DCADRE(F2,TB2,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 75,IER
          IF (IER .GT. 0) WRITE(7,75) IER
        ENDIF
C
C
      ELSE IF (OPT .EQ. 2) THEN
        CONST=5.*FALL*GD*(FCW*RHOW/(GD*DGAMMA))**3
        IF (TB1 .NE. 0.0) THEN
          SEDXC=2.*CONST*DCADRE(F3,0.0,TB1,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 85,IER
          IF (IER .GT. 0) WRITE(7,85) IER
  85      FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F3')
          SEDYC=2.*CONST*DCADRE(F4,0.0,TB1,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 95,IER
          IF (IER .GT. 0) WRITE(7,95) IER
  95      FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F4')
        ELSE
          SEDXC=2.*CONST*DCADRE(F3,0.0,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 85,IER
          IF (IER .GT. 0) WRITE(7,85) IER
          SEDYC=2.*CONST*DCADRE(F4,0.0,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 95,IER
          IF (IER .GT. 0) WRITE(7,95) IER
        ENDIF
C
        IF (TB2 .NE. 0.0) THEN
          SEDXT=2.*CONST*DCADRE(F3,TB2,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 85,IER
          IF (IER .GT. 0) WRITE(7,85) IER
          SEDYT=2.*CONST*DCADRE(F4,TB2,PER/2.,0.01,0.0,ER,IER)
          IF (IER .GT. 0) PRINT 95,IER
          IF (IER .GT. 0) WRITE(7,95) IER
        ENDIF
C
C
      ELSE IF (OPT .EQ. 3) THEN
        AB=UB*PER/(2.*PI)
        CALL FRIC3(UB,AB,PER,GD,KB,FCW)
        TAUOW=RHOW*FCW/2.*UB**2
        PRINT 105
```

```
105       FORMAT(//,' BAGNOLD''S METHOD REQUIRES A COEFFICIENT OF ',
     @    'PROPORTIONALITY, K',/,' WHICH RANGES BETWEEN 0.0 AND 1.0',/,
     @    ' PLEASE ENTER A VALUE FOR K')
          READ*, K
          SED=K*TAUOW*U100/(COSH(200.*PI/WL)*DGAMMA)
          SEDDIR=CDIR
C
C
        ELSE IF (OPT .EQ. 4) THEN
          ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          USTAR=SQRT(FCW*ALPHA/2.)*UB
          A=2.45*SQRT(TAUCRB/DGAMMA/GD)*(RHOW/RHOS)**0.4
          CONST=0.635*GD*USTAR
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F5,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 115,IER
            IF (IER .GT. 0) WRITE(7,115) IER
115         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F5')
            SEDYC=2.*CONST*DCADRE(F6,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 125,IER
            IF (IER .GT. 0) WRITE(7,125) IER
125         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F6')
          ELSE
            SEDXC=2.*CONST*DCADRE(F5,0.0,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 115,IER
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYC=2.*CONST*DCADRE(F6,0.0,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 125,IER
            IF (IER .GT. 0) WRITE(7,125) IER
          ENDIF
C
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F5,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 115,IER
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYT=2.*CONST*DCADRE(F6,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) PRINT 125,IER
            IF (IER .GT. 0) WRITE(7,125) IER
          ENDIF
C
C
        ELSE
          GO TO 50
        ENDIF
C
C
C
C
        IF (OPT .NE. 3) THEN
          SEDX=(SEDXC+SEDXT)/PER
          SEDY=(SEDYC+SEDYT)/PER
```

```
          SED=SQRT(SEDX**2+SEDY**2)
          PHIS=ATAN2(SEDY,SEDX)
          DIF=SIGN((PHI100-PHIS)*180./PI,CDIR-WDIR)
          CWDIF=ABS(CDIR-WDIR)
          IF(CWDIF .LE. 90.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 180.0 .AND. CWDIF .GT. 90.0) SEDDIR=CDIR+DIF
          IF (CWDIF .LE. 270.0 .AND. CWDIF .GT. 180.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 360.0 .AND. CWDIF .GT. 270.0) SEDDIR=CDIR+DIF
          IF (SEDDIR .LT. 0.0) SEDDIR=SEDDIR+360.0
          IF (SEDDIR .GE. 360.0) SEDDIR=SEDDIR-360.0
        ENDIF
      ENDIF
  999 RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F1(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F1=UX*(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F2(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F2=UY*(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F3(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F3=UX*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F4(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F4=UY*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
```

```
C***********************************************************************
      FUNCTION F5(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F5=S*(1.-ALOG(1.+A*S)/(A*S))*UX/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F6(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F6=S*(1.-ALOG(1.+A*S)/(A*S))*UY/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE OUTOUT(UB,AB,WL,FCW,UA,PHIB,VCB,VCS,TS1,TB1,TS2,TB2,
     @PERBED,PERSUSP,SED,SEDDIR,OPT)
      INTEGER OPT
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE OUTPUT PARAMETERS FROM ALL
C  SUBROUTINES
C
      PRINT 15
      WRITE(7,15)
 15   FORMAT(///,T4,'RESULTS:',//)
C
      PRINT 25,UB,AB,WL/100.
      WRITE(7,25) UB,AB,WL/100.
 25   FORMAT(T11,'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'VELOCITY, FROM LINEAR WAVE THEORY',T56,'=',F7.2,' CM/SEC',/,T11,
     @'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'DISPLACEMENT, FROM LINEAR WAVE THEORY',T56,'=',F8.2,' CM',/,T11,
     @'WAVELENGTH, FROM LWT DISPERSION EQUATION =',F7.2,' M',/)
C
      PRINT 35,FCW
      WRITE(7,35) FCW
 35   FORMAT(T11,'BOTTOM FRICTION FACTOR =',F7.4)
      IF (UB .EQ. 0.0) THEN
        PRINT 45
        WRITE(7,45)
 45     FORMAT(T11,'(STERNBERG, 1971)')
      ELSE IF (UA .EQ. 0.0) THEN
        PRINT 55
```

```
        WRITE(7,55)
  55    FORMAT(T11,'(JONSSON, 1966)')
      ELSE
        PRINT 65
        WRITE(7,65)
  65    FORMAT(T11,'(GRANT AND MADSEN, 1979)')
      ENDIF
C
      PRINT 75,UA,PHIB*90./ASIN(1.)
      WRITE(7,75) UA,PHIB*90./ASIN(1.)
  75  FORMAT(T11,'CURRENT SPEED TO BE USED IN BOTTOM STRESS',/,T11,
     @'CALCULATIONS',T53,'=',F7.2,' CM/SEC',/,T11,
     @'ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS',/,T11,
     @'WITHIN WAVE BOUNDARY LAYER',T53,'=',F7.2,' DEGREES',/,T11,
     @'NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY',/)
C
      PRINT 85,VCB,VCS
      WRITE(7,85) VCB,VCS
  85  FORMAT(T11,'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'BEDLOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/,T11,
     @'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'SUSPENDED LOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/)
C
      PRINT 95,TS1,TB1,TS2,TB2
      WRITE(7,95) TS1,TB1,TS2,TB2
  95  FORMAT(T11,'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT RECOMMENCES       =',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT RECOMMENCES              =',F6.2,' SEC',/)
C
      PRINT 105,PERBED,PERSUSP
      WRITE(7,105) PERBED,PERSUSP
 105  FORMAT(T11,'PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =',F7.2,/,
     @T11,'PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =',F7.2,/)
C
      PRINT 115,SEDDIR,SED
      WRITE(7,115) SEDDIR,SED
 115  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
C
      IF (UA .NE. 0.0) THEN
C
        IF (OPT .EQ. 1) THEN
          PRINT 125
          WRITE(7,125)
 125      FORMAT(T11,'(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)')
```

```
        ELSE IF (OPT .EQ. 2) THEN
          PRINT 135
          WRITE(7,135)
 135      FORMAT(T11,'(EINSTEIN-BROWN (1950) BEDLOAD EQUATION)')
        ELSE IF (OPT .EQ. 4) THEN
          PRINT 145
          WRITE(7,145)
 145      FORMAT(T11,'(YALIN (1963) BEDLOAD EQUATION)')
        ELSE IF (UB .EQ. 0.0) THEN
          PRINT 155
          WRITE(7,155)
 155      FORMAT(T11,'(MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION)')
        ELSE
          PRINT 165
          WRITE(7,165)
 165      FORMAT(T11,'(BAGNOLD (1963) TOTAL LOAD EQUATION)')
        ENDIF
C
      ENDIF
C
      PRINT 175
      WRITE(7,175)
 175  FORMAT(T11,'NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER
     @THAN',/,T18,'SOIL VOLUME TRANSPORT RATE',/)
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE BEDFORM(U100,UB,GD,KB)
      REAL KB
C
C  THIS SUBROUTINE PRINTS OUT THE EXPECTED TYPE OF BEDFORM FOR THE GIVEN
C  FLOW CONDITIONS (PURE WAVE OR PURE CURRENT CONDITIONS ONLY).  THE
C  BEDFORM TYPE IS ONLY APPROXIMATE SINCE IT IS BASED ON A VELOCITY
C  MEASUREMENT ONLY.  THE LIMITS ARE FROM C. L. AMOS, IN PROGRESS.
C
C  INPUT VARIABLES:
C
C            U100 = CURRENT SPEED AT 1 M. ABOVE SEABED ( CM/SEC)
C            UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C            GD = SEDIMENT GRAIN SIZE (CM)
C            KB = BOTTOM ROUGHNESS (CM)
C
C  INTERMEDIATE VARIABLES:
C
C            U30 = CURRENT SPEED 30 CM. ABOVE SEABED (CM/SEC)
C
C  FIRST, CALCULATE U30
```

```
C
      IF (KB .EQ. 0.0) KB=GD
      U30=U100*ALOG(900./KB)/ALOG(3000./KB)
C
C  SET UP FORMAT STATEMENTS
C
      PRINT 15
      WRITE(7,15)
  15  FORMAT(//,T11,'EXPECTED BEDFORMS ARE (C. L. AMOS):',/)
  25  FORMAT(T21,'WAVE RIPPLES')
  35  FORMAT(T21,'WAVE-INDUCED FLAT BED')
  355 FORMAT(T21,'WAVE RIPPLES OR WAVE-INDUCED FLAT BED')
  45  FORMAT(T21,'CURRENT RIPPLES')
  55  FORMAT(T21,'FLAT BED (LOWER)')
  65  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES')
  75  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES OR SAND WAVES')
  85  FORMAT(T21,'2-D MEGARIPPLES')
  95  FORMAT(T21,'2-D MEGARIPPLES OR SAND WAVES')
 105  FORMAT(T21,'SAND WAVES')
 115  FORMAT(T21,'SAND WAVES OR 3-D MEGARIPPLES')
 125  FORMAT(T21,'3-D MEGARIPPLES')
 135  FORMAT(T21,'FLAT BED (UPPER) AND SAND RIBBONS')
 145  FORMAT(T21,'SEDIMENT IN SUSPENSION')
 155  FORMAT(T21,'NO TRANSPORT')
 165  FORMAT(T21,'BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS')
C
C  VERY COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      IF (GD .LE. 0.2 .AND. GD .GT. 0.1) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 30.0) PRINT 155
          IF (UB .LT. 30.0) WRITE(7,155)
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) PRINT 25
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) WRITE(7,25)
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) PRINT 355
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) WRITE(7,355)
          IF (UB .GE. 200.0) PRINT 35
          IF (UB .GE. 200.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U30 .LT. 40.0) PRINT 155
          IF (U30 .LT. 40.0) WRITE(7,155)
          IF (U30 .GE. 40.0 .AND. U30 .LE. 45.0) PRINT 95
          IF (U30 .GE. 40.0 .AND. U30 .LE. 45.0) WRITE(7,95)
          IF (U30 .GE. 45.0 .AND. U30 .LE. 50.0) PRINT 75
          IF (U30 .GE. 45.0 .AND. U30 .LE. 50.0) WRITE(7,75)
          IF (U30 .GE. 50.0 .AND. U30 .LE. 60.0) PRINT 95
          IF (U30 .GE. 50.0 .AND. U30 .LE. 60.0) WRITE(7,95)
```

```
          IF (U30 .GE. 60.0 .AND. U30 .LE. 100.0) PRINT 105
          IF (U30 .GE. 60.0 .AND. U30 .LE. 100.0) WRITE(7,105)
          IF (U30 .GE. 100.0 .AND. U30 .LE. 295.0) PRINT 135
          IF (U30 .GE. 100.0 .AND. U30 .LE. 295.0) WRITE(7,135)
          IF (U30 .GE. 295.0) PRINT 145
          IF (U30 .GE. 295.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.1 .AND. GD .GT. 0.05) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 20.0) PRINT 155
          IF (UB .LT. 20.0) WRITE(7,155)
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) PRINT 25
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) WRITE(7,25)
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) PRINT 355
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) WRITE(7,355)
          IF (UB .GE. 125.0) PRINT 35
          IF (UB .GE. 125.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U30 .LT. 25.0) PRINT 155
          IF (U30 .LT. 25.0) WRITE(7,155)
          IF (U30 .GE. 25.0 .AND. U30 .LT. 35.0) PRINT 45
          IF (U30 .GE. 25.0 .AND. U30 .LT. 35.0) WRITE(7,45)
          IF (U30 .GE. 35.0 .AND. U30 .LT. 40.0) PRINT 55
          IF (U30 .GE. 35.0 .AND. U30 .LT. 40.0) WRITE(7,55)
          IF (U30 .GE. 40.0 .AND. U30 .LT. 45.0) PRINT 65
          IF (U30 .GE. 40.0 .AND. U30 .LT. 45.0) WRITE(7,65)
          IF (U30 .GE. 45.0 .AND. U30 .LT. 50.0) PRINT 85
          IF (U30 .GE. 45.0 .AND. U30 .LT. 50.0) WRITE(7,85)
          IF (U30 .GE. 50.0 .AND. U30 .LT. 60.0) PRINT 95
          IF (U30 .GE. 50.0 .AND. U30 .LT. 60.0) WRITE(7,95)
          IF (U30 .GE. 60.0 .AND. U30 .LT. 100.0) PRINT 115
          IF (U30 .GE. 60.0 .AND. U30 .LT. 100.0) WRITE(7,115)
          IF (U30 .GE. 100.0 .AND. U30 .LT. 150.0) PRINT 125
          IF (U30 .GE. 100.0 .AND. U30 .LT. 150.0) WRITE(7,125)
          IF (U30 .GE. 150.0 .AND. U30 .LT. 240.0) PRINT 135
          IF (U30 .GE. 150.0 .AND. U30 .LT. 240.0) WRITE(7,135)
          IF (U30 .GE. 240.0) PRINT 145
          IF (U30 .GE. 240.0) WRITE(7,145)
```

```
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  MEDIUM SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.05 .AND. GD .GT. 0.025) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 13.0) PRINT 155
          IF (UB .LT. 13.0) WRITE(7,155)
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) PRINT 25
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) WRITE(7,25)
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) PRINT 355
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) WRITE(7,355)
          IF (UB .GE. 100.0) PRINT 35
          IF (UB .GE. 100.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U30 .LT. 20.0) PRINT 155
          IF (U30 .LT. 20.0) WRITE(7,155)
          IF (U30 .GE. 20.0 .AND. U30 .LT. 50.0) PRINT 45
          IF (U30 .GE. 20.0 .AND. U30 .LT. 50.0) WRITE(7,45)
          IF (U30 .GE. 50.0 .AND. U30 .LT. 60.0) PRINT 85
          IF (U30 .GE. 50.0 .AND. U30 .LT. 60.0) WRITE(7,85)
          IF (U30 .GE. 60.0 .AND. U30 .LT. 100.0) PRINT 115
          IF (U30 .GE. 60.0 .AND. U30 .LT. 100.0) WRITE(7,115)
          IF (U30 .GE. 100.0 .AND. U30 .LT. 150.0) PRINT 125
          IF (U30 .GE. 100.0 .AND. U30 .LT. 150.0) WRITE(7,125)
          IF (U30 .GE. 150.0 .AND. U30 .LT. 170.0) PRINT 135
          IF (U30 .GE. 150.0 .AND. U30 .LT. 170.0) WRITE(7,135)
          IF (U30 .GE. 170.0) PRINT 145
          IF (U30 .GE. 170.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  FINE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.025 .AND. GD .GT. 0.0125) THEN
```

```
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 10.0) PRINT 155
          IF (UB .LT. 10.0) WRITE(7,155)
          IF (UB .GE. 10.0 .AND. UB .LT. 70.0) PRINT 25
          IF (UB .GE. 10.0 .AND. UB .LT. 70.0) WRITE(7,25)
          IF (UB .GE. 70.0) PRINT 35
          IF (UB .GE. 70.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U30 .LT. 13.0) PRINT 155
          IF (U30 .LT. 13.0) WRITE(7,155)
          IF (U30 .GE. 13.0 .AND. U30 .LT. 60.0) PRINT 45
          IF (U30 .GE. 13.0 .AND. U30 .LT. 60.0) WRITE(7,45)
          IF (U30 .GE. 60.0 .AND. U30 .LT. 85.0) PRINT 135
          IF (U30 .GE. 60.0 .AND. U30 .LT. 85.0) WRITE(7,135)
          IF (U30 .GE. 85.0) PRINT 145
          IF (U30 .GE. 85.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
      ENDIF
      RETURN
      END
```

A Re-evaluation of SED1D and SED2D: Sediment Transport Models for the Continental Shelf

by

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NOTATION

a = height above seabed corresponding to velocity $\vec{u}_a$

a_1 = parameter used in Yalin's method for calculating sediment transport

A_b = maximum wave-induced bottom particle displacement

d = water depth

D = sediment grain diameter

f = bottom friction factor

f_{cw} = bottom friction factor for mixed flow conditions

g = acceleration due to gravity

g_s = sediment transport rate in volume of sediment grains transported per unit bed width per unit time

H = wave height

H_b = breaking wave height

k = wave number $(2\Pi/L)$

k_b = bottom roughness height

k_{bc} = apparent bottom roughness height

K = coefficient used in Bagnold's method for calculating sediment transport

ℓ = length scale for bottom boundary layer $(\kappa|u_{*cw}|/\omega)$

L = wave length

R_{e*} = grain Reynolds number $(\frac{D}{\nu}\sqrt{\frac{\tau_b}{\rho}})$

s = parameter used in Yalin's method for calculating sediment transport

t = time

T = wave period

$\vec{u}$ = instantaneous velocity vector

$\vec{u}_a$ = steady current velocity used in bottom stress calculations

$\vec{u}_b$ = maximum wave-induced bottom orbital velocity

$\vec{u}_c$ = steady current velocity used in Bagnold's method for calculating sediment transport

$\vec{u}_{100}$ = steady current velocity measured 100 cm above the seabed

$\vec{u}_z$ = steady current velocity measured z cm above the seabed

$\vec{u}_*$ = shear velocity

$\vec{u}_{*c}$ = shear velocity within current boundary layer for mixed flow conditions

$\vec{u}_{*cw}$ = shear velocity within wave boundary layer for mixed flow conditions

$\vec{u}(\delta_w)$ = steady current velocity at top of wave boundary layer

v_{cb} = critical velocity for initiation of bedload transport

v_{cs} = critical velocity for initiation of suspended load transport

V = mean flow velocity used in Engelund-Hansen method for calculating sediment transport

W = sediment fall velocity

β = coefficient used in Gadd's method for calculating sediment transport

δ_c = thickness of current boundary layer

δ_w = thickness of wave boundary layer

ζ_o = dimensionless bottom roughness height ($k_b/30\ell$)

κ = von Karman's constant

μ = dynamic viscosity of fluid

ν = kinematic viscosity of fluid

ρ = density of fluid

ρ_s = density of sediment grains

$\vec{\tau}_b$ = instantaneous bottom stress vector

τ_{bw} = magnitude of wave-induced bottom stress under mixed flow conditions

τ_{cb} = critical bottom stress for initiation of bedload transport

τ_{cs} = critical bottom stress for initiation of suspended load transport

τ_{sf} = skin friction component of total bottom shear stress

Φ = grain size unit ($\Phi = -\log_2 D$, D in mm)

Φ_b = angle between $\vec{u}_a$ and $\vec{u}_b$

Φ_z = angle between $\vec{u}_z$ and $\vec{u}_b$

ω = wave angular frequency ($2\Pi/T$)

1. INTRODUCTION

Sediment transport on a continental shelf has been the subject of several recent studies conducted by Martec Ltd. (Martec, 1982, 1983 and 1984) for the Atlantic Geoscience Centre of the Geological Survey of Canada. These studies have been concerned with development (Martec, 1982, 1983) and analysis (Martec, 1984) of numerical models to predict sediment transport under continental shelf conditions. Two models have been developed: SED1D, which predicts the instantaneous sediment transport at a single point under given wave, current and seabed conditions, and SED2D, a two-dimensional model developed particularly for the Sable Island and Banquereau Banks. SED1D is an improved version of the original model for sediment transport at a point, SEDMO, developed during the initial contract awarded to Martec in 1982 (see Martec, 1984).

Much of the theoretical formulation embedded in the present models has not been verified for continental shelf conditions. Both models use Grant and Madsen's (1979) approach to estimate bottom stresses under the combined influence of waves and a steady current; SED1D allows the user a choice of four methods to calculate resulting sediment transport, while SED2D uses the Einstein-Brown formulation. Grant and Madsen's method has not been compared in detail with enough field measurements to give confidence in its use, while all of the sediment transport algorithms were originally developed from river and flume data and have met with mixed success when applied in a marine environment (see Heathershaw, 1981 and Lees, 1983).

Previous studies (Seaconsult, 1984; Sundermann and Klocker, 1983) have recommended that, before further model modifications are considered, an appropriate data set be obtained for calibration of the existing models.

In order to fulfill this objective, the Environmental Studies Revolving Fund (ESRF) Bottom Sediment Committee has initiated a study of sediment motion at two sites near Sable Island. This study has been designed to obtain measurements of wave and current conditions at the designated sites for a period of several months during both fall and winter conditions, along with periodic measurements of net sediment motion. The project will continue through the winter of 1985.

The present contract was issued to Martec Ltd. with the main objective of calibrating the numerical model for sediment transport at a point, SED1D, using the results from the above ESRF study. However, the timing of the respective projects was such that the necessary data would not become available until after the termination date of this study. The contract objectives were therefore redefined, in conjunction with the scientific authority, to continue analysis and review of the theory and structure of both SED1D and SED2D.

This report will summarize the theoretical basis and assumptions involved in the use of both numerical models, as well as the differences between present and previous versions of these models. Chapters 2 and 4 of this report address SED1D and SED2D, respectively, while Chapter 3 summarizes the results of an extensive sensitivity analysis conducted on SED1D. The Appendices contain complete user instructions for the models, as well as a program listing for SED1D.

2. MODEL STRUCTURE - SED1D

SED1D is a user-interactive computer model written in FORTRAN V. The program structure is such that the process of computing sediment transport from a given set of wave, current and seabed conditions is broken down into component form and each component is contained in a separate subroutine. This modular approach allows each component of the computational process to be separately modified without rewriting the entire program. There are ten components to the model SED1D:

1. MAIN PROGRAM - controls passage of information between various subroutines where calculations are performed;
2. SUBROUTINE READIN - interactive user input of data required to run SED1D;
3. SUBROUTINE INOUT - echoes the input data from subroutine READIN to user;
4. SUBROUTINE OSCIL - calculates necessary wave parameters from input data;
5. SUBROUTINE FRICFAC - calculates bottom friction factor and other parameters required for bottom stress calculation;
6. SUBROUTINE THRESH - calculates the threshold fluid velocity for initiation of both bedload and suspended load transport;
7. SUBROUTINE TIMING - calculates times during a wave cycle when the respective critical velocities for bedload and suspended load transport are exceeded;
8. SUBROUTINE TRANSPO - calculates the time-averaged net sediment transport by one of several available methods;
9. SUBROUTINE OUTOUT - prints the values of the output parameters from all subroutines;

10. SUBROUTINE BEDFORM - prints out the expected type of bedform for the given flow conditions.

The various subroutines and the various theories and calculations involved will be described in the next section of this report.

2.1 SED1D Subroutines

In order to calculate sediment transport resulting from a given set of wave, current and seabed conditions, it is necessary to first make some estimate of the instantaneous bottom shear stress. This step is contained in subroutines OSCIL and FRICFAC. Once the bottom stress is known, the threshold conditions for sediment motion are determined in subroutine THRESH. Next, the instantaneous sediment transport must be integrated over those parts of the wave cycle where threshold conditions are exceeded; these steps are contained in TIMING and TRANSPO. Subroutine BEDFORM gives an indication of what types of bedforms are likely to be encountered under the existing flow conditions. These subroutines will now be described in more detail.

2.1.1 Subroutine OSCIL

It is common practice to describe the characteristics of wind-induced surface waves in terms of three variables: water depth (d), wave height (H) and wave period (T). However, the parameters required for bottom stress calculations are the maximum wave orbital velocity (u_b) and the maximum bottom particle displacement (A_b) at the seabed; these are given by

$$u_b = \frac{\pi H}{T} \frac{1}{\sinh (kd)} \qquad (1)$$

$$A_b = \frac{H}{2} \frac{1}{\sinh (kd)} \tag{2}$$

where k, the wave number, is determined from the linear wave theory dispersion equation

$$\omega^2 = gk \tanh (kd) \tag{3}$$

ω, the wave angular frequency, is given by

$$\omega = \frac{2\pi}{T} \tag{4}$$

and g is the acceleration due to gravity. Due to the transcendental nature of the dispersion equation it is necessary to solve for k using an iterative procedure; a Newton-Raphson root-finding scheme was chosen.

The use of linear wave theory limits the range of validity of the above equations to cases where $H/L < 1/20$, a restriction which often is exceeded on the continental shelf, especially in shallow water. However, choosing a more appropriate wave theory is not a simple matter (see discussion in Sarpkaya and Isaacson, 1981). Although attempts have been made to indicate, in a general sense, the most accurate wave theory to use for a given wave height, period and water depth, it has been found that the most appropriate theory often depends on the particular wave characteristic of interest. For example, Figure 2.1 indicates that linear wave theory is not valid for shallow water waves and for much of the intermediate depth wave range. Contrary to this conclusion, Grace (1976) has shown, by experimental measurements, that linear wave theory predicts fairly accurately the near-bottom orbital wave velocities for shallow water conditions.

Thus, the accuracy of linear wave theory for the range of wave conditions likely to be encountered on the continental shelf has not been satisfactorily resolved. However, linear wave theory does possess the

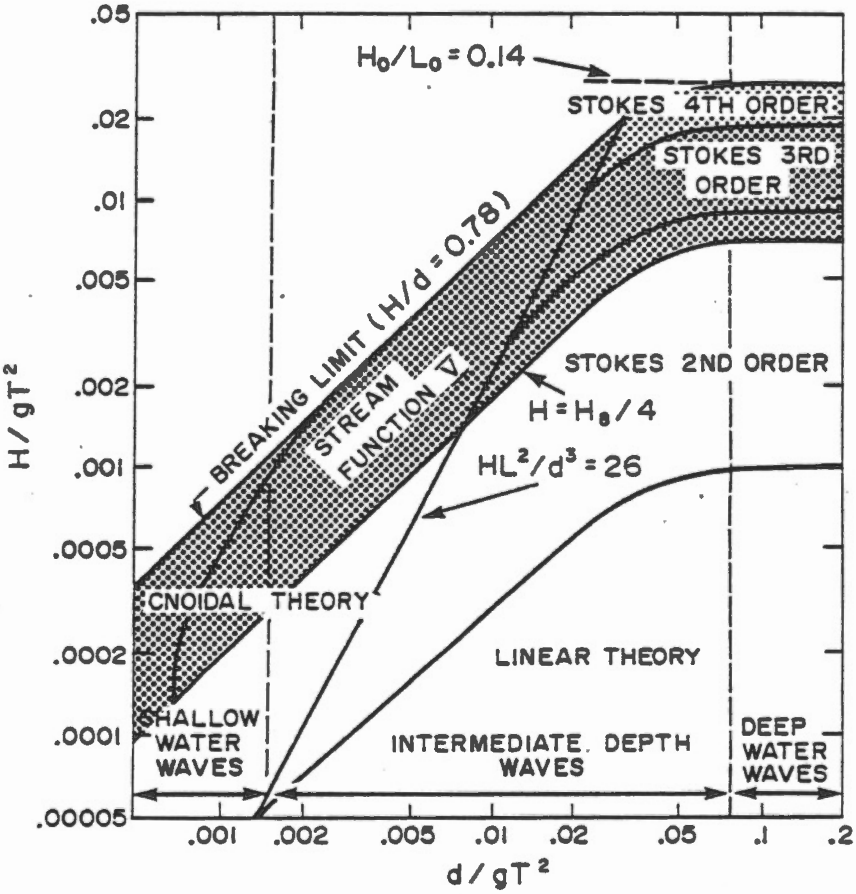

Figure 2.1. Approximate limits of validity for various wave theories (LeMéhauté, 1976).

advantages of being easy to use, requiring no intermediate numerical solutions as in other wave theories, and being generally accepted as the standard method. As well, Grant and Madsen's method for calculating bottom stress has been formulated in terms of linear wave theory. Although it may be possible to reformulate this method in terms of some other wave theory, it is felt at present that the errors introduced by the basic assumptions in the method are probably greater than those introduced by inaccuracies in the wave theory. The exception to this may be where waves are close to the breaking point.

A check for breaking waves is made using the Miche (1944) criterion, where the height at which a wave breaks, H_b, is given by

$$H_b = 0.142 \ L \tanh (kd) \tag{5}$$

and L is the wavelength. If the wave height H exceeds H_b, a warning message is sent to the user while execution continues.

One additional implication of linear wave theory is the absence of a net wave-induced current. This current may be significant when steady currents arising from other sources are small; unfortunately, the magnitude, and even direction, of the near-bed wave-induced current is debatable. It is left to the user to determine the relative importance, and magnitude, of such a current; it can easily be included in model calculations by a simple vector addition with any other current components.

2.1.2 Subroutine FRICFAC

A quadratic drag law was chosen to represent bottom stress as in the previous models:

$$\vec{\tau}_b = \frac{\rho}{2} f \ \vec{u} \ \left|\vec{u}\right| \tag{6}$$

where $\vec{\tau}_b$ is the instantaneous bottom stress vector, f is a friction factor and $\vec{u}$ is the instantaneous velocity vector. This subroutine is subdivided into three cases: (i) the pure wave case with no current, (ii) the pure current case with no waves, and (iii) mixed wave and current conditions.

(i) Pure wave case

The friction factor for the pure wave case is calculated using the method of Jonsson (1966) as modified by Nielsen (1979):

$$f = \exp\,[5.213\,(\frac{k_b}{A_b})^{0.194} - 5.977] \quad \text{for } \frac{A_b}{k_b} > 1.7 \tag{7}$$

$$f = 0.28 \quad \text{for } \frac{A_b}{k_b} \leq 1.7 \tag{8}$$

where k_b is the bottom roughness height, usually related to the bedform height or, in the absence of bedforms, the grain diameter.

Bottom stress is considered to be the product of two main components: that due to form drag associated with individual bedform elements and that due to skin friction evaluated at the granular level at the fluid-solid interface. Recent work (Madsen and Grant, 1976) has indicated that sediment transport is related to the skin friction component of total bottom stress only. Thus the sediment grain diameter (D) is used to determine bottom roughness height irrespective of the actual bedforms present on the seabed.

The instantaneous velocity vector for the pure wave case is given by

$$\vec{u} = \vec{u}_b \cos \omega t \tag{9}$$

where $\vec{u}_b$ and ω are calculated using linear wave theory in subroutine OSCIL.

(ii) Pure current case

Based on the field experiments of Sternberg (1972), the friction factor (as used in equation 6) is assumed to have a constant value of 6.0 x 10^{-3} for the pure current case. This value relates bottom stress to the square of the velocity when the current velocity is measured 100 cm above the seabed; if the current is measured at any other level, an intermediate step calculates u_{100} based on a logarithmic velocity profile:

$$u_{100} = u_z \frac{\log (3000/k_b)}{\log (30\ z/k_b)} \qquad (10)$$

where z is the height above the seabed, in cm, where u_z is measured. Previous model versions allow only u_{100}, rather than u_z, to be used as input.

(iii) Mixed wave and current conditions

The method described by Grant and Madsen (1979) is used to calculate both the friction factor and the appropriate velocity for calculating bottom stress under mixed wave and current conditions. It is assumed that the presence of the wave motion acts to increase the bottom roughness affecting the velocity profile and the bottom stress. As shown in Figure 2.2, the presence of the wave motion creates two distinct boundary layers: a thin, wave boundary layer where frictional dissipation due to both the oscillatory and steady components of motion is important, and a larger, current boundary layer where only the steady component of flow leads to

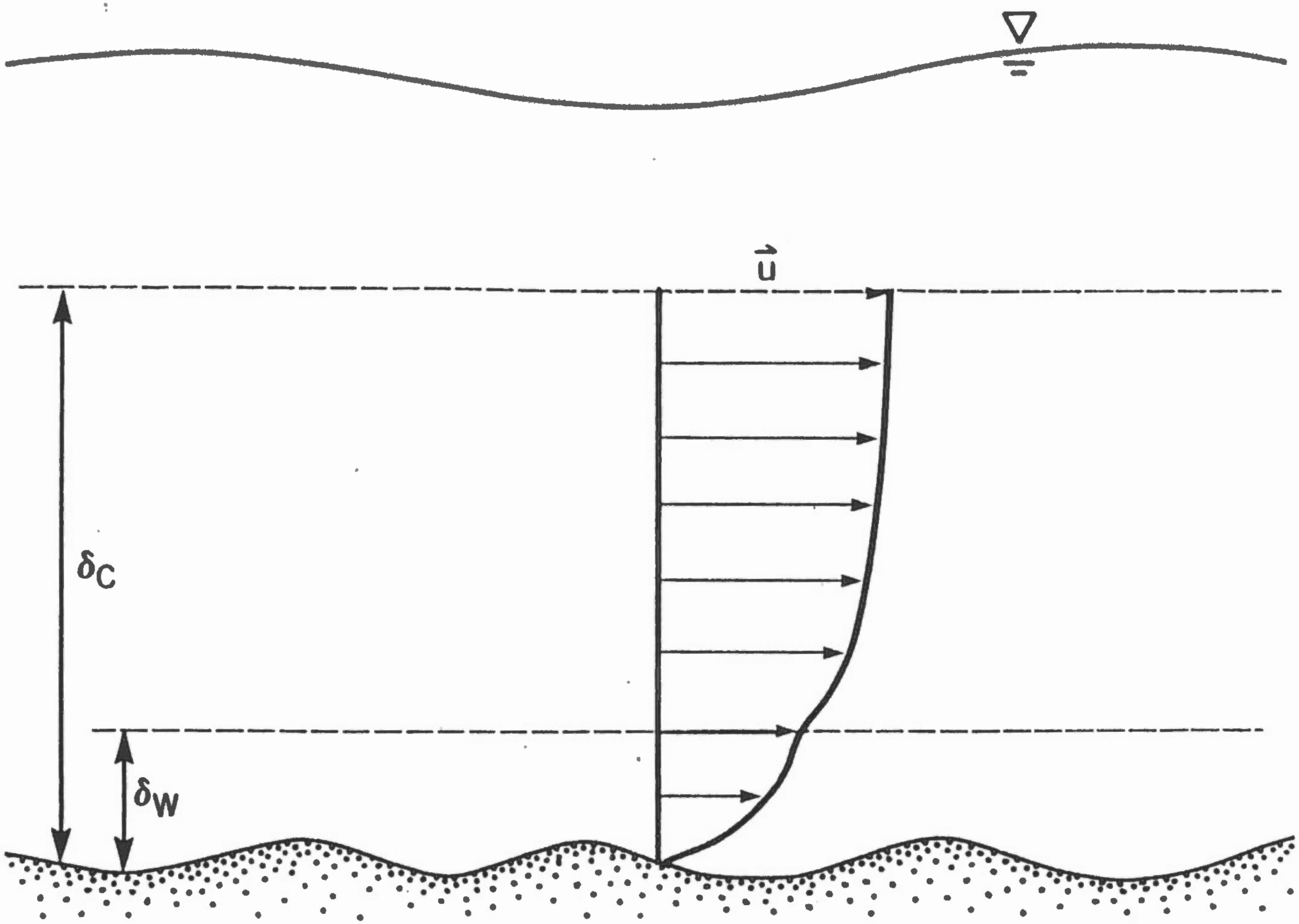

Figure 2.2. Bottom boundary layer when both waves and a steady current are present.

frictional dissipation since the wave-induced oscillatory motion is assumed to be inviscid.

This method is an iterative procedure based on four non-dimensional input parameters: k_b/A_b (as previously defined); ϕ_c, the angle between the wave and current directions outside the wave boundary layer; $|\vec{u}_z|/|\vec{u}_b|$ where $\vec{u}_z$ is the steady current velocity measured at a height z above the seabed; and z_r/k_b. Grant and Madsen's method is outlined in detail in Appendix A.

Although Grant and Madsen's method is used over the entire range of mixed wave and current conditions, its range of validity is limited to the case where current velocities are of the same order of magnitude as the bottom wave orbital velocity maximum. Outside this range the solutions may be less valid and a warning message is sent to the user while execution continues. This topic is discussed more fully in the next chapter. A warning message is also sent to the user if the height at which the input velocity is measured is found to be within the thin wave boundary layer.

Recent research has suggested that bottom shear stress be considered as the sum of two distinct components: that due to skin friction at the fluid-solid interface, and that due to the horizontal component of form drag which occurs when bedforms are present on the seabed. The reader is referred to Seaconsult (1984) for a further discussion of these two components. It is thought that sediment transport is related to the skin friction component of bottom stress, although the form drag influences the shape of the velocity profile in the upper boundary layer. However, it is not clear how to separate the two components of bottom shear stress. As suggested by Grant and Madsen, this separation is accomplished by calculating u_a, the steady component of velocity used in bottom stress calculations, by including the influence of bottom bedforms; but calculating f_{cw}, the bottom friction factor, using the sediment grain diameter alone to determine bottom roughness height.

Previous versions of the model for sediment transport at a point, SED1D, did not allow the friction factor to fall below a minimum value of 0.006 for mixed wave and current conditions. This value was obtained in a field study described by Sternberg (1972). However, Sternberg's observations were made in essentially unidirectional flows over varied bed conditions including rippled beds, and thus reflect the total bottom stress including form drag. The present version of SED1D computes the total bottom stress using both Sternberg's method and Grant and Madsen's method, using bedform height to determine bottom roughness; if the stress calculated from Grant and Madsen's method is less than that from Sternberg's method, the velocity u_a defaults to a new value such that the two stresses are equal. The velocity u_a was chosen rather than the friction factor since the friction factor represents only the skin friction component of total bottom stress, while the value of u_a also includes the contribution of form drag.

Grant and Madsen's method is based on a time-invariant eddy viscosity and friction factor. This study examined the possibility of incorporating time variation into this method; unfortunately, the difficulty of this problem placed it beyond the scope of this project. Recent work on turbulent wave boundary layers by Trowbridge and Madsen (1984a, 1984b) has shown the importance of time variation to bottom stress calculations, especially when nonlinearities in wave steepness are included. This conclusion has particular importance to the study of sediment transport, where the sediment is thought to respond in a nonlinear fashion to the instantaneous bed shear stress (see Madsen and Grant, 1976). Although this work has not been extended to wave-current boundary layers, it is expected that a time-varying eddy viscosity model may help to explain anomalous experimental results such as those obtained by Inman and Bowen (1963), where, in one case, sediment was found to move in a direction opposite to the wave propagation and current directions.

An extensive sensitivity analysis has been conducted on SED1D; this analysis is discussed in Chapter 3. However, one important conclusion should be mentioned here. It has been found that model results are very sensitive to the input value for bottom roughness height, k_b. This value must be estimated by the user from available information on bedform height, shape and distribution. There are many alternate equations available for calculating k_b for a given seabed configuration; for an example, the reader is referred to Grant and Glenn (1983). Furthermore, intense suspended sediment transport may lead to stratification within the bottom boundary layer, which is not considered in the present model. The reader is referred to Grant and Glenn (1983) and Gust and Southard (1983) for discussions of the effects of sediment transport on boundary layer structure.

Wave-current interaction effects, in particular the modification of a wave train by interaction with a current, have not been considered in the present model. These effects may be significant when the wave and current data used as model input are obtained from separate sources, for example, from separate numerical models. However, if the wave and current characteristics are obtained from in-situ measurements, this problem is avoided.

2.1.3 Subroutine THRESH

In this subroutine the critical conditions for initiation of both bedload and suspended load transport are determined. The critical stress for initiation of bedload transport (τ_{cb}) is determined from a modified Shields curve (see Miller et al. 1977) as follows:

$$\tau_{cb} = 0.04\ \Delta\rho g D \qquad \text{for } Re_* > 10 \tag{11}$$

$$\tau_{cb} = 0.096\ \Delta\rho g D\ Re_*^{-1/3} \qquad \text{for } Re_* \leq 10 \tag{12}$$

where $\Delta\rho = \rho_s - \rho_f$,

and ρ_s is the sediment density, ρ_f is the fluid density, g is the acceleration due to gravity, D is the sediment grain diameter and Re_* is the grain Reynolds Number given by

$$Re_* = \frac{D}{\nu} \sqrt{\frac{\overline{\tau}_b}{\rho}} \tag{13}$$

where ν is the kinematic viscosity of the fluid.

The critical stress for initiation of suspended load transport (τ_{cs}) is from Bagnold (1966):

$$\tau_{cs} = 0.64\ \rho W^2 \tag{14}$$

where W, the fall velocity of the sediment grains, is given by Gibbs et al. (1971) as:

$$W = \frac{-3\mu + [9\mu^2 + gD^2/4\ \rho\Delta\rho\ (0.015476 + 0.099205\ D)]^{1/2}}{\rho(0.011607 + 0.074405\ D)} \tag{15}$$

where μ is the dynamic viscosity of the fluid. These critical stresses for transport are transformed to critical velocities using the quadratic stress law and the appropriate friction factor.

Although the Shields criterion for initiation of bedload transport was originally derived for steady flow conditions over a flat bed of uniform sediment, it has been found to apply to more complicated conditions such as those considered in this study. Unfortunately, the accuracy of the Shields criterion is such that threshold conditions can only be predicted to within a factor of two, at best. The large scatter in both experimental and field measurements of threshold conditions can be attributed to several factors. First, the definition of the exact threshold of sediment motion is itself imprecise, varying from study to study. Secondly, turbulence near the seabed can cause high fluctuations in local stress conditions; usually the onset of sediment motion is related to average stress values rather than the high, localized values which may have caused the sediment to move. A third factor to be considered is the influence of biological action on the seabed, with respect to both bioturbation and biologically induced cohesion. Finally, variations in sediment characteristics such as shape and soil structure may lead to different thresholds for apparently similar sediments. The reader is referred to Seaconsult (1984) for a more complete discussion of these factors.

When dealing with fine sediments ($D \lesssim 0.2$ mm), it was found that the critical velocity for suspension was less than that for bedload transport. It is thought that these fine sediments go directly into suspension without passing through the intermediate bedload transport phase. This phenomenon has been included in the present version of SED1D; however, the user must be cautioned that the uncertainty in the calculation of critical velocities for fine sediments is fairly large and the direct suspension mechanism is under some dispute.

2.1.4 Subroutine TIMING

Once the critical velocities for transport are known , the next step is to determine when during a wave cycle these critical velocities are exceeded. For the pure wave case, this involves the solution of the following simple equations for t:

$$\left|\vec{u}_b \cos \omega t\right| = v_{cb} \tag{16}$$

$$\left|\vec{u}_b \cos \omega t\right| = v_{cs} \tag{17}$$

where v_{cb} and v_{cs} are the critical velocities for initiation of bedload and suspended load transport, respectively. Two roots to each equation are possible, one occurring during the passage of the wave crest and the other during the wave trough.

The combined wave and current case is somewhat more complex. Taking the magnitude of the instantaneous velocity vector and equating to the respective critical velocities results in these quadratic equations:

$$\cos \omega t = \frac{-1}{|\vec{u}_b|} [|\vec{u}_a| \cos \Phi_b \pm (v_{cb}^2 - |\vec{u}_a|^2 \sin^2 \Phi_b)^{1/2}] \tag{18}$$

$$\cos \omega t = \frac{-1}{|\vec{u}_b|} [|\vec{u}_a| \cos \Phi_b \pm (v_{cs}^2 - |\vec{u}_a|^2 \sin^2 \Phi_b)^{1/2}] \tag{19}$$

$\vec{u}_a$ is the steady current velocity used in bottom stress calculations and Φ_b is the angle between the wave and current directions inside the wave boundary layer.

This subroutine is based on the assumption that the instantaneous bottom shear stress is given by a quadratic drag law, as in Equation A-1, where the bottom friction factor, f_{cw}, and current speed, u_a, are determined using the method of Grant and Madsen (1979). However, the use of a time-invariant friction factor based on maximum stress conditions may not adequately represent the conditions throughout a wave cycle, especially when the phase shift between bottom velocity and shear stress is considered.

The percent time spent in each transport phase (no transport, bedload transport, suspended load transport) is also calculated in this subroutine.

2.1.5 Subroutine TRANSPO

In this subroutine the instantaneous sediment transport is numerically integrated over the course of a wave cycle. For the pure current case no integration is required since the conditions are constant. No net sediment transport occurs for the pure wave case due to the symmetry resulting from the use of linear wave theory (higher order wave theories include a wave-induced drift current).

The user must choose during each computer run one of four methods for calculating sediment transport. The options are:

(i) The Engelund-Hansen (1967) total load equation, where

$$g_s = 0.05V^2 \frac{(|\tau_b|^3 \rho)^{1/2}}{gD\Delta\rho^2} \tag{20}$$

and g_s is the volume rate of sediment transport per unit width of bed (cm^2/sec). This formula was originally based on flume experiments where V represented the mean flow velocity (discharge/cross-sectional area). For the present application it has been assumed that $V = |\vec{u}_{100}|$, the steady current velocity 1 m above the seabed; however, this assumption has not been verified.

This equation was developed for dune-covered beds and does not apply to rippled beds since the ratio of skin friction to total drag is not the same for both cases. It is not recommended for use when the mean grain size is less than 0.15 mm or when the geometric standard deviation of the sediment grain size distribution is greater than two. It has not been used under oscillatory flow conditions, but, it has been included in the present model for comparison purposes with the other transport formulae, and also because it is a total load formula rather than a bedload formula.

The user should be warned that an error was found in the previous version of SED1D, in the calculation of sediment transport using the Engelund-Hansen method. The friction factor was omitted from the calculation of bottom stress, τ_b, in the above equation; this error has been corrected in the present version of SED1D.

(ii) The Einstein-Brown (1950) bedload equation, where

$$g_s = 40 \, WD \left(\frac{|\vec{\tau}_b|}{\Delta\rho g D}\right)^3 \tag{21}$$

Grant and Madsen (1976) tested this equation for the instantaneous transport under waves alone and found that it agreed well with available data provided that $\vec{\tau}_b$, the bottom shear stress, was evaluated as the skin friction component only; however, the errors are significant near to the threshold of sediment motion. This equation was also based on flume data with well-sorted sediments covering a range of grain sizes (0.3 mm - 28.6 mm) and specific gravities (1.25 - 4.2).

(iii) The Yalin (1963) bedload equation, where

$$g_s = 0.635 \, D \, u_* s \left[1 - \frac{1}{a_1 s} \ln (1 + a_1 s)\right] \tag{22}$$

$$s = \frac{|\vec{u}|^2}{v^2_{cb}} - 1 \tag{23}$$

$$a_1 = 2.45 \left[\frac{\tau_{cb}}{g\Delta\rho D}\right]^{1/2} \left(\frac{\rho}{\rho_s}\right)^{0.4} \tag{24}$$

and $$u_* = \sqrt{\frac{\tau_b}{\rho}} \tag{25}$$

The instantaneous velocity vector, $\vec{u}$, is taken as $\vec{u}_{100}$ for the pure current case and as the vector sum $\vec{u}_a + \vec{u}_b \cos \omega t$ for mixed flow conditions.

This is the only method of the four considered to include threshold conditions for the mixed flow case. Again, the empirical coefficients have been derived from flume experiments under unidirectional flow conditions. Although this model uses only the skin friction component of bottom stress to calculate sediment transport, it has been suggested that the total bottom stress should be used (Seaconsult, 1984) with Yalin's method.

During the sensitivity analysis portion of this study, a problem was encountered when using Yalin's method for small grain sizes. For the case where the critical velocity for suspended load transport, v_{cs}, is less than the critical velocity for bedload transport, v_{cb}, the variable s in the above equations may become negative and lead to negative sediment transport. It is therefore recommended that Yalin's method not be used for grain sizes smaller than about 0.2 mm.

(iv) The Bagnold (1963) total load equation for mixed flow conditions, where

$$g_s = K \tau_{bw} \vec{u}_c \tag{26}$$

Bagnold assumed that the bottom stresses induced by the wave motion cause sediments to be suspended above the bottom, but, because the wave orbits are closed, a steady current component, $\vec{u}_c$, is required to cause net transport. Transport is assumed to be in the direction of this steady current.

The shear stress on the bottom due to the waves alone, τ_{bw}, is determined using Grant and Madsen's results, where

$$\tau_{bw} = \frac{0.2\ \rho\ \left|\vec{u}_{*cw}\right| \left|\vec{u}_b\right|}{[\mathrm{Ker}^2\ 2\zeta_0^{1/2} + \mathrm{Kei}^2\ 2\zeta_0^{1/2}]^{1/2}} \qquad (27)$$

All variables are as defined in Appendix A. The steady current component is assumed to be u_a, as determined using Grant and Madsen's method. K, a coefficient of proportionality, ranges between 0 and 1.0 and is chosen by the user. Unfortunately, it is difficult to estimate. In this form, Bagnold's method requires no integration.

Previous versions of SED1D used the quadratic stress law with a friction factor as defined by Jonsson (1966) to determine the shear stress on the bottom due to the wave-induced component of flow. It has since been decided that Grant and Madsen's method provides a more accurate representation of the maximum bottom stress due to the oscillatory component of motion when a steady current component is also present.

Alternatively, for the pure current case, Bagnold's bedload equation as modified by Gadd et al. (1978) is used. This method states that

$$g_s = \frac{\beta}{\rho_s} (u_{100} - v_{cb})^3 \qquad (28)$$

where β is a coefficient whose value depends on the sediment grain size. Based on numerous flume tests, Gadd et al. report values of β for grain sizes of 0.18 mm and 0.45 mm; for intermediate grain sizes the present program interpolates between the reported values. This method has been tested with moderate success in a marine environment by Heathershaw (1981).

Where numerical integration is required, an IMSL (International Mathematical and Statistical Library) routine, DCADRE, is used. This routine uses cautious adaptive Romberg extrapolation to estimate the value of the given integral. The IMSL library must be accessible in order to run SED1D for the mixed wave and current case.

Sediment transport is calculated as the volume of sediment grains transported per unit width of bed, per unit time. This is not the same as total soil transport rate; the two rates differ by a factor of 1-n, where n is the soil porosity. The user should be aware of the disparity between references in the units used for sediment transport. The more common variations include mass rate of transport, immersed weight transport rate and volume transport rate. All are simply related by factors such as the specific gravity of the sediment particles and the density of water.

2.1.6 Subroutine BEDFORM

In this subroutine, an estimate is made of the type of bedform likely to be encountered under the given flow conditions. This estimate is based only on near-bed flow velocities (u_{100} for currents, u_b for waves) so it is approximate. Corresponding seabed stresses were calculated using a quadratic drag law, as in Equation (6), and a friction factor of 0.006. At the present time, only the pure wave and pure current cases are considered. Expected bedform type is determined from Table 2.1, after Amos (in prep.).

A. Non Cohesive Sediment

BEDFORM	BOUNDS	SAND			
		FINE	MEDIUM	COARSE	V. COARSE
Current Ripples	Upper	60 cm/s	50 cm/s	35 cm/s	no ripples
	Lower	13 cm/s	20 cm/s	25 cm/s	
Flat Bed (Lower)	Upper	no flat bed	no flat bed	45 cm/s	50 cm/s
	Lower			40 cm/s	45 cm/s
2-D Megaripples	Upper	no 2-D mega-ripples	60 cm/s	60 cm/s	60 cm/s
	Lower		50 cm/s	40 cm/s	40 cm/s
Sand Waves	Upper	no sand waves	100 cm/s	100 cm/s	100 cm/s
	Lower		60 cm/s	50 cm/s	40 cm/s
3-D Megaripples	Upper	no 3-D mega-ripples	150 cm/s	150 cm/s	no 3-D mega's
	Lower		60 cm/s	60 cm/s	
Flat Bed (Upper)	Upper	85 cm/s	170 cm/s	240 cm/s	295 cm/s
	Lower	60 cm/s	150 cm/s	150 cm/s	120 cm/s
Wave Ripples	Upper	70 cm/s	100 cm/s	125 cm/s	200 cm/s
	Lower	10 cm/s	13 cm/s	20 cm/s	30 cm/s
Wave Induced Flat Bed	Upper	--	--	--	--
	Lower	70 cm/s	80 cm/s	90 cm/s	100 cm/s

B. Cohesive Sediment

BEDFORM	Soft Sediment S_v=0-50 pa	Stiff Sediment S_v=25 kpa
Megaflutes	12-36 cm/s	200 cm/s (U_{100})
Mud Furrows	12-36 cm/s	200 cm/s (U_{100})
Mud Waves	20 cm/s	20 cm/s (U_{100})

Table 2.1. Bottom bedform type based on near-bed flow velocitis (after Amos, in prep.).

3. SENSITIVITY ANALYSIS

An extensive sensitivity analysis has been conducted on the model for sediment transport at a point, SED1D. This analysis has looked at the behaviour of most of the intermediate variables in the calculation of bottom stress and resulting sediment transport under a variety of input conditions. Output from the sensitivity analysis is in the form of tables, as shown in Figure 3.1. Each table reflects the variation in a particular intermediate variable for different combinations of velocities u_{100} (steady current velocity measured 100 cm above the seabed) and u_b (maximum wave-induced bottom orbital velocity). Other input parameters are held constant for the generation of each table but are varied between tables. These input parameters are wave period, T; angle between wave and current directions, ϕ_b; sediment grain size, D; bottom roughness height, k_b; sediment density, ρ_s; and fluid density, ρ. Sediment and fluid densities are held constant for the generation of all the tables with values of 2.65 and 1.03 g/cm^3, respectively. Each of the other four input parameters has two possible values; this gives a total of sixteen tables for each intermediate variable to be examined. The values of the four input parameters used in this sensitivity analysis are given in Table 3.1, along with a list of the intermediate variables examined.

For example, Figure 3.1 shows the behaviour of the bottom friction factor, f_{cw}, for different combinations of u_{100} and u_b, each ranging from 0 to 100 cm/sec. This table was generated for a wave period of 10 seconds, sediment grain size of 1.0 mm, bottom roughness height of 10 cm and wave and current directions colinear. The behaviour of the bottom friction factor with respect to these parameters will be described later in this Chapter.

u_{100} (cm/sec)

Ub (cm/sec)	0.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
0.00	.0060	.0060	.0060	.0060	.0060	.0060	.0060	.0060	.0060	.0060	.0060
10.00	.0178	.0155	.0073	.0051	.0043	.0038	.0034	.0032	.0030	.0028	.0027
20.00	.0139	.0134	.0115	.0069	.0052	.0043	.0039	.0035	.0032	.0030	.0029
30.00	.0123	.0119	.0113	.0095	.0065	.0050	.0043	.0038	.0035	.0033	.0031
40.00	.0113	.0109	.0107	.0099	.0083	.0061	.0049	.0043	.0038	.0035	.0033
50.00	.0106	.0102	.0101	.0097	.0089	.0075	.0058	.0047	.0042	.0038	.0035
60.00	.0101	.0097	.0097	.0094	.0089	.0081	.0068	.0054	.0046	.0041	.0037
70.00	.0097	.0093	.0093	.0091	.0088	.0083	.0074	.0063	.0051	.0045	.0040
80.00	.0093	.0090	.0090	.0089	.0087	.0083	.0077	.0068	.0058	.0049	.0043
90.00	.0091	.0087	.0087	.0096	.0085	.0082	.0079	.0072	.0065	.0055	.0047
100.00	.0088	.0084	.0084	.0084	.0083	.0081	.0078	.0073	.0067	.0060	.0052

Wave Period = 10.00 sec
Angle Between Wave and Current Directions = 0.00 Degrees
Sediment Grain Size = 1.00 mm
Bottom Roughness Height = 10.00 cm
Sediment Density = 2.65 g/cm^3
Fluid Density = 1.03 g/cm^3

Figure 3.1. Sample sensitivity analysis results for bottom friction factor, f_{cw}.

Input Parameter	Assigned Values
T = wave period	10, 15 sec
D = sediment grain size	1.0, 0.1 mm
k_b = bottom roughness height	10, 0 cm
ϕ_{100} = angle between wave and current directions	0°, 90°

Intermediate Variables

f_{cw} = bottom friction factor

k_{bc} = apparent bottom roughness

u_a = velocity used in bottom stress calculation

a = height above seabed at which u_a is measured

ϕ_b = angle between wave and current directions within wave boundary layer

δ_w = wave boundary layer thickness

$u(\delta_w)$ = velocity at top of wave boundary layer

u_{*cw} = shear velocity within wave boundary layer

u_{*c} = shear velocity within current boundary layer

τ_b = total bottom shear stress

τ_{sf} = skin friction component of bottom shear stress

τ_{cb} = critical stress for initiation of bedload transport

τ_{cs} = critical stress for initiation of suspended load transport

v_{cb} = critical velocity for initiation of bedload transport

v_{cs} = critical velocity for initiation of suspended load transport

TABLE 3.1 INPUT PARAMETERS AND INTERMEDIATE VARIABLES USED IN SENSITIVITY ANALYSIS

The rest of this Chapter will describe the general behaviour of the intermediate variables with respect to changes in the input parameters. In addition, several important limitations to the use of the model will be discussed. Two separate sets of tables were generated for this sensitivity analysis: the first set follows Grant and Madsen's method for calculating bottom stress exactly, the second set includes the velocity default described in Section 2.1.2. The impacts of this velocity default on sediment transport will also be discussed.

The following discussion will remain qualitative in nature rather than quantitative due to the limited range of input conditions considered. However, the input parameter values have been chosen to realistically represent conditions likely to be encountered on a continental shelf, particularly off of Eastern Canada.

3.1 Intermediate Variable Behaviour

This section will summarize the results of the sensitivity analysis with respect to the behaviour of the intermediate variables listed in Table 3.1. Although the pure current and pure wave conditions were included in the sensitivity analysis ($u_b = 0$ and $u_{100} = 0$, respectively), this discussion will focus on the mixed wave and current case where bottom stress calculations were based on the method of Grant and Madsen (1979).

In general, it was found that the bottom friction factor, f_{cw}, decreases as the steady current component, u_{100}, increases, for a fixed value of the wave-induced current, u_b. For equal flow velocities, the friction factor is significantly higher when that velocity is due to oscillatory wave motion rather than a steady current. This seems to indicate that wave-induced flows are more important than steady current flows in increasing bottom stress, however, it must be remembered that bottom stress is not a function of the friction factor alone (see Equation A-1).

As expected, it was found that f_{cw} is independent of the input bottom roughness height for a given grain size and flow conditions. This reflects the assumption that stress can be divided into form drag and skin friction components; only the skin friction component, which is independent of bedform size, is included in the calculation of the bottom friction factor. As expected, the friction factor was found to decrease with decreasing grain size.

No consistent behaviour was recognized to relate the value of the friction factor to the relative angle between wave and current directions; sometimes f_{cw} was greater when waves and current were colinear, sometimes when they were perpendicular. An increase in wave period from 10 to 15 seconds seemed to decrease the friction factor slightly. Overall, the variation in the value of the friction factor was approximately one order of magnitude.

The apparent bottom roughness, k_{bc}, was also found to decrease with increasing u_{100} for a fixed wave velocity, u_b, as well as increasing with increasing u_b for a fixed current velocity, u_{100}. This is as expected since it is assumed that the waves act to increase the apparent roughness felt by the steady current above the wave boundary layer.

The apparent bottom roughness depends strongly on the input bottom roughness height. Indeed, increasing k_b from 0 to 10 cm can result in an increase in k_{bc} of up to three orders of magnitude. The user should be aware of this strong dependence on the input bottom roughness height, k_b, especially since it is not easily quantified from seabed characteristics.

The influence of angle between wave and current conditions on k_{bc} was slight, with slightly lower apparent roughness occurring for perpendicular flow conditions. As well, the response of k_{bc} to an increase in wave period was found to be dependent on the u_{100}/u_b ratio.

The bottom velocity to be used in bottom stress calculations, u_a, was calculated along with a, the height above the seabed to which this velocity value corresponds. These values were found to behave similarly to the bottom friction factor, f_{cw}, although they were found to increase as the bottom roughness height decreased, thus reflecting the effects of form drag. As form drag increases (k_b increases) the velocity u_a decreases, indicating the increased drag on the flow.

The thickness of the wave boundary layer, δ_w, and the velocity at the top of this layer, $u(\delta_w)$, were also found to follow a similar behaviour pattern. However, some apparent contradictions arose when this set of tables was compared with the previous set. Grant and Madsen's method assumes that the velocity used in bottom stress calculations, u_a, is measured somewhere within the wave boundary layer. Thus, on comparing the two sets of tables, one should find that $u(\delta_w)$ is greater than u_a and that δ_w is greater than a. However, this was often not the case, as can be seen by comparing Figure 3.2 with Figure 3.3.

There are two possible explanations for this contradiction. The first is of minor consequence and arises through the definition of the thickness of the wave boundary layer, δ_w. This definition is somewhat arbitrary. Grant and Madsen define δ_w as

$$\delta_w = 2\,\ell \qquad (29)$$

where

u_{100} (cm/sec)

Ub (cm/sec)	0.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
0.00	0.00 0.00 0.00	10.00 0.00 0.00	20.00 0.00 0.00	30.00 0.00 0.00	40.00 0.00 0.00	50.00 0.00 0.00	60.00 0.00 0.00	70.00 0.00 0.00	80.00 0.00 0.00	90.00 0.00 0.00	100.00 0.00 0.00
10.00	0.00 0.00 0.00	3.13 .34 0.00	14.62 28.16 0.00	26.44 85.12 0.00	37.90 131.74 0.00	49.55 176.98 0.00	61.43 224.53 0.00	73.55 275.75 0.00	85.88 331.23 0.00	98.42 391.22 0.00	111.14 455.86 0.00
20.00	0.00 0.00 0.00	2.54 .25 0.00	9.26 .98 0.00	22.39 32.62 0.00	35.97 136.14 0.00	49.19 239.32 0.00	61.83 329.18 0.00	74.48 411.99 0.00	87.21 492.91 0.00	100.06 574.56 0.00	113.05 653.44 0.00
30.00	0.00 0.00 0.00	2.37 .27 0.00	7.09 .55 0.00	15.09 2.34 0.00	30.55 38.59 0.00	45.82 172.34 0.00	60.56 333.03 0.00	74.01 474.48 0.00	87.38 603.94 0.00	100.70 724.96 0.00	114.05 841.48 0.00
40.00	0.00 0.00 0.00	2.29 .29 0.00	6.60 .48 0.00	12.91 1.10 0.00	23.03 4.91 0.00	39.59 50.07 0.00	56.07 207.95 0.00	70.91 405.15 0.00	84.29 610.55 0.00	100.31 791.00 0.00	114.18 958.58 0.00
50.00	0.00 0.00 0.00	2.25 .33 0.00	6.34 .47 0.00	11.96 .44 0.00	19.52 1.97 0.00	31.73 8.61 0.00	49.50 68.21 0.00	66.77 248.52 0.00	82.31 481.74 0.00	97.18 724.65 0.00	111.71 958.88 0.00
60.00	0.00 0.00 0.00	2.19 .35 0.00	6.19 .48 0.00	11.44 .75 0.00	18.27 1.40 0.00	27.55 3.54 0.00	41.73 15.70 0.00	60.08 92.94 0.00	77.90 296.64 0.00	94.01 561.91 0.00	109.42 847.17 0.00
70.00	0.00 0.00 0.00	2.17 .38 0.00	6.10 .50 0.00	11.11 .71 0.00	17.40 1.15 0.00	25.10 2.20 0.00	36.46 6.09 0.00	52.04 25.49 0.00	71.45 127.00 0.00	89.44 353.34 0.00	106.01 648.69 0.00
80.00	0.00 0.00 0.00	2.15 .41 0.00	6.03 .52 0.00	10.90 .70 0.00	16.84 1.04 0.00	24.14 1.72 0.00	33.30 3.55 0.00	46.55 10.41 0.00	63.00 39.61 0.00	83.15 168.15 0.00	101.35 419.34 0.00
90.00	0.00 0.00 0.00	2.14 .44 0.00	5.98 .53 0.00	10.75 .70 0.00	16.46 .97 0.00	23.30 1.50 0.00	31.28 2.57 0.00	42.31 5.63 0.00	55.32 14.70 0.00	74.51 53.32 0.00	95.31 218.73 0.00
100.00	0.00 0.00 0.00	2.14 .47 0.00	5.96 .55 0.00	10.65 .70 0.00	16.19 .94 0.00	22.70 1.36 0.00	30.45 2.15 0.00	39.70 3.86 0.00	52.04 8.74 0.00	67.76 25.28 0.00	86.59 85.67 0.00

u_a (cm/sec)	Wave Period = 10.00 sec
a (cm)	Angle Between Wave and Current Directions = 0.00 Degrees
ϕ_b (degrees)	Sediment Grain Size = 1.00 mm
	Bottom Roughness Height = 0.00 cm
	Sediment Density = 2.65 g/cm^3
	Fluid Density = 1.03 g/cm^3

Figure 3.2. Sample sensitivity analysis results for bottom velocity, u_a.

u_{100} (cm/sec)

Ub (cm/sec)	0.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00	0.00 0.00
10.00	10.00 .32	4.13 1.47	10.26 1.89	17.09 2.35	24.13 2.81	31.37 3.28	38.83 3.76	46.41 4.23	54.13 4.71	61.96 5.18	69.90 5.66
20.00	20.00 .54	3.86 2.35	9.75 2.73	16.72 3.18	23.68 3.62	31.28 4.09	38.82 4.56	46.49 5.02	54.27 5.49	62.16 5.97	70.15 6.44
30.00	30.00 .74	3.71 3.18	9.67 3.55	16.30 3.97	23.47 4.41	30.75 4.85	38.82 5.34	46.54 5.80	54.40 6.26	62.36 6.73	70.39 7.20
40.00	40.00 .91	3.63 3.98	9.50 4.34	16.16 4.74	23.26 5.17	30.57 5.61	38.11 6.09	45.89 6.51	54.48 7.01	62.53 7.48	70.64 7.95
50.00	50.00 1.08	3.57 4.76	9.39 5.11	16.03 5.50	22.88 5.91	30.51 6.36	38.00 6.80	45.73 7.24	53.65 7.70	61.70 8.16	69.84 8.62
60.00	60.00 1.24	3.47 5.52	9.30 5.85	15.93 6.25	23.00 6.66	30.29 7.08	38.10 7.53	45.66 7.97	53.55 8.41	61.61 8.87	69.78 9.33
70.00	70.00 1.39	3.44 6.27	9.25 5.50	15.85 6.98	22.93 7.39	29.99 7.79	37.93 8.25	45.78 8.69	53.62 9.14	61.55 9.58	69.72 10.03
80.00	80.00 1.53	3.42 7.00	9.21 7.33	15.80 7.71	22.88 8.11	30.26 8.53	37.72 8.95	45.97 9.41	53.65 9.84	61.70 10.29	69.71 10.73
90.00	90.00 1.68	3.40 7.72	9.19 8.05	15.76 8.42	22.84 8.82	30.24 9.24	37.50 9.64	45.63 10.09	53.10 10.51	61.67 10.98	69.96 11.44
100.00	100.00 1.81	3.39 8.44	9.17 8.76	15.74 9.13	22.82 9.53	30.23 9.94	37.86 10.36	45.47 10.78	53.70 11.23	61.90 11.68	69.83 12.12

$u(\delta_w)$ (cm/sec)
δ_w(cm)

Wave Period = 10.00 sec
Angle Between Wave and Current Directions = 0.00 Degrees

Sediment Grain Size = 1.00 mm
Bottom Roughness Height = 0.00 cm
Sediment Density = 2.65 g/cm^3
Fluid Density = 1.03 g/cm^3

Figure 3.3. Sample sensitivity analysis results for velocity at top of wave boundary layer, $u(\delta_w)$.

$$\ell = \kappa \left|\vec{u}_{*cw}\right| / \omega \qquad (30)$$

However, they state that the definition $\delta_\omega = 4\ell$ could just as easily be used in the present context (see Grant and Madsen, 1979). This uncertainty in the thickness of the wave boundary layer may explain the cases where δ_ω and a are close in value but of the wrong relative magnitude.

The second possible explanation is of much more importance to the use of this method for calculating bottom stress. On examining Figure 3.2, it can be seen that there is a region, towards the upper right corner of the table, where the velocities u_a are very high, indeed, often higher than the input velocity, u_{100}. It is generally thought that the wave boundary layer is quite thin, on the order of centimeters thick (see Seaconsult, 1984 and Figure 3.3). Thus, the velocities u_a should be significantly lower than the input velocity u_{100}, if u_a is assumed to be measured within the wave boundary layer.

A simple scaling of the equation of motion on which Grant and Madsen's method is based shows that the advective acceleration terms, neglected by Grant and Madsen, become important when the ratio u_a/u_b approaches unity. This value is exceeded in the upper right hand portion of each table generated during this sensitivity analysis. The anomalous values shown in Figure 3.2 confirm the assumption that Grant and Madsen's method is not valid in this region and should not be used. Indeed, it is suggested that the user restrict the use of this method to cases where the ratio u_{100}/u_b is less than one, and use it with caution when approaching this limit.

The shear velocities u_{*c} and u_{*cw} were found to increase with both increasing u_{100} and increasing u_b. It was found that increasing

u_{100} for a given u_b had a greater effect on the shear velocity in the upper current boundary layer, u_{*c}, than on the shear velocity in the wave boundary layer, u_{*cw}; the opposite was also found to be true. The shear velocities represent total bottom stress rather than just the skin friction component and thus were found to increase with increasing bottom roughness height. In general, the shear velocity in the wave boundary layer, u_{*cw}, was 4 to 7 times greater than that in the current boundary layer, u_{*c}; this reflects the assumption that the wave-induced component of flow is inviscid and does not contribute to shear stress above the wave boundary layer. Shear velocities were found to be slightly lower for perpendicular flow conditions than for colinear conditions, and an increase in wave period from 10 to 15 seconds was found to simultaneously increase u_{*c} slightly while decreasing u_{*cw}.

Maximum bottom shear stresses were also computed and the skin friction component compared with the total drag. The two are equal in the absence of bedforms, but a bottom roughness height of 10 cm can cause the total drag to be up to 10 times greater than the skin friction component. It should be noted that the bottom stress, in the absence of bedforms, is slightly greater than the skin friction component of total stress when bedforms are present. Since sediment transport is generally thought to depend on the bottom stress raised to some power greater than one, the use of the total drag as opposed to the skin friction component of bottom stress can lead to variations of several orders of magnitude in the calculated sediment transport. The user should be aware that the present model for sediment transport at a point, SED1D, is based upon the skin friction component only.

The critical stresses for both suspended load transport and bedload transport depend mainly on the sediment grain size. For small Reynolds number ($Re_* < 10$), the critical stress for bedload transport increases with decreasing bottom stress; however, this response is generally confined to small grain sizes. Also, for small grain sizes the critical stress for bedload transport can be greater than that for suspended load transport. These critical stresses can be converted into critical velocities using the quadratic stress law and the friction factor previously discussed. As expected, the critical velocity for suspension was found to be less than that for bedload transport for small grain sizes.

3.2 Sediment Transport

Sediment transport is generally considered to be proportional to the near-bed flow velocity (or bottom shear stress) raised to some power greater than one; the exact power varies from method to method. The Engelund-Hansen method gives sediment transport as a function of u^5, where u is the appropriate flow velocity, while the Einstein-Brown method assumes a u^6 dependency. Bagnold's method uses an exponent of 3, while the velocity dependency in Yalin's method is somewhat unclear due to the logarithmic terms. These exponents are only approximate for mixed wave and current conditions since the friction factor is also dependent upon the hydrodynamics. However, the differences in these exponents do explain the observed differences in the behaviour of the four methods for calculating sediment transport.

The response of the calculated sediment transport to variations in the input parameters reflects the dependency of sediment transport on bottom stress. As flow velocities increase, the sediment transport increases for all four methods. Sediment transport is slightly higher in the absence of bedforms than when bedforms are present for all except the Bagnold method. This is probably due to the method used to calculate the oscillatory portion of bottom shear stress, τ_{bw}, which has a nonlinear dependence on bottom roughness height.

In general, Bagnold's method gave the highest estimate of sediment transport rates; however, this method is highly dependent on the assumed value of K, the efficiency factor. The Engelund-Hansen total load equation gave the lowest estimate of sediment transport rate, often by more than one order of magnitude. For low transport rates the Einstein-Brown prediction was usually less than that given by the Yalin method; this was reversed at high transport rates. Interestingly, both the highest and lowest predictions were given by total load equations. It should also be noted that the sediment transport rates would all be several orders of magnitude higher if total bed shear stress were used rather than the skin friction component alone.

3.3 Influence of the Velocity Default

As mentioned previously, two sets of tables were generated for this sensitivity analysis. The first set followed Grant and Madsen's method for calculating bottom stresses exactly; the second set included a velocity default as described in Section 2.1.2. This velocity default insures that the total bottom stress under mixed flow conditions will always be at least equal to the average stress measured by Sternberg (1972) under essentially unidirectional flow conditions.

When the two sets of tables were compared, there were surprisingly few differences. The friction factors, apparent bottom roughnesses, wave boundary layer thicknesses and velocities at the top of the wave boundary layer all remained unchanged. The velocity default was found to occur only for cases where the bottom roughness height was zero; even then the default was confined to cases where the ratio u_{100}/u_b was very high (upper right hand corner of tables). Sternberg's measurements were made over a variety of bed conditions, most of which were not smooth. Thus, using his measurements to represent a minimum value for the shear stress over a flat bed probably overestimates the actual conditions. However, the default only occurs in regions where Grant and Madsen's method is not valid. The user is advised to use the results of this default with caution; a warning message is sent to the user if it occurs.

Variables influenced by the velocity default include the shear velocities, total bed shear and skin friction component, the critical stresses and velocities for transport, and the resulting sediment transport. Again, these variables were only influenced by the default when the input bottom roughness height was zero. As expected, the shear velocities were increased where the default occurred, as were the total drag and skin friction component of bottom shear stress. The maximum effect noted was a tripling of the bed shear stress, leading to roughly an order of magnitude increase in sediment transport. The critical stesses and velocities were found to decrease somewhat for a grain size of 0.1 mm, reflecting their dependency on Reynolds number in this size range.

4. TWO-DIMENSIONAL MODEL, SED2D

A two-dimensional model for sediment transport on the Sable Island and Banquereau Banks was developed during a previous contract awarded to Martec Ltd. This model is fully described in Martec (1983) and thus will only be summarized here. Although one of the objectives of the present contract was to review the structure of SED2D, it was decided that any major modifications should await the results of the calibration of the model for sediment transport at a point, SED1D.

SED2D was originally developed to model sediment transport under realistic conditions which are far more complex than the simple environment represented by SED1D. The complications introduced into SED2D are the use of random waves, characterized by a directional spectra; a seabed composed of many different grain size components; and a consideration of sediment accumulation or erosion. The model is designed to be time-stepped over the duration of a storm to allow the comparison of the impacts of different atmospheric events.

In order to model sediment transport over a large area, for the duration of a storm, including the complex conditions described above, requires a very large number of calculations. To minimize the computer times involved in using this model, a set of lookup tables containing the sediment transport rate resulting from various combinations of the input parameters was generated. When SED2D is run, these lookup tables are accessed and the appropriate values extracted; this saves recalculating sediment transport for a given set of conditions each time the model is used. However, computing times are still large, as are storage requirements for the lookup tables.

The sediment transport algorithm used in SED2D is based on SED1D; Grant and Madsen's method for calculating bottom stress is used along with the Einstein-Brown bedload equation. However, no allowance is made for the effects of bedforms; bottom roughness height is based solely on grain size. The inclusion of bedform height would significantly increase the size of the lookup tables and computing time for the model, although it may be necessary in order to calculate the skin friction component of total bottom stress.

The grid size used in this model (approximately 7.4 km by 5.2 km) is a major limitation to its accuracy. Conditions such as seabed grain size distribution and water depth are assumed constant for each grid square; however, spatial variations within each grid element may significantly affect the resulting sediment transport. For example, the sand waves and ridges commonly encountered on Sable Island Bank cannot be modelled at the present grid size, although they are thought to have a significant effect on the hydrodynamics and resulting sediment transport.

Several modifications must be made to the two-dimensional model before its use is considered. The most significant of these is the regeneration of the lookup tables for sediment transport. The original tables were generated for a range of Φ values which is not representative of the area under consideration. The appropriate programs (MKTRANS) and INTERPO) have been modified to correct this error, along with several others discovered during the analysis of this model. The lookup tables have not been regenerated since it is felt that this should wait until the basic subroutines for sediment transport have been calibrated using the results of the ongoing ESRF project described in the Introduction to this report.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has continued with the analysis and review of the existing models for sediment transport under continental shelf conditions, SED1D and SED2D. Emphasis has been placed on a thorough sensitivity analysis of the model for sediment transport at a point, SED1D. Several major conclusions have been reached:

- the model output is highly sensitive to the input value of bottom roughness height, k_b. This is reflected in the total bottom stress values being up to an order of magnitude larger for $k_b = 10$ cm than for flat bed conditions. The sediment transport rates do not reflect such a high sensitivity to bottom roughness height; however, this is due to the separation of bottom stress into form drag and skin friction components. It is assumed that sediment transport rate is proportional to only the skin friction component of total bottom shear stress.
- Grant and Madsen's method for calculating bottom stress is not valid when the radio u_{100}/u_b is greater than one, due to their neglect of the advective acceleration terms in the equation of motion. It is recommended that results be used with caution when approaching this limit, and that some alternate method be developed for calculating bottom stress under mixed flow conditions when the steady current component of flow is dominant.
- The separation of bottom stress into skin friction and form drag components has a major impact on the resulting sediment transport rates. If the total stress were to be used in

transport calculations, it is expected that transport rates would increase by more than one order of magnitude.

- A major limitation to the use of the two-dimensional model, SED2D, is the large grid size. Spatial variations in hydrodynamics and bed characteristics within each grid may be significant but cannot be resolved by the present model.

Further progress on the modelling of sediment transport under continental shelf conditions is severely constrained by the lack of an appropriate data set for calibration of the present models. It is hoped that the present ESRF project will provide data that can be used to either verify or disprove many of the assumptions made in the formulation of the present model, as well as to provide insight into the most accurate method for calculating sediment transport on the Scotian Shelf.

The modelling of sediment transport over a large area such as that covered by SED2D is a very expensive and time-consuming operation. SED2D requires the use of a super computer for runs covering the duration of a storm, and the results may be of questionable validity due to the limitation imposed by the large grid size. Reducing the grid size to a more reasonable scale would greatly increase the computing time.

It is recommended that another approach be invesigated for modelling sediment transport over large areas. One possibility is to develop an empirical relationship, such as that given by Thorn (1979), which gives sediment transport as a very simple function of current speed and wave intensity. Such a simple formulation could be used with a relatively fine grid size without exceeding the available computing power. However, such a relationship would have to be developed from experimental data and would probably be specific to that area where measurements were made.

Another possible approach would be to develop a large scale parametric relationship for sediment transport based on a model for sediment-transport at a point. For example, it may be possible to develop a simple relationship for sediment transport over a ridge by analyzing the results of a detailed, small scale, two-dimensional model based on SED1D. The large-scale parametric relationship could then be applied to large areas covered by sand ridges, such as those encountered on the Sable Island Bank.

REFERENCES

AMOS, C.L. (In prep). Bedforms. Modern Sedimentation Processes, Ch. 5, EG-1, DNAG Series.

BAGNOLD, R.A. 1963. Mechanics of marine sedimentation. In: The Sea, M.H. Hill (ed.) Publ. Wiley-Interscience, New York, N.Y.: 507-582.

BAGNOLD, R.A. 1966. An approach to the sediment transport problem from general physics. U.S. Geol. Surv. Prof. Paper 4421, 37 pp.

BROWN, C.B. 1950. In Rouse H., ed., Engineering Hydraulics, John Wiley and Sons, N.Y.: 1039 pp.

ENGELUND, F. and E. HANSEN. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen, Denmark.

GADD, P.E., J.W. LAVELLE and D.J.P. SWIFT. 1978. Estimates of sand transport on the New York shelf using near-bottom current-meter observations. J. Sedim. Petrol., 48: 239-252.

GIBBS, R.J., M.D. MATHEWS and D.A. LINK. 1971. The relationship between sphere size and settling velocity. J. Sedim. Petrol., 41 (1): 7-18.

GRACE, R.A. 1976. Near-bottom water motion under ocean waves. Proc. 15th Coastal Eng. Conf., Honolulu, 3: 2371-2386.

GRANT, W.D. and O.S. MADSEN. 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res., 84 (4): 1797-1808.

GRANT, W.D. and S.M. GLENN. 1983. Continental shelf bottom boundary layer model, Vol. I-III. Report to Pipeline Research Committee, American Gas Association, Project No. 1 PR-153-126.

GUST, G. and J.B. SOUTHARD. 1983. Effects of weak bed load on the universal law of the wall. J. Geophys. Res., 88 (C10): 5939-5952.

HEATHERSHAW, A.D. 1981. Comparisons of measured and predicted sediment transport rates in tidal currents. Mar. Geol., 42: 75-104.

INMAN, D.L. and A.J. BOWEN. 1963. Flume experiments on sand transport by waves and currents. Proc. 8th Coastal Eng. Conf., p. 137-150.

JONSSON, E.G. 1966. Wave boundary layers and friction factors. Proc. Coastal Eng. Conf. 10th, I: 127-148.

LE MÉHAUTÉ, B. 1976. An Introduction to Hydrodynamics and Water Waves, Springer-Verlag, Dusseldorf.

LEES, B.J. 1983. The relationship of sediment transport rates and paths to sandbanks in a tidally dominated area off the coast of East Anglia, U.K. Sedimentology, 30: 461-483.

MADSEN, O.S. and W.D. GRANT. 1976. Quantitative description of sediment transport by waves. Proc. Coastal Eng. Conf. 15th, II: 1093-1112.

MARTEC LIMITED. 1982. Sediment transport on a continental shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-1-M571, 91 pp.

MARTEC LIMITED. 1983. A 2-D sediment transport model for continental shelves. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-2-M777, 63 pp.

MARTEC LIMITED. 1984. SED1D: A Sediment Transport Model for the Continental Shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract IOSC. 23420-3-M753, 63 p.

MICHE, R. 1944. Mouvements ondulatoires des mers en profondeur constante on décroissante. Annales des Ponts et Chaussées, p. 25-78: 131-164, 270-292, 369-406.

MILLER, M.C., J.N. McCAVE and P.D. KOMAR. 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24: 507-527.

NIELSON, P. 1979. Some basic concepts of wave sediment transport. Inst. Hydrodynamics and Hydraulic Eng., Tech. Univ. of Denmark, Sed. Paper 20.

SARPKAYA, T. and M. ISAACSON. 1981. Mechanics of Wave Forces on Offshore Structures, Van Nostrand Reinhold Ltd., Toronto, Ontario, 651 p.

SEACONSULT. 1984. Bottom sediment transport - present knowledge and industry needs. Draft Report submitted to the Environmental Studies Revolving Funds Sediment Transport Committee, 299 p.

SMITH, J.D. 1977. Modelling of sediment transport on continental shelves. The Sea, 6, Publ. Wiley-Interscience, New York.

STERNBERG, R.W. 1972. Predicting initial motion and bedload transport of sediment particles in the shallow marine environment. In: Shelf Sediment Transport, Process and Pattern, D.J.P. Swift, D.B. Duane and O.H. Pilkey (eds.), Dowden, Hutchinson & Ross, Inc. 61-83.

SUNDERMANN, J. and R. KLOCKER. 1983. Sediment transport modelling with applications to the North Sea, in: Sundermann, J. and W. Lenz (eds.). North Sea Dynamics, Springer-Verlag, 453-471.

THORN, M.F.C. 1979. The effects of waves on the tidal transport of sand. Hydraulic Research Station Notes, 21: 4-5.

TROWBRIDGE, J. and O.S. MADSEN. 1984a. Turbulent wave boundary layers, 1, model formulation and first-order solution. J. Geophys. Res., 89 (C5): 79-89-7997.

TROWBRIDGE, J. and O.S. MADSEN. 1984b. Turbulent wave boundary layers, 2, second-order theory and mass transport. J. Geophys. Res., 89 (C5): 799-8007.

U.S. ARMY CORPS. OF ENGINEERS. 1977. Shore Protection Manual, Publ. Coastal Engineering Research Center, 3 vols.

YALIN, M.S. 1963. An expression for bedload transportation. Proc. A.S.C.E. 89, HY 3.

APPENDIX A

Grant and Madsen's (1979) method for calculating stress under the combined influence of waves and currents.

The mathematical formulation of this method for calculating bottom stress, as used in SED1D, will be reviewed here. For a theoretical justification of the following, see Grant and Madsen (1979).

The input variables to this routine are:

u_z = current speed measured z cm above the seabed (cm/sec)

ϕ_z = angle between the wave and current directions z cm above the seabed (radians)

u_b = maximum wave-induced bottom particle velocity from potential flow theory (cm/sec)

A_b = maximum wave-induced bottom particle displacement (cm)

k_b = bottom roughness (cm)

The output variables are:

f_{cw} = bottom friction factor for the combined wave and current case

u_a = current speed to be used in bottom stress calculations (cm/sec)

ϕ_b = angle between wave and current directions within the wave boundary layer (radians)

The instantaneous bottom stress is calculated from the output variables using

$$\left|\vec{\tau}_b\right| = \frac{\rho}{2} f_{cw}\left|\vec{u}_a + \vec{u}_b \cos \omega t\right|^2 \qquad \text{(A-1)}$$

where the current and wave velocities are added vectorally and the instantaneous stress is assumed to act colinearly with the instantaneous velocity vector. The procedure for calculating the output values is an iterative process and involves these steps:

1. Estimate u_a, Φ_b and, initially, f_{cw}. The initial estimates are

$$\Phi_{bo} = \Phi_z \tag{A-2}$$

$$f_{cwo} = \exp\left[5.213 \left(\frac{k_b}{A_b}\right)^{0.194} - 5.977\right] \quad \text{for } \frac{A_b}{k_b} > 1.7 \tag{A-3}$$

$$= 0.28 \quad \text{for } \frac{A_b}{K_b} \leq 1.7 \tag{A-4}$$

$$u_{ao} = u_z \frac{\log\left(\frac{30a_2}{k_b}\right)}{\log\left(\frac{30z}{k_b}\right)} \tag{A-5}$$

where a_2, the thickness of the wave boundary layer (Smith, 1977), is given by

$$a_2 = 0.4\ A_b \left(\frac{f_{cw}}{2}\right)^{1/2} \tag{A-6}$$

All subsequent estimates of u_a and Φ_b are obtained using the error in the previous estimate.

2. Calculate magnitude and direction of time-averaged shear stress. It is assumed that the time-averaged shear stress acts in the same direction as the steady current outside the wave boundary layer. Φ_c, the calculated angle between the wave and current directions outside the wave boundary layer, is given by

$$\Phi_c = \tan^{-1}\left(\frac{B}{A}\right) \tag{A-7}$$

where $A = 2\int_{-\pi/2}^{\pi/2} g_x(g_x^{\,2} + g_y^{\,2})^{1/2} d\theta$

$$B = \int_{-\pi/2}^{\pi/2} g_y (g_x^2 + g_y^2)^{1/2} \, d\theta \qquad \text{(A-9)}$$

$$g_x = \sin\theta + \frac{u_a}{u_b} \cos\phi_b \qquad \text{(A-10)}$$

$$g_y = \frac{u_a}{u_b} \sin\phi_b \qquad \text{(A-11)}$$

The magnitude of the time-averaged shear stress, $\vec{\tau}_c$, is given by

$$\left| \vec{\tau}_c \right| = \frac{\rho}{2} f_{cw} V_2 \left| \vec{u}_b \right|^2 \qquad \text{(A-12)}$$

where $$V_2 = \frac{(A^2 + B^2)^{1/2}}{2\pi} \qquad \text{(A-13)}$$

3. Next, calculate the bottom friction factor. This in itself is an iterative procedure, however, three iterations have been found to be sufficient for convergence (Martec, 1983).

$$f_{cw} = \left| \frac{0.097 \, K \left(\frac{k_b}{A_b}\right)^{1/2}}{\left(\frac{\alpha^{3/2}}{4} - C^2 \sin^2 \phi_z\right)^{1/2} - C \cos \phi_z} \right|^{4/3} \qquad \text{(A-14)}$$

where $$\alpha = 1 + \left(\frac{u_a}{u_b}\right)^2 + 2\left(\frac{u_a}{u_b}\right) \cos\phi_b \qquad \text{(A-15)}$$

$$C = \frac{V_2}{2\alpha^{1/4}} \qquad \text{(A-16)}$$

$$K = \frac{1}{2\zeta_0^{1/2} \left[\mathrm{Ker}^2(2\zeta_0^{1/2}) + \mathrm{Kei}^2(2\zeta_0^{1/2})\right]^{1/2}} \qquad \text{(A-17)}$$

$$\zeta_0 = \frac{k_b}{30\ell} \qquad \text{(A-18)}$$

$$\ell = 0.4\ A_b\ [\frac{f_{cw}\ \alpha}{2}]^{1/2} \qquad \text{(A-19)}$$

Ker and Kei are Kelvin functions of order zero.

4. The apparent bottom roughness, k_{bc}, is next calculated using

$$k_{bc} = k_b\ [24\ (\frac{A_b}{k_b})\ (\frac{f_{cw}\alpha}{2})^{1/2}]^{\beta} \qquad \text{(A-21)}$$

where $\beta = 1 - (\frac{V_2}{\alpha})^{1/2}$ (A-21)

5. The variables calculated in steps 2, 3 and 4 define a velocity profile for which the steady current velocity at z cm above the seabed, u_c, can be determined.

$$u_c = 2.5\ (\frac{f_{cw}V_2}{2})^{1/2}\ u_b\ \log\ (\frac{30z}{k_b}) \qquad \text{(A-22)}$$

6. Convergence is checked by comparing the calculated values u_c and Φ_c to the input values u_z and Φ_z, respectively. The allowable error has been set to 1.0%; steps 1-6 are repeated until this error level is achieved.

APPENDIX B

Description of SED1D

SED1D is a user-interactive computer model written in FORTRAN V. Although the user instructions contained in this appendix are specific to the CDC Cyber system at BIO, the model can readily be adapted for use on another system.

The required program input data is entered directly from the terminal following the appropriate user prompts. Once data entry is complete, all input data is echoed to the screen for vertification. All output parameters from each subroutine are also printed on the screen for immediate examination. A backup copy of input and output data is stored on the local file TAPE7; this file can be sent to the line printer or made permanent if future reference is required.

The present version of SED1D is stored in a file named SED1DE. In order to retrieve SED1DE from the user catalogue and produce a compiled version, two commands are required:

```
GET, SED1DE
FTN5, I=SED1DE, L=0, ANSI=0, B=SED1DEB
```

The compiled version of SED1DE is here given the name SED1DEB (or any admissible name of the user's choice). The compiled version can be made permanent so that this step does not have to be repeated in future terminal sessions. The command is

```
SAVE, SED1DEB
```

Two commands are needed to access the IMSL library:

```
ATTACH, IMSLIB/UN=LIBRARY
LIBRARY, IMSLIB/A
```

Program execution is initiated simply by repeating the name of the file containing the compiled version.

The above procedures are illustrated in the sample terminal session on the following pages. Entries made by the user are preceded by either a / or a ? and are in lower case type.

At the end of a terminal session, results of the entire session may be sent to the line printer by typing

```
REWIND, TAPE7
COPYSBF, TAPE7,OUT
ROUTE, OUT, DC=LP
```

The file TAPE7 can also be added to the user's permanent catalogue by using the SAVE command,

```
SAVE, TAPE7
```

```
 Get,sed1de
/ftn5,i=sed1de,l=0,ansi=0,b=sed1deb
     8.069 CP SECONDS COMPILATION TIME.
/attach,imslib/un=library
/library,imslib/a
LIBRARY,IMSLIB/A.
/save,sed1deb
/sed1deb

          SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
                   SHELF CONDITIONS

          VERSION IV  DEC. 15, 1984   SUSAN DAVIDSON, MARTEC LTD.



          THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
          AND THEIR LIMITATIONS


IF YUU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE
          TO ANY OF THE FOLLOWING QUESTIONS


 ENTER RUN NUMBER (1 - 9999)
? 1


 ENTER WATER DEPTH (M)
? 50


 ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE SEABED
 (CM/SEC, DEGREES TRUE, CM)
? 50,90,100


 ENTER WAVE HEIGHT, PERIOD AND DIRECTION
 (METRES,SECONDS,DEGREES TRUE)
? 10,10,0


 ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY
 (MM, GRAMS/CUBIC CM)
? 1.00,2.65


 ENTER BOTTOM ROUGHNESS HEIGHT (CM)
? 10


 ENTER FLUID DENSITY (GRAMS/CUBIC CM)
? 1.03
```

```
                    RUN NUMBER    1


  INPUT DATA:


         WATER DEPTH =  50.00 M
         CURRENT SPEED =  50.00 CM/SEC
         CURRENT DIRECTION =  90.00 DEGREES TRUE
         HEIGHT ABOVE BED = 100.00 CM
         WAVE HEIGHT =  10.00 M
         WAVE PERIOD = 10.00 SEC
         WAVE DIRECTION =    .00 DEGREES TRUE

         SEDIMENT GRAIN SIZE =  1.00 MM
         SEDIMENT DENSITY = 2.65 GRAMS/CUBIC CM

         BOTTOM ROUGHNESS HEIGHT =  10.00 CM


         FLUID DENSITY = 1.03 GRAMS/CUBIC CM






 PERCENT TIME SPENT AS BEDLOAD =  74.62
 PERCENT TIME SPENT IN SUSPENSION =    .00


 CHOOSE BETWEEN:
   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
   3 - BAGNOLD (1963) TOTAL LOAD EQUATION
   4 - YALIN (1963) BEDLOAD EQUATION
 ENTER 1,2,3 OR 4
? 2
```

```
RESULTS:


       MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
       VELOCITY, FROM LINEAR WAVE THEORY                =  80.04 CM/SEC
       MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
       DISPLACEMENT, FROM LINEAR WAVE THEORY            =  127.38 CM
       WAVELENGTH, FROM LWT DISPERSION EQUATION = 151.30 M

       BOTTOM FRICTION FACTOR =  .0082
       (GRANT AND MADSEN, 1979)
       CURRENT SPEED 1 M. ABOVE SEABED               =  49.99 CM/SEC
       CURRENT SPEED TO BE USED IN BOTTOM STRESS
       CALCULATIONS                                  =  23.42 CM/SEC
       ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
       WITHIN WAVE BOUNDARY LAYER                    =  90.00 DEGREES
       NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

       CRITICAL FLUID VELOCITY FOR INITIATION OF
       BEDLOAD TRANSPORT                             =  38.91 CM/SEC
       CRITICAL FLUID VELOCITY FOR INITIATION OF
       SUSPENDED LOAD TRANSPORT                      = 182.49 CM/SEC

       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       SUSPENDED LOAD TRANSPORT CEASES                 =   .00 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       BEDLOAD TRANSPORT CEASES                        =  1.87 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       SUSPENDED LOAD TRANSPORT RECOMMENCES            =   .00 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       BEDLOAD TRANSPORT RECOMMENCES                   =  3.13 SEC

       PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =  74.62
       PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =     .00

       DIRECTION OF NET SEDIMENT TRANSPORT =  90.00 DEGREES TRUE
       TIME-AVERAGED NET SEDIMENT TRANSPORT =   .3615E-01 CM**2/SEC
       (EINSTEIN-BROWN (1950) BEDLOAD EQUATION)
       NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER  THAN
              SOIL VOLUME TRANSPORT RATE



       EXPECTED BEDFORMS ARE (C. L. AMOS):

                 BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS


 ENTER 1 TO DO ANOTHER RUN, 0 TO STOP
? 0
   STOP
   0.699 CP SECONDS EXECUTION TIME.
/bye
```

APPENDIX C

Program Listing

```
      PROGRAM SED1DE(INPUT,OUTPUT,TAPE7)
      REAL KB,KBC
      INTEGER OPT
C
C  THIS PROGRAM CALCULATES SEDIMENT TRANSPORT UNDER A VARIETY OF WAVE
C  AND CURRENT CONDITIONS FOR HORIZONTAL BEDS ONLY.  A CHOICE OF
C  TRANSPORT FORMULAE IS AVAILABLE TO THE USER, HOWEVER, IT MUST BE
C  REMEMBERED THAT NONE OF THESE FORMULAE HAVE BEEN CALIBRATED FOR
C  COMBINED WAVE AND CURRENT CONDITIONS.
C
C  THIS VERSION ALLOWS THE VELOCITY TO BE INPUT AT ANY LEVEL WITHIN
C  THE BOTTOM LOGARITHMIC LAYER AND CONSIDERS THE AUTOSUSPENSION
C  PHENOMENON.  AS WELL, THIS VERSION HAS BEEN CHANGED SO THAT THE
C  VELOCITY USED IN BOTTOM STRESS CALCULATIONS, UA, DEFAULTS TO A
C  VALUE CORRESPONDING TO THE PURE CURRENT CASE ONLY WHEN THE TOTAL
C  BOTTOM STRESS IS LESS THAN THAT FOR A CURRENT ALONE.
C
C
      PRINT 5
      WRITE(7,5)
    5 FORMAT(/,T11,'SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL',
     @/,'                         SHELF CONDITIONS',//,
     @T11,'VERSION IV  DEC. 15, 1984   SUSAN DAVIDSON, MARTEC LTD.',////,
     @T11,'THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED',/,
     @T11,'AND THEIR LIMITATIONS',//)
    1 CALL READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW,QI)
      IF (QI .EQ. 1.0) GO TO 10
      CALL INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW)
C
C  CHANGE GRAIN SIZE FROM MM TO CM
C
      GD=GD*0.10
C
C  DO CALCULATIONS AND PRINT RESULTS
C
      CALL OSCIL(HT,PER,D,UB,AB,WL)
      CALL FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      CALL THRESH(U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
      CALL TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,TS1,
     @TS2,TB1S,TB2S)
      CALL TRANSPO(UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,RHOW,
     @VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,OPT,
     @TB1S,TB2S)
      CALL OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,TB2,
     @PERBED,PERSUSP,SED,SEDDIR,OPT)
      CALL BEDFORM(U100,UB,GD,KBC)
C
C  GIVE USER THE OPTION OF DOING ANOTHER RUN
C
   10 PRINT 15
   15 FORMAT(///,' ENTER 1 TO DO ANOTHER RUN, 0 TO STOP')
      READ*, IND
      IF (IND .EQ. 1) GO TO 1
      STOP
      END
```

```
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW,QI)
      REAL KB
C
C  THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING
C  SED1D.
C
C  OUTPUT VARIABLES:
C
C          IRUN = RUN NUMBER
C          D = WATER DEPTH (M)
C          UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C          Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (CM)
C          CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH, DEG.)
C          HT = WAVE HEIGHT (M)
C          PER = WAVE PERIOD (SEC)
C          WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C          GD = SEDIMENT GRAIN SIZE (MM)
C          KB = BOTTOM ROUGHNESS (CM)
C          RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C          RHOW = FLUID DENSITY ( GRAMS/CM**3)
C          QI = QUIT INDEX
C
      PRINT 15
   15 FORMAT('IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE',/,
     @T11,'TO ANY OF THE FOLLOWING QUESTIONS')
C
C  INITIALIZE QUIT INDEX TO 0
C
      QI=0.0
C
C  ENTER DATA
C
      PRINT 25
   25 FORMAT(//,' ENTER RUN NUMBER (1 - 9999)')
      READ*, IRUN
C
      PRINT 35
   35 FORMAT(//,' ENTER WATER DEPTH (M)')
      READ*, D
      IF ( D .EQ. -99.) GO TO 998
C
      PRINT 45
   45 FORMAT(//,' ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE SEABED',
     @/,' (CM/SEC, DEGREES TRUE, CM)')
      READ*, UZ,CDIR,Z
      IF (UZ .EQ. -99. .OR. CDIR .EQ. -99. .OR. Z .EQ. -99.) GO TO 998
C
      PRINT 55
   55 FORMAT(//,' ENTER WAVE HEIGHT, PERIOD AND DIRECTION',/,
     @' (METRES,SECONDS,DEGREES TRUE)')
      READ*, HT,PER,WDIR
      IF (HT .EQ. -99. .OR. PER .EQ. -99. .OR. WDIR .EQ. -99.) GO TO 998
```

```
C
      PRINT 65
   65 FORMAT(//,' ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY',/,
     @' (MM, GRAMS/CUBIC CM)')
      READ*, GD,RHOS
      IF (GD .EQ. -99. .OR. RHOS .EQ. -99.) GO TO 998
C
      PRINT 75
   75 FORMAT(//,' ENTER BOTTOM ROUGHNESS HEIGHT (CM)')
      READ*, KB
      IF (KB .EQ. -99.) GO TO 998
C
      PRINT 85
   85 FORMAT(//,' ENTER FLUID DENSITY (GRAMS/CUBIC CM)')
      READ*, RHOW
      IF (RHOW .EQ. -99) GO TO 998
C
      GO TO 999
  998 QI=1.0
  999 RETURN
      END
C
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW)
      REAL KB
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE INPUT PARAMETERS FROM
C  SUBROUTINE READIN
C
      PRINT 15, IRUN
      WRITE(7,15) IRUN
   15 FORMAT(////,T21,'RUN NUMBER ',I4,////,T4,'INPUT DATA:',//)
C
      PRINT 25, D,UZ,CDIR,Z
      WRITE(7,25) D,UZ,CDIR,Z
   25 FORMAT(T11,'WATER DEPTH =',F7.2,' M',/,T11,'CURRENT SPEED =',F7.2,
     @' CM/SEC',/,T11,'CURRENT DIRECTION =',F7.2,' DEGREES TRUE',/,
     @T11,'HEIGHT ABOVE BED =',F7.2,' CM')
C
      PRINT 35, HT,PER,WDIR
      WRITE(7,35) HT,PER,WDIR
   35 FORMAT(T11,'WAVE HEIGHT =',F7.2,' M',/,T11,'WAVE PERIOD =',F6.2,
     @' SEC',/,T11,'WAVE DIRECTION =',F7.2,' DEGREES TRUE',/)
C
      PRINT 45, GD,RHOS
      WRITE(7,45) GD,RHOS
   45 FORMAT(T11,'SEDIMENT GRAIN SIZE =',F6.2,' MM',/,T11,
     @'SEDIMENT DENSITY =',F5.2,' GRAMS/CUBIC CM',/)
C
      PRINT 55, KB,RHOW
      WRITE(7,55) KB,RHOW
   55 FORMAT(T11,'BOTTOM ROUGHNESS HEIGHT =',F7.2,' CM',//,T11,
     @'FLUID DENSITY =',F5.2,' GRAMS/CUBIC CM',///)
```

```
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE OSCIL(HT,PER,D,UB,AB,WL)
      REAL KD,KDO,K
C
C  THIS SUBROUTINE CALCULATES WAVE-INDUCED BOTTOM PARTICLE VELOCITY
C  AND DISPLACEMENT USING LINEAR WAVE THEORY.  A CHECK IS ALSO MADE
C  FOR WAVE BREAKING.
C
C  INPUT VARIABLES:
C        HT = WAVE HEIGHT (M)
C        PER = WAVE PERIOD (SEC)
C        D = WATER DEPTH (M)
C
C  OUTPUT VARIABLES:
C
C        UB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE VELOCITY (CM/SEC)
C        AB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE DISPLACEMENT(CM)
C        WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C
C  INTERMEDIATE VARIABLES:
C
C        G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C        C = CONVERSION FACTOR TO CGS UNITS
C        W = WAVE ANGULAR FREQUENCY (RAD/SEC)
C        K = WAVE NUMBER (RAD/CM)
C        KD = K*D
C        HB = BREAKING WAVE HT. FOR GIVEN WAVE PERIOD, WATER DEPTH (CM)
C
      IF (HT .EQ. 0.0) THEN
        UB=0.0
        AB=0.0
        WL=0.0
C
C  CALCULATE WAVELENGTH BY NEWTON-RAPHSON SOLUTION OF LWT DISPERSION
C  EQUATION.
C
      ELSE
      G=981.
      PI=2.*ASIN(1.)
      C=100.
      HT=HT*C
      D=D*C
      W=2.*PI/PER
      KDO=W**2*D/G
      KD=KDO
   20 CONTINUE
      DKD=(1./TANH(KD)-KD/KDO)/(1./KDO+1./SINH(KD)**2)
      KD=KD+DKD
      IF (ABS(DKD) .GE. 1.0E-4) GO TO 20
      WL=2.*PI*D/KD
```

```
C
C  NEXT CHECK FOR BREAKING WAVES USING THE MICHE (1944) CRITERION
C
      HB=0.142*WL*TANH(KD)
      IF (HT .GE. HB) THEN
      PRINT 25
      WRITE(7,25)
  25  FORMAT(///,' ***WARNING***',/,' THIS CASE CORRESPONDS TO BREAKING',
     @' WAVE CONDITIONS WHERE',/,' LINEAR WAVE THEORY IS NOT VALID')
      ENDIF
C
C  CALCULATE WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND DISPLACEMENT
C
      UB=PI*HT/(PER*SINH(KD))
      AB=UB/W
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      REAL KB,KBC
C
C  THIS SUBROUTINE CONTROLS THE CALCUATION OF THE BOTTOM FRICTION
C  FACTOR FOR VARIOUS WAVE AND CURRENT CONDITIONS.  ALTHOUGH THERE
C  IS NO NET SEDIMENT TRANSPORT IN THE ABSENCE OF A CURRENT, BED
C  MOBILITY AND BEDFORM GENERATION MUST STILL BE CONSIDERED.
C
C  INPUT VARIABLES:
C
C         UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C         CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH)
C         Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (CM)
C         WDIR = WAVE DIRECTION (AZIMUTH)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         KBC = APPARENT BOTTOM ROUGHNESS (CM)
C         FCW= BOTTOM FRICTION FACTOR
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)
C                  NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED
C                  OUTSIDE THE WAVE BOUNDARY LAYER.
```

```
C
C  INTERMEDIATE VARIABLES:
C
C         FBAD = BOTTOM FRICTION FACTOR INCLUDING FORM DRAG
C         UBAD = CURRENT SPEED NEGLECTING FORM DRAG (CM/SEC)
C         PHIBAD = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS, WITHIN
C                  WAVE B.L. AND NEGLECTING FORM DRAG (RADIANS)
C         RATIO = UA/UB;  DETERMINES VALIDITY OF EQUATION OF MOTION
C                 USED BY GRANT AND MADSEN (1979)
C
C  PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        CALL FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
        PHIB=0.0
        PHI100=0.0
        KBC=KB
C
C  WAVES AND CURRENT CASE (CHECK FOR VALIDITY OF METHOD)
C
      ELSE IF (UZ .NE. 0.0) THEN
        PHI100=AMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
     @  360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
        IF (KB .EQ. 0.0) THEN
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBC,FCW,UA,PHIB,U100)
        ELSE
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FBAD,UA,PHIB,U100)
          CALL CHECK(U100,UA,UB,PHIB,FBAD)
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBCBAD,FCW,UBAD,PHIBAD,
     @    UBAD100)
        ENDIF
        RATIO=UA/UB
        IF (RATIO .GT. 1.0) PRINT 15
        IF (RATIO .GT. 1.0) WRITE(7,15)
  15    FORMAT(///,' ***WARNING*** ',/,' UA/UB > 1.0',5X,'GRANT AND',
     @ ' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
C
C  PURE WAVES CASE
C
      ELSE
        CALL FRIC3(UB,AB,PER,GD,KB,FCW)
        UA=0.0
        U100=0.0
        PHIB=0.0
        PHI100=0.0
        KBC=KB
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
      REAL KB
```

```
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  CURRENT CASE.  A CONSTANT FRICTION FACTOR IS ASSUMED, BASED ON THE
C  WORK OF STERNBERG (1971).  THIS IS MOST LIKELY INADEQUATE AND WILL
C  BE REVISED IN THE FUTURE.
C
C  INPUT VARIABLES:
C
C        UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C        GD = SEDIMENT GRAIN SIZE (CM)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        FCW = BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C
      FCW=6.0E-3
      IF(KB .EQ. 0.0) KB=GD
      U100=UZ*ALOG(3000./KB)/ALOG(30.*Z/KB)
      UA=U100
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FCW,UA,PHIB,U100)
      REAL K,KB,KBC,L
      EXTERNAL FUN1,FUN2
      COMMON /FUNCTS/U,GY
C
C  THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND
C  CURRENT CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1979).  THIS
C  METHOD IS NOT VALID FOR UA/UB > 1.0 (APPROXIMATELY) DUE TO THE REL-
C  ATIVE IMPORTANCE OF THE CONVECTIVE ACCELERATION TERMS IN THE EQUATION
C  OF MOTION.
C
C  INPUT VARIABLES:
C
C        UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C        PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                 ABOVE SEABED (RADIANS)  (NB:  PHI100 = PHIZ)
C        UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C        AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C        PER = WAVE PERIOD (SEC)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        FCW = BOTTOM FRICTION FACTOR FOR THE COMBINED CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C               WAVE BOUNDARY LAYER (RADIANS)
```

```
C
C  INTERMEDIATE VARIABLES:
C
C         PHIC = CALCULATED ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
C                AT 1 M. ABOVE SEABED (RADIANS) - SHOULD CONVERGE TO
C                PHI100.
C         UC = CALCULATED CURRENT VELOCITY AT 1 M. ABOVE SEABED (CM/SEC)
C         A2 = INITIAL ESTIMATE OF WAVE BOUNDARY LAYER THICKNESS, AFTER
C              SMITH (1977) (CM)
C         ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2
C         KBC = APPARENT BOTTOM ROUGHNESS (CM)
C         K = FACTOR USED IN COMPUTATION OF BOTTOM SHEAR STRESS
C         A = FACTOR RELATING MEAN SHEAR STRESS COMPONENT IN WAVE
C             DIRECTION TO RHO*UB**2*FRW/2
C         B = FACTOR RELATING MEAN SHEAR STRESS COMPONENT NORMAL TO WAVE
C             DIRECTION TO RHO*UB**2*FCW/2
C         V2 = FACTOR RELATING MAGNITUDE OF MEAN SHEAR STRESS TO
C              RHO*UB**2*FCW/2
C         L = WAVE BOUNDARY LAYER LENGTH SCALE (CM)
C         U = RATIO OF CURRENT TO WAVE VELOCITIES IN WAVE DIRECTION
C         V = RATIO OF CURRENT TO WAVE VELOCITIES NORMAL TO WAVE
C              DIRECTION
C         IT = ITERATION COUNTER
C         UA0,UC0,UA1,UDIF,DIF ARE VARIABLES USED TO ESTIMATE A NEW
C         VALUE FOR UA
C         PHIB0,PHIC0,PHIB1,PHIDIF,DIF ARE VARIABLES USED TO ESTIMATE A
C         NEW VALUE FOR PHIB
C
C  INITIALIZE ITERATION PARAMETERS
C
      UA0=0.0
      UC0=0.0
      UDIF=UZ/4.
      PHIB0=0.0
      PHIC0=0.0
      PHIDIF=PHI100/4.
      BEST=2.0
      IT=1
C
C  INITIAL ESTIMATE OF FCW (JONSSON,1966), A2 (SMITH, 1977), UA AND PHIB
C
      PI=2.*ASIN(1.)
      FCW1=EXP(5.213*(KB/AB)**0.194-5.977)
      FCW=AMIN1(FCW1,0.28)
      A2=0.4*AB*SQRT(FCW/2.)
      UA=UZ*ALOG(30.*A2/KB)/ALOG(30.*Z/KB)
      PHIB=PHI100
C
C  ITERATION LOOP:  FIRST, DETERMINE MAGNITUDE AND DIRECTION OF MEAN
C  SHEAR STRESS FOR ESTIMATED UA AND PHIB.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
 100  ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      U=UA*COS(PHIB)/UB
      GY=UA*SIN(PHIB)/UB
```

```
C
      A=2.*DCADRE(FUN1,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) WRITE(7,5) IER
   5  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN1')
      B=2.*DCADRE(FUN2,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) WRITE(7,15) IER
  15  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN2')
C
      V2=SQRT(A*A+B*B)/(2.*PI)
      PHIC=ATAN2(B,A)
C
C  THE EQUATION FOR THE BOTTOM FRICTION FACTOR IS TRANSCENDENTAL AND
C  THUS MUST BE SOLVED ITERATIVELY.  THREE ITERATIONS WERE FOUND
C  SUFFICIENT TO OBTAIN A REASONABLE VALUE (MARTEC, 1983).
C  NOTE:  MMKELO IS AN IMSL SUBROUTINE TO COMPUTE KELVIN FUNCTIONS OF
C  ORDER ZERO.  THE IMSL LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS
C  PROGRAM.
C
      DO 30 I=1,3
      L=0.4*AB*SQRT(FCW*ALPHA/2.)
      ZETAO=KB/(30.*L)
      CALL MMKELO(2.*SQRT(ZETAO),DUMMY1,DUMMY2,XKER,XKEI,IER)
      IF (IER .GT. 0) WRITE(7,25) IER
  25  FORMAT(///,' ***MMKELO ERROR*** ',I3)
      K=1./(2.*SQRT(ZETAO)*SQRT(XKER**2+XKEI**2))
      C=V2/(2.*ALPHA**0.25)
      FCW=ABS(0.097*K*SQRT(KB/AB)/(SQRT(ALPHA**1.5/4.-(C*SIN(PHI100))
     @**2)-C*COS(PHI100)))**(4./3.)
  30  CONTINUE
C
C  CALCULATE APPARENT BOTTOM ROUGHNESS AND RESULTING CURRENT VELOCITY
C  AT HEIGHT Z (CM) ABOVE SEABED
C
      KBC=KB*(24.*(AB/KB)*SQRT(ALPHA*FCW/2.))**(1.-SQRT(V2/ALPHA))
      UC=UB*SQRT(V2*FCW/2.)*ALOG(30.*Z/KBC)/0.4
C
C  CHECK CONVERGENCE OF UC TO UZ AND PHIC TO PHI100.  THE ERROR LIMIT
C  HAS BEEN SET TO 0.01 (OR 1.0 PERCENT).
C
      IF (PHI100 .NE. 0.0) THEN
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(1.0-PHIC/PHI100))
      ELSE
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(PHIC-PHI100))
      ENDIF
      IF (ERR .LT. BEST) THEN
        BEST=ERR
        IF (BEST .LT. 0.01) GO TO 999
        BFCW=FCW
        BUA=UA
        BPHIB=PHIB
      ELSE IF (IT .EQ. 50) THEN
        FCW=BFCW
        UA=BUA
        PHIB=BPHIB
        PRINT 35,UZ,PHI100,UB,PER,KB,BEST
        WRITE(7,35) UZ,PHI100,UB,PER,KB,BEST
```

```
  35    FORMAT(///,' ***WARNING*** ',/,' FOR UZ=',F8.2,', PHI100=',
     @  F7.4,', UB=',F8.2,', PER=',F6.2,/,' AND KB=',F7.3,', THE BEST',
     @  ' ESTIMATE AFTER 50 ITERATIONS HAS',/,' AN ERROR OF',F5.2)
        GO TO 999
      ENDIF
C
C  INCREMENT ITERATION COUNTER AND MAKE NEW ESTIMATE OF UA AND PHIB.
C
      IT=IT+1
      UA1=UA
      DIF=(UZ-UC)*(UA-UA0)/(UC-UC0)
      IF (DIF .LT. -UA) DIF=UA*UA/DIF
      DIF=SIGN(AMIN1(ABS(DIF),ABS(UDIF)),DIF)
      UDIF=DIF*2.
      UA=UA+DIF
      UA0=UA1
      UC0=UC
C
      IF (PHIC .NE. 0.0) THEN
        PHIB1=PHIB
        IF (PHIC .NE. PHIC0) THEN
          DIF=(PHI100-PHIC)*(PHIB-PHIB0)/(PHIC-PHIC0)
          DIF=SIGN(AMIN1(ABS(DIF),ABS(PHIDIF)),DIF)
          PHIDIF=DIF*2.
          PHIB=PHIB+DIF
        ELSE
          PHIB=PHI100
        ENDIF
        PHIB0=PHIB1
        PHIC0=PHIC
      ELSE
        PHIB=0.
      ENDIF
C
C  REPEAT ITERATION; RETURN TO MAIN PROGRAM WHEN ERROR LIMIT OR
C  ITERATION COUNT IS SATISFIED.
C
      GO TO 100
 999  DELTAW=2.*L
      IF (DELTAW .GT. Z) THEN
        PRINT 55
        WRITE(7,55)
  55    FORMAT(///,' ***WARNING***',/,' DELTAW > Z',5X,'GRANT AND',
     @' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
      ENDIF
      IF (DELTAW .GT. 100) THEN
        U100=UB*V2*SQRT(FCW/(2.*ALPHA))*ALOG(3000./KB)/0.4
      ELSE
        U100=UB*SQRT(V2*FCW/2.)*ALOG(3000./KBC)/0.4
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN1(X)
      COMMON /FUNCTS/U,GY
```

```
      GX=SIN(X)+U
      FUN1=GX*SQRT(GX**2+GY**2)
      RETURN
      END
C**********************************************************************
C**********************************************************************
      FUNCTION FUN2(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN2=GY*SQRT(GX**2+GY**2)
      RETURN
      END
C**********************************************************************
C**********************************************************************
C**********************************************************************
C**********************************************************************
      SUBROUTINE FRIC3(UB,AB,PER,GD,KB,FCW)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  WAVE CONDITION USING THE METHOD OF JONSSON (1966) AS MODIFIED BY
C  NIELSEN (197?).  THE BOTTOM ROUGHNESS IS TAKEN AS THE GRAIN DIAMETER
C  AS IN GRANT AND MADSEN (1976).
C
C  INPUT VARIABLES:
C
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         FCW = BOTTOM FRICTION FACTOR FOR THE PURE WAVE CASE
C
      FCW=AMIN1(EXP(5.213*(GD/AB)**0.194-5.977),0.28)
      RETURN
      END
C**********************************************************************
C**********************************************************************
C**********************************************************************
C**********************************************************************
      SUBROUTINE THRESH(U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
C
C  THIS SUBROUTINE CALCULATES THE THRESHOLD FLUID VELOCITY FOR SEDIMENT
C  TRANSPORT FOR BOTH BEDLOAD AND SUSPENDED LOAD.  THE CRITICAL STRESSES
C  ARE FROM MARTEC (1982).  THE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS
C  BASED ON THE WORK OF MILLER ET AL. (1977); THE CRITICAL STRESS FOR
C  SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966), WHERE THE
C  PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971).
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
```

```
C                  WAVE BOUNDARY LAYER (RADIANS)
C           UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C           FCW = BOTTOM FRICTION FACTOR
C           GD = SEDIMENT GRAIN SIZE (CM)
C           RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C           RHOW = FLUID DENSITY (GRAMS/CM**3)
C
C     OUTPUT VARIABLES:
C
C           VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C                 TRANSPORT (CM/SEC)
C           VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C                 LOAD TRANSPORT (CM/SEC)
C
C     INTERMEDIATE VARIABLES:
C
C           ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2.
C           DRHO = SEDIMENT DENSITY - FLUID DENSITY (GRAMS/CM**3)
C           VISC = DYNAMIC VISCOSITY OF THE FLUID (GRAMS/CM*SEC)
C           G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C           RE = GRAIN REYNOLDS NUMBER
C           FALL = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS
C                  ET AL. (1971) (CM/SEC)
C           TCB = CRITICAL BOTTOM STRESS FOR INITIATION OF BEDLOAD
C                 TRANSPORT (DYNES/CM**2)
C           TCS = CRITICAL BOTTOM STRESS FOR INITIATION OF SUSPENDED LOAD
C                 TRANSPORT (DYNES/CM**2)
C
C     INITIALIZE CONSTANTS
C
      G= 981.
      VISC=13.E-3
      DRHO=RHOS-RHOW
C
C     CALCULATE THRESHOLD VELOCITY FOR BEDLOAD TRANSPORT, VCB
C
      IF (UB .EQ. 0.0) THEN
        RE=GD*UA*SQRT(FCW/2.)*RHOW/VISC
      ELSE
        ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
        TAUB=RHOW/2.*FCW*ALPHA*UB**2
        RE=GD*SQRT(TAUB*RHOW)/VISC
      ENDIF
      IF (RE .EQ. 0.0) THEN
        TCB=9.99E99
      ELSE
        TCB=0.04*DRHO*G*GD
        IF (RE .LT. 10.0) TCB=TCB*2.4/RE**0.33
      ENDIF
      VCB=SQRT(2.*TCB/(RHOW*FCW))
C
C     CALCULATE THRESHOLD VELOCITY FOR SUSPENDED LOAD TRANSPORT, VCS
C
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TCS=0.64*RHOW*FALL**2
```

```
      VCS=SQRT(2.*TCS/(RHOW*FCW))
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE CHECK(U100,UA,UB,PHIB,FBAD)
C
C  THIS SUBROUTINE CHECKS TO SEE IF THE TOTAL BOTTOM STRESS (INCLUDING
C  FORM DRAG), CALCULATED USING GRANT AND MADSEN'S METHOD, IS AT LEAST
C  AS LARGE AS THAT CALCULATED USING STERNBERG'S METHOD.  IF NOT, THE
C  VELOCITY UA DEFAULTS TO A NEW VALUE SUCH THAT THE TWO STRESSES ARE
C  EQUAL.
C
      ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      FSC=6.0E-03
      RATIO=FBAD*ALPHA*UB**2/(FSC*U100**2)
      IF (RATIO .LT. 1.0) THEN
        ALPHA=ALPHA/RATIO
        UA=(SQRT(COS(PHIB)**2+(ALPHA-1.0))-COS(PHIB))*UB
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,
     @TS1,TS2,TB1S,TB2S)
C
C  THIS SUBROUTINE CALCULATES THE DURATION OF SEDIMENT TRANSPORT PHASES
C  (NO TRANSPORT, BEDLOAD TRANSPORT, SUSPENDED LOAD TRANSPORT) BY
C  CALCULATING WHEN THE RESPECTIVE CRITICAL VELOCITIES ARE EXCEEDED.
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C       PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C        PER = WAVE PERIOD (SEC)
C        VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C        VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C
C  OUTPUT VARIABLES:
C
C        TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT CEASES (SEC)
C        TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C        TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT CEASES (SEC)
C        TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
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C               LOAD TRANSPORT RECOMMENCES (SEC)
C         TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT RECOMMENCES (SEC)
C         PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C         PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                   PHASE
C
C  INTERMEDIATE VARIABLES:
C
C         XS1 = COS(W*TS1), WHERE W IS THE WAVE ANGULAR FREQUENCY
C         XB1 = COS(W*TB1),             "                   "
C         XS2 = COS(W*TS2),             "                   "
C         XB2 = COS(W*TB2),             "                   "
C         B = -B/2A, AS IN EQ'N. FOR ROOTS OF A QUADRATIC EQUATION
C         B24AC = (B**2-4*A*C)/(2*A)**2, AS IN QUADRATIC EQ'N. SOLUTION
C
C  FIRST, SET DEFAULT VALUES TO ZERO
C
      PI=2.*ASIN(1.)
      TS1=0.0
      TB1=0.0
      TS2=0.0
      TB2=0.0
      PERSUSP=0.0
      PERBED=0.0
      TB1S=0.0
      TB2S=0.0
      S=1.0E-10
C
C  CONSIDER PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        IF (UA .GE. VCS) PERSUSP=100.
        IF (UA .GE. VCB .AND. UA .LT. VCS) PERBED=100.
        RETURN
C
C  CONSIDER PURE WAVE CASE
C
      ELSE IF (UA .EQ. 0.0) THEN
          IF (VCS .LT. UB) THEN
            TS1=PER/(2.*PI)*ACOS(VCS/UB)
            TS2=PER/2.-TS1
            PERSUSP=400.*TS1/PER
          ENDIF
          IF (VCB .LT. VCS .AND. VCB .LT. UB) THEN
            TB1=PER/(2.*PI)*ACOS(VCB/UB)
            TB2=PER/2.-TB1
            PERBED=400.*(TB1-TS1)/PER
          ENDIF
C
        RETURN
C
C  CONSIDER COMBINATION OF WAVES AND A CURRENT.  FIRST CALCULATE TIMES
C  FOR SUSPENDED LOAD, THEN BEDLOAD (SEE FLOWCHART IN USER'S GUIDE)
C
      ELSE
```

```
      B24ACS=(VCS**2-(UA*SIN(PHIB))**2)/(UB**2)
      IF (B24ACS .LE. 0.0) THEN
        TS1=PER/2.
        PERSUSP=100.0
        PERBED=0.0
        RETURN
      ELSE
        B=-UA*COS(PHIB)/UB
        XS1=B+SQRT(B24ACS)
C
        IF (XS1 .GE. 1.0) THEN
          PERSUSP=0.0
          GO TO 50
        ELSE IF (XS1 .LE. -1.0) THEN
          TS1=PER/2.
          PERSUSP=100.0
          PERBED=0.0
          RETURN
        ELSE
          TS1=PER/(2.*PI)*ACOS(XS1)
        ENDIF
C
        XS2=B-SQRT(B24ACS)
C
        IF (XS2 .LE. -1.0) THEN
          PERSUSP=200.*TS1/PER
        ELSE
          TS2=PER/(2.*PI)*ACOS(XS2)
          PERSUSP=(2.*(TS1-TS2)+PER)/PER*100.
        ENDIF
C
      ENDIF
C
C  CALCULATE TIMES FOR BEDLOAD ONLY IF VCB < VCS
C
 50   IF (VCB .LT. VCS) THEN
      B24ACB=(VCB**2-(UA*SIN(PHIB))**2)/(UB**2)
      B24ACBS=(VCB**2*(S+1)-(UA*SIN(PHIB))**2)/(UB**2)
C
     IF (B24ACB .LE. 0.0) THEN
        TB1=PER/2.
        TB1S=PER/2.
        PERBED=100.-PERSUSP
        RETURN
      ELSE
        B=-UA*COS(PHIB)/UB
        XB1=B+SQRT(B24ACB)
        XB1S=B+SQRT(B24ACBS)
C
        IF (XB1 .GE. 1.0) THEN
          PERBED=0.0
          RETURN
        ELSE IF (XB1 .LE. -1.0) THEN
          TB1=PER/2.
          TB1S=PER/2.
          PERBED=100.-PERSUSP
```

```
            RETURN
          ELSE
          TB1=PER/(2.*PI)*ACOS(XB1)
          TB1S=PER/(2.*PI)*ACOS(XB1S)
          ENDIF
C
          XB2=B-SQRT(B24ACB)
          XB2S=B-SQRT(B24ACBS)
C
          IF (XB2 .LE. -1.0) THEN
            PERBED=200.*TB1/PER-PERSUSP
          ELSE
            TB2=PER/(2.*PI)*ACOS(XB2)
            TB2S=PER/(2.*PI)*ACOS(XB2S)
            PERBED=(2.*(TB1-TB2)+PER)/PER*100.-PERSUSP
          ENDIF
C
        ENDIF
        ENDIF
C
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TRANSPO(UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,
     @RHOW,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,
     @OPT,TB1S,TB2S)
      REAL K,KB,L
      INTEGER OPT
      EXTERNAL F1,F2,F3,F4,F5,F6
      COMMON UAX,UAY,UBB,W,A,VCBB
C
C  THIS SUBROUTINE CALCULATES THE TIME-AVERAGED NET SEDIMENT TRANSPORT
C  BY A CHOICE OF METHODS.  FOR THE PURE WAVE CASE THERE IS NO NET
C  TRANSPORT SINCE TRANSPORT DURING THE WAVE CREST IS EQUAL AND OPPOSITE
C  TO THAT DURING THE WAVE TROUGH (DUE TO THE USE OF LWT).  FOR THE PURE
C  CURRENT AND MIXED CONDITIONS, THE USER MAKES A CHOICE BETWEEN TRANS-
C  PORT FORMULAE, HOWEVER IF SUSPENDED LOAD TRANSPORT IS SIGNIFICANT IT
C  IS RECOMMENDED THAT A TOTAL LOAD FORMULA BE USED.
C
C  INPUT VARIABLES:
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         PER = WAVE PERIOD (SEC)
C         WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
```

```
C         FCW = BOTTOM FRICTION FACTOR
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY (GRAMS/CM**3)
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C         TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT CEASES (SEC)
C         TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT RECOMMENCES (SEC)
C         TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT CEASES (SEC)
C         TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT RECOMMENCES (SEC)
C         PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C         PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                   PHASE
C         WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C         CDIR = CURRENT DIRECTION (AZIMUTH, DEGREES)
C
C  OUTPUT VARIABLES:
C
C         SED = TIME-AVERAGED NET SEDIMENT TRANSPORT AS VOLUME OF SEDIMENT
C               TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME (CM**2/SEC)
C               NOTE:  THIS IS NOT THE SAME AS VOLUME OF SOIL TRANSPORTED!
C         SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH, DEGREES)
C
      G=981.
      VISC=13.E-3
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TAUCRB=RHOW*FCW/2.*VCB**2
      TAUCRS=RHOW*FCW/2.*VCS**2
      UAX=UA*COS(PHIB)
      UAY=UA*SIN(PHIB)
      W=2.*PI/PER
      VCBB=VCB
      UBB=UB
      SED=0.0
      SEDDIR=0.0
      VC=0.0
C
C
      PRINT 15,PERBED,PERSUSP
      WRITE(7,15) PERBED,PERSUSP
   15 FORMAT(///,' PERCENT TIME SPENT AS BEDLOAD =',F7.2,/,
     @' PERCENT TIME SPENT IN SUSPENSION =',F7.2)
C
C  FOR THE PURE WAVE CASE NO NET TRANSPORT OCCURS
C
      IF (UA .EQ. 0.0) THEN
        SED=0.0
```

```
        SEDDIR=0.0
C
C  NO INTEGRATION IS REQUIRED FOR THE PURE CURRENT CASE.  WHEN TRANSPORT
C  IS AS SUSPENDED LOAD, THE TOTAL TRANSPORT FORMULA OF ENGELUND AND
C  HANSEN (1967) IS USED.  WHEN TRANSPORT IS AS BEDLOAD, THE USER HAS
C  A CHOICE OF FORMULAE.
C
      ELSE IF (UB .EQ. 0.0) THEN
        TAUO=RHOW*FCW/2.*UA**2
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
        ELSE IF (PERBED .EQ. 0.0) THEN
          PRINT 25
          WRITE (7,25)
   25     FORMAT(/,' SEDIMENT TRANSPORT WILL BE CALCULATED USING THE',/,
     @    ' ENGELUND-HANSEN TOTAL LOAD FORMULA')
          V=U100
          SED=0.05*V**2*SQRT(TAUO**3*RHOW)/(GD*DGAMMA**2)
          SEDDIR=CDIR
        ELSE
   30     PRINT 35
   35     FORMAT(//,' CHOOSE BETWEEN:',/,
     @    '    1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
     @    '    2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
     @    '    3 - MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION',/,
     @    '    4 - YALIN (1963) BEDLOAD EQUATION',/,
     @    ' ENTER 1,2,3 OR 4')
          READ*, OPT
          IF (OPT .EQ. 1) THEN
            V=U100
            SED=0.05*V**2*SQRT(TAUO**3*RHOW)/(GD*DGAMMA**2)
          ELSE IF (OPT .EQ. 2) THEN
            SED=40.0*FALL*GD*(TAUO/(DGAMMA*GD))**3
          ELSE IF (OPT .EQ. 3) THEN
            BETA=1.73E-05
            IF (GD .LE. 0.031) BETA=7.22E-05
            SED=BETA/RHOS*(U100-VCB)**3
          ELSE IF (OPT .EQ. 4) THEN
            USTAR=SQRT(FCW/2.)*UA
            S=(UA/VCB)**2-1.0
            A=2.45*(RHOW/RHOS)**0.4*SQRT(TAUCRB/(G*DRHO*GD))
            SED=0.635*GD*USTAR*S*(1.0-ALOG(1.0+A*S)/(A*S))
          ELSE
            GO TO 30
          ENDIF
C
         SEDDIR=CDIR
        ENDIF
C
C  THE COMBINED WAVE AND CURRENT CASE REQUIRES INTEGRATION OF THE
C  INSTANTANEOUS TRANSPORT OVER THE WAVE PERIOD.  THE USE OF LWT ALLOWS
C  INTEGRATION TO BE DONE OVER ONLY HALF A WAVE CYCLE.  BAGNOLD'S METHOD
C  DOES NOT REQUIRE INTEGRATION.
C  THE X- AND Y- COMPONENTS OF TRANSPORT ARE CONSIDERED SEPARATELY,
C  WHERE THE X-COMPONENT IS PARALLEL TO THE WAVE DIRECTION AND THE
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C  Y-COMPONENT IS NORMAL TO THE WAVE DIRECTION.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
      ELSE
        IF (TB1 .EQ. 0.0 .AND. TS1 .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
          GO TO 999
        ENDIF
        SEDXC=0.0
        SEDXT=0.0
        SEDYC=0.0
        SEDYT=0.0
 50     PRINT 55
 55     FORMAT (//,' CHOOSE BETWEEN:',/,
     @  '    1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
     @  '    2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
     @  '    3 - BAGNOLD (1963) TOTAL LOAD EQUATION',/,
     @  '    4 - YALIN (1963) BEDLOAD EQUATION',/,
     @  ' ENTER 1,2,3 OR 4')
        READ*,OPT
        IF (OPT .EQ. 1) THEN
          V=U100
          CONST=0.0177*FCW**1.5*(V*RHOW/DGAMMA)**2/GD
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F1,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
 65         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F1')
            SEDYC=2.*CONST*DCADRE(F2,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
 75         FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F2')
          ELSE
            SEDXC=2.*CONST*DCADRE(F1,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYC=2.*CONST*DCADRE(F2,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ENDIF
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F1,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYT=2.*CONST*DCADRE(F2,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ELSE IF (TS2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F1,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYT=2.*CONST*DCADRE(F2,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ENDIF
C
C
        ELSE IF (OPT .EQ. 2) THEN
          CONST=5.*FALL*GD*(FCW*RHOW/(GD*DGAMMA))**3
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F3,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,85) IER
```

```
 85        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F3')
           SEDYC=2.*CONST*DCADRE(F4,0.0,TB1,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,95) IER
 95        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F4')
         ELSE
           SEDXC=2.*CONST*DCADRE(F3,0.0,TS1,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,85) IER
           SEDYC=2.*CONST*DCADRE(F4,0.0,TS1,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,95) IER
         ENDIF
C
         IF (TB2 .NE. 0.0) THEN
           SEDXT=2.*CONST*DCADRE(F3,TB2,PER/2.,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,85) IER
           SEDYT=2.*CONST*DCADRE(F4,TB2,PER/2.,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,95) IER
         ELSE IF (TS2 .NE. 0.0) THEN
           SEDXT=2.*CONST*DCADRE(F3,TS2,PER/2.,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,85) IER
           SEDYT=2.*CONST*DCADRE(F4,TS2,PER/2.,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,95) IER
         ENDIF
C
C
       ELSE IF (OPT .EQ. 3) THEN
         ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
         USTAR=SQRT(FCW*ALPHA/2.)*UB
         L=0.4*USTAR*PER/(2.*PI)
         ZETAO=KB/(30.*L)
         CALL MMKELO(2.*SQRT(ZETAO),DUMMY1,DUMMY2,XKER,XKEI,IER)
         TAUOW=0.2*RHOW*USTAR*UB/SQRT(XKER**2+XKEI**2)
         PRINT 105
 105     FORMAT(//,' BAGNOLD''S METHOD REQUIRES A COEFFICIENT OF ',
     @   'PROPORTIONALITY, K',/,' WHICH RANGES BETWEEN 0.0 AND 1.0',/,
     @   ' PLEASE ENTER A VALUE FOR K')
         READ*, K
         SED=K*TAUOW*UA/DGAMMA
         SEDDIR=CDIR
C
C
       ELSE IF (OPT .EQ. 4) THEN
         ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
         USTAR=SQRT(FCW*ALPHA/2.)*UB
         A=2.45*SQRT(TAUCRB/DGAMMA/GD)*(RHOW/RHOS)**0.4
         CONST=0.635*GD*USTAR
         IF (TB1 .NE. 0.0) THEN
           SEDXC=2.*CONST*DCADRE(F5,0.0,TB1S,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,115) IER
 115       FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F5')
           SEDYC=2.*CONST*DCADRE(F6,0.0,TB1S,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,125) IER
 125       FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F6')
         ELSE
           SEDXC=2.*CONST*DCADRE(F5,0.0,TS1,0.01,0.0,ER,IER)
           IF (IER .GT. 0) WRITE(7,115) IER
           SEDYC=2.*CONST*DCADRE(F6,0.0,TS1,0.01,0.0,ER,IER)
```

```
            IF (IER .GT. 0) WRITE(7,125) IER
          ENDIF
C
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F5,TB2S,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYT=2.*CONST*DCADRE(F6,TB2S,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
          ELSE IF (TS2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F5,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYT=2.*CONST*DCADRE(F6,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
          ENDIF
C
C
        ELSE
          GO TO 50
        ENDIF
C
C
C
C
        IF (OPT .NE. 3) THEN
          SEDX=(SEDXC+SEDXT)/PER
          SEDY=(SEDYC+SEDYT)/PER
          SED=SQRT(SEDX**2+SEDY**2)
          PHIS=ATAN2(SEDY,SEDX)
          DIF=SIGN((PHI100-PHIS)*180./PI,CDIR-WDIR)
          CWDIF=ABS(CDIR-WDIR)
          IF(CWDIF .LE. 90.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 180.0 .AND. CWDIF .GT. 90.0) SEDDIR=CDIR+DIF
          IF (CWDIF .LE. 270.0 .AND. CWDIF .GT. 180.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 360.0 .AND. CWDIF .GT. 270.0) SEDDIR=CDIR+DIF
          IF (SEDDIR .LT. 0.0) SEDDIR=SEDDIR+360.0
          IF (SEDDIR .GE. 360.0) SEDDIR=SEDDIR-360.0
        ENDIF
      ENDIF
  999 RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F1(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F1=UX*(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F2(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F2=UY*(UX**2+UY**2)
```

```
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F3(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F3=UX*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F4(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F4=UY*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F5(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F5=S*(1.-ALOG(1.+A*S)/(A*S))*UX/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F6(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F6=S*(1.-ALOG(1.+A*S)/(A*S))*UY/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,
     @TB2,PERBED,PERSUSP,SED,SEDDIR,OPT)
      INTEGER OPT
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE OUTPUT PARAMETERS FROM ALL
C  SUBROUTINES
C
      PRINT 15
      WRITE(7,15)
  15  FORMAT(///,T4,'RESULTS:',//)
C
      PRINT 25,UB,AB,WL/100.
```

```
      WRITE(7,25) UB,AB,WL/100.
  25  FORMAT(T11,'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'VELOCITY, FROM LINEAR WAVE THEORY',T56,'=',F7.2,' CM/SEC',/,T11,
     @'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'DISPLACEMENT, FROM LINEAR WAVE THEORY',T56,'=',F8.2,' CM',/,T11,
     @'WAVELENGTH, FROM LWT DISPERSION EQUATION =',F7.2,' M',/)
C
      PRINT 35,FCW
      WRITE(7,35) FCW
  35  FORMAT(T11,'BOTTOM FRICTION FACTOR =',F7.4)
      IF (UB .EQ. 0.0) THEN
        PRINT 45
        WRITE(7,45)
  45    FORMAT(T11,'(STERNBERG, 1971)')
      ELSE IF (UA .EQ. 0.0) THEN
        PRINT 55
        WRITE(7,55)
  55    FORMAT(T11,'(JONSSON, 1966)')
      ELSE
        PRINT 65
        WRITE(7,65)
  65    FORMAT(T11,'(GRANT AND MADSEN, 1979)')
      ENDIF
C
      PRINT 75,U100,UA,PHIB*90./ASIN(1.)
      WRITE(7,75) U100,UA,PHIB*90./ASIN(1.)
  75  FORMAT(T11,'CURRENT SPEED 1 M. ABOVE SEABED',T53,'=',F7.2,
     @' CM/SEC',/,T11,'CURRENT SPEED TO BE USED IN BOTTOM STRESS',/,T11,
     @'CALCULATIONS',T53,'=',F7.2,' CM/SEC',/,T11,
     @'ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS',/,T11,
     @'WITHIN WAVE BOUNDARY LAYER',T53,'=',F7.2,' DEGREES',/,T11,
     @'NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY',/)
C
      PRINT 85,VCB,VCS
      WRITE(7,85) VCB,VCS
  85  FORMAT(T11,'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'BEDLOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/,T11,
     @'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'SUSPENDED LOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/)
C
      PRINT 95,TS1,TB1,TS2,TB2
      WRITE(7,95) TS1,TB1,TS2,TB2
  95  FORMAT(T11,'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT RECOMMENCES       =',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT RECOMMENCES              =',F6.2,' SEC',/)
C
      PRINT 105,PERBED,PERSUSP
      WRITE(7,105) PERBED,PERSUSP
 105  FORMAT(T11,'PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =',F7.2,/,
     @T11,'PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =',F7.2,/)
C
```

```
      PRINT 115,SEDDIR,SED
      WRITE(7,115) SEDDIR,SED
 115  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
C
      IF (UA .NE. 0.0) THEN
C
        IF (OPT .EQ. 1) THEN
          PRINT 125
          WRITE(7,125)
 125      FORMAT(T11,'(ENGELUND-HA
```

```
PRINT 115,SEDDIR,SED
      WRITE(7,115) SEDDIR,SED
 115  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
C
      IF (UA .NE. 0.0) THEN
C
        IF (OPT .EQ. 1) THEN
          PRINT 125
          WRITE(7,125)
 125      FORMAT(T11,'(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)')
        ELSE IF (OPT .EQ. 2) THEN
          PRINT 135
          WRITE(7,135)
 135      FORMAT(T11,'(EINSTEIN-BROWN (1950) BEDLOAD EQUATION)')
        ELSE IF (OPT .EQ. 4) THEN
          PRINT 145
          WRITE(7,145)
 145      FORMAT(T11,'(YALIN (1963) BEDLOAD EQUATION)')
        ELSE IF (UB .EQ. 0.0) THEN
          PRINT 155
          WRITE(7,155)
 155      FORMAT(T11,'(MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION)')
        ELSE
          PRINT 165
          WRITE(7,165)
 165      FORMAT(T11,'(BAGNOLD (1963) TOTAL LOAD EQUATION)')
        ENDIF
C
      ENDIF
C
      PRINT 175
      WRITE(7,175)
 175  FORMAT(T11,'NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER
     @THAN',/,T18,'SOIL VOLUME TRANSPORT RATE',/)
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE BEDFORM(U100,UB,GD,KBC)
      REAL KBC
C
C  THIS SUBROUTINE PRINTS OUT THE EXPECTED TYPE OF BEDFORM FOR THE GIVEN
C  FLOW CONDITIONS (PURE WAVE OR PURE CURRENT CONDITIONS ONLY).  THE
C  BEDFORM TYPE IS ONLY APPROXIMATE SINCE IT IS BASED ON A VELOCITY
C  MEASUREMENT ONLY.  THE LIMITS ARE FROM C. L. AMOS, IN PROGRESS.
C
C  INPUT VARIABLES:
C
C            U100 = CURRENT SPEED AT 1 M. ABOVE SEABED ( CM/SEC)
C            UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C            GD = SEDIMENT GRAIN SIZE (CM)
```

```
C             KBC = APPARENT BOTTOM ROUGHNESS (CM)
C
      IF (KBC .EQ. 0.0) KBC=GD
C
C  SET UP FORMAT STATEMENTS
C
      PRINT 15
      WRITE(7,15)
  15  FORMAT(//,T11,'EXPECTED BEDFORMS ARE (C. L. AMOS):',/)
  25  FORMAT(T21,'WAVE RIPPLES')
  35  FORMAT(T21,'WAVE-INDUCED FLAT BED')
  355 FORMAT(T21,'WAVE RIPPLES OR WAVE-INDUCED FLAT BED')
  45  FORMAT(T21,'CURRENT RIPPLES')
  55  FORMAT(T21,'FLAT BED (LOWER)')
  65  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES')
  75  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES OR SAND WAVES')
  85  FORMAT(T21,'2-D MEGARIPPLES')
  95  FORMAT(T21,'2-D MEGARIPPLES OR SAND WAVES')
 105  FORMAT(T21,'SAND WAVES')
 115  FORMAT(T21,'SAND WAVES OR 3-D MEGARIPPLES')
 125  FORMAT(T21,'3-D MEGARIPPLES')
 135  FORMAT(T21,'FLAT BED (UPPER) AND SAND RIBBONS')
 145  FORMAT(T21,'SEDIMENT IN SUSPENSION')
 155  FORMAT(T21,'NO TRANSPORT')
 165  FORMAT(T21,'BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS')
C
C  VERY COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      IF (GD .LE. 0.2 .AND. GD .GT. 0.1) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 30.0) PRINT 155
          IF (UB .LT. 30.0) WRITE(7,155)
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) PRINT 25
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) WRITE(7,25)
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) PRINT 355
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) WRITE(7,355)
          IF (UB .GE. 200.0) PRINT 35
          IF (UB .GE. 200.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 40.0) PRINT 155
          IF (U100 .LT. 40.0) WRITE(7,155)
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) PRINT 95
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) WRITE(7,95)
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) PRINT 75
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) WRITE(7,75)
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) PRINT 95
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) WRITE(7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) PRINT 105
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) WRITE(7,105)
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) PRINT 135
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) WRITE(7,135)
          IF (U100 .GE. 295.0) PRINT 145
```

```
          IF (U100 .GE. 295.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.1 .AND. GD .GT. 0.05) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 20.0) PRINT 155
          IF (UB .LT. 20.0) WRITE(7,155)
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) PRINT 25
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) WRITE(7,25)
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) PRINT 355
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) WRITE(7,355)
          IF (UB .GE. 125.0) PRINT 35
          IF (UB .GE. 125.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 25.0) PRINT 155
          IF (U100 .LT. 25.0) WRITE(7,155)
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) PRINT 45
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) WRITE(7,45)
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) PRINT 55
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) WRITE(7,55)
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) PRINT 65
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) WRITE(7,65)
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) PRINT 85
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) WRITE(7,85)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) PRINT 95
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE(7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) PRINT 115
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE(7,115)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) PRINT 125
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE(7,125)
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) PRINT 135
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) WRITE(7,135)
          IF (U100 .GE. 240.0) PRINT 145
          IF (U100 .GE. 240.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  MEDIUM SAND
C  FIRST, DO PURE WAVE CASE
```

```
C
      ELSE IF (GD .LE. 0.05 .AND. GD .GT. 0.025) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 13.0) PRINT 155
          IF (UB .LT. 13.0) WRITE(7,155)
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) PRINT 25
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) WRITE(7,25)
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) PRINT 355
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) WRITE(7,355)
          IF (UB .GE. 100.0) PRINT 35
          IF (UB .GE. 100.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 20.0) PRINT 155
          IF (U100 .LT. 20.0) WRITE(7,155)
          IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) PRINT 45
          IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) WRITE(7,45)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) PRINT 85
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE(7,85)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) PRINT 115
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE(7,115)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) PRINT 125
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE(7,125)
          IF (U100 .GE. 150.0 .AND. U100 .LT. 170.0) PRINT 135
          IF (U100 .GE. 150.0 .AND. U100 .LT. 170.0) WRITE(7,135)
          IF (U100 .GE. 170.0) PRINT 145
          IF (U100 .GE. 170.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  FINE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.025 .AND. GD .GT. 0.0125) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 10.0) PRINT 155
          IF (UB .LT. 10.0) WRITE(7,155)
          IF (UB .GE. 10.0 .AND. UB .LT. 70.0) PRINT 25
          IF (UB .GE. 10.0 .AND. UB .LT. 70.0) WRITE(7,25)
          IF (UB .GE. 70.0) PRINT 35
          IF (UB .GE. 70.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 13.0) PRINT 155
          IF (U100 .LT. 13.0) WRITE(7,155)
          IF (U100 .GE. 13.0 .AND. U100 .LT. 60.0) PRINT 45
          IF (U100 .GE. 13.0 .AND. U100 .LT. 60.0) WRITE(7,45)
```

```
          IF (U100 .GE. 60.0 .AND. U100 .LT. 85.0) PRINT 135
          IF (U100 .GE. 60.0 .AND. U100 .LT. 85.0) WRITE(7,135)
          IF (U100 .GE. 85.0) PRINT 145
          IF (U100 .GE. 85.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
      ENDIF
      RETURN
      END
```

SED1D: A MICROCOMPUTER VERSION

prepared for

The Atlantic Geoscience Centre
Bedford Institute of Oceanography
Dartmouth, Nova Scotia

by

Susan Davidson

ASA Consulting Ltd.
Dartmouth, Nova Scotia

7 November 1986

SED1D: A MICROCOMPUTER VERSION

The Atlantic Geoscience Centre of the Geological Survey of Canada has developed a numerical model to predict sediment transport under continental shelf conditions (Martec, 1982, 1983 and 1984; Davidson and Amos, 1985; Martec (in press)). This model, called SED1D, was developed for the Cyber computer at the Bedford Institute of Oceanography; the purpose of the present contract was to develop a version for use on IBM compatible microcomputers. A microcomputer version would increase the usability of the model as well as allow for more widespread distribution to various users.

Software Requirements

The microcomputer version has been developed in Fortran and compiled under Microsoft Fortran version 3.31. This version of Fortran closely resembles Fortran 77; the only MS - Fortran feature not included in Fortran 77 utilized by this program is the $DEBUG compiler metacommand. The source code, as well as an executable code version of the model, have been supplied so that the user may use other versions of Fortran if so desired. However, recompilation of the source code under other versions of microcomputer Fortran will require removal of the $DEBUG command; other slight modifications may also be required depending on the particular features of the Fortran software used.

MS - Fortran version 3.31 is designed to work with DOS 2.0; the floppy disks with the executable code have been supplied with this version of DOS. Problems may arise when running the program under a different version of DOS; these problems may be avoided by rebooting the computer using the supplied DOS.

MS - Fortran has the capability to utilize the 8087 numeric coprocessor if available. The supplied executable code will utilize the 8087 under certain machine configurations but may require recompilation under other configurations. The user should refer to the MS - Fortran documentation for further information on customizing the executable code for the desired hardware configuration.

In order to minimize code size, many of the comment lines have been removed from the Cyber version of this model. In addition, the source code has been split into four separate files: SEDAW1.FOR, SEDAW2.FOR, SEDAW3.FOR and SEDAW4.FOR. These files may be compiled separately but then must be linked, together with the appropriate Fortran library, to provide an executable code.

Model Structure

The microcomputer version of SED1D has retained the same basic structure as the BIO Cyber version. For a complete description of the model structure, the theoretical assumptions and model limitations, the

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The IMSL routine MMKELO is used to calculate Kelvin functions of order zero. MMKELO has been replaced by subroutine KERKEI in the microcomputer version, which uses series expansions given by Abramowitz and Stegun (1965). These expansions are

$$\text{ker } x = - \ln \left(\frac{x}{2}\right) \text{ ber } x + \frac{\pi}{4} \text{ bei } x$$

$$+ \sum_{k=0}^{\infty} (-)^k \frac{\psi(2k + 1)}{((2k)!)^2} \left(\frac{x^2}{4}\right)^{2k} \qquad (1)$$

$$\text{kei } x = - \ln \left(\frac{x}{2}\right) \text{ bei } x - \frac{\pi}{4} \text{ ber } x$$

$$+ \sum_{k=0}^{\infty} (-)^k \frac{\psi(2k + 2)}{((2k+1)!)^2} \left(\frac{x^2}{4}\right)^{2k+1} \qquad (2)$$

where

$$\text{ber } x = 1 - \frac{\left(\frac{x^2}{4}\right)^2}{(2!)^2} + \frac{\left(\frac{x^2}{4}\right)^4}{(4!)^2} - \ldots \tag{3}$$

$$\text{bei } x = \frac{x^2}{4} - \frac{\left(\frac{x^2}{4}\right)^3}{(3!)^2} + \frac{\left(\frac{x^2}{4}\right)^5}{(5!)^2} - \ldots \tag{4}$$

$$\psi(n) = -\gamma + \sum_{k=1}^{n-1} k^{-1}, \quad n \geq 2 \tag{5}$$

$$\psi(1) = -\gamma \tag{6}$$

and

$$\gamma = 0.57721\ 56649\ldots \quad \text{(Euler's constant)} \tag{7}$$

Ten terms were found to give adequate accuracy for all of the series expansions.

The IMSL routine DCADRE is used to perform numerical integrations. It has been replaced by subroutine ROMBIN in the microcomputer version of SED1D. Subroutine ROMBIN performs numerical integrations using the Romberg integration algorithm. This algorithm is based on repeated applications of the trapezoidal integration formula over increasing numbers of subintervals of the total integration interval. The resulting sequence of integral estimates is then used to calculate more accurate integral estimates based on the Richardson extrapolation technique. For more information on this approach to numerical integration, the reader should refer to one of the many available texts on numerical methods, i.e. Carnahan, Luther and Wilkes (1969). Along with the replacement of the IMSL routine DCADRE with the subroutine ROMBIN, it was found necessary to slightly modify the program structure such that the name of the function to be integrated was not passed as a subroutine parameter. This modification does not in any way affect either the accuracy or operation of the program.

It was found that the integration routine required the greatest amount of computing time of any portion of the program. For this reason it was decided to limit the number of iterations in this subroutine, although this limit decreases the computational accuracy somewhat. Execution of the program on a computer equipped with an 8087 math coprocessor decreases the execution time from roughly two minutes to about ten seconds at a 4 MHz clock speed; any increase in clock speed will further decrease execution time. If additional computational accuracy is desired, the user may increase the number of iterations in subroutine ROMBIN and may also want to consider using double precision variables.

Program Verification

The new subroutines KERKEI and ROMBIN have been individually checked for their computational accuracy. KERKEI was checked by comparing to tabulated Kelvin function values and ROMBIN was checked against known analytic solutions. In addition, program output was

UB	U100										
	00.00	20.00	40.00	60.00	80.00	100.00	120.00	140.00	160.00	180.00	200.00
00.00	.0000	.0000	.0071	.0537	.2262	.6902	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0034	.0385	.2163	.8251	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0009	.1422	.7187	2.0462	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0012	.0715	.3068	.8081	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0000	.0088	.1150	.4357	1.0950	2.2259	3.9691	6.4719	9.8874
20.00	.0000	.0000	.0000	.0067	.0323	.1061	.2629	.5692	1.1926	2.1894	3.7757
	.0000	.0000	.0000	.0016	.0071	.0243	.0681	.1673	.4036	.8349	1.6103
	.0000	.0000	.0000	.2970	.5024	.7497	1.0394	1.3727	1.7917	2.2334	2.7240
	.0000	.0000	.0000	.0010	.0128	.0474	.1254	.2656	.5177	.8643	1.3415
	.0000	.0000	.0000	.0000	.0033	.0369	.1622	.4735	1.1649	2.2967	4.0702
40.00	.0000	.0005	.0043	.0129	.0592	.1654	.3916	.8131	1.5411	2.7214	4.5426
	.0000	.0021	.0041	.0061	.0297	.0794	.1864	.3997	.7951	1.4879	2.6450
	.0000	.0609	.2033	.5161	1.1577	1.7765	2.4648	3.2390	4.0984	5.0452	6.0816
	.0000	.0041	.0075	.0116	.0547	.1294	.2634	.4826	.8054	1.2508	1.8383
	.0000	.0000	.0000	.0006	0277	.1779	.3508	.8154	1.6442	2.9817	4.9927
60.00	.0000	.0009	.0097	.0312	.0776	.2282	.5583	1.1096	2.0314	3.5122	5.7527
	.0000	.0120	.0321	.0397	.0640	.1718	.4536	.8773	1.5916	2.7072	4.6759
	.0000	.1110	.3547	.7392	1.5103	2.7808	4.1294	5.4587	6.9057	8.4898	10.1799
	.0000	.0181	.0519	.0670	.1013	.2445	.4727	.7773	1.2048	1.7800	2.5359
	.0000	.0008	.0031	.0100	.0475	.2212	.6101	1.2582	2.3307	3.9975	6.4247
80.00	.0000	.0014	.0162	.0606	.1288	.2880	.6858	1.3798	2.6345	4.4392	7.1563
	.0000	.0415	.1172	.1900	.2076	.3529	.8439	1.6297	3.0296	5.0010	8.0080
	.0000	.1764	.5409	1.0847	1.8584	3.3808	5.5556	7.6809	10.0653	12.3942	14.9041
	.0000	.0406	.1215	.2079	.2400	.3629	.6870	1.1015	1.7146	2.4394	3.3630
	.0000	.0076	.0230	.0482	.0973	.2860	.8130	1.6810	3.1447	5.1653	8.0579
100.00	.0000	.0021	.0239	.0936	.2245	.4143	.8245	1.7033	3.0908	5.2146	8.7263
	.0000	.1098	.3124	.5473	.7146	.8161	1.3730	2.8182	4.9101	7.9937	13.1015
	.0000	.2561	.7637	1.4893	2.4876	3.9458	6.4847	9.7989	12.9902	16.2776	20.0438
	.0000	.0710	.2116	.3870	.5325	.6208	.9070	1.4952	2.1929	3.0734	4.3035
	.0000	.0225	.0655	.1271	.2206	.4070	.9464	2.1069	3.7891	6.1838	9.8396
120.00	.0000	.0029	.0329	.1300	.3312	.6178	1.0989	1.9888	3.7000	6.2149	9.8701
	.0000	.2450	.6950	1.2366	1.7825	2.0917	2.5997	4.2508	7.7878	12.5611	19.2285
	.0000	.3507	1.0244	1.9534	3.1960	4.7861	7.3829	11.1983	15.8632	20.3239	24.8881
	.0000	.1088	.3207	.5932	.8851	1.0868	1.3176	1.8560	2.7897	3.8492	5.1365
	.0000	.0470	.1336	.2505	.4125	.6474	1.1743	2.3501	4.4880	7.3490	11.1978
140.00	.0000	.0039	.0432	.1712	.4453	.8947	1.5031	2.4461	4.2501	7.2798	11.5096
	.0000	.4861	1.3698	2.4504	3.6449	4.7089	5.4631	6.8623	11.2079	18.7507	28.4724
	.0000	.4607	1.3240	2.4811	3.9895	5.9403	8.5109	12.3687	17.9294	24.1165	30.0398
	.0000	.1543	.4489	.8301	1.2698	1.6881	2.0042	2.4050	3.3464	4.6980	6.1975
	.0000	.0823	.2306	.4235	.6764	1.0257	1.5683	2.6647	4.9180	8.4231	12.8800
160.00	.0000	.0050	.0549	.2170	.5693	1.1714	2.0383	3.2069	4.9508	8.2795	13.2570
	.0000	.8848	2.4720	4.4207	6.6514	8.8965	11.1185	12.6940	16.1746	26.1286	40.6017
	.0000	.5868	1.6624	3.0731	4.8725	7.1441	9.9780	13.9532	19.4591	27.0718	34.9199
	.0000	.2075	.5958	1.0969	1.6904	2.3122	2.9084	3.3637	4.0272	5.5155	7.3472
	.0000	.1300	.3595	.6505	1.0186	1.4982	2.1565	3.2683	5.3152	9.1554	14.4469
180.00	.0000	.0062	.0680	.2678	.7044	1.4671	2.5191	4.1151	5.9640	9.2775	15.0280
	.0000	1.5074	4.1668	7.4412	11.2318	15.2732	18.6926	22.5492	25.7686	34.9396	55.4330
	.0000	.7297	2.0379	3.7304	5.8470	8.4682	11.5216	15.8421	21.0174	29.0489	39.0620
	.0000	.2686	.7607	1.3937	2.1492	2.9775	3.7252	4.5167	5.1259	6.3291	8.5173
	.0000	.1915	.5226	.9364	1.4453	2.0836	2.8675	4.1184	5.9416	9.6220	15.6767
200.00	.0000	.0078	.0824	.3237	.8514	1.7838	3.2141	5.1539	7.7604	11.2563	16.3211
	.0000	2.4706	6.6741	11.8737	17.9134	24.5348	31.3808	38.2010	44.4883	53.6984	69.9818
	.0000	.9025	2.4571	4.4547	6.9154	9.9134	13.5789	18.0099	23.9655	31.6804	41.5525
	.0000	.3426	.9458	1.7217	2.6486	3.6874	4.7756	5.8326	6.7986	7.8860	9.4451
	.0000	.2719	.7242	1.2857	1.9629	2.7889	3.8331	5.1973	7.2995	10.6713	16.1761

Table 1. Sediment transport values (cm^2/sec) from the Cyber version of SED1D for values of u_b and u_{100} ranging from 0 to 200 cm/sec. Other input variables are: water depth = 50 m, wave period = 10 sec, sediment grain size = 0.5 mm, sediment density = 2.65 g/cm^3, bottom roughness = 5 cm and fluid density = 1.03 g/cm^3.

U100

UB	00.00	20.00	40.00	60.00	80.00	100.00	120.00	140.00	160.00	180.00	200.00
00.00	.0000	.0000	.0071	.0537	.2262	.6902	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0034	.0385	.2163	.8251	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0009	.1422	.7187	2.0462	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0012	.0715	.3068	.8081	1.7175	3.7122	7.2375	13.0422	22.0871
	.0000	.0000	.0000	.0088	.1150	.4357	1.0950	2.2259	3.9691	6.4719	9.8874
20.00	.0000	.0000	.0000	.0067	.0323	.1061	.2629	.5692	1.1926	2.1894	3.7757
	.0000	.0000	.0000	.0016	.0071	.0243	.0681	.1673	.4036	.8349	1.6103
	.0000	.0000	.0000	.2970	.5024	.7497	1.0394	1.3727	1.7917	2.2334	2.7240
	.0000	.0000	.0000	.0010	.0128	.0474	.1254	.2656	.5177	.8643	1.3415
	.0000	.0000	.0000	.0000	.0033	.0369	.1622	.4735	1.1649	2.2967	4.0702
40.00	.0000	.0005	.0043	.0129	.0592	.1654	.3916	.8131	1.5411	2.7214	4.5426
	.0000	.0021	.0041	.0061	.0297	.0794	.1864	.3997	.7951	1.4878	2.6450
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	.0000	.0000	.0000	.0006	.0277	.1229	.3508	.8155	1.6442	2.9817	4.9927
60.00	.0000	.0009	.0097	.0312	.0777	.2282	.5583	1.1096	2.0314	3.5122	5.7527
	.0000	.0122	.0321	.0397	.0641	.1918	.4536	.8773	1.5916	2.7872	4.6759
	.0000	.1130	.3547	.7392	1.5111	2.7808	4.1294	5.4587	6.9057	8.4898	10.1999
	.0000	.0184	.0519	.0670	.1014	.2445	.4722	.7773	1.2048	1.7880	2.5359
	.0000	.0008	.0031	.0100	.0476	.2212	.6101	1.2582	2.3307	3.9975	6.4247
80.00	.0000	.0014	.0162	.0606	.1288	.2883	.6858	1.3798	2.6345	4.4392	7.1563
	.0000	.0415	.1172	.1900	.2075	.3534	.8439	1.6297	3.0296	5.0010	8.0780
	.0000	.1766	.5409	1.0847	1.8582	3.3830	5.5556	7.6809	10.0652	12.3962	14.9041
	.0000	.0407	.1215	.2079	.2399	.3633	.6870	1.1015	1.7146	2.4394	3.3630
	.0000	.0076	.0230	.0482	.0973	.2863	.8130	1.6810	3.1447	5.1653	8.0579
100.00	.0000	.0021	.0239	.0936	.2245	.4141	.8255	1.7033	3.0708	5.2146	8.7264
	.0000	.1098	.3124	.5474	.7146	.8153	1.3753	2.8182	4.9101	7.9937	13.1015
	.0000	.2564	.7637	1.4893	2.4876	3.9454	6.4895	9.7989	12.9902	16.2776	20.0438
	.0000	.0710	.2114	.3870	.5325	.6204	.9081	1.4952	2.1929	3.0734	4.3035
	.0000	.0225	.0655	.1271	.2206	.4070	.9477	2.1069	3.7891	6.1838	9.8396
120.00	.0000	.0029	.0329	.1300	.3312	.6177	1.0986	1.9910	3.7011	6.2149	9.8701
	.0000	.2451	.6951	1.2365	1.7824	2.0915	2.5981	4.2571	7.7904	12.5609	19.2285
	.0000	.3510	1.0244	1.9532	3.1961	4.7840	7.3823	11.2053	15.8653	20.3238	24.8881
	.0000	.1089	.3207	.5931	.8851	1.0867	1.3171	1.8579	2.7903	3.8491	5.1365
	.0000	.0470	.1336	.2505	.4125	.6474	1.1742	2.3526	4.4891	7.3490	11.1978
140.00	.0000	.0039	.0433	.1711	.4453	.8947	1.5033	2.4398	4.2490	7.2798	11.5095
	.0000	.4864	1.3699	2.4503	3.6451	4.7091	5.4646	6.8265	11.2035	18.7508	28.4722
	.0000	.4610	1.3240	2.4810	3.9895	5.9403	8.5112	12.3612	17.9265	24.1165	30.0397
	.0000	.1544	.4489	.8301	1.2698	1.6882	2.0045	2.3977	3.3456	4.6980	6.1975
	.0000	.0824	.2306	.4235	.6764	1.0257	1.5684	2.6625	4.9167	8.4231	12.8800
160.00	.0000	.0050	.0549	.2170	.5693	1.1713	2.0385	3.2062	4.9509	8.2766	13.2570
	.0000	.8853	2.4721	4.4205	6.6512	8.8954	11.1195	12.6887	16.1783	26.1171	40.6018
	.0000	.5872	1.6625	3.0729	4.8725	7.1440	9.9786	13.9522	19.4610	27.0670	34.9200
	.0000	.2076	.5959	1.0968	1.6903	2.3121	2.9086	3.3629	4.0277	5.5140	7.3472
	.0000	.1301	.3595	.6505	1.0186	1.4982	2.1566	3.2680	5.3160	9.1527	14.4469
180.00	.0000	.0062	.0680	.2678	.7044	1.4671	2.5192	4.1142	5.9630	9.2809	15.0213
	.0000	1.5081	4.1731	7.4415	11.2316	15.2744	18.6932	22.5423	25.7618	34.9567	55.4034
	.0000	.7301	2.0410	3.7303	5.8470	8.4685	11.5218	15.8408	21.0175	29.0540	39.0535
	.0000	.2687	.7619	1.3938	2.1492	2.9776	3.7253	4.5159	5.1252	6.3310	8.5146
	.0000	.1916	.5234	.9363	1.4453	2.0837	2.8676	4.1180	5.9417	9.6245	15.6711
200.00	.0000	.0078	.0825	.3237	.8513	1.7838	3.2139	5.1543	7.7619	11.2454	16.3390
	.0000	2.4708	6.6836	11.8738	17.9116	24.5367	31.3772	38.2043	44.5054	53.6151	70.0731
	.0000	.9027	2.4607	4.4547	6.9148	9.9134	13.5767	18.0110	23.9468	31.6686	41.5777
	.0000	.3427	.9472	1.7217	2.6484	3.6874	4.7753	5.8329	6.8001	7.8790	9.4526
	.0000	.2719	.7252	1.2856	1.9627	2.7889	3.8330	5.1977	7.2999	10.6662	16.1912

Table 2. Sediment transport values from the microcomputer version of SED1D for the same input conditions as used in Table 1. Values are tabulated for each of the five sediment transport formulae in this order: Engelund - Hansen (top), Einstein - Brown, Bagnold, Yalin and Ackers - White (bottom).

compared with the output from the Cyber version of SED1D. Tables 1 and 2 show the results of runs under identical input conditions for both the microcomputer and Cyber versions of SED1D. Computationally, the microcomputer version is less accurate than the Cyber version, although the maximum error is less than 1 %, which is certainly adequate considering the inherent uncertainties in any sediment transport calculation. As mentioned previously, the user may increase the computational accuracy by increasing the number of iterations in the numerical integration routine.

User Instructions

The microcomputer version of SED1D is very simple to use. The user simply inserts the disk with the executable code into a disk drive and then types (a:)sed1d. The disk drive specification may or may not be required, depending on the default drive at the time. The user is first prompted for the name of a file to which the program output will be written; again, this may or may not require a disk drive specification. The user is then prompted for the required input data and given a choice of sediment transport formulae. The program results are shown on the computer terminal as well as stored in the specified output file. The user is given a choice between terminating program execution and doing another run. Once the program is stopped, the user may review the results stored in the output file. This file has a standard ASCII format which can easily be modified by a variety of available word processors. A sample terminal session follows.

```
  a:sed1d

          SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
                   SHELF CONDITIONS

          ASA CONSULTING  LTD.             OCTOBER, 1986


          THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
          AND THEIR LIMITATIONS



 ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED
 a:test
 IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE
          TO ANY OF THE FOLLOWING QUESTIONS


 ENTER RUN NUMBER (1 - 9999)
 1


 ENTER WATER DEPTH (M)
 30


 ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE SEABED
 (CM/SEC, DEGREES TRUE, CM)
 50,0,100


 ENTER WAVE HEIGHT, PERIOD AND DIRECTION
 (METRES,SECONDS,DEGREES TRUE)
 3,10,45


 ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY
 (MM, GRAMS/CUBIC CM)
 .3,2.65


 ENTER BOTTOM ROUGHNESS HEIGHT (CM)
 10


 ENTER FLUID DENSITY (GRAMS/CUBIC CM)
 1.03


 CHOOSE BETWEEN:
   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
   3 - BAGNOLD (1963) TOTAL LOAD EQUATION
   4 - YALIN (1963) BEDLOAD EQUATION
   5 - ACKERS-WHITE TOTAL LOAD EQUATION
 ENTER 1,2,3,4 OR 5
 2
```

```
  RESULTS:


         MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
         VELOCITY, FROM LINEAR WAVE THEORY            =  51.03 CM/SEC
         MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
         DISPLACEMENT, FROM LINEAR WAVE THEORY        =   81.22 CM
         WAVELENGTH, FROM LWT DISPERSION EQUATION = 137.29 M

         BOTTOM FRICTION FACTOR =  .0055
         (GRANT AND MADSEN, 1979)
         CURRENT SPEED 1 M. ABOVE SEABED           =  49.76 CM/SEC
         CURRENT SPEED TO BE USED IN BOTTOM STRESS
         CALCULATIONS                              =  20.76 CM/SEC
         ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
         WITHIN WAVE BOUNDARY LAYER                =  60.28 DEGREES
         NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

         CRITICAL FLUID VELOCITY FOR INITIATION OF
         BEDLOAD TRANSPORT                         =  28.61 CM/SEC
         CRITICAL FLUID VELOCITY FOR INITIATION OF
         SUSPENDED LOAD TRANSPORT                  =  55.98 CM/SEC

         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         SUSPENDED LOAD TRANSPORT CEASES            =   .92 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         BEDLOAD TRANSPORT CEASES                   =  2.12 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         SUSPENDED LOAD TRANSPORT RECOMMENCES       =   .00 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         BEDLOAD TRANSPORT RECOMMENCES              =  3.60 SEC

         PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =  52.07
         PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =  18.43

         DIRECTION OF NET SEDIMENT TRANSPORT =  23.01 DEGREES TRUE
         TIME-AVERAGED NET SEDIMENT TRANSPORT =   .1044E-01 CM**2/SEC
         (EINSTEIN-BROWN (1950) BEDLOAD EQUATION)
         NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER  THAN
                SOIL VOLUME TRANSPORT RATE



         EXPECTED BEDFORMS ARE (C. L. AMOS):

                   BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS



ENTER 1 TO DO ANOTHER RUN, 0 TO STOP
0
Stop - Program terminated.

C>
```

REFERENCES

ABRAMOWITZ, A. and I.A. STEGUN, 1965. Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables. Dover Publications, Inc., New York, New York, 1046 pp.

CARNAHAN, B., H.A. LUTHER and J.O. WILKES, 1969. Applied Numerical Methods. John Wiley & Sons, Inc., New York, New York, 604 pp.

DAVIDSON, S. and C.L. AMOS, 1985. A re-evaluation of SED1D and SED2D: sediment transport models for the continental shelf. Unpublished report submitted to the Geological Survey of Canada, 74 pp.

MARTEC LTD., 1982. Sediment transport on a continental shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-1-M571, 91 pp.

MARTEC LTD., 1983. A 2-D sediment transport model for continental shelves. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-2-M777, 63 pp.

MARTEC LTD., 1984. SED1D: A sediment transport model for the continental shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-3-M753, 63 pp.

Program Listing

```
        PROGRAM SED1DF
$DEBUG
      REAL KB,KBC
      CHARACTER*15 NAME
C
C  THIS PROGRAM CALCULATES SEDIMENT TRANSPORT UNDER A VARIETY OF WAVE
C  AND CURRENT CONDITIONS FOR HORIZONTAL BEDS ONLY.  A CHOICE OF
C  TRANSPORT FORMULAE IS AVAILABLE TO THE USER, HOWEVER, IT MUST BE
C  REMEMBERED THAT NONE OF THESE FORMULAE HAVE BEEN CALIBRATED FOR
C  COMBINED WAVE AND CURRENT CONDITIONS.
C  THE AVAILABLE OPTIONS ARE:
C  IOPT = 1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
C         2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
C         3 - BAGNOLD (1963) TOTAL LOAD EQUATION
C         4 - YALIN (1963) BEDLOAD EQUATION
C         5 - ACKERS-WHITE TOTAL LOAD EQUATION
C
C  THIS VERSION ALLOWS THE VELOCITY TO BE INPUT AT ANY LEVEL WITHIN
C  THE BOTTOM LOGARITHMIC LAYER AND CONSIDERS THE AUTOSUSPENSION
C  PHENOMENON.  AS WELL, THIS VERSION HAS BEEN CHANGED SO THAT THE
C  VELOCITY USED IN BOTTOM STRESS CALCULATIONS, UA, DEFAULTS TO A
C  VALUE CORRESPONDING TO THE PURE CURRENT CASE ONLY WHEN THE TOTAL
C  BOTTOM STRESS IS LESS THAN THAT FOR A CURRENT ALONE.
C
C
      WRITE (*,5)
  5   FORMAT(/,T11,'SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL'
     @/,'                       SHELF CONDITIONS',//,
     @T11,'ASA CONSULTING  LTD.                OCTOBER, 1986',///,
     @T11,'THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED',/,
     @T11,'AND THEIR LIMITATIONS',//)
      WRITE (*,2)
  2   FORMAT(/,' ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED')
      READ (*,3) NAME
  3   FORMAT(A15)
      OPEN (7,FILE=NAME,STATUS='NEW')
      WRITE (7,5)
   1  CALL READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW,
     @            QI,IOPT)
      IF (QI .EQ. 1.0) GO TO 10
      CALL INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW)
C
C  CHANGE GRAIN SIZE FROM MM TO CM
C
      GD=GD*0.10
C
C  DO CALCULATIONS AND PRINT RESULTS
C
      CALL OSCIL(HT,PER,D,UB,AB,WL)
      CALL FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      CALL THRESH(D,U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS,DGR,
     @            AGR,RGR,IOPT)
      CALL TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,TS1,
     @TS2,TB1S,TB2S)
      CALL TRANSPO(D,UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,RHOW,
     @VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,IOPT,
     @TB1S,TB2S,DGR,AGR,RGR)
      CALL OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,TB2,
     @PERBED,PERSUSP,SED,SEDDIR,IOPT)
```

```
      CALL BEDFORM(U100,UB,GD,KBC)
C
C  GIVE USER THE OPTION OF DOING ANOTHER RUN
C
 10   WRITE (*,15)
 15   FORMAT(///,' ENTER 1 TO DO ANOTHER RUN, 0 TO STOP')
      READ (*,*) IND
      IF (IND .EQ. 1) GO TO 1
      STOP
      END
C************************************************************************
C************************************************************************
C************************************************************************
C************************************************************************
      SUBROUTINE READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,      AW
     @                  RHOW,QI,IOPT)                                   AW
      REAL KB
C
C  THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING
C  SED1D.
C
      WRITE (*,15)
 15   FORMAT(' IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE',/,
     @T11,'TO ANY OF THE FOLLOWING QUESTIONS')
C
C  INITIALIZE QUIT INDEX TO 0
C
      QI=0.0
C
C  ENTER DATA
C
      WRITE (*,25)
 25   FORMAT(//,' ENTER RUN NUMBER (1 - 9999)')
      READ (*,*) IRUN
C
      WRITE (*,35)
 35   FORMAT(//,' ENTER WATER DEPTH (M)')
      READ (*,*) D
      IF ( D .EQ. -99.) GO TO 998
C
      WRITE (*,45)
 45   FORMAT(//,' ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE SEABED',
     @/,' (CM/SEC, DEGREES TRUE, CM)')
      READ (*,*)  UZ,CDIR,Z
      IF (UZ .EQ. -99. .OR. CDIR .EQ. -99. .OR. Z .EQ. -99.) GO TO 998
C
      WRITE (*,55)
 55   FORMAT(//,' ENTER WAVE HEIGHT, PERIOD AND DIRECTION',/,
     @' (METRES,SECONDS,DEGREES TRUE)')
      READ (*,*) HT,PER,WDIR
      IF (HT .EQ. -99. .OR. PER .EQ. -99. .OR. WDIR .EQ. -99.) GO TO 998
C
      WRITE (*,65)
 65   FORMAT(//,' ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY',/,
     @' (MM, GRAMS/CUBIC CM)')
      READ (*,*) GD,RHOS
      IF (GD .EQ. -99. .OR. RHOS .EQ. -99.) GO TO 998
C
      WRITE (*,75)
 75   FORMAT(//,' ENTER BOTTOM ROUGHNESS HEIGHT (CM)')
```

```
      READ (*.*) KB
      IF (KB .EQ. -99.) GO TO 998
C
      WRITE (*,85)
 85   FORMAT(//,' ENTER FLUID DENSITY (GRAMS/CUBIC CM)')
      READ (*.*) RHOW
      IF (RHOW .EQ. -99) GO TO 998
C
 90     WRITE (*,95)
 95     FORMAT (//,' CHOOSE BETWEEN:',/,
     @ '    1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/.
     @ '    2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
     @ '    3 - BAGNOLD (1963) TOTAL LOAD EQUATION',/,
     @ '    4 - YALIN (1963) BEDLOAD EQUATION',/.
     @ '    5 - ACKERS-WHITE TOTAL LOAD EQUATION',/,
     @ ' ENTER 1,2,3,4 OR 5')
        READ (*,*) IOPT
        IF (IOPT .EQ. -99) GO TO 998
      IF (IOPT .LT. 1 .OR. IOPT .GT. 5) GO TO 90
C
      GO TO 999
998   QI=1.0
999   RETURN
      END
C*******************************************************************
C*******************************************************************
C*******************************************************************
C*******************************************************************
      SUBROUTINE INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD.KB,RHOS,RHOW)
      REAL KB
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE INPUT PARAMETERS FROM
C  SUBROUTINE READIN
C
C     WRITE (*,15) IRUN
      WRITE (7,15) IRUN
 15   FORMAT(////,T21,'RUN NUMBER ',I4,////,T4,'INPUT DATA:',//)
C
C     WRITE (*,25) D,UZ,CDIR,Z
      WRITE (7,25) D,UZ,CDIR,Z
 25   FORMAT(T11,'WATER DEPTH =',F7.2,' M',/,T11,'CURRENT SPEED =',F7.2,
     @' CM/SEC',/,T11,'CURRENT DIRECTION =',F7.2,' DEGREES TRUE',/,
     @T11,'HEIGHT ABOVE BED =',F7.2,' CM')
C
C     WRITE (*,35) HT,PER,WDIR
      WRITE (7,35) HT,PER,WDIR
 35   FORMAT(T11,'WAVE HEIGHT =',F7.2,' M',/,T11,'WAVE PERIOD =',F6.2,
     @' SEC',/,T11,'WAVE DIRECTION =',F7.2,' DEGREES TRUE',/)
C
C     WRITE (*,45) GD,RHOS
      WRITE (7,45) GD,RHOS
 45   FORMAT(T11,'SEDIMENT GRAIN SIZE =',F6.2,' MM',/,T11,
     @'SEDIMENT DENSITY =',F5.2,' GRAMS/CUBIC CM',/)
C
C     WRITE (*,55) KB,RHOW
      WRITE (7,55) KB,RHOW
 55   FORMAT(T11,'BOTTOM ROUGHNESS HEIGHT =',F7.2,' CM',//,T11,
     @'FLUID DENSITY =',F5.2,' GRAMS/CUBIC CM',///)
C
      RETURN
```

```
      END
C*****************************************************************************
C*****************************************************************************
C*****************************************************************************
C*****************************************************************************
      SUBROUTINE OSCIL(HT,PER,D,UB,AB,WL)
      REAL KD,KDO,K
C
C  THIS SUBROUTINE CALCULATES WAVE-INDUCED BOTTOM PARTICLE VELOCITY
C  AND DISPLACEMENT USING LINEAR WAVE THEORY.  A CHECK IS ALSO MADE
C  FOR WAVE BREAKING.
C
      IF (HT .EQ. 0.0) THEN
        UB=0.0
        AB=0.0
        WL=0.0
C       CHANGE DEPTH TO CM FOR ACKERS-WHITE FORMULA FOR CURRENTS ALONE  AW
        D=100.*D                                                        AW
C
C  CALCULATE WAVELENGTH BY NEWTON-RAPHSON SOLUTION OF LWT DISPERSION
C  EQUATION.
C
      ELSE
      G=981.
      PI=2.*ASIN(1.)
      C=100.
      HT=HT*C
      D=D*C
      W=2.*PI/PER
      KDO=W**2*D/G
      KD=KDO
   20 CONTINUE
      DKD=(1./TANH(KD)-KD/KDO)/(1./KDO+1./SINH(KD)**2)
      KD=KD+DKD
      IF (ABS(DKD) .GE. 1.0E-4) GO TO 20
      WL=2.*PI*D/KD
C
C  NEXT CHECK FOR BREAKING WAVES USING THE MICHE (1944) CRITERION
C
      HB=0.142*WL*TANH(KD)
      IF (HT .GE. HB) THEN
      WRITE (*,25)
      WRITE (7,25)
   25 FORMAT(///,' ***WARNING***',/,' THIS CASE CORRESPONDS TO BREAKING',
     @' WAVE CONDITIONS WHERE',/,' LINEAR WAVE THEORY IS NOT VALID')
      ENDIF
C
C  CALCULATE WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND DISPLACEMENT
C
      UB=PI*HT/(PER*SINH(KD))
      AB=UB/W
      ENDIF
C
      RETURN
      END

C*****************************************************************************
C*****************************************************************************
C*****************************************************************************
C*****************************************************************************
```

```
      SUBROUTINE FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      REAL KB,KBC
C
C  THIS SUBROUTINE CONTROLS THE CALCUATION OF THE BOTTOM FRICTION
C  FACTOR FOR VARIOUS WAVE AND CURRENT CONDITIONS.  ALTHOUGH THERE
C  IS NO NET SEDIMENT TRANSPORT IN THE ABSENCE OF A CURRENT, BED
C  MOBILITY AND BEDFORM GENERATION MUST STILL BE CONSIDERED.
C
C  PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        CALL FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
        PHIB=0.0
        PHI100=0.0
        KBC=KB
C
C  WAVES AND CURRENT CASE (CHECK FOR VALIDITY OF METHOD)
C
      ELSE IF (UZ .NE. 0.0) THEN
        PHI100=AMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
     @  360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
        IF (KB .EQ. 0.0) THEN
C ------------------------------------------------------------------    A
C THIS STATEMENT WAS ADDED TO PREVENT THE EXECUTION FROM TERMINATING    A
C WHEN USING BAGNOLD'S FORMULA WITH AN INPUT VALUE OF KB = 0 FOR        A
C THE WAVES AND CURRENT CASE                                            A
          KB = GD                                                       A
C ------------------------------------------------------------------    A
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBC,FCW,UA,PHIB,U100)
        ELSE
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FBAD,UA,PHIB,U100)
          CALL CHECK(U100,UA,UB,PHIB,FBAD)
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBCBAD,FCW,UBAD,PHIBAD,
     @    UBAD100)
        ENDIF
        RATIO=UA/UB
        IF (RATIO .GT. 1.0) WRITE (*,15)
        IF (RATIO .GT. 1.0) WRITE (7,15)
  15    FORMAT(///,' ***WARNING*** ',/,' UA/UB > 1.0',5X,'GRANT AND',
     @ ' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE').
C
C  PURE WAVES CASE
C
      ELSE
        CALL FRIC3(UB,AB,PER,GD,KB,FCW)
        UA=0.0
        U100=0.0
        PHIB=0.0
        PHI100=0.0
        KBC=KB
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
```

```
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  CURRENT CASE.  A CONSTANT FRICTION FACTOR IS ASSUMED, BASED ON THE
C  WORK OF STERNBERG (1971).  THIS IS MOST LIKELY INADEQUATE AND WILL
C  BE REVISED IN THE FUTURE.
C
C  INPUT VARIABLES:
C
C        UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C        GD = SEDIMENT GRAIN SIZE (CM)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        FCW = BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C
      FCW=6.0E-3
      IF(KB .EQ. 0.0) KB=GD
      U100=UZ*ALOG(3000./KB)/ALOG(30.*Z/KB)
      UA=U100
      RETURN
      END
C*********************************************************************
C*********************************************************************
C*********************************************************************
C*********************************************************************

      SUBROUTINE FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FCW,UA,PHIB,U100)
      REAL K,KB,KBC,L,LOWER
      COMMON /FUNCTS/U,GY
C
C  THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND
C  CURRENT CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1979).  THIS
C  METHOD IS NOT VALID FOR UA/UB > 1.0 (APPROXIMATELY) DUE TO THE REL-
C  ATIVE IMPORTANCE OF THE CONVECTIVE ACCELERATION TERMS IN THE EQUATION
C  OF MOTION.
C
C  INITIALIZE ITERATION PARAMETERS
C
      UA0=0.0
      UC0=0.0
      UDIF=UZ/4.
      PHIB0=0.0
      PHIC0=0.0
      PHIDIF=PHI100/4.
      BEST=2.0
      IT=1
C
C  INITIAL ESTIMATE OF FCW (JONSSON,1966), A2 (SMITH, 1977), UA AND PHIB
C
      PI=2.*ASIN(1.)
      FCW1=EXP(5.213*(KB/AB)**0.194-5.977)
      FCW=AMIN1(FCW1,0.28)
      A2=0.4*AB*SQRT(FCW/2.)
      UA=UZ*ALOG(30.*A2/KB)/ALOG(30.*Z/KB)
      PHIB=PHI100
C
```

```
C  ITERATION LOOP:  FIRST, DETERMINE MAGNITUDE AND DIRECTION OF MEAN
C  SHEAR STRESS FOR ESTIMATED UA AND PHIB.
C
 100  ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      U=UA*COS(PHIB)/UB
      GY=UA*SIN(PHIB)/UB
C
C  CALL INTEGRATION ROUTINE, ROMBIN
C
      NMAX = 6
      JMAX = 5
      LOWER = -PI/2.
      UPPER = PI/2.
      NINT1 = 1
      NINT2 = 2
      CALL ROMBIN(NMAX,LOWER,UPPER,NINT1,JMAX,RSLT1,ERR1)
      CALL ROMBIN(NMAX,LOWER,UPPER,NINT2,JMAX,RSLT2,ERR2)
      A=2.*RSLT1
      B=2.*RSLT2
C
      V2=SQRT(A*A+B*B)/(2.*PI)
      PHIC=ATAN2(B,A)
C
C  THE EQUATION FOR THE BOTTOM FRICTION FACTOR IS TRANSCENDENTAL AND
C  THUS MUST BE SOLVED ITERATIVELY.  THREE ITERATIONS WERE FOUND
C  SUFFICIENT TO OBTAIN A REASONABLE VALUE (MARTEC, 1983).
C
      DO 30 I=1,3
      L=0.4*AB*SQRT(FCW*ALPHA/2.)
      ZETA0=KB/(30.*L)
      CALL KERKEI(2.*SQRT(ZETA0),XKER,XKEI)
      K=1./(2.*SQRT(ZETA0)*SQRT(XKER**2+XKEI**2))
      C=V2/(2.*ALPHA**0.25)
      FCW=ABS(0.097*K*SQRT(KB/AB)/(SQRT(ALPHA**1.5/4.-(C*SIN(PHI100))
     @**2)-C*COS(PHI100)))**(4./3.)
  30  CONTINUE
C
C  CALCULATE APPARENT BOTTOM ROUGHNESS AND RESULTING CURRENT VELOCITY
C  AT HEIGHT Z (CM) ABOVE SEABED
C
      KBC=KB*(24.*(AB/KB)*SQRT(ALPHA*FCW/2.))**(1.-SQRT(V2/ALPHA))
      UC=UB*SQRT(V2*FCW/2.)*ALOG(30.*Z/KBC)/0.4
C
C  CHECK CONVERGENCE OF UC TO UZ AND PHIC TO PHI100.  THE ERROR LIMIT
C  HAS BEEN SET TO 0.01 (OR 1.0 PERCENT).
C
      IF (PHI100 .NE. 0.0) THEN
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(1.0-PHIC/PHI100))
      ELSE
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(PHIC-PHI100))
      ENDIF
      IF (ERR .LT. BEST) THEN
        BEST=ERR
        IF (BEST .LT. 0.01) GO TO 999
        BFCW=FCW
        BUA=UA
        BPHIB=PHIB
      ELSE IF (IT .EQ. 50) THEN
        FCW=BFCW
        UA=BUA
```

```
        PHIB=BPHIB
        WRITE (*,35) UZ,PHI100,UB,PER,KB,BEST
        WRITE (7,35) UZ,PHI100,UB,PER,KB,BEST
  35    FORMAT(///,' ***WARNING*** ',/,' FOR UZ=',F8.2,', PHI100=',
     @  F7.4,', UB=',F8.2,', PER=',F6.2,/,' AND KB=',F7.3,', THE BEST',
     @  ' ESTIMATE AFTER 50 ITERATIONS HAS',/,' AN ERROR OF',F5.2)
        GO TO 999
      ENDIF
C
C  INCREMENT ITERATION COUNTER AND MAKE NEW ESTIMATE OF UA AND PHIB.
C
      IT=IT+1
      UA1=UA
      DIF=(UZ-UC)*(UA-UA0)/(UC-UC0)
      IF (DIF .LT. -UA) DIF=UA*UA/DIF
      DIF=SIGN(AMIN1(ABS(DIF),ABS(UDIF)),DIF)
      UDIF=DIF*2.
      UA=UA+DIF
      UA0=UA1
      UC0=UC
C
      IF (PHIC .NE. 0.0) THEN
        PHIB1=PHIB
        IF (PHIC .NE. PHIC0) THEN
          DIF=(PHI100-PHIC)*(PHIB-PHIB0)/(PHIC-PHIC0)
          DIF=SIGN(AMIN1(ABS(DIF),ABS(PHIDIF)),DIF)
          PHIDIF=DIF*2.
          PHIB=PHIB+DIF
        ELSE
          PHIB=PHI100
        ENDIF
        PHIB0=PHIB1
        PHIC0=PHIC
      ELSE
        PHIB=0.
      ENDIF
C
C  REPEAT ITERATION; RETURN TO MAIN PROGRAM WHEN ERROR LIMIT OR
C  ITERATION COUNT IS SATISFIED.
C
      GO TO 100
 999  DELTAW=2.*L
      IF (DELTAW .GT. Z) THEN
        WRITE (*,55)
        WRITE (7,55)
  55    FORMAT(///,' ***WARNING***',/,' DELTAW > Z',5X,'GRANT AND',
     @' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
      ENDIF
      IF (DELTAW .GT. 100) THEN
        U100=UB*V2*SQRT(FCW/(2.*ALPHA))*ALOG(3000./KB)/0.4
      ELSE
        U100=UB*SQRT(V2*FCW/2.)*ALOG(3000./KBC)/0.4
      ENDIF
      RETURN
      END
```

```
      FUNCTION FUN1(X)
$DEBUG
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN1=GX*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN2(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN2=GY*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC3(UB,AB,PER,GD,KB,FCW)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  WAVE CONDITION USING THE METHOD OF JONSSON (1966) AS MODIFIED BY
C  NIELSEN (197?).  THE BOTTOM ROUGHNESS IS TAKEN AS THE GRAIN DIAMETER
C  AS IN GRANT AND MADSEN (1976).
C
C  INPUT VARIABLES:
C
C          UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C          AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C          PER = WAVE PERIOD (SEC)
C          GD = SEDIMENT GRAIN SIZE (CM)
C          KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C          FCW = BOTTOM FRICTION FACTOR FOR THE PURE WAVE CASE
C
      FCW=AMIN1(EXP(5.213*(GD/AB)**0.194-5.977),0.28)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE THRESH(D,U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS,
     @                  DGR,AGR,RGR,IOPT)                                AW
      REAL N
C
C  THIS SUBROUTINE CALCULATES THE THRESHOLD FLUID VELOCITY FOR SEDIMENT
C  TRANSPORT FOR BOTH BEDLOAD AND SUSPENDED LOAD.  THE CRITICAL STRESSES
C  ARE FROM MARTEC (1982).  THE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS
C  BASED ON THE WORK OF MILLER ET AL. (1977); THE CRITICAL STRESS FOR
C  SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966). WHERE THE
C  PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971).
C
C  INPUT VARIABLES:
C
C          UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
```

```
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         FCW = BOTTOM FRICTION FACTOR
C         GD = SEDIMENT GRAIN SIZE (CM)
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY (GRAMS/CM**3)
C         IOPT = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA         AW
C
C  OUTPUT VARIABLES:
C
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C         AGR = CRITICAL MOBILITY NUMBER USED IN ACKERS-WHITE FORMULA   AW
C         DGR = DIMENSIONLESS GRAIN DIAMETER IN ACKERS-WHITE FORMULA    AW
C         RGR = REYNOLDS NUMBER AS A FUNCTION OF DGR, AS GIVEN BY       AW
C               SWART AND FLEMING (1980)                                AW
C
C  INTERMEDIATE VARIABLES:
C
C         ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2.
C         DRHO = SEDIMENT DENSITY - FLUID DENSITY (GRAMS/CM**3)
C         VISC = DYNAMIC VISCOSITY OF THE FLUID (GRAMS/CM*SEC)
C         G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C         RE = GRAIN REYNOLDS NUMBER
C         FALL = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS
C                ET AL. (1971) (CM/SEC)
C         TCB = CRITICAL BOTTOM STRESS FOR INITIATION OF BEDLOAD
C               TRANSPORT (DYNES/CM**2)
C         TCS = CRITICAL BOTTOM STRESS FOR INITIATION OF SUSPENDED LOAD
C               TRANSPORT (DYNES/CM**2)
C         DS = DIFFERENCE BETWEEN SPECIFIC GRAVITY OF SEDIMENT AND      AW
C              WATER                                                    AW
C         VISK = KINEMATIC VISCOSITY OF FLUID (CM**2/SEC)               AW
C
C  INITIALIZE CONSTANTS
C
      G= 981.
      VISC=13.E-3
      DRHO=RHOS-RHOW
C
C  CALCULATE THRESHOLD VELOCITY FOR BEDLOAD TRANSPORT, VCB
C
      IF (IOPT .NE. 5) THEN                                             AW
C     MODIFIED SHIELDS CURVE (MILLER ET AL., 1977)                      AW
        IF (UB .EQ. 0.0) THEN
          RE=GD*UA*SQRT(FCW/2.)*RHOW/VISC
        ELSE
          ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          TAUB=RHOW/2.*FCW*ALPHA*UB**2
          RE=GD*SQRT(TAUB*RHOW)/VISC
        ENDIF
        IF (RE .EQ. 0.0) THEN
          TCB=9.99E8
        ELSE
          TCB=0.04*DRHO*G*GD
          IF (RE .LT. 10.0) TCB=TCB*2.4/RE**0.33
        ENDIF
```

```
        VCB=SQRT(2.*TCB/(RHOW*FCW))
      ELSE IF (IOPT .EQ. 5) THEN                                        AW
C     ACKERS-WHITE CRITERIA                                             A
        DS = DRHO/RHOW                                                  A
        VISK = VISC/RHOW                                                AW
        DGR = GD*(G*DS/VISK**2)**(1./3.)                                A
        IF (DGR .LE. 1.) THEN                                           A
        WRITE (*,5)                                                     AW
        STOP                                                            AW
   5    FORMAT ('FINE SEDIMENT - THEORY NOT APPLICABLE')                AW
        ENDIF                                                           AW
        IF (UB .EQ. 0.) THEN
C     CURRENTS ONLY (ACKERS AND WHITE,1973)                             A
          IF (DGR .GT. 60.) THEN                                        AW
            AGR = 0.17                                                  AW
            GO TO 10                                                    A
          ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN                 AW
            AGR = (0.23/SQRT(DGR)) + 0.14                               AW
            GO TO 10                                                    A
          ENDIF                                                         A
        ELSE                                                            AW
C     WAVES AND CURRENTS (SWART AND FLEMING,1980)                       A
          RGR = 10.**(0.092*(ALOG10(DGR)**2)+1.158*ALOG10(DGR)-0.367)   A
          AGR = RGR*(DGR)**(-1.5)                                       AW
          GO TO 10                                                      AW
        ENDIF                                                           A
  10    CONTINUE                                                        AW
          TCB = RHOW*G*GD*DS*AGR**2                                     AW
        IF (DGR .GT. 60.) THEN
          N = 0.
        ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN
          N = 1.0 - 0.56*ALOG10(DGR)
        ELSE
          WRITE (*,135)
          WRITE (7,135)
 135      FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')
          STOP
        ENDIF
      VST = AGR*SQRT(G*GD*DS)*(SQRT(FCW/2.)*5.75*
     @    ALOG10(10.*D/GD))**(1.-N)
      VCB = VST/SQRT(FCW/2.)
      ENDIF                                                             AW
C
C  CALCULATE THRESHOLD VELOCITY FOR SUSPENDED LOAD TRANSPORT, VCS
C
        IF (IOPT .EQ. 5) THEN
          VCS = VCB
        ELSE
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TCS=0.64*RHOW*FALL**2
      VCS=SQRT(2.*TCS/(RHOW*FCW))
        ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
```

```
      SUBROUTINE CHECK(U100,UA,UB,PHIB,FBAD)
C
C  THIS SUBROUTINE CHECKS TO SEE IF THE TOTAL BOTTOM STRESS (INCLUDING
C  FORM DRAG), CALCULATED USING GRANT AND MADSEN'S METHOD, IS AT LEAST
C  AS LARGE AS THAT CALCULATED USING STERNBERG'S METHOD.  IF NOT, THE
C  VELOCITY UA DEFAULTS TO A NEW VALUE SUCH THAT THE TWO STRESSES ARE
C  EQUAL.
C
      ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      FSC=6.0E-03
      RATIO=FBAD*ALPHA*UB**2/(FSC*U100**2)
      IF (RATIO .LT. 1.0) THEN
        ALPHA=ALPHA/RATIO
        UA=(SQRT(COS(PHIB)**2+(ALPHA-1.0))-COS(PHIB))*UB
      ENDIF
      RETURN
      END
C*********************************************************************
C*********************************************************************
C*********************************************************************
C*********************************************************************
      SUBROUTINE ROMBIN(NMAX,A,B,FIND,JMAX,RSLT,ERR)
      REAL TABLE(20,20)
      INTEGER FIND
      H = B - A
        IF (FIND .EQ. 1) THEN
          TABLE(1,1) = (FUN1(A) + FUN1(B))*H/2.0
        ELSE IF (FIND .EQ. 2) THEN
          TABLE(1,1) = (FUN2(A) + FUN2(B))*H/2.0
        ENDIF
C
C  First column of Romberg tableau
C
        DO 20 N=1,NMAX
        TABLE(N+1,1) = 0.0
        FR = H/2.0**N
        IMAX = 2**N - 1
          DO 10 I=1,IMAX,2
            IF (FIND .EQ. 1) THEN
              TABLE(N+1,1) = TABLE(N+1,1) + FUN1(A + FLOAT(I)*FR)
            ELSE IF (FIND .EQ. 2) THEN
              TABLE(N+1,1) = TABLE(N+1,1) + FUN2(A + FLOAT(I)*FR)
            ENDIF
  10      CONTINUE
        TABLE(N+1,1) = FR*TABLE(N+1,1) + TABLE(N,1)/2.0
  20    CONTINUE
C
C  Remaining columns
C
        DO 30 J=2,JMAX
        NMAXJ = NMAX - J + 2
        CONSTJ = 4.0**(J-1)
          DO 30 N=1,NMAXJ
          TABLE(N,J) = (CONSTJ*TABLE(N+1,J-1) - TABLE(N,J-1))/(CONSTJ -
     @    1.0)
  30    CONTINUE
C
C  Estimate integral value and associated error
C
      NJMAX = NMAX - JMAX + 2
```

```
      RSLT = TABLE(NJMAX,JMAX)
      ERR1 = RSLT - TABLE(NJMAX-1,JMAX)
      ERR2 = RSLT - TABLE(NJMAX+1,JMAX-1)
      ERR = (ERR1 + ERR2)/2.0
      RETURN
      END
```

```
      SUBROUTINE TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,
     @TS1,TS2,TB1S,TB2S)
$debug
C
C  THIS SUBROUTINE CALCULATES THE DURATION OF SEDIMENT TRANSPORT PHASES
C  (NO TRANSPORT, BEDLOAD TRANSPORT, SUSPENDED LOAD TRANSPORT) BY
C  CALCULATING WHEN THE RESPECTIVE CRITICAL VELOCITIES ARE EXCEEDED.
C
C  FIRST, SET DEFAULT VALUES TO ZERO
C
      PI=2.*ASIN(1.)
      TS1=0.0
      TB1=0.0
      TS2=0.0
      TB2=0.0
      PERSUSP=0.0
      PERBED=0.0
      TB1S=0.0
      TB2S=0.0
      S=1.0E-9
C
C  CONSIDER PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        IF (UA .GE. VCS) PERSUSP=100.
        IF (UA .GE. VCB .AND. UA .LT. VCS) PERBED=100.
        RETURN
C
C  CONSIDER PURE WAVE CASE
C
      ELSE IF (UA .EQ. 0.0) THEN
          IF (VCS .LT. UB) THEN
            TS1=PER/(2.*PI)*ACOS(VCS/UB)
            TS2=PER/2.-TS1
            PERSUSP=400.*TS1/PER
          ENDIF
          IF (VCB .LT. VCS .AND. VCB .LT. UB) THEN
            TB1=PER/(2.*PI)*ACOS(VCB/UB)
            TB2=PER/2.-TB1
            PERBED=400.*(TB1-TS1)/PER
          ENDIF
C
        RETURN
C
C  CONSIDER COMBINATION OF WAVES AND A CURRENT.  FIRST CALCULATE TIMES
C  FOR SUSPENDED LOAD, THEN BEDLOAD (SEE FLOWCHART IN USER'S GUIDE)
C
      ELSE
        B24ACS=(VCS**2-(UA*SIN(PHIB))**2)/(UB**2)
        IF (B24ACS .LE. 0.0) THEN
          TS1=PER/2.
          PERSUSP=100.0
          PERBED=0.0
          RETURN
        ELSE
          B=-UA*COS(PHIB)/UB
          XS1=B+SQRT(B24ACS)
C
          IF (XS1 .GE. 1.0) THEN
            PERSUSP=0.0
```

```
            GO TO 50
          ELSE IF (XS1 .LE. -1.0) THEN
            TS1=PER/2.
            PERSUSP=100.0
            PERBED=0.0
            RETURN
          ELSE
            TS1=PER/(2.*PI)*ACOS(XS1)
          ENDIF
C
          XS2=B-SQRT(B24ACS)
C
          IF (XS2 .LE. -1.0) THEN
            PERSUSP=200.*TS1/PER
          ELSE
            TS2=PER/(2.*PI)*ACOS(XS2)
            PERSUSP=(2.*(TS1-TS2)+PER)/PER*100.
          ENDIF
C
        ENDIF
C
C  CALCULATE TIMES FOR BEDLOAD ONLY IF VCB < VCS
C
  50    IF (VCB .LT. VCS) THEN
        B24ACB=(VCB**2-(UA*SIN(PHIB))**2)/(UB**2)
        B24ACBS=(VCB**2*(S+1)-(UA*SIN(PHIB))**2)/(UB**2)
C
       IF (B24ACB .LE. 0.0) THEN
          TB1=PER/2.
          TB1S=PER/2.
          PERBED=100.-PERSUSP
          RETURN
        ELSE
          B=-UA*COS(PHIB)/UB
          XB1=B+SQRT(B24ACB)
          XB1S=B+SQRT(B24ACBS)
C
          IF (XB1 .GE. 1.0) THEN
            PERBED=0.0
            RETURN
          ELSE IF (XB1 .LE. -1.0) THEN
            TB1=PER/2.
            TB1S=PER/2.
            PERBED=100.-PERSUSP
            RETURN
          ELSE
          TB1=PER/(2.*PI)*ACOS(XB1)
          TB1S=PER/(2.*PI)*ACOS(XB1S)
          ENDIF
C
          XB2=B-SQRT(B24ACB)
          XB2S=B-SQRT(B24ACBS)
C
          IF (XB2 .LE. -1.0) THEN
            PERBED=200.*TB1/PER-PERSUSP
          ELSE
            TB2=PER/(2.*PI)*ACOS(XB2)
            TB2S=PER/(2.*PI)*ACOS(XB2S)
            PERBED=(2.*(TB1-TB2)+PER)/PER*100.-PERSUSP
          ENDIF
```

```
C
        ENDIF
        ENDIF
C
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TRANSPO(D,UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,   AW
     @RHOW,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR, AW
     @IOPT,TB1S,TB2S,DGR,AGR,RGR)                                       AW
      REAL K,KB,L,M,N,LOWERC,LOWERT                                     AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                               AW
C
C  THIS SUBROUTINE CALCULATES THE TIME-AVERAGED NET SEDIMENT TRANSPORT
C  BY A CHOICE OF METHODS.  FOR THE PURE WAVE CASE THERE IS NO NET
C  TRANSPORT SINCE TRANSPORT DURING THE WAVE CREST IS EQUAL AND OPPOSITE
C  TO THAT DURING THE WAVE TROUGH (DUE TO THE USE OF LWT).  FOR THE PURE
C  CURRENT AND MIXED CONDITIONS, THE USER MAKES A CHOICE BETWEEN TRANS-
C  PORT FORMULAE. HOWEVER IF SUSPENDED LOAD TRANSPORT IS SIGNIFICANT IT
C  IS RECOMMENDED THAT A TOTAL LOAD FORMULA BE USED.
C
      G=981.
      VISC=13.E-3
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TAUCRB=RHOW*FCW/2.*VCB**2
      TAUCRS=RHOW*FCW/2.*VCS**2
      UAX=UA*COS(PHIB)
      UAY=UA*SIN(PHIB)
      IF (PER .NE. 0.0) W=2.*PI/PER
      VCBB=VCB
      UBB=UB
      SED=0.0
      SEDDIR=0.0
      VC=0.0
C
C
C  FOR THE PURE WAVE CASE NO NET TRANSPORT OCCURS
C
      IF (UA .EQ. 0.0) THEN
        SED=0.0
        SEDDIR=0.0
C
C  NO INTEGRATION IS REQUIRED FOR THE PURE CURRENT CASE.  WHEN TRANSPORT
C  IS AS SUSPENDED LOAD, THE TOTAL TRANSPORT FORMULA OF ENGELUND AND
C  HANSEN (1967) IS USED.  WHEN TRANSPORT IS AS BEDLOAD, THE USER HAS
C  A CHOICE OF FORMULAE.
C
      ELSE IF (UB .EQ. 0.0) THEN
        TAU0=RHOW*FCW/2.*UA**2
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
```

```
      ELSE IF (PERBED .EQ. 0.0 .AND. IOPT .NE. 5) THEN                 A
         WRITE (*,25)
         WRITE (7,25)
 25     FORMAT(/,' SEDIMENT TRANSPORT WILL BE CALCULATED USING THE',/,
     @  ' ENGELUND-HANSEN TOTAL LOAD FORMULA')
        V=U100
        SED=0.05*V**2*SQRT(TAU0**3*RHOW)/(GD*DGAMMA**2)
        SEDDIR=CDIR
      ELSE
 30     CONTINUE
        IF (IOPT .EQ. 1) THEN
          V=U100
          SED=0.05*V**2*SQRT(TAU0**3*RHOW)/(GD*DGAMMA**2)
        ELSE IF (IOPT .EQ. 2) THEN
          SED=40.0*FALL*GD*(TAU0/(DGAMMA*GD))**3
        ELSE IF (IOPT .EQ. 3) THEN
          BETA=1.73E-05
          IF (GD .LE. 0.031) BETA=7.22E-05
          SED=BETA/RHOS*(U100-VCB)**3
        ELSE IF (IOPT .EQ. 4) THEN
          USTAR=SQRT(FCW/2.)*UA
          S=(UA/VCB)**2-1.0
          A=2.45*(RHOW/RHOS)**0.4*SQRT(TAUCRB/(G*DRHO*GD))
          SED=0.635*GD*USTAR*S*(1.0-ALOG(1.0+A*S)/(A*S))
        ELSE IF (IOPT .EQ. 5) THEN                                      AW
          S = RHOS/RHOW                                                 AW
          DS = DGAMMA/(RHOW*G)                                          AW
          IF (DGR .GT. 60.) THEN                                        AW
            N = 0.                                                      AW
            M = 1.50                                                    AW
            C = 0.025                                                   AW
          ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN                 AW
            N = 1.00 - 0.56*ALOG10(DGR)                                 AW
            M = (9.66/DGR) + 1.34                                       AW
            C = 10.**(2.86*ALOG10(DGR)-(ALOG10(DGR))**2-3.53)           AW
          ELSE                                                          AW
            WRITE (*,35)                                                AW
 35         FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')           AW
            STOP                                                        AW
          ENDIF                                                         AW
          VST = SQRT(FCW/2.)*UA                                         AW
          FGR = (VST**N/SQRT(G*GD*DS))*                                 AW
     @            (UA/(5.75*ALOG10(10.*D/GD)))**(1.-N)
          IF (FGR .LT. AGR) THEN                                        AW
            WRITE (*,36)
            WRITE (7,36)
 36         FORMAT (' ACKERS-WHITE MOBILITY NUMBER "FGR" IS LESS',)
     @      ' THAN "AGR",',/,' WHERE AGR IS THE CRITICAL MOBILITY',
     @      ' NUMBER',/,' CALCULATED USING THE ACKERS-WHITE METHOD')
            CDIR = 0.
            GGR = 0.                                                    AW
            X = 0.                                                      AW
            SED = 0.                                                    AW
            GO TO 40                                                    AW
          ELSE                                                          AW
            GGR = C*((FGR/AGR)-1.)**M                                   AW
            X = (S*GD*GGR/D)*(U100/VST)**N                              AW
            SED = U100*GD*GGR*(U100/VST)**N                             AW
          ENDIF                                                         AW
 40       CONTINUE                                                      AW
```

```
          ENDIF                                                             AW
C
         SEDDIR=CDIR
        ENDIF
C
C  THE COMBINED WAVE AND CURRENT CASE REQUIRES INTEGRATION OF THE
C  INSTANTANEOUS TRANSPORT OVER THE WAVE PERIOD.  THE USE OF LWT ALLOWS
C  INTEGRATION TO BE DONE OVER ONLY HALF A WAVE CYCLE.  BAGNOLD'S METHOD
C  DOES NOT REQUIRE INTEGRATION.
C  THE X- AND Y- COMPONENTS OF TRANSPORT ARE CONSIDERED SEPARATELY,
C  WHERE THE X-COMPONENT IS PARALLEL TO THE WAVE DIRECTION AND THE
C  Y-COMPONENT IS NORMAL TO THE WAVE DIRECTION.
C
      ELSE
        IF (TB1 .EQ. 0.0 .AND. TS1 .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
          GO TO 999
        ENDIF
        SEDXC=0.0
        SEDXT=0.0
        SEDYC=0.0
        SEDYT=0.0
        LOWERC = 0.0
        LOWERT = 0.0
        UPPERC = 0.0
        UPPERT = 0.0
        NMAX = 6
        JMAX = 5
 50     CONTINUE
C
        IF (IOPT .EQ. 1) THEN
          IND1 = 1
          IND2 = 2
          V=U100
          CONST=0.0177*FCW**1.5*(V*RHOW/DGAMMA)**2/GD
          IF (TB1 .NE. 0.0) THEN
            LOWERC = 0.0
            UPPERC = TB1
          ELSE
            LOWERC = 0.0
            UPPERC = TS1
          ENDIF
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND1,JMAX,RSLT1C,ERR1C)
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND2,JMAX,RSLT2C,ERR2C)
          SEDXC = 2.*CONST*RSLT1C
          SEDYC = 2.*CONST*RSLT2C
          IF (TB2 .NE. 0.0) THEN
            LOWERT = TB2
            UPPERT = PER/2.
          ELSE IF (TS2 .NE. 0.0) THEN
            LOWERT = TS2
            UPPERT = PER/2.
          ENDIF
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND1,JMAX,RSLT1T,ERR1T)
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND2,JMAX,RSLT2T,ERR2T)
          SEDXT = 2.*CONST*RSLT1T
          SEDYT = 2.*CONST*RSLT2T
C
C
```

```
        ELSE IF (IOPT .EQ. 2) THEN
          IND1 = 3
          IND2 = 4
          CONST=5.*FALL*GD*(FCW*RHOW/(GD*DGAMMA))**3
          IF (TB1 .NE. 0.0) THEN
            LOWERC = 0.0
            UPPERC = TB1
          ELSE
            LOWERC = 0.0
            UPPERC = TS1
          ENDIF
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND1,JMAX,RSLT3C,ERR3C)
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND2,JMAX,RSLT4C,ERR4C)
          SEDXC = 2.*CONST*RSLT3C
          SEDYC = 2.*CONST*RSLT4C
C
          IF (TB2 .NE. 0.0) THEN
            LOWERT = TB2
            UPPERT = PER/2.
          ELSE IF (TS2 .NE. 0.0) THEN
            LOWERT = TS2
            UPPERT = PER/2.
          ENDIF
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND1,JMAX,RSLT3T,ERR3T)
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND2,JMAX,RSLT4T,ERR4T)
          SEDXT = 2.*CONST*RSLT3T
          SEDYT = 2.*CONST*RSLT4T
C
C
        ELSE IF (IOPT .EQ. 3) THEN
          ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          USTAR=SQRT(FCW*ALPHA/2.)*UB
          L=0.4*USTAR*PER/(2.*PI)
          ZETA0=KB/(30.*L)
          CALL KERKEI(2.*SQRT(ZETA0),XKER,XKEI)
          TAU0W=0.2*RHOW*USTAR*UB/SQRT(XKER**2+XKEI**2)
           WRITE (*,105)
 105      FORMAT(//,' BAGNOLD''S METHOD REQUIRES A COEFFICIENT OF ',
     @    'PROPORTIONALITY, K',/,' WHICH RANGES BETWEEN 0.0 AND 1.0',/,
     @    ' PLEASE ENTER A VALUE FOR K')
          READ (*,*) K
          SED=K*TAU0W*UA/DGAMMA
          SEDDIR=CDIR
C
C
        ELSE IF (IOPT .EQ. 4) THEN
          IND1 = 5
          IND2 = 6
          ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          USTAR=SQRT(FCW*ALPHA/2.)*UB
          A=2.45*SQRT(TAUCRB/DGAMMA/GD)*(RHOW/RHOS)**0.4
          CONST=0.635*GD*USTAR
          IF (TB1 .NE. 0.0) THEN
            LOWERC = 0.0
            UPPERC = TB1S
          ELSE
            LOWERC = 0.0
            UPPERC = TS1
          ENDIF
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND1,JMAX,RSLT5C,ERR5C)
```

```
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND2,JMAX,RSLT6C,ERR6C)
          SEDXC = 2.*CONST*RSLT5C
          SEDYC = 2.*CONST*RSLT6C
C
          IF (TB2 .NE. 0.0) THEN
            LOWERT = TB2S
            UPPERT = PER/2.
          ELSE IF (TS2 .NE. 0.0) THEN
            LOWERT = TS2
            UPPERT = PER/2.
          ENDIF
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND1,JMAX,RSLT5T,ERR5T)
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND2,JMAX,RSLT6T,ERR6T)
          SEDXT = 2.*CONST*RSLT5T
          SEDYT = 2.*CONST*RSLT6T
C
C
        ELSE IF (IOPT .EQ. 5) THEN                                      AW
          IND1 = 7
          IND2 = 8
          DS = DGAMMA/(RHOW*G)                                          AW
          IF (DGR .GT. 60.) THEN                                        AW
            N = 0.                                                      AW
            M = 1.50                                                    AW
            C = 0.025                                                   AW
          ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN                 AW
            N = 1.0 - 0.56*ALOG10(DGR)                                  AW
            M = (9.66/DGR) + 1.34                                       AW
            C = 10.**(2.86*ALOG10(DGR) - (ALOG10(DGR))**2 - 3.53)       AW
          ELSE                                                          AW
            WRITE (*,135)                                               AW
 135        FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')           AW
            STOP                                                        AW
          ENDIF                                                         AW
          COEFF = (1./(AGR*SQRT(DS*G*GD)))*                             AW
     @            (SQRT(FCW/2.))**N*                                    AW
     @            (1./(5.75*ALOG10(10.*D/GD)))**(1.-N)                  AW
          CONST = GD*C*(SQRT(2./FCW))**N                                AW
          IF (TB1 .NE. 0.) THEN                                         AW
            LOWERC = 0.0
            UPPERC = TB1
          ELSE                                                          AW
            LOWERC = 0.0
            UPPERC = TS1
          ENDIF                                                         AW
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND1,JMAX,RSLT7C,ERR7C)
          CALL ROMB2(NMAX,LOWERC,UPPERC,IND2,JMAX,RSLT8C,ERR8C)
          SEDXC = 2.*CONST*RSLT7C
          SEDYC = 2.*CONST*RSLT8C
C                                                                       AW
          IF (TB2 .NE. 0.0) THEN                                        AW
            LOWERT = TB2
            UPPERT = PER/2.
          ELSE IF (TS2 .NE. 0.) THEN                                    AW
            LOWERT = TS2
            UPPERT = PER/2.
          ENDIF                                                         AW
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND1,JMAX,RSLT7T,ERR7T)
          CALL ROMB2(NMAX,LOWERT,UPPERT,IND2,JMAX,RSLT8T,ERR8T)
          SEDXT = 2.*CONST*RSLT7T
```

```
          SEDYT = 2.*CONST*RSLT8T
        ENDIF
C
C
        IF (IOPT .NE. 3) THEN
          SEDX=(SEDXC+SEDXT)/PER
          SEDY=(SEDYC+SEDYT)/PER
          SED=SQRT(SEDX**2+SEDY**2)
          IF (SEDY .EQ. 0. .AND. SEDX .EQ. 0.) THEN
            SEDDIR = 0.
          ELSE
            PHIS=ATAN2(SEDY,SEDX)
            DIF=SIGN((PHI100-PHIS)*180./PI,CDIR-WDIR)
            CWDIF=ABS(CDIR-WDIR)
            IF(CWDIF .LE. 90.0) SEDDIR=CDIR-DIF
            IF (CWDIF .LE. 180.0 .AND. CWDIF .GT. 90.0) SEDDIR=CDIR+DIF
            IF (CWDIF .LE. 270.0 .AND. CWDIF .GT. 180.0) SEDDIR=CDIR-DIF
            IF (CWDIF .LE. 360.0 .AND. CWDIF .GT. 270.0) SEDDIR=CDIR+DIF
            IF (SEDDIR .LT. 0.0) SEDDIR=SEDDIR+360.0
            IF (SEDDIR .GE. 360.0) SEDDIR=SEDDIR-360.0
          ENDIF
        ENDIF
      ENDIF
  999 RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE KERKEI(X,KERX,KEIX)
C
C  Ten term expansions for ker(x) and kei(x).
C
      REAL KERX,KEIX
      PI = 2.*ASIN(1.)
      Y = 0.25*X**2
      KERX = PSI(1)
      KEIX = PSI(2)*Y
        DO 100 L=1,9
        KERX = KERX + (-1)**L*PSI(2*L+1)*Y**(2*L)/(FACT(2*L)**2)
        KEIX = KEIX + (-1)**L*PSI(2*L+2)*Y**(2*L+1)/(FACT(2*L+1)**2)
  100   CONTINUE
      CALL BERBEI(X,BERX,BEIX)
      KERX = KERX - LOG(X/2.)*BERX + PI/4.*BEIX
      KEIX = KEIX - LOG(X/2.)*BEIX - PI/4.*BERX
      RETURN
      END
C
C
      SUBROUTINE BERBEI(X,BERX,BEIX)
C
C  Ten term Kelvin function expansions
C
      Y = 0.25*X**2
      BERX = 1.0
      BEIX = Y
        DO 10 I=1,9
        BERX = BERX + (-1)**I*Y**(2*I)/(FACT(2*I)**2)
        BEIX = BEIX + (-1)**I*Y**(2*I+1)/(FACT(2*I+1)**2)
  10   CONTINUE
```

```
      RETURN
      END
C
C
      FUNCTION PSI(N)
      EULER = 0.577215665
      PSI = - EULER
      IF (N .LE. 1) RETURN
      DO 10 I=1,N-1
  10  PSI = PSI + 1./FLOAT(I)
      RETURN
      END
C
C
      FUNCTION FACT(N)
      FACT = 1.
      IF (N .LE. 1) RETURN
      DO 10 I=2,N
  10  FACT = FACT*I
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE ROMB2(NMAX,A,B,FINDEX,JMAX,RSLT,ERR)
      INTEGER FINDEX
      REAL TABLE(20,20)
      H = B - A
        IF (FINDEX .EQ. 1) THEN
          TABLE(1,1) = (F1(A) + F1(B))*H/2.0
        ELSE IF (FINDEX .EQ. 2) THEN
          TABLE(1,1) = (F2(A) + F2(B))*H/2.0
        ELSE IF (FINDEX .EQ. 3) THEN
          TABLE(1,1) = (F3(A) + F3(B))*H/2.0
        ELSE IF (FINDEX .EQ. 4) THEN
          TABLE(1,1) = (F4(A) + F4(B))*H/2.0
        ELSE IF (FINDEX .EQ. 5) THEN
          TABLE(1,1) = (F5(A) + F5(B))*H/2.0
        ELSE IF (FINDEX .EQ. 6) THEN
          TABLE(1,1) = (F6(A) + F6(B))*H/2.0
        ELSE IF (FINDEX .EQ. 7) THEN
          TABLE(1,1) = (F7(A) + F7(B))*H/2.0
        ELSE IF (FINDEX .EQ. 8) THEN
          TABLE(1,1) = (F8(A) + F8(B))*H/2.0
        ENDIF
C
C  First column of Romberg tableau
C
        DO 20 N=1,NMAX
        TABLE(N+1,1) = 0.0
        FR = H/2.0**N
        IMAX = 2**N - 1
          DO 10 I=1,IMAX,2
            IF (FINDEX .EQ. 1) THEN
              TABLE(N+1,1) = TABLE(N+1,1) + F1(A + FLOAT(I)*FR)
            ELSE IF (FINDEX .EQ. 2) THEN
              TABLE(N+1,1) = TABLE(N+1,1) + F2(A + FLOAT(I)*FR)
            ELSE IF (FINDEX .EQ. 3) THEN
              TABLE(N+1,1) = TABLE(N+1,1) + F3(A + FLOAT(I)*FR)
```

```
          ELSE IF (FINDEX .EQ. 4) THEN
            TABLE(N+1,1) = TABLE(N+1,1) + F4(A + FLOAT(I)*FR)
          ELSE IF (FINDEX .EQ. 5) THEN
            TABLE(N+1,1) = TABLE(N+1,1) + F5(A + FLOAT(I)*FR)
          ELSE IF (FINDEX .EQ. 6) THEN
            TABLE(N+1,1) = TABLE(N+1,1) + F6(A + FLOAT(I)*FR)
          ELSE IF (FINDEX .EQ. 7) THEN
            TABLE(N+1,1) = TABLE(N+1,1) + F7(A + FLOAT(I)*FR)
          ELSE IF (FINDEX .EQ. 8) THEN
            TABLE(N+1,1) = TABLE(N+1,1) + F8(A + FLOAT(I)*FR)
          ENDIF
 10     CONTINUE
      TABLE(N+1,1) = FR*TABLE(N+1,1) + TABLE(N,1)/2.0
 20   CONTINUE
C
C  Remaining columns
C
      DO 30 J=2,JMAX
      NMAXJ = NMAX - J + 2
      CONSTJ = 4.0**(J-1)
        DO 30 N=1,NMAXJ
        TABLE(N,J) = (CONSTJ*TABLE(N+1,J-1) - TABLE(N,J-1))/(CONSTJ -
     @  1.0)
 30   CONTINUE
C
C  Estimate integral value and associated error
C
      NJMAX = NMAX - JMAX + 2
      RSLT = TABLE(NJMAX,JMAX)
      ERR1 = RSLT - TABLE(NJMAX-1,JMAX)
      ERR2 = RSLT - TABLE(NJMAX+1,JMAX-1)
      ERR = (ERR1 + ERR2)/2.0
      RETURN
      END
C*********************************************************************
C*********************************************************************
      FUNCTION F1(X)
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F1=UX*(UX**2+UY**2)
      RETURN
      END
C*********************************************************************
C*********************************************************************
      FUNCTION F7(X)                                                  AW
      REAL M                                                          AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                             AW
      UX = UAX + UBB*COS(W*X)                                         AW
      UY = UAY                                                        AW
        IF (COEFF*SQRT(UX**2+UY**2) .LE. 1.) THEN
          F7 = 0.
        ELSE
          F7 = UX*(COEFF*SQRT(UX**2+UY**2) - 1.)**M
        ENDIF
      RETURN                                                          AW
      END                                                             AW
C*********************************************************************
C*********************************************************************
      FUNCTION F2(X)
```

```
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F2=UY*(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F3(X)
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F3=UX*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F4(X)
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F4=UY*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F5(X)
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
        IF (S .GT. 0.) THEN
          F5=S*(1.-ALOG(1.+A*S)/(A*S))*UX/SQRT(UX**2+UY**2)
        ELSE
          F5=0.
        ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F6(X)
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
        IF (S .GT. 0.) THEN
          F6=S*(1.-ALOG(1.+A*S)/(A*S))*UY/SQRT(UX**2+UY**2)
        ELSE
          F6=0.
        ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F8(X)                                                    AW
      REAL M                                                            AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                               AW
      UX = UAX + UBB*COS(W*X)                                           AW
      UY = UAY                                                          AW
        IF (COEFF*SQRT(UX**2+UY**2) .LE. 1.) THEN
```

```
    F8 = 0.
  ELSE
    F8 = UY*(COEFF*SQRT(UX**2+UY**2) - 1.)**M
  ENDIF
RETURN
END
```

```
      SUBROUTINE OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,
     @TB2,PERBED,PERSUSP,SED,SEDDIR,IOPT)
$DEBUG
C
C  THIS SUBROUTINE WRITES THE VALUES OF THE OUTPUT PARAMETERS FROM ALL
C  SUBROUTINES
C
      WRITE (*,15)
      WRITE (7,15)
  15  FORMAT(///,T4,'RESULTS:',//)
C
      WRITE (*,25) UB,AB,WL/100.
      WRITE (7,25) UB,AB,WL/100.
  25  FORMAT(T11,'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'VELOCITY, FROM LINEAR WAVE THEORY',T56,'=',F7.2,' CM/SEC',/,T11,
     @'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'DISPLACEMENT, FROM LINEAR WAVE THEORY',T56,'=',F8.2,' CM',/,T11,
     @'WAVELENGTH, FROM LWT DISPERSION EQUATION =',F7.2,' M',/)
C
      WRITE (*,35) FCW
      WRITE (7,35) FCW
  35  FORMAT(T11,'BOTTOM FRICTION FACTOR =',F7.4)
      IF (UB .EQ. 0.0) THEN
        WRITE (*,45)
        WRITE (7,45)
  45    FORMAT(T11,'(STERNBERG, 1971)')
      ELSE IF (UA .EQ. 0.0) THEN
        WRITE (*,55)
        WRITE (7,55)
  55    FORMAT(T11,'(JONSSON, 1966)')
      ELSE
        WRITE (*,65)
        WRITE (7,65)
  65    FORMAT(T11,'(GRANT AND MADSEN, 1979)')
      ENDIF
C
      WRITE (*,75) U100,UA,PHIB*90./ASIN(1.)
      WRITE (7,75) U100,UA,PHIB*90./ASIN(1.)
  75  FORMAT(T11,'CURRENT SPEED 1 M. ABOVE SEABED',T53,'=',F7.2,
     @' CM/SEC',/,T11,'CURRENT SPEED TO BE USED IN BOTTOM STRESS',/,T11,
     @'CALCULATIONS',T53,'=',F7.2,' CM/SEC',/,T11,
     @'ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS',/,T11,
     @'WITHIN WAVE BOUNDARY LAYER',T53,'=',F7.2,' DEGREES',/,T11,
     @'NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY',/)
C
      WRITE (*,85) VCB,VCS
      WRITE (7,85) VCB,VCS
  85  FORMAT(T11,'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'BEDLOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/,T11,
     @'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'SUSPENDED LOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/)
        IF (IOPT .EQ. 5) THEN
          WRITE (*,86)
          WRITE (7,86)
  86    FORMAT(T11,'NOTE:  CRITICAL VELOCITY FOR BEDLOAD TRANSPORT IS',
     @  /,T17,'CALCULATED USING THE ACKERS-WHITE METHOD RATHER THAN',/,
     @  T17,'THE SHIELDS CURVE.  THE CRITICAL VELOCITY FOR SUSPENDED',
     @  /,T17,'LOAD TRANSPORT IS NOT USED AND HAS BEEN SET EQUAL TO THE'
     @  ,/,T17,'CRITICAL VELOCITY FOR BEDLOAD TRANSPORT',/)
        ENDIF
```

```
C
      WRITE (*,95) TS1,TB1,TS2,TB2
      WRITE (7,95) TS1,TB1,TS2,TB2
   95 FORMAT(T11,'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT RECOMMENCES         =',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT RECOMMENCES                =',F6.2,' SEC',/)
C
      WRITE (*,105) PERBED,PERSUSP
      WRITE (7,105) PERBED,PERSUSP
  105 FORMAT(T11,'PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =',F7.2,/,
     @T11,'PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =',F7.2,/)
C
      WRITE (*,115) SEDDIR,SED
      WRITE (7,115) SEDDIR,SED
  115 FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
C
      IF (UA .NE. 0.0) THEN
C
        IF (IOPT .EQ. 1) THEN
          WRITE (*,125)
          WRITE (7,125)
  125     FORMAT(T11,'(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)')
        ELSE IF (IOPT .EQ. 2) THEN
          WRITE (*,135)
          WRITE (7,135)
  135     FORMAT(T11,'(EINSTEIN-BROWN (1950) BEDLOAD EQUATION)')
        ELSE IF (IOPT .EQ. 4) THEN
          WRITE (*,145)
          WRITE (7,145)
  145     FORMAT(T11,'(YALIN (1963) BEDLOAD EQUATION)')
        ELSE IF (IOPT .EQ. 5) THEN                                      AW
          WRITE (*,185)                                                 AW
          WRITE (7,185)                                                 AW
  185     FORMAT (T11,'(ACKERS-WHITE TOTAL LOAD EQUATION)')             AW
        ELSE IF (UB .EQ. 0.0) THEN
          WRITE (*,155)
          WRITE (7,155)
  155     FORMAT(T11,'(MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION)')
        ELSE
          WRITE (*,165)
          WRITE (7,165)
  165     FORMAT(T11,'(BAGNOLD (1963) TOTAL LOAD EQUATION)')
        ENDIF
C
      ENDIF
C
      WRITE (*,175)
      WRITE (7,175)
  175 FORMAT(T11,'NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER
     @THAN',/,T18,'SOIL VOLUME TRANSPORT RATE',/)
C
      RETURN
      END
```

```
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE BEDFORM(U100,UB,GD,KBC)
      REAL KBC
C
C  THIS SUBROUTINE WRITES OUT THE EXPECTED TYPE OF BEDFORM FOR THE GIVEN
C  FLOW CONDITIONS (PURE WAVE OR PURE CURRENT CONDITIONS ONLY).  THE
C  BEDFORM TYPE IS ONLY APPROXIMATE SINCE IT IS BASED ON A VELOCITY
C  MEASUREMENT ONLY.  THE LIMITS ARE FROM C. L. AMOS, IN PROGRESS.
C
C  INPUT VARIABLES:
C
C            U100 = CURRENT SPEED AT 1 M. ABOVE SEABED ( CM/SEC)
C            UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C            GD = SEDIMENT GRAIN SIZE (CM)
C            KBC = APPARENT BOTTOM ROUGHNESS (CM)
C
      IF (KBC .EQ. 0.0) KBC=GD
C
C  SET UP FORMAT STATEMENTS
C
      WRITE (*,15)
      WRITE (7,15)
  15  FORMAT(//,T11,'EXPECTED BEDFORMS ARE (C. L. AMOS):',/)
  25  FORMAT(T21,'WAVE RIPPLES')
  35  FORMAT(T21,'WAVE-INDUCED FLAT BED')
  355 FORMAT(T21,'WAVE RIPPLES OR WAVE-INDUCED FLAT BED')
  45  FORMAT(T21,'CURRENT RIPPLES')
  55  FORMAT(T21,'FLAT BED (LOWER)')
  65  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES')
  75  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES OR SAND WAVES')
  85  FORMAT(T21,'2-D MEGARIPPLES')
  95  FORMAT(T21,'2-D MEGARIPPLES OR SAND WAVES')
 105  FORMAT(T21,'SAND WAVES')
 115  FORMAT(T21,'SAND WAVES OR 3-D MEGARIPPLES')
 125  FORMAT(T21,'3-D MEGARIPPLES')
 135  FORMAT(T21,'FLAT BED (UPPER) AND SAND RIBBONS')
 145  FORMAT(T21,'SEDIMENT IN SUSPENSION')
 155  FORMAT(T21,'NO TRANSPORT')
 165  FORMAT(T21,'BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS')
C
C  VERY COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      IF (GD .LE. 0.2 .AND. GD .GT. 0.1) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 30.0) WRITE (*,155)
          IF (UB .LT. 30.0) WRITE (7,155)
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) WRITE (*,25)
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) WRITE (7,25)
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) WRITE (*,355)
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) WRITE (7,355)
          IF (UB .GE. 200.0) WRITE (*,35)
          IF (UB .GE. 200.0) WRITE (7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
```

```
          IF (U100 .LT. 40.0) WRITE (*,155)
          IF (U100 .LT. 40.0) WRITE (7,155)
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) WRITE (*,95)
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) WRITE (7,95)
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) WRITE (*,75)
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) WRITE (7,75)
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) WRITE (*,95)
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) WRITE (7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) WRITE (*,105)
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) WRITE (7,105)
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) WRITE (*,135)
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) WRITE (7,135)
          IF (U100 .GE. 295.0) WRITE (*,145)
          IF (U100 .GE. 295.0) WRITE (7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          WRITE (*,165)
          WRITE (7,165)
        ENDIF
C
C  COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.1 .AND. GD .GT. 0.05) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 20.0) WRITE (*,155)
          IF (UB .LT. 20.0) WRITE (7,155)
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) WRITE (*,25)
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) WRITE (7,25)
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) WRITE (*,355)
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) WRITE (7,355)
          IF (UB .GE. 125.0) WRITE (*,35)
          IF (UB .GE. 125.0) WRITE (7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 25.0) WRITE (*,155)
          IF (U100 .LT. 25.0) WRITE (7,155)
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) WRITE (*,45)
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) WRITE (7,45)
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) WRITE (*,55)
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) WRITE (7,55)
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) WRITE (*,65)
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) WRITE (7,65)
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) WRITE (*,85)
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) WRITE (7,85)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE (*,95)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE (7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE (*,115)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE (7,115)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE (*,125)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE (7,125)
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) WRITE (*,135)
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) WRITE (7,135)
          IF (U100 .GE. 240.0) WRITE (*,145)
          IF (U100 .GE. 240.0) WRITE (7,145)
C
```

```
C   COMBINED WAVES AND CURRENT CASE
C
          ELSE
            WRITE (*,165)
            WRITE (7,165)
          ENDIF
C
C   MEDIUM SAND
C   FIRST, DO PURE WAVE CASE
C
        ELSE IF (GD .LE. 0.05 .AND. GD .GT. 0.025) THEN
          IF (U100 .EQ. 0.0) THEN
            IF (UB .LT. 13.0) WRITE (*,155)
            IF (UB .LT. 13.0) WRITE (7,155)
            IF (UB .GE. 13.0 .AND. UB .LT. 80.0) WRITE (*,25)
            IF (UB .GE. 13.0 .AND. UB .LT. 80.0) WRITE (7,25)
            IF (UB .GE. 80.0 .AND. UB .LT. 100.0) WRITE (*,355)
            IF (UB .GE. 80.0 .AND. UB .LT. 100.0) WRITE (7,355)
            IF (UB .GE. 100.0) WRITE (*,35)
            IF (UB .GE. 100.0) WRITE (7,35)
C
C   PURE CURRENT CASE
C
          ELSE IF (UB .EQ. 0.0) THEN
            IF (U100 .LT. 20.0) WRITE (*,155)
            IF (U100 .LT. 20.0) WRITE (7,155)
            IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) WRITE (*,45)
            IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) WRITE (7,45)
            IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE (*,85)
            IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE (7,85)
            IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE (*,115)
            IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE (7,115)
            IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE (*,125)
            IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE (7,125)
            IF (U100 .GE. 150.0 .AND. U100 .LT. 170.0) WRITE (*,135)
            IF (U100 .GE. 150.0 .AND. U100 .LT. 170.0) WRITE (7,135)
            IF (U100 .GE. 170.0) WRITE (*,145)
            IF (U100 .GE. 170.0) WRITE (7,145)
C
C   COMBINED WAVES AND CURRENT CASE
C
          ELSE
            WRITE (*,165)
            WRITE (7,165)
          ENDIF
C
C   FINE SAND
C   FIRST, DO PURE WAVE CASE
C
        ELSE IF (GD .LE. 0.025 .AND. GD .GT. 0.0125) THEN
          IF (U100 .EQ. 0.0) THEN
            IF (UB .LT. 10.0) WRITE (*,155)
            IF (UB .LT. 10.0) WRITE (7,155)
            IF (UB .GE. 10.0 .AND. UB .LT. 70.0) WRITE (*,25)
            IF (UB .GE. 10.0 .AND. UB .LT. 70.0) WRITE (7,25)
            IF (UB .GE. 70.0) WRITE (*,35)
            IF (UB .GE. 70.0) WRITE (7,35)
C
C   PURE CURRENT CASE
C
```

```
         ELSE IF (UB .EQ. 0.0) THEN
           IF (U100 .LT. 13.0) WRITE (*,155)
           IF (U100 .LT. 13.0) WRITE (7,155)
           IF (U100 .GE. 13.0 .AND. U100 .LT. 60.0) WRITE (*,45)
           IF (U100 .GE. 13.0 .AND. U100 .LT. 60.0) WRITE (7,45)
           IF (U100 .GE. 60.0 .AND. U100 .LT. 85.0) WRITE (*,135)
           IF (U100 .GE. 60.0 .AND. U100 .LT. 85.0) WRITE (7,135)
           IF (U100 .GE. 85.0) WRITE (*,145)
           IF (U100 .GE. 85.0) WRITE (7,145)
C
C   COMBINED WAVES AND CURRENT CASE
C
         ELSE
           WRITE (*,165)
           WRITE (7,165)
         ENDIF
C
       ENDIF
       RETURN
       END
```

THE COMPARISON BETWEEN OBSERVED AND PREDICTED SEDIMENT TRANSPORT FOR THE RADIO-ACTIVE SAND TRACER STUDY AND SED1D MODEL UPGRADING

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NOMENCLATURE

A_{gr} - value of F_{gr} at nominal initial motion
C - dimensionless coefficient in sediment transport function
$C_{h,cg}$ - Chezy coefficient for coarse grains
c_1 - parameter used in integration of Ackers-White formula
c_2 - parameter used in integration of Ackers-White formula
D - sediment grain diameter
D_{gr} - dimensionless grain size
d - water depth
$E_f(t)$ - dimensionless sediment transport efficiency
F_{gr} - dimensionless sediment mobility number for current only
Flag - indicator of real or infilled data.

$F_{gr}(t)$ - dimensionless sediment mobility number for waves and current
f - friction factor for current only
f_{wc} - friction factor for waves and current
$f_7(t)$ - function used in integration of Ackers-White formula
$f_8(t)$ - function used in integration of Ackers-White formula
G_{gr} - dimensionless sediment transport rate
g - acceleration due to gravity
g_s - volumetric sediment transport rate (Appendix F only)
H_s - significant or characteristic wave height.
K - constant for wave steepness, i.e. $T = K\sqrt{H}$.
m - dimensionless exponent in sediment transport function

NOMENCLATURE (Continued)

n - dimensionless transition exponent depending on sediment size

$P_{cg}(t)$ - stream power for coarse grains

$P_{fg}(t)$ - stream power for fine grains

Q_x - time integrated sediment transport rate in x-direction

Q_y - time integrated sediment transport rate in y-direction

q - volumetric sediment transport rate for current only

$q(t)$ - instantaneous sediment transport rate vector for waves and current

$q_x(t)$ - x-component of $q(t)$

$q_y(t)$ - y-component of $q(t)$

R_{gr} - Reynolds number based on mean shear stress at incipient motion

s - specific gravity of sediment

T_p - peak spectral wave period.

T_z - average zero-crossing wave period.

u - instantaneous velocity vector (Appendix F only)

U - ambient current (storm plus tidal, etc.) at a height of 0.5 m above the seafloor. This should be the temporally averaged current for the three hours represented by the month/day/hour given.

U_{cb} - critical velocity for sediment movement as bedload.

u_a - steady current.

u_b - maximum wave induced orbital velocity.

u_x - instantaneous water particle velocity in the x-direction for each digital recording during the burst sampling interval.

u_y - instantaneous water particle velocity in the y-direction for each digital recording during the burst sampling interval.

$\overline{u}_x$ - velocity in the x-direction averaged over the burst sampling interval.

NOMENCLATURE (Continued)

$\overline{u}_y$ - velocity in the y-direction averaged over the burst sampling interval.

$u_{x_{rms}}$ - root-mean-square water particle velocity in the x-direction for the burst sampling interval.

$u_{y_{rms}}$ - root-mean-square water particle velocity in the y-direction for the burst sampling interval.

V - mean flow velocity

v_{cr} - critical velocity for initiation of bedload transport

$v_r(t)$ - instantaneous velocity vector

$v_x(t)$ - x-component of $v_r(t)$

$v_y(t)$ - y-component of $v_r(t)$

v_* - shear velocity for transitional sizes of sediment

v_{*cg} - shear velocity for coarse grains for current only

$v_{*cg}(t)$ - instantaneous shear velocity for coarse grains for waves and current

v_{*fg} - shear velocity for fine grains for current only

$v_{*fg}(t)$ - instantaneous shear velocity for fine grains for waves and current

W_b - sediment load

X - dimensionless sediment flux

α - coefficient in rough-turbulent equation

β - azimuth direction in degrees true

ν_s - unit weight of sediment

θ - direction of resultant velocity vector relative to x-axis

μ - dynamic viscosity of fluid

ν - kinematic viscosity of fluid

ρ - fluid density

NOMENCLATURE (Continued)

ρ_s - sediment density

τ_{cg} - shear stress for coarse grains for waves and current

$(\tau_{cg})_{cr}$ - critical shear stress for coarse grains for current only

$(\tau_{cg}(t))_{cr}$ - critical shear stress for coarse grains for waves and current

$\overline{\tau}_{cr}$ - mean shear stress at incipient motion

τ_{fg} - shear stress for fine grains for current only

$\tau_{fg}(t)$ - instantaneous shear stress for fine grains for waves and current

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1.0 INTRODUCTION

1.1 Summary

The objective of this study was to complete the calibration of the Atlantic Geoscience Centre (AGC) sediment transport model SED1DE. SED1DE stands for Sediment Transport 1-Dimensional version E and the model is used to predict sediment transport rates in the X and Y directions due to waves and/or currents at one place of interest. A calibration of the AGC sediment transport model SED1DE is necessary in order to obtain accurate estimates of sediment transport near Sable Island and other locales. Descriptions of this model, which was the latest version (there is now a version SED1DF) of the model SEDMO, are available from Martec (1982, 1984 and, Davidson and Amos 1985), therefore a detailed description of the model is not presented in this report.

At the time that the proposal for this study was submitted, there was an ongoing field program with the purpose of measuring sediment transport rates and obtaining the oceanographic (i.e. hydrodynamic) data which control rates of sediment transport around Sable Island. The sediment transport rates were to be inferred by detecting, at regular intervals, the location of mildly radioactive tracer sediments. The hydrodynamic parameters were to be in the form of X-Y water velocities sampled instantaneously at a height of 0.5 m above the seabed in the vicinity of the tracer sediments. The water particle velocities were to be sampled at 1 Hz for 17 minutes every 3 hours during the first 10 months of the sediment tracer study (September 1984 to June 1985).

The tracer study was initiated as an Environmental Studies Revolving Fund (ESRF) project. At first it was conducted by SeaConsult Marine Research Ltd. and it was then continued after March 1985 by Dr. C.L. Amos of the Atlantic Geoscience Centre (AGC). The two phases of the tracer study are described in Seaconsult (1985) and Amos (1986).

The initial objective of this study (i.e. calibration of SED1DE) was frustrated by the almost complete failure of the water velocity recording devices. Near-bottom water velocity data was only available at the Venture tracer site for the period of January 17, 1985 to February 20, 1985 (tracer detections #3 to #4). For all other time intervals, at both the Venture and Olympia sites, the Seadata brand velocity meters failed to sample and/or record for various reasons. In addition to this, Seaconsult Marine Research found that it was not possible to hindcast wind driven currents and as a result could not infill the missing oceanographic data with hindcast data. Because of these problems it was only possible to conduct a comparison of the SED1DE predictions of sediment transport rates with the sediment transport rates inferred from the sediment tracer detections for the period of January 17, 1985 to February 20, 1985. The salient point of the comparison was that the predicted sediment transport was an order of magnitude less than, and in the opposite direction to, the sediment transport inferred by the tracer study. Reasons for this are discussed in Section 2 of this report. It was not possible to calibrate SED1DE on the basis of this single comparison.

After consultation with the scientific authority, Dr. C.L. Amos of AGC, the scope of work for this study was modified because of the fact that insufficient data was available to complete the original terms of reference. The revised scope of work included the sediment transport comparison mentioned above, and an upgrading of SED1DE to include the work of Ackers and White (1973). The upgraded model is called SED1DF.

Martec Ltd. also verified that there was no oceanographic data recorded on the Seadata type meters during deployment from March to June 1985. It is worth noting that AGC purchased a Seadata-635 type current meter for use during the extension of the tracer study and that a two week long verification test was conducted at BIO prior to field deployment. The data from the test was verified by Seaconsult Marine Research Ltd. but Martec Ltd. subsequently discovered that after roughly twelve hours of successful data recording, the current meter recorded only zeros. It should have been recording the action of "stirring" the water in the test tank at least once or twice per day and so the indication is that it was probably not functioning properly before it was deployed in the field.

The details of sediment transport comparison and the details of the model upgrading are presented in Chapters 2 and 3 respectively, both of which are intended as independent reports on the work.

To provide a clear synopsis of how the original terms of reference were dealt with, each of the original tasks are addressed individually below.

1.2 Treatment of Original Statement of Work

The original Statement of Work in the Request for Proposal was as follows:

1. To provide outputs of sediment discharge, (volume of sediment solids transported per unit width of the seabed per unit time) derived using the AGC sediment transport model SED1DE, modified to read appropriate time-series from the ESRF sediment tracer study. The outputs should correspond to the tracer detection periods of the ESRF study.
2. To compare the sediment transport outputs against three methods of defining the input time-series: (1) spectral representation of wave climate (with background currents); (2) time averaged wave height (with background currents); and (3) hindcasted (wave and current) data. The three time series will be provided by SeaConsult as part of the ESRF study.
3. To estimate the sediment transport at the Venture and Olympia sites having a probability of excedence in any year, of 1%, 10%, 30%, 50%, 80%, and 100%.
4. To investigate analytically the effect of wave-current interactions on the computation of near-bed instantaneous velocities derived using SED1DE.
5. Compare the burst sample time series from the Seadata meters to wind records recorded on Sable Island.

Changes in the work statement were required after project initiation.

The reasons for the needed changes are described below with reference to each task item.

Task 1: This task was completed for the one tracer detection period for which there was an appropriate time-series available. The methodology and results of this item of work are presented in Section 2 of this report.

Task 2: The three different types of time series could not be provided in their entirety by SeaConsult due to their inability to produce time series of non tidal (storm driven) currents. For this reason, Task 2 could not be addressed. It is important to note that preparation of appropriate software was initiated by Martec Ltd. prior to discovering that data would not be available for its use. This software is not fully tested nor is it complete and so it is not described in this report.

Task 3: This work was not conducted because it would be of quite questionable validity without a calibration of the sediment transport model and the best methodology of dealing with input oceanographic data could not be established without completion of Task 2.

Task 4: This task required both independent surface wave data and independent current data for comparison between SED1DE near bottom instantaneous velocities with those obtained by near bottom burst sampling. As mentioned above, the independent current data was not available and so this work could not be carried out.

Task 5: This item was required to provide an independent verification of the validity of infilled burst data and hindcast storm currents. Since infilled burst data and hindcast storm currents were not available, this item of work was no longer required by the Scientific Authority.

2.0 COMPARISON BETWEEN PREDICTED AND OBSERVED SAND TRANSPORT

2.1 Introduction

The Environmental Studies Revolving Fund (ESRF) study of radio-active sand transport at the Venture and Olympia detection sites, Sable Island Bank, was initiated for three principal reasons:

1. to develop a practical method to measure active sand transport on Canadian continental shelves;
2. to determine the periods during which sand transport takes place and the magnitude and direction of this transport; and
3. to use the observations to 'calibrate' or compare to an existing numerical model of sediment transport.

The purpose of this section is to document activities carried out by Martec for the Atlantic Geoscience Centre (AGC) under Objective 3. Objectives 1 and 2 were to be carried out by SeaConsult Marine Research Ltd.

The period covered by Phase I of the tracer study and the subject of this report (see SeaConsult, 1985) was from the initial deployment of the radio-active sand on 27 September 1984 to the 4th detection period on 19 February 1985. The tracer study was subsequently extended under an agreement between Geological Survey of Canada and ESRF (Phase II). The results of the study extension will be presented in a separate report by Amos (1986) of AGC.

The nature of the data collected in the first phase is documented by SeaConsult (1985). As discussed in Section 1, near-bed measurements of currents were available for the Venture site only and were restricted to the period between detections 3 and 4 (17 January 1985 to 19 February 1985). Thus only 800 hours of data were available. Because of this, a comparison between predicted and measured sediment movement was made for this set of tracer observations only and calibration of the model was not possible due to the lack of sufficiently long-period in situ hydraulic data.

No data set is known to exist which is suitable for calibrating numeric models of sediment transport under waves and currents. Such a data set should include the following parameters:

1. continuous measurements of wave and current near-bed flow at the detection site;
2. analyses of seabed sediment character (grain size distribution and grain density);
3. water depth and general morphology;
4. bedform distribution in space and time;
5. field determination of threshold conditions for initiation of bedload and suspended load sediment transport;
6. field determination of measurements of net sediment mass transport (magnitude and direction);
7. direct measures of bed shear stress or near-bed water velocity profiles; and
8. the effects, if any, of biological agents.

A numerical model of sediment transport has been under development at the Geological Survey of Canada (see Martec, 1982, 1983, 1984 and, Davidson and Amos, 1985). The working version of this model used for this study is called SED1DE; it has since been upgraded to SED1DF as discussed in Section 3. The SED1DE model essentially is two-tiered; first it determines the magnitude and direction of the bed shear stress under the combined influences of waves and currents; and secondly it determines sediment transport rate and direction as a function of the bed shear stress. The model follows the method outlined by Grant and Madsen (1979). The validity of the hydraulic component has been verified by results of the CODE experiment (Grant and Glenn, 1983) and more recently by work carried out by Huntley and co-workers (1986). The aspects of the model which remain uncalibrated are: (1) conversion of the hydraulic conditions to that part of the shear stress which causes sediment transport, (2) the threshold conditions for the onset of bedload and suspended load sediment transport in complex flows which typify storms, and (3) the relationship between these flows and the mode of sediment transport (bedload or suspension) and magnitude and direction of the instantaneous or net transport.

The hydraulic and sediment measurements to be made in this tracer experiment were to become the basis of the calibration exercise of SED1DE. These data were to be supplied by SeaConsult Marine Research Ltd. and the analyses were to be carried out by Martec Limited.

The general analyses that were to be performed by Martec, given a sufficient number of calibration data points, are as follows:

1. an evaluation of the threshold condition for incipient motion as bedload based on measured near-bed bottom velocities (the modified Shield's Parameter; Miller et al., 1977) and under which conditions sediment moves;
2. estimations of the dispersion and net transport of sediment at the Olympia and Venture Site for the period 27 September 1984 to 19 February 1985 in order that a comparison could be made between predicted and observed values.
3. a comparison between the measured and predicted bed stress;
4. a comparison between the measured and predicted mean transport of sediment for each of the three intervals between detections and at each of the two sites, i.e. 6 detection intervals;
5. a comparison between the measured and predicted net dispersion of sediment for each of the three intervals between detections and at each of the two sites, i.e. 6 detection intervals; and

It was only possible to perform items 2, 4, and 5 of the above for one detection period at one site. The data base available and the methodology followed for the performance of this task are described below.

2.2 The Data Base

As mentioned above, the data collected are documented in SeaConsult (1985). Near-bed measurements of water velocities were available only at the Venture site and were restricted to the 800 hour period between detections 3 and 4 (17 January 1985 to 19 February 1985).

No measures of bed stress or near bottom velocity profiles were made and so an evaluation of the method used to derive this parameter could not be made.

In view of the lack of field measurements a request was made by AGC to SeaConsult for a hindcast time series of current for the period 27 September 1984 to 19 February 1985. The specifics of this time series are given in Table 2.1.

The hindcast data set was to be provided at 3 hour intervals for the duration of Phase I. Unfortunately, the magnitude and direction of the storm driven flow could not be produced.

2.3 Methods

2.3.1 Summary

The specific tasks that were to be undertaken in the calibration of the sediment transport model are listed below and an overview of the study approach, as originally proposed by Martec Ltd., follows:

1. a verification of the applicability of infilling the missing field data from the ESRF study (Task 5 of the Request for Proposal). Infilling was to be perfomed by SeaConsult);
2. a calibration/selection procedure to determine near bottom velocities from the hydrodynamic and oceanographic measurements of hindcasts (Tasks 2 and 4 of the Request for Proposal);
3. to obtain results of the tracer detection from the ESRF study;
4. to perform a calibration (Task 1 of the Request for Proposal) of the model's sediment transport parameters. The specific parameters which were to be estimated and evaluated are:
    a. the appropriate friction factor (i.e. should it be indexed as a function of bed roughness or skin friction?);
    b. the initiation of bedload and suspended sediment transport (i.e. what are the appropriate critical shear stresses?);
    c. the empirical relationships between excess shear stress and sediment movement (i.e. which transport formulae are most applicable?).

TABLE 2.1

TIME SERIES REQUIRED FOR CALIBRATION OF SED1D

Raw Data (for Task 1)	Reduced (for Task 2)	Hindcast Data (for Task 2)
Month/Day/Hour	Month/Day/Hour	Month/Day/Hour
u_{x1}, u_{y1},Flag	$\overline{u}_x, \overline{u}_y, [\tan^{-1}(u_x/u_y)]_{avg}$	$H_s, T_p, T_z, \beta_{waves}$, spread of β_{waves}, $K, U, \beta_{current}$, spectrum shape parameters
u_{x2}, u_{y2},Flag	$u_{x_{rms}}, u_{y_{rms}}, [\tan^{-1}(u_x/u_y)]_{rms}$	
. .		Month/Day/Hour
. .	Month/Day/Hour	. . .
. .	. . .	. . .
u_{xn}, u_{yn},Flag	. . .	. . .
Month/Day/Hour	. . .	
. . .		
. . .		
. . .		

NOTES:

1. Magnetic tape(s) should be 9 track, with an unlabelled tape header and with a density of no more than 1600 bpi. The maximum block size should be 5120. Either EBCDIC or ASCII form is acceptable. The block size, line length, and/or blocking factor are required information.

   A printout of the first 30 or 50 lines of data should be provided if possible.

2. X- or Y-direction in azimuth degrees true will be required.

3. It is assumed that u_x and u_y are given for a height of 0.5 m above the seafloor.

4. Hindcast data should not be corrected with respect to the near bottom current measurements (raw data).

5. Raw data gaps should be filled to provide a continuous 3 hour time series for the duration of all the detections (23 Sept. 1984 -April 1985).

5. to predict storm event sediment transport (Task 3 of the Request for Proposal)

Figure 2.1 outlines the complete calibration procedure as proposed by Martec Ltd.

Table 2.1 outlines the various types of time series data required to perform the work.

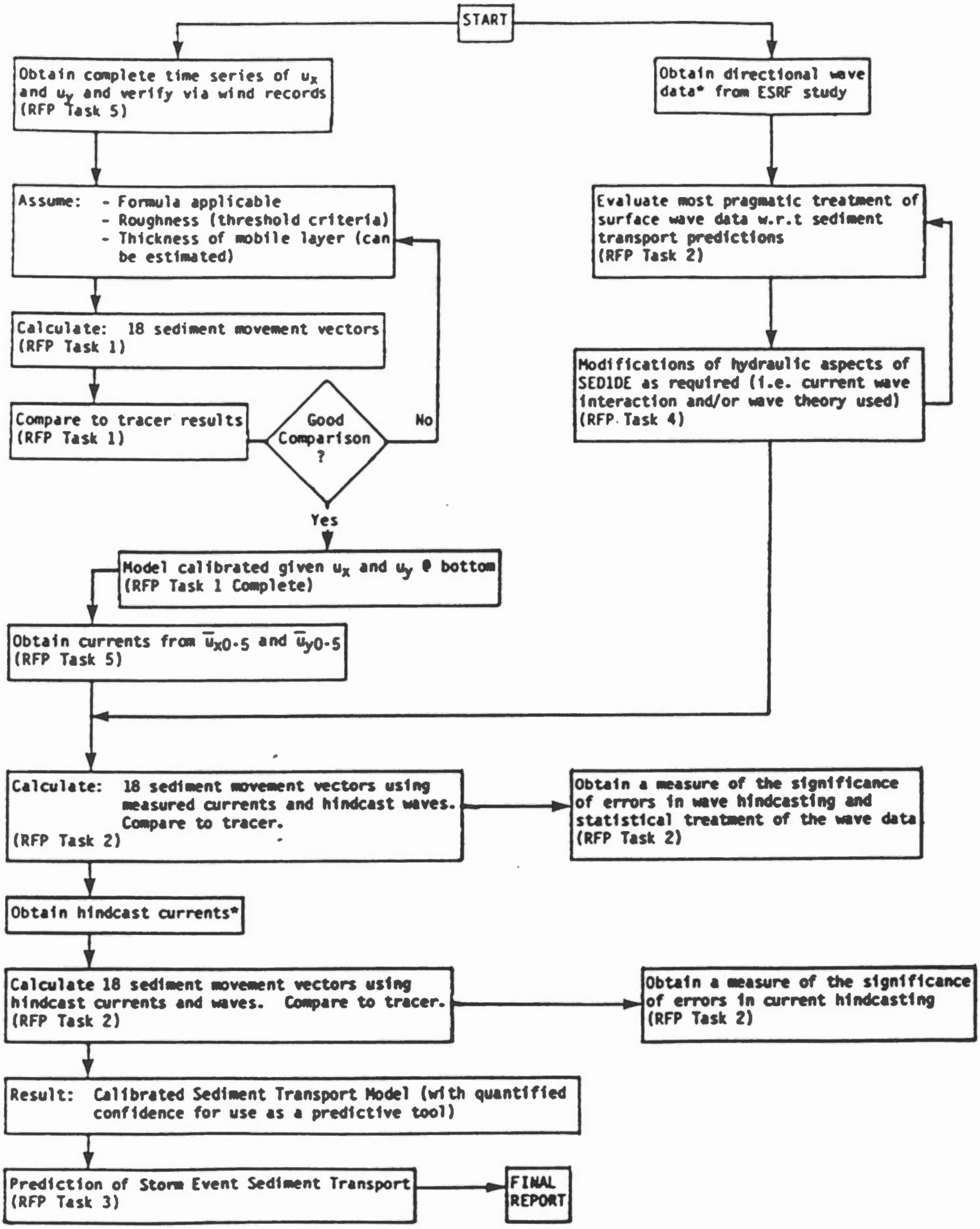
As outlined in Section 1, the procedures followed by Martec had to be altered from the above due to the lack of data. The following details the actual methodology adopted for the comparison exercise.

2.3.2 The Method of Analysis for Current Meter Data

The instantaneous X-Y water velocity (Y vector at 328° true) was sampled at 1 Hz for 1,024 seconds (17 minutes 4 seconds) every 3 hours from 1800 hrs AST, January 14, 1985, 1200 hrs AST, February 20, 1985. This data set was trimmed to correspond to the actual tracer detection time period of 1400 hrs AST, January 17, 1985 to 1400 hrs AST, February 19, 1985. The data was reformatted into two files. The first contained the raw data with a header line containing date, time and number of samples for each burst. The index containing the number of samples in each burst was necessary as it deviated occasionally from the "pure" value of 1,024. Each data record was flagged with a letter indicating data quality so that only "good" data was used in subsequent calculations. The second file contained average X and Y currents for each set of burst data.

The data quality was checked for erroneous spikes which could bias results. This was done both numerically and visually by plotting the instantaneous and average data. It was determined that only "reasonable" data was flagged as "good" data.

The data was interrogated to determine whether or not there were significant intervals of time when the velocity never exceeded critical for initiation of sand transport. This was done to determine if blocks of data



* It is assumed that the hindcast data obtained will have had its accuracy verified/determined with respect to the raw u_x, u_y data.

FIGURE 2.1

FLOW CHART OF CALIBRATION PROCEDURE

could be eliminated in order to reduce computer time requirements. While there were occasional bursts of data containing no velocities greater than 20 cm/s (the approximate threshold value), there were not enough of these events to significantly reduce computer requirements and so all the data was used in subsequent calculations.

The methods of Grant and Madsen (1979), Jonsson (1966), and Bijker (1968), were used for calculating combined wave and current friction factors. These methods require current speed and direction, peak wave-induced orbital velocity, wave period, wave orbital amplitude (maximum wave-induced water particle excursion distance) and wave direction. The mean free flow current at 100 cm off the bottom is used in the method of Grant and Madsen (1979) and was computed in their standard iterative method (which involves assumed bed roughness). The requisite initial estimate of mean free flow current was obtained by resolving the average X and Y velocity vectors for each burst into average speed and direction in degrees true. The wave parameters were obtained from a zero crossing analysis performed on the raw data. Appendix A provides sample burst data output and the mean X-Y velocity time series. Appendix B lists the program code used to read the data and perform the zero crossing analysis.

2.3.3 The Computation of Sediment Transport

A variety of procedures were used in order to derive sediment discharge. The specific procedure was predicated on the relative strengths of the oscillatory and combined flows and on the basis of the friction factor adopted in the computation of bed stress. The specific procedures for estimating the friction factors are as follows:

1. The SED1DE method.

   The friction factor was computed after Jonsson (1966) for the pure wave case, after Sternberg (1972) for the pure current case, and after Grant and Madsen (1979) for mixed wave and current conditions.

2. The Jonsson (1966) method (as modified by Nielson, 1979) to compute friction factors.
3. The Bijker (1967) method to compute friction factors.
4. The constant friction factor method.

Sediment transport was determined using each of the four transport calculation methods that are resident in SED1DE. These are:

1. Einstein-Brown (1950);
2. Bagnold (1963);
3. Engelund and Hansen (1967); and
4. Yalin (1963).

These four transport predictors have been tested for programming accuracy (Davidson and Amos, 1985). Methods 1 and 4 were developed to compute bedload discharge, whereas methods 2 and 3 were developed to simulate total (bedload and suspension) load. Sediment discharge is given as the volume of sediment solids transported per unit width of the seabed per unit time. This output was transformed into sediment movement on the basis of the following assumptions:

1. a sediment porosity of 30%;
2. a mobile layer thickness of 0.15 m;
3. a constant transport rate with depth in the mobile layer;
4. no biological reworking;
5. no influences due to bedform generation and kinematics; and
6. linear interpolation between data bursts.

The applicability of the model and the limitations of the sediment discharge equations are given in Davidson and Amos (1985). The Bagnold (1963) method is the only one intended for use in mixed flow conditions which typify Sable Island Bank. It is noted that the grain sizes used in the Venture detection (0.3-0.4 mm) are within the range considered valid for the application of Bagnold (1963).

Sediment advection, and an estimate of the dispersion, for the period between detections 3 and 4 were calculated as follows:

1. a friction factor was derived for each wave in each burst of data (a zero-crossing analysis of the velocity data was conducted to arrive at wave parameters);
2. estimates were made of the critical velocities for initiation of sediment transport (threshold conditions) under mixed flow conditions;
3. solution of the instantaneous sediment transport rate and direction for times when critical velocities were exceeded;
4. the assignment of the instantaneous sediment transport for each burst into one of eight bins corresponding to direction, i.e. N, NE, E, etc. (to indicate dispersion);
5. calculation of net sediment transport X and Y vectors for each burst of velocity data;
6. linear interpolation of sediment transport results for the 2 hour:43 minute period between each 17 minute burst;
7. repetition of the above for all bursts of velocity data to calculate the gross transport in each of the eight directions (i.e. dispersion) and the net sediment transport vectors (i.e. advection) for the entire 800 hour duration.

Three sediment grain diameters were used in the evaluation. These were:

0.2 mm (the mean diameter at the site)

0.3 mm (the minimum diameter of the tracer sand)

0.4 mm (the maximum diameter of the tracer sand)

The sediment density was assumed to be 2.65 g/cm^3 and the fluid density 1.025 g/cm^3.

The results are described below.

2.4 Results of Comparison

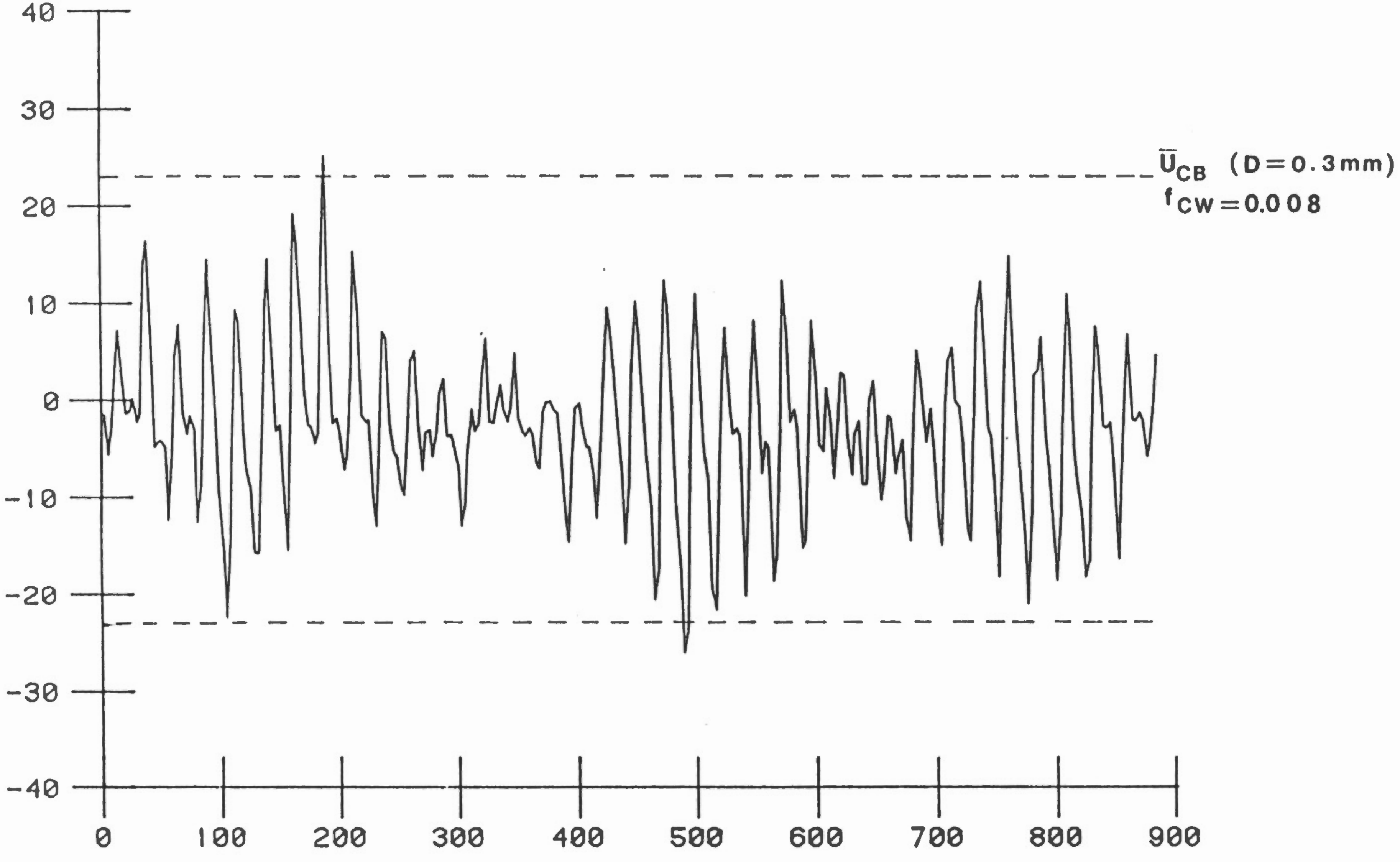
1. No evaluation of the SED1DE threshold condition for incipient motion of bedload could be made as no time-lapse photography was available.

2. No evaluation of the SED1DE threshold condition for incipient motion as suspended load could be made for the reason given above.
3. No evaluation of the SED1DE measures of bed stress could be made due to the absence of boundary layer measures or direct measures of stress at the bed.
4. A comparison was made between the observed and predicted mean sediment transport for detection period 3 to 4. The details of this comparison follow.

The average velocities in the X-and Y-directions are plotted in Figures 2.2 and 2.3, respectively. The orientation of the X-axis for the Venture data was 58°T. These plots show the mean current after filtering out the presence of surface gravity waves. Mean currents dominate in the north/south quadrants. The resultant speed is plotted in Figure 2.4. First approximations of threshold conditions for bedload transport are also shown.

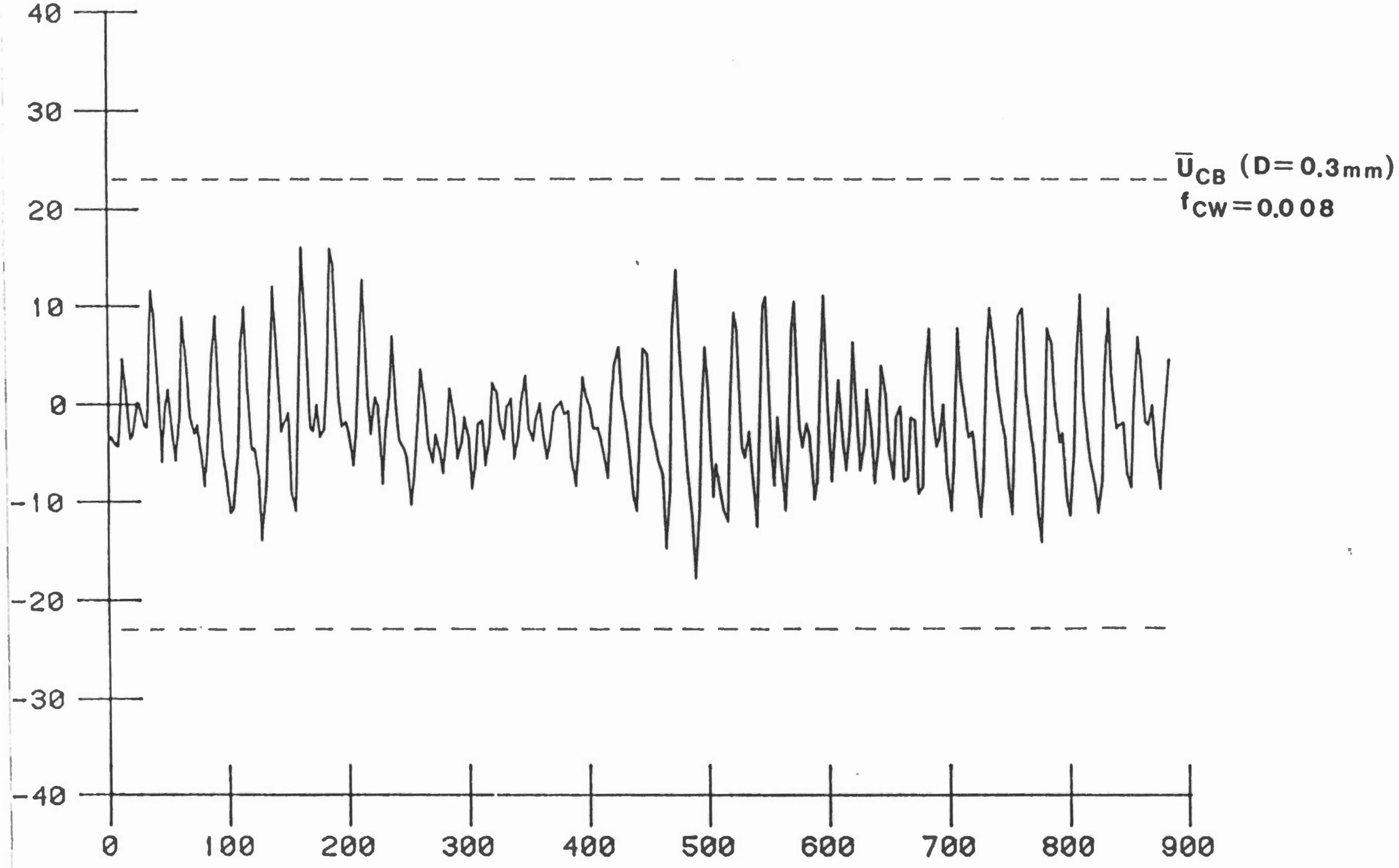
Figures 2.5 and 2.6 illustrate the unfiltered near-bed flows in the X- and Y- axes for a 17 minute record beginning at 0000 hours (GMT) on 17 January 1985. The records illustrate conditions during the passage of a typical winter storm, and show the dominating influences of wave motion (u_b) over the steady current (u_a). Threshold conditions for bedload and suspension transport were exceeded during this period, but only for very short periods of time, i.e. during the passage of each wave.

Sediment transport was initally determined from the evaluated time series using the unaltered subroutines from the program SED1DE. Under conditions of sediment motion, the ratio of the steady current velocity (u_a) and the maximum wave-induced orbital velocity (u_b) was less than unity. Thus, the Grant and Madsen (1979) method was not strictly valid. Under most conditions of transport, during the period between detection 3 and 4, u_b was greater than u_a by approximately one order of magnitude. Thus the estimations of bed stresses using the Grant and Madsen (1979) method are suspect. Notwithstanding this, a comparison was made between the observations and this method, the results of which are listed in Tables 2.2, 2.3 and 2.4 (presented at the end of this section) for grain diameters of 0.2, 0.3 and 0.4 mm, and bed roughness of 20, 40 and 60 mm. The tables show



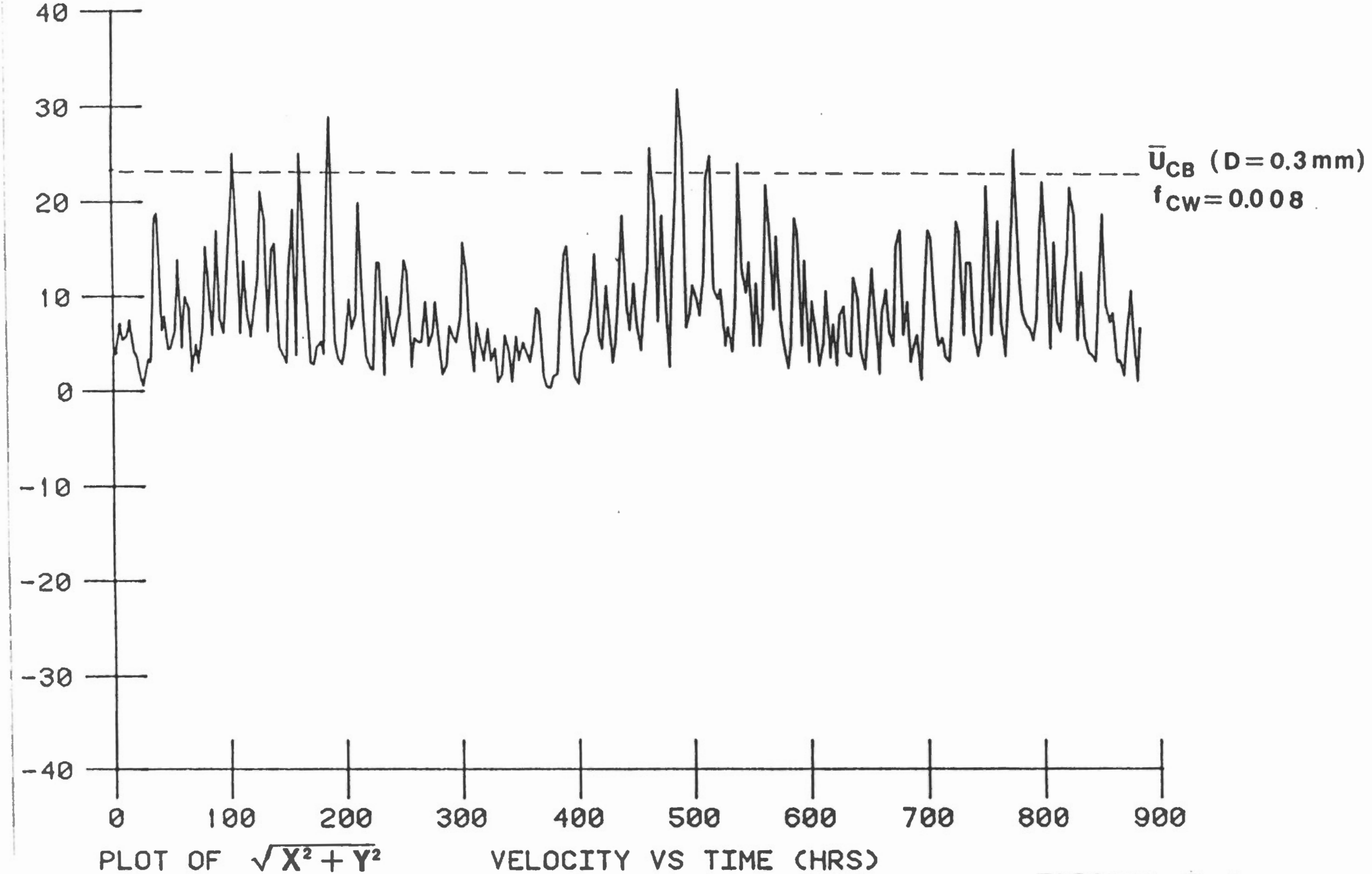
PLOT OF X-AVERAGE VELOCITY VS TIME (HRS)

FIGURE 2.2



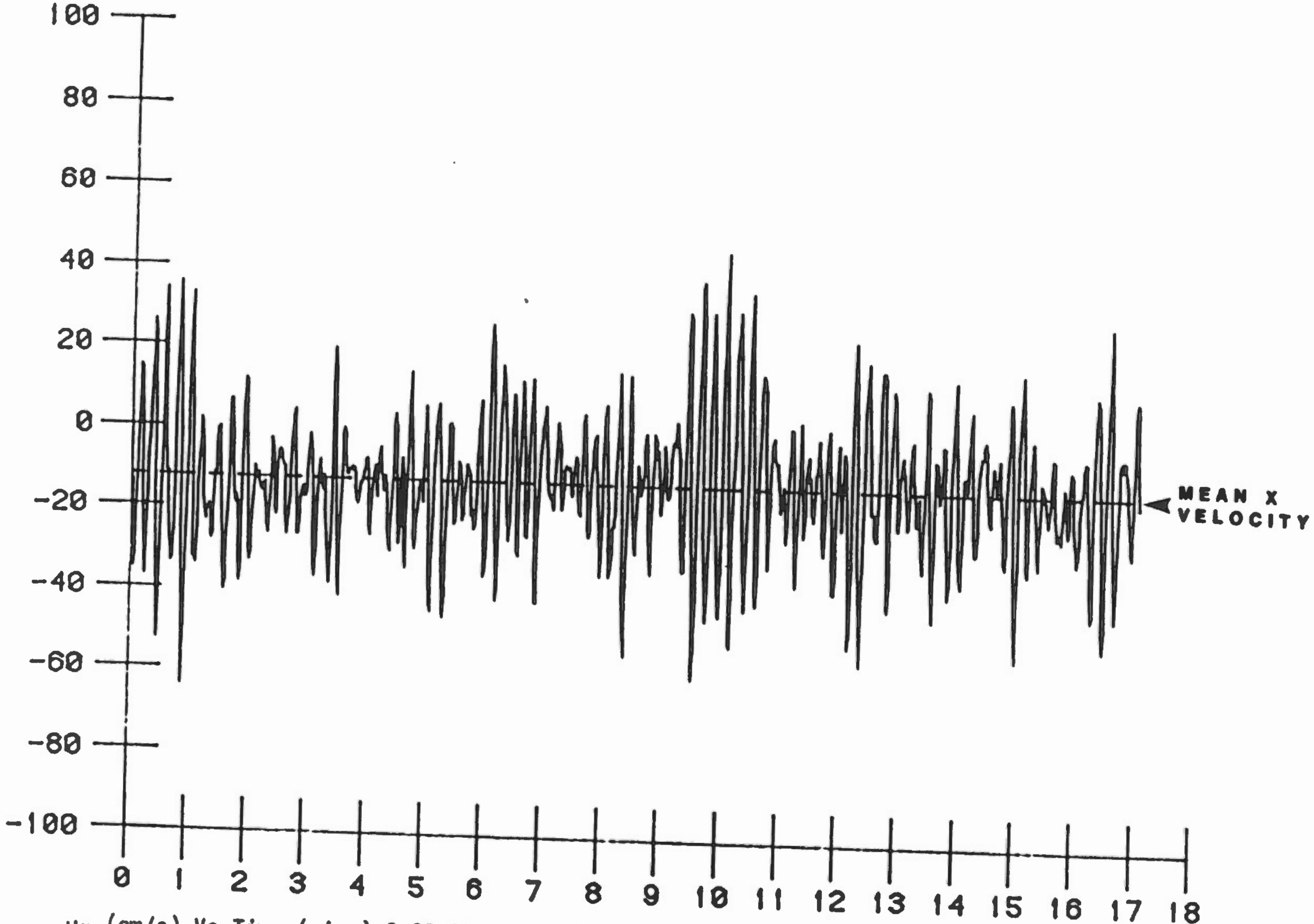
PLOT OF Y-AVERAGE VELOCITY VS TIME (HRS)

FIGURE 2.3



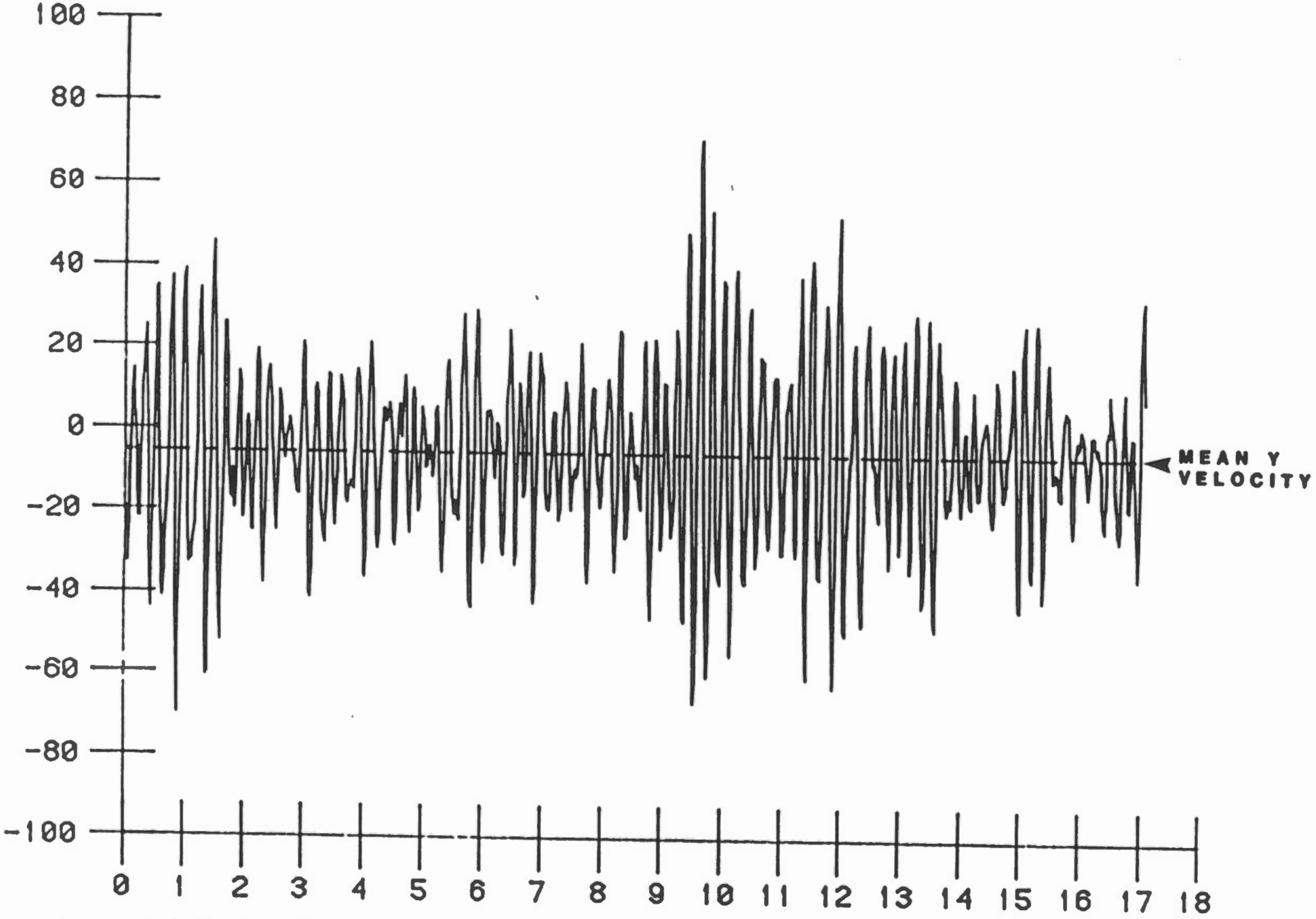
PLOT OF $\sqrt{X^2+Y^2}$ VELOCITY VS TIME (HRS)

FIGURE 2.4



v_x (cm/s) Vs Time (min.) @ 00:00 hrs. GMT, Jan. 17, 1985

FIGURE 2.5



Uy (cm/s) Vs Time (min.) @ 00:00 hrs. GMT, Jan. 17, 1985

FIGURE 2.6

total transport distance (in metres) within each of eight directions and the net transport magnitude and direction (in degrees true). Maximum transport was derived using the Bagnold (1963) method; least transport was derived in all cases using Yalin's (1963) method. Differences in transport distances for all methods varied between factors of 2 and 20 for 0.4 and grain diameters of 0.2 mm respectively. Net transport was in all cases to the south (174-182°) and was never greater than 6 m. Dispersion was anisotropic being greatest to the north and south and ranging in values between 6 and 100 m. This dispersion was estimated to be greatest using the Bagnold (1963) method and the least using the Yalin (1963) method.

The second approach was to replace the Grant and Madsen (1979) method for deriving friction factors with that of Johsson (1966) as modified by Nielsen (1979). Derived friction factors and sediment transport results are listed at the end of this section in Tables 2.5 to 2.11. The following list reviews the major input and intermediate variables used in this approach:

Table #	Grain Size (mm)	Bed Roughness (mm)	Friction Factor	Critical Velocity (cm/s)
2.5	.20	60	0.0106	21.7
2.6	.20	40	0.0095	23.1
2.7	.20	20	0.008	25.4
2.8	.30	90	0.012	23.2
2.9	.30	60	0.0106	24.8
2.10	.30	30	0.0088	27.5
2.11	.40	80	0.0115	26.1

Maximum sediment transport distance from the second approach was derived using the Bagnold (1963) method and the minimum values were derived using the Yalin (1963) method. The maximum dispersion values ranged from 8 to 138 m for the detection period as a whole and was in the north/south direction. The net sediment transport distances integrated over the detection period ranged from 1.4 to 10.7 m and was always to the south. The least transport was derived using parameters listed in Table 2.11 and the greatest transport resulted using the parameters in Table 2.5.

The third approach undertaken was to replace the modified Jonsson (1966) method for deriving friction factors with the Bijker (1976) method. Subsequently, SED1DE was used to compute all remaining terms. Table 2.12 reviews the results using the following input and intermediate variables: grain size = 0.3 mm; bed roughness = 60 mm; mean friction factor = 0.0045; and mean critical threshold for traction = 42.9 cm/s. The greatest dispersion and net transport were derived using Bagnold (1963) and the least using Yalin (1963). Dispersion was greatest to the south and was between 8 and 85 m. Dispersion was also significant to the north, but negligible to the east and west. Net sediment discharge was in all cases to the south (183-185°) and varied between 1.5 and 11.2 m.

The fourth and final method was to use a constant friction factor irrespective of wave or current conditions. SED1DE was subsequently used to compute all remaining terms. Tables 2.13, 2.14 and 2.15 review the results for given friction factors of 0.007, 0.01 and 0.012 respectively. Each table gives the results of calculations using given grain sizes of 0.2, 0.3 and 0.4 mm. The critical velocities were derived from the Shield's Parameter and represents the mean value for the grain sizes presented. The maximum sediment transport distance again resulted from the Bagnold (1963) method and the minimum from the method of Yalin (1963) and in instances Engelund and Hansen (1967). Dispersion was principally to the north and south with values ranging up to 128 m. Net transport was to the south (173-186°) and varied from 0.2 to 8.1 m.

As can be seen from the above, all the methods gave results which were similar in magnitude and virtually identical in direction. In all cases, dispersion was anisotropic and in the north/south direction. Results predict a cloud length of approximately 200 m and a width (east/west) of less than 10 m. Net transport was always to the south and ranged between 1 and 11.2 m.

The results of the SED1DE sediment transport predictions conflicted with the results of the tracer experiment. Predictions underestimated the derived tracer cloud migration by approximately one order of magnitude and was always in the opposite direction. The estimated dispersion was an order of magnitude smaller than the observed values in the E-W direction and approximately a factor of 2 too small in the N-S direction. The computer programs were extensively checked to ensure that these discrepancies were not the result of a coding error. In addition, the raw burst data was checked for residual water transport above threshold velocities of 0.0, 0.1, 0.2 ... 0.9 m/s, and was in all cases found to have a residual flow in a direction between south-east and south-west.

The discrepancies between observed and predicted dispersion of sediment can be plausibly explained by:

1. errors in converting raw water velocity data to engineering values (direction and/or magnitude), and/or
2. problems in deriving net sediment transport from the tracer experiment, and/or
3. errors because the sediment transport model is uncalibrated.

Future investigation to compare hindcast wave induced near bottom orbital velocities with those of the burst data would provide a means of checking Item 1. However, at the present time ther is no rationale which supports one explanation more than the other.

The discrepancy between the magnitude of the observed and predicted cloud migration may be explained by:

4. partial burial of the cloud, and/or
5. errors in navigation during tracer detections and/or
6. erroneous assumptions concerning whether or not the "hot-spot" of the cloud is spatially fixed.

All of the above stand as possible explanations for the complete directional discrepancy between observed and predicted cloud migration plus:

7. errors in the +/- sense of the burst data either due to a factory error or because inversion of the current meter (to sample at 0.5 m from the seabed) was not properly accounted for when the initial post processing of the data was conducted by SeaConsult (1985).

The possibility of errors in SED1D (Item 2) being responsible for the directional discrepancy is extremely remote. This is because the direction of the raw data residuals agrees with the direction of the predicted cloud migration. Other than this, selecting any of the above as "most probable" explanations remains speculative and the subject of debate. It is Martec's opinion that the evidence, particulary the directional discrepancy, points towards Items 4, 5 and 7 or a combination of them being the most plausible explanation for the difference between numerically predicted and tracer measured sediment transport.

TABLE 2.2

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	0.20	12.8	.08	0.3	1.0	14.2	0.9	0.1	1.1	1.4 181°
Einstein-Brown (1950) (Bedload)	0.20	8.2	0.3	0.1	0.5	9.4	0.4	0.1	0.5	1.3 182°
Bagnold (1963) (Total Load)	0.20	94.2	6.0	1.9	7.0	100.2	5.9	0.7	7.7	5.6 172°
Yalin (1963) (Bedload)	0.20	5.5	0.4	0.1	0.5	6.0	0.4	0.1	0.5	0.5 177°

Bed Roughness: 20 mm, 40 mm and 60 mm

Friction Factor From Grant and Madsen (1979): 0.00625

Critical Velocity: 28.9 cm/s

TABLE 2.3

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.30	9.8	0.6	0.2	0.7	10.9	0.7	0.1	0.8	1.1 180°
Einstein-Brown (1950) (Bedload)	.30	8.8	0.3	0.1	0.5	10.1	0.5	0.1	0.6	1.3 182°
Bagnold (1963) (Total Load)	.30	82.2	4.8	1.5	5.8	87.7	4.8	0.5	6.4	5.2 174°
Yalin (1963) (Bedload)	.30	6.4	0.4	0.1	0.5	7.0	0.4	0.1	0.6	0.6 177°

Bed Roughness: 30 mm, 60 mm, and 90 mm

Friction Factor From Grant and Madsen (1979): 0.007

Critical Velocity: 31.1 cm/s

TABLE 2.4

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.40	8.2	0.5	0.2	0.6	9.0	0.6	0.1	0.7	0.9 180°
Einstein-Brown (1950) (Bedload)	.40	8.9	0.3	0.1	0.5	10.2	0.5	0.1	0.6	1.3 181°
Bagnold (1963) (Total Load)	.40	17.9	1.0	0.3	1.2	19.0	1.0	0.1	1.3	1.1 174°
Yalin (1963) (Bedload)	.40	7.1	0.4	0.1	0.6	7.8	0.5	0.1	0.6	0.7 177°

Bed Roughness: 40 mm

Friction Factor From Grant and Madsen (1979): 0.0076

Critical Velocity: 32.7 cm/s

TABLE 2.5

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.20	23.2	1.7	0.5	1.7	25.4	2.6	0.3	1.9	2.7 191°
Einstein-Brown (1950) (Bedload)	.20	26.7	1.3	0.4	1.5	28.4	2.0	0.2	1.7	2.1 191°
Bagnold (1963) (Total Load)	.20	128.5	10.4	3.0	10.7	138.2	12.8	1.4	11.7	10.7 185°
Yalin (1963) (Bedload)	.20	12.8	1.2	0.3	1.2	14.1	1.8	0.2	1.3	1.7 192°

Bed Roughness: 60 mm

Friction Factor From Jonsson (1966): 0.0106

Critical Velocity: 21.7 cm/s

TABLE 2.6

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.20	20.4	1.5	0.4	1.5	22.2	2.2	0.2	1.7	2.2 191°
Einstein-Brown (1950) (Bedload)	.20	20.6	1.0	0.3	1.1	21.9	1.5	0.1	1.3	1.5 190°
Bagnold (1963) (Total Load)	.20	111.9	9.3	2.7	9.7	128.3	11.1	1.2	10.6	9.1 183°
Yalin (1963) (Bedload)	.20	10.5	0.9	0.3	0.9	11.5	1.3	0.1	1.0	1.2 190°

Bed Roughness: 40 mm

Friction Factor From Jonsson (1966): 0.0095

Critical Velocity: 23.08 cm/s

TABLE 2.7

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.20	16.7	1.2	0.3	1.2	18.1	1.7	0.2	1.4	1.7 189°
Einstein-Brown (1950) (Bedload)	.20	13.9	0.7	0.2	0.7	14.7	0.9	0.1	0.9	1.0 188°
Bagnold (1963) (Total Load)	.20	106.9	7.7	2.3	8.2	113.9	8.8	1.0	9.1	7.2 180°
Yalin (1963) (Bedload)	.20	7.7	0.6	0.2	0.7	8.3	0.8	0.1	0.7	0.7 187°

Bed Roughness: 20 mm

Friction Factor From Jonsson (1966): 0.008

Critical Velocity: 25.4 cm/s

TABLE 2.8

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.30	17.8	1.3	0.4	1.3	19.4	2.0	0.2	1.5	2.0 191°
Einstein-Brown (1950) (Bedload)	.30	28.5	1.4	0.4	1.6	30.4	2.2	0.2	1.8	2.3 191°
Bagnold (1963) (Total Load)	.30	115.4	8.7	2.6	9.2	123.6	10.6	1.1	10.1	8.9 183°
Yalin (1963) (Bedload)	.30	15.4	1.3	0.4	1.4	16.8	2.0	0.2	1.5	1.9 191°

Bed Roughness: 90 mm

Friction Factor From Jonsson (1966): 0.012

Critical Velocity: 23.23 cm/s

TABLE 2.9

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.30	15.4	11.1	0.3	1.1	16.8	1.6	0.2	1.3	1.7 193°
Einstein-Brown (1950) (Bedload)	.30	21.6	1.1	0.3	1.2	22.9	1.6	0.1	1.3	1.6 188°
Bagnold (1963) (Total Load)	.30	106.2	7.7	2.3	8.2	113.4	9.0	1.0	9.0	7.6 181°
Yalin (1963) (Bedload)	.30	12.3	1.0	0.3	1.1	13.4	1.4	0.1	1.2	1.3 187°

Bed Roughness: 60 mm

Friction Factor From Jonsson (1966): 0.0106

Critical Velocity: 24.84 cm/s

TABLE 2.10

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.30	12.4	0.9	0.3	0.9	13.0	1.0	0.1	1.0	1.2 189°
Einstein-Brown (1950) (Bedload)	.30	14.0	0.7	0.2	0.8	15.0	1.0	0.1	0.9	1.0 189°
Bagnold (1963) (Total Load)	.30	92.6	6.1	1.9	6.7	98.4	6.9	0.7	7.4	5.8 179°
Yalin (1963) (Bedload)	.30	8.7	0.7	0.2	0.7	9.3	0.8	0.1	0.8	0.7 185°

Bed Roughness: 30 mm

Friction Factor From Jonsson (1966): 0.0088

Critical Velocity: 27.5 cm/s

TABLE 2.11

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.40	12.7	0.9	0.3	0.9	13.9	1.3	0.1	1.0	1.4 190°
Einstein-Brown (1950) (Bedload)	.40	21.5	1.1	0.3	1.2	22.9	1.6	0.1	1.3	1.7 181°
Bagnold (1963) (Total Load)	.40	23.2	1.6	0.5	1.7	24.7	1.8	0.2	1.9	1.6 181°
Yalin (1963) (Bedload)	.40	13.6	1.1	0.3	1.1	14.8	1.5	0.2	1.2	1.4 188°

Bed Roughness: 80 mm

Friction Factor From Jonsson (1966): 0.0115

Critical Velocity: 26.08 cm/s

TABLE 2.12

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.30	10.1	0.5	0.1	0.7	11.8	0.7	0.1	0.7	1.8 183°
Einstein-Brown (1950) (Bedload)	.30	11.2	0.3	0.1	0.6	14.2	0.6	0.0	0.6	3.1 184°
Bagnold (1963) (Total Load)	.30	75.5	3.0	1.0	5.4	85.4	4.8	0.4	5.5	11.2 184°
Yalin (1963) (Bedload)	.30	6.5	0.3	0.1	0.5	7.7	0.5	0.0	0.5	1.5 185°

Bed Roughness: 60 mm

Friction Factor From Bijker (1967): 0.0045

Critical Velocity: 42.91 cm/s

TABLE 2.13

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.20 .30 .40	19.2 12.8 9.6	1.3 0.9 0.6	0.4 0.2 0.2	1.3 0.9 0.7	20.6 13.8 10.3	1.5 1.0 0.8	0.2 0.1 0.1	1.5 1.0 0.7	1.4 / 183° 6.0 / 183° 0.7 / 183°
Einstein-Brown (1950) (Bedload)	.20 .30 .40	19.2 15.5 12.8	0.8 0.7 0.6	0.3 0.2 0.2	1.0 0.8 0.6	20.4 16.5 13.5	1.0 0.8 0.7	0.1 0.1 0.1	1.1 0.9 0.7	1.1 / 182° 0.9 / 182° 0.8 / 182°
Bagnold (1963) (Total Load)	.20 .30 .40	72.1 72.1 17.3	4.3 4.3 1.0	1.3 1.3 0.3	4.7 4.7 1.1	76.3 76.3 18.3	4.2 4.2 1.0	0.4 0.4 0.1	5.3 5.3 1.3	3.8 / 173° 3.8 / 173° 0.9 / 173°
Yalin (1963) (Bedload)	.20 .30 .40	4.2 5.8 7.2	0.3 0.4 0.5	0.1 0.1 0.1	0.3 0.4 0.5	4.4 6.1 7.7	0.3 0.4 0.5	0.0 0.0 0.1	0.3 0.5 0.6	0.2 / 180° 0.3 / 173° 0.4 / 173°

Friction Factor Constant at 0.007

Critical Velocity: 31.1 cm/s

TABLE 2.14

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen (1967) (Total Load)	.20 .30 .40	33.1 22.1 16.6	2.3 1.5 1.1	0.7 0.4 0.3	2.3 1.6 1.2	35.7 23.8 17.8	2.9 1.9 1.4	0.3 0.2 0.2	2.6 1.8 1.3	2.8 /186° 1.9 /186° 1.4 /186°
Einstein-Brown (1950) (Bedload)	.20 .30 .40	56.1 45.3 37.3	2.5 2.0 1.7	0.8 0.6 0.5	2.8 2.3 1.9	59.6 48.2 39.6	3.0 2.4 2.0	0.3 0.2 0.2	3.3 2.7 2.2	3.5 /184° 2.8 /184° 2.3 /184°
Bagnold (1963) (Total Load)	.20 .30 .40	105.8 105.8 25.4	7.8 7.8 1.9	2.2 2.2 0.5	8.1 8.1 1.9	112.6 112.6 27.0	8.2 8.2 2.0	0.9 0.9 0.2	8.9 8.9 2.1	6.5 /176° 6.5 /176° 1.6 /176°
Yalin (1963) (Bedload)	.20 .30 .40	10.2 14.3 18.0	0.9 1.2 1.5	0.2 0.3 0.4	0.9 1.2 1.5	11.0 19.3 19.3	1.0 1.4 1.7	0.1 0.2 0.2	1.0 1.3 1.7	0.8 /180° 1.0 /179° 1.3 /179°

Friction Factor Constant at 0.01

Critical Velocity: 25.0 cm/s

TABLE 2.15

VENTURE SITE - GROSS SEDIMENT MOVEMENT BY DIRECTION (m)

Predictor	Grain Size (mm)	N	NE	E	SE	S	SW	W	NW	NET
Englund-Hansen	.20	43.6	3.0	0.9	3.1	47.0	3.9	0.4	3.5	3.8 /186°
(1967)	.30	29.1	2.0	0.6	2.1	31.4	2.6	0.3	2.3	2.5 /186°
(Total Load)	.40	21.8	1.5	0.4	1.6	23.5	1.9	0.2	1.7	1.9 /186°
Einstein-Brown	.20	97.0	4.4	1.4	4.9	103.1	5.3	0.5	5.8	6.1 /184°
(1950)	.30	78.4	3.5	1.1	4.0	83.3	4.3	0.4	4.7	4.9 /184°
(Bed Load)	.40	64.4	2.9	0.9	3.3	68.5	3.5	0.4	3.8	4.1 /184°
Bagnold	.20	119.8	9.5	2.7	9.6	127.4	10.3	1.2	10.5	8.1 /178°
(1963)	.30	119.8	9.5	2.7	9.6	127.9	10.3	1.2	10.5	8.1 /178°
(Total Load)	.40	28.7	2.3	0.6	2.3	30.7	2.5	0.3	2.9	1.9 /178°
Yalin	.20	14.6	1.4	0.4	1.3	15.7	1.6	0.2	1.4	1.2 /183°
(1963)	.30	20.5	1.9	0.5	1.8	22.0	2.1	0.3	2.0	1.7 /182°
(Bed Load)	.40	25.9	2.3	0.6	2.3	27.9	2.7	0.3	2.5	2.1 /182°

Friction Factor Constant at 0.012

Critical Velocity: 23.0 cm/s

3.0 UPGRADING OF SED1DE TO SED1DF

The SED1DE sediment transport model of the Atlantic Geoscience Centre (AGC) (see Davidson and Amos, 1985) has been modified to include the Ackers-White formula as a fifth user option. In the new version, SED1DF, the calculation of sediment transport rate for currents alone is based on the original formula of Ackers and White (1973), and the calculation for waves and currents is based on the adapted Ackers-White formula developed by Swart and Lenhoff (see Swart and Fleming, 1980).

During the development of SED1DF, the sediment transport rates computed using the Ackers-White formula were checked manually for 8 different combinations of waves, current and grain size. The sediment transport rates computed by SED1DE and SED1DF using the other four formulas were then compared to ensure that the modifications did not alter the existing program logic.

The theoretical background, description of the source code and documentation of the program checks are presented in the following sections. The development of equations that is presented in this section was required to arrive at the equations which could be utilized in the SED1DF. A program listing of SED1DF is provided in Appendix D and the manual checking of the computations is described in Appendix E.1 for the current only case and in Appendix E.2 for the waves and current case. A comparison of SED1DE and SED1DF for a selected run is documented in Appendix E.3 and a summary of the Ackers-White option, suitable for use as an addendum to Davidson and Amos (1985), is presented in Appendix F.

3.1 Theoretical Background

The Ackers-White formula for the transport of non-cohesive sediments by a steady uniform flow of fluid in an open channel was developed by Ackers (1972) and Ackers and White (1973). The general sediment transport function was developed in terms of three dimensionless groups: D_{gr} (grain size), F_{gr} (sediment mobility) and G_{gr} (transport parameter). The sediment transport formula is applicable to coarse sediment with grain diameters in excess of 2.5 mm (D_{gr} 60) and to transitional sizes of sediment with grain diameters in excess of 0.04 mm, ranging up to 2.5 mm (1 D_{gr} 60). The theory is not applicable to fine sediments with grain diameters less than or equal to 0.04 mm (D_{gr} 1), since these materials would, in general, exhibit cohesive properties.

The Ackers-White formula includes a critical sediment mobility number A_{gr} that represents the F_{gr} value at which transport of sediment begins. The criteria for initiation of sediment movement is based on the analysis of experiments with established motion of sediment, rather than the commonly used Shields curve. The results are comparable in the range 4 D_{gr} 60. However, for lower D_{gr} values, the results agree more closely with the curve proposed by Grass (1970), which is midway between the Shields curve and the data of White (1970). For coarse sediments, the results agree with the findings of Neill (1967) and cast further doubts upon the rise in the Shields curve in the region of coarse sediments.

The original Ackers-White formula has been adapted by several researchers to include the effect of wave action. Swart and Fleming (1980) have examined the different versions of the adapted Ackers-White formula and concluded that only the Swart and Lenhoff version is correct. Consequently, the adapted Ackers-White formula used in SED1DF is based on the description of the Swart and Lenhoff version provided by Swart and Fleming (1980). A new empirical relationship is used to determine the critical mobility number A_{gr} as a function of Reynolds number and the dimensionless grain size D_{gr}. Expressions for the original Ackers-White formula, the adapted Ackers-White formula and the threshold values for incipient motion are listed in the remainder of this section.

3.1.1 Ackers-White Formula for Currents Only

A dimensionless expression for grain diameter is defined as the cube root of the ratio of immersed weight to viscous forces

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3} \tag{1}$$

where D = sediment diameter
g = acceleration due to gravity
s = specific gravity of sediment
ν = kinematic viscosity of fluid

A general sediment transport function is expressed in terms of four coefficients that vary with the sediment size D_{gr}. Experimental data were used to optimize the values of these coefficients for coarse and transitional sizes of sediment. For coarse sediments ($D_{gr} > 60$), these coefficients are

$$n = 0 \tag{2.a}$$
$$A_{gr} = 0.17 \tag{2.b}$$
$$m = 1.50 \tag{2.c}$$
$$C = 0.025 \tag{2.d}$$

and for transitional sizes of sediment ($1 < D_{gr} \leq 60$) these coefficients are expressed as

$$n = 1.00 - 0.56 \log D_{gr} \tag{3.a}$$

$$A_{gr} = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{3.b}$$

$$m = \frac{9.66}{\sqrt{D_{gr}}} + 1.34 \tag{3.c}$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53 \tag{3.d}$$

where n is a transition exponent, A_{gr} is the critical value of the mobility number F_{gr} (to be discussed below), m and C are the exponent and coefficient, respectively, in the sediment transport function, and the logarithm is to the base 10.

The shear stress velocity for coarse sediments can be written as (see Willis, 1978)

$$v_{*cg} = \sqrt{\frac{\tau_{cg}}{\rho}} = \frac{V}{5.75\log(\alpha d/D)} \tag{4}$$

where ρ = density of water
V = mean velocity of flow
d = mean depth of flow
α = 10 = empirical coefficient in rough turbulent equation
τ_{cg} = shear stress for coarse grains

For fine sediments the shear velocity is

$$v_{*fg} = \sqrt{\frac{\tau_{fg}}{\rho}} = \sqrt{\frac{f/2\rho V^2}{\rho}} = V\sqrt{\frac{f}{2}} \tag{5}$$

The sediment mobility number is defined as

$$F_{gr} = \frac{(v_{*fg})^n}{\sqrt{gD(s-1)}}\left[\frac{V}{5.75\log\alpha d/D}\right]^{1-n} \tag{6.a}$$

This expression can be written in the form

$$F_{gr} = \frac{V}{\sqrt{gD\,(s-1)}}\left(\sqrt{\frac{f}{2}}\right)^n\left[\frac{1}{5.75\log\alpha d/D}\right]^{1-n} \tag{6.b}$$

The dimensionless sediment transport rate is defined as

$$G_{gr} = C\left(\frac{F_{gr}}{A_{gr}} - 1\right)^m \tag{7}$$

The sediment flux X is expressed as

$$X = \frac{sD}{D}\,G_{gr}\left(\frac{V}{v_{*fg}}\right)^n \tag{8.a}$$

or, alternatively,

$$X = \frac{W_b}{\rho g V d} \tag{8.b}$$

where W_b is the sediment load (weight per unit width per unit time) and $\rho g V d$ is the mass flow rate. Consequently, the sediment load can be written as

$$\begin{aligned} W_b &= X \rho g V d \\ &= \frac{SD}{d} \, G_{gr} \left(\frac{V}{v_{*fg}} \right)^n \rho g V d \\ &= \gamma_s V D G_{gr} \left(\frac{V}{v_{*fg}} \right)^n \text{ gm/sec}^3 \end{aligned} \tag{9}$$

where γ_s is the unit weight of sediment. The volumetric sediment transport rate q is determined by dividing W_b by the unit weight of sediment

$$q = V D G_{gr} \left(\frac{V}{v_{*fg}} \right)^n \text{ cm}^3\text{/sec/cm} \tag{10}$$

The program modifications discussed in Section 3.2.1 are based on equations (1) through (3), (5), (6.a) (7), (8.a) and (10) which are used to compute D_{gr}, n, A_{gr}, m, C, v_{*fg}, F_{gr}, G_{gr}, X and q. The program modifications discussed in Section 3.2.3 are based on equations (1), (2.b) and (3.b) which defines values of D_{gr} and A_{gr} for coarse and transitional size sediment for the current only case.

3.1.2 Adapted Ackers-White Formula for Waves and Currents

The dimensionless grain diameter is defined in equation (1) for the current only case. The coefficients n, m and C are defined in (2.a), (2.c) and (2.d) for coarse sediments and in (3.a), (3.c) and (3.d) for transitional sediments. However, a new empirical relationship is used to determine the critical sediment mobility number in terms of the Reynolds number

$$R_{gr} = \sqrt{\frac{\overline{\tau}_{cr}}{\rho}} \quad D/\nu \tag{11}$$

where $\overline{\tau}_{cr}$ is the mean shear stress at incipient motion. The relationship between R_{gr} and D_{gr} is

$$\log R_{gr} = 0.092 (\log D_{gr})^2 + 1.158 \log D_{gr} - 0.367 \tag{12}$$

and the critical mobility number is expressed as

$$A_{gr} = R_{gr} D_{gr}^{-1.5} \tag{13}$$

The instantaneous shear velocity for coarse sediments can be written as (Willis, 1978)

$$v_{*cg}(t) = \sqrt{\frac{\tau_{cg}(t)}{\rho}} \tag{14}$$

where $\tau_{cg}(t) = \rho \dfrac{[v_r(t)]^2}{C_{h,cg}{}^2}$ = shear stress for coarse grains

$v_r(t)$ = instantaneous resultant velocity

$C_{h,cg} = 5.75 \log \dfrac{11d}{D}$ = Chezy coefficient for coarse grains

If it is assumed that (Ackers and White, 1973)

$$C_{h,cg} = 5.75 \log \frac{\alpha d}{D} \tag{15}$$

where $\alpha = 10$

then the shear stress for coarse grains is

$$\tau_{cg}(t) = \frac{\rho \; [v_r(t)\;]^2}{(5.75 \log \alpha \, d/D)^2} \tag{16}$$

and the shear velocity is

$$v_{*cg}(t) = \frac{v_r(t)}{5.75 \log \alpha d/D} \tag{17}$$

The instantaneous shear velocity for fine sediments can be written as

$$\begin{aligned} v_{*fg}(t) &= \sqrt{\frac{\tau_{fg}(t)}{\rho}} \\ &= \sqrt{\frac{[f_{wc}/2]\rho[v_r(t)]^2}{\rho}} \\ &= v_r(t)\sqrt{\frac{f_{wc}}{2}} \end{aligned} \tag{18}$$

and the shear stress for fine grains is

$$\tau_{fg}(t) = \frac{f_{wc}}{2}\rho[v_r(t)]^2 \tag{19}$$

where f_{wc} is the friction factor derived from Grant and Madsen (1979).

The instantaneous stream power for coarse sediments is defined as

$$P_{cg}(t) = v_r(t)\tau_{cg}(t) = \frac{\rho[v_r(t)]^3}{(5.75 \log \alpha d/D)^2} \tag{20}$$

For fine sediments, the instantaneous stream power is written as

$$P_{fg}(t) = v_r(t)\tau_{fg}(t) = \frac{f_{wc}}{2}\rho[v_r(t)]^3 \tag{21}$$

The instantaneous value of the efficiency term is given by

$$E_f(t) = \left[\frac{\frac{P_{fg}(t)}{\rho}}{[v_{*fg}(t)]^3}\right]^n \left[\frac{\frac{P_{cg}(t)}{\rho}}{[v_{*cg}(t)]^2 v_r(t)}\right]^{1-n} \tag{22.a}$$

Substitution of (17), (18), (20), and (21) into (22.a) reduces this expression to the form

$$E_f(t) = \left(\sqrt{\frac{2}{f_{wc}}}\right)^n \qquad (22.b)$$

The instantaneous sediment mobility number is defined as

$$F_{gr}(t) = \frac{[v_{*fg}(t)]^n\,[v_{*cg}(t)]^{1-n}}{\sqrt{(s-1)gD}} \qquad (23.a)$$

This expression can be combined with (17) and (18) to derive the relationship

$$F_{gr}(t) = \frac{v_r(t)}{\sqrt{(s-1)gD}}\left[\sqrt{\frac{f_{wc}}{2}}\right]^n \left[\frac{1}{5.75\,\log \alpha d/D}\right]^{1-n} \qquad (23.b)$$

The instantaneous sediment transport rate vector $\vec{q}(t)$ can be determined from the formula

$$\vec{q}(t) = \vec{v}_r(t)\;DC\;E_f(t)\left[\frac{F_{gr}(t)}{A_{gr}} - 1\right]^m \qquad (24.a)$$

Substitution of (22.b) and (23.b) into (24.a) gives

$$\vec{q}(t) = \vec{v}_r(t)\;DC\left(\sqrt{\frac{2}{f_{wc}}}\right)^n \left[\frac{|\vec{v}_r(t)|}{A_{gr}\sqrt{(s-1)gD}}\left(\sqrt{\frac{f_{wc}}{2}}\right)^n \left(\frac{1}{5.75\,\log \alpha d/D}\right)^{1-n} - 1\right]^m \qquad (24.b)$$

The program modifications discussed in Section 3.2.2 are based on equations (1) through (3), (12), (13) and (24.b), which are used to compute D_{gr}, n, m, C, R_{gr}, A_{gr} and $\vec{q}(t)$. However, $\vec{q}(t)$ must be expressed in a slightly different form to be used in the time integration algorithm of SED1DE as discussed in Section 3.2.2. The program modifications discussed in Section 3.2.3 are based on equations (1), (12) and (13) which define D_{gr}, R_{gr} and A_{gr} for the waves and currents case.

3.1.3 Threshold Values

The Ackers-White formula defines the initiation of motion in terms of a critical sediment mobility number A_{gr} instead of the threshold velocity $_{cr}$ used in the SED1DE model. For the current only case, A_{gr} is defined by equation (2.b) for coarse sediments ($D_{gr} > 60$) or equation (3.b) for transitional sizes of sediment. For the waves and current case, A_{gr} is defined by equations (12) and (13). In order to incorporate the Ackers-White formula into the SED1DE model, the determination of the critical velocity v_{cr} corresponding to the value of A_{gr} must be included.

For coarse sediments ($D_{gr} > 60$), the transition exponent n has a value of zero. For the currents only case, equation (6.a) with n=0 for initial sediment movement can be written as

$$A_{gr} = \frac{1}{\sqrt{gD(s-1)}} \; \frac{V}{5.75 \log \alpha d/D} \tag{26.a}$$

Substitution of (4) into (26.a) gives

$$A_{gr} = \frac{1}{\sqrt{gD(s-1)}} \sqrt{\frac{(\tau_{cg})_{cr}}{\rho}} \tag{26.b}$$

The critical shear stress is

$$(\tau_{cg})_{cr} = \rho gD(s-1)A_{gr}^{2} \tag{27}$$

Similarly, for the waves and current case, substitution of (17) and (14) into (23.a) with n=0 yields an equation of the same form

$$(\tau_{cg}(t))_{cr} = \rho gD(s-1)A_{gr}^{2} \tag{28}$$

For the transitional sizes of sediment ($1 < D_{gr} \leq 60$), the transition exponent n has a value between 0 and 1. For the current only case, equation (6.a) for initial sediment movement can be written as

$$A_{gr} = \frac{(v_*)^n}{\sqrt{gD(s-1)}} \left[\frac{V}{5.75 \log \alpha d/D}\right]^{1-n} \qquad (29.a)$$

Substitution of (4) into (29.a) reduces this expression to the form

$$A_{gr} = \frac{(\sqrt{\tau_{cr}/\rho})^n}{\sqrt{gD(s-1)}}\left(\sqrt{\frac{(\tau_{cg})_{cr}}{\rho}}\right)^{1-n} \qquad (29.b)$$

By substituting (27) into (29.b), it can be shown that the critical shear stress is

$$\tau_{cr} = \rho gD(s-1)A_{gr}^2 \qquad (30)$$

Similarly, for the waves and current case, substitution of (14) and (28) into (23.a) reduces the critical shear stress to the same form

$$(\tau(t))_{cr} = \rho gD(s-1)A_{gr}^2 \qquad (31)$$

The critical velocity corresponding to A_{gr} is then determined from the relation

$$v_{cr} = \sqrt{\frac{2\tau_{cr}}{\rho f_{wc}}} \qquad (32)$$

for the current only case and the waves and current case.

The program modifications discussed in Section 3.2.3 are based on equations (1), (2.b), (3.b), (12), (13), (27), (29), (30), (31) and (32) which are used to compute D_{gr}, A_{gr}, R_{gr}, τ_{cr} or $\tau(t)_{cr}$ and v_{cr}.

3.2 Program Modifications for the Ackers-White Option

A complete listing for SED1DF is provided in Appendix D. The parameter OPT that was used in SED1DE was changed to IOPT in SED1DF. Other changes made to SED1DE to incorporate the Ackers-White option were identified by inserting the code "AW" in the identification field of these statements. Additional write statements used to print intermediate variables in the

Ackers-White formula (i.e. for manual checking of the new code were identified by the letters "INTVR" (see Section 3.3.1). Similarly, the code "DEBUG" was added to write statements used to compare SED1DE and SED1DF for the case when execution of SED1DE was terminated due to an infinite value (see Section 3.3.2). It should be noted that lines containing "INTVR" and "DEBUG" have been "commented out" in the final version, SED1DF.

Some minor revisions were required to upgrade SED1DE and these are listed in Appendix D. The major additions that were required to incorporate the Ackers-White option into the model are contained in subroutines TRANSPO and THRESH, as described in the remainder of this section.

3.2.1 Currents Only Case

In subroutine TRANSPO, a modification was made to the statement that applies the Engelund-Hansen total load formula when the sediment is transported as suspended load in the current only case. Since the Ackers-White formula is another total load formula, this statement was changed so that it has no effect if the user chooses the Ackers-White option (IOPT=5). When this option is selected, the parameters n, m and C are calculated for coarse ($D_{gr} > 60$) and transitional ($1 < D_{gr} \leq 60$) sizes of sediment according to equations (2.a), (2.c) and (2.d) or (3.a), (3.c) and (3.d). For finer ($D_{gr} \leq 1$) sizes of sediment, a message is printed to indicate that the theory is not applicable and execution is terminated. For the coarse and transitional sizes of sediment, the parameters v_{*fg} and F_{gr} are computed using equations (5) and (6.a) and F_{gr} is compared against the critical value of the mobility number A_{gr} based on equations (2.b) or (3.b). If F_{gr} is less than A_{gr}, then the parameters G_{gr}, X and q (i.e. variable "SED") are set equal to zero, otherwise they are computed according to equations (7), (8.a) and (10).

3.2.2 Waves and Current Case

When the user selects IOPT=5 for the waves and current case, the parameters n, m and C are computed in subroutine TRANSPO for coarse and transitional sizes of sediment using equations (2.a), (2.c) and (2.d) or (3.a), (3.c) and (3.d). For fine sediments, the program execution is terminated and a message is printed to indicate that the theory is not applicable. The original SED1DE model resolves the sediment transport rate for the other four options into x- and y-components and performs a time integration over the interval during a wave cycle when the respective critical velocities for bedload and suspended load transport are exceeded. Consequently, a similar approach was applied to the Ackers-White formula for IOPT=5.

The x-component $v_x(t)$ and the y-component $v_y(t)$ of the resultant velocity vector $\vec{v}_r(t)$ can be expressed as

$$v_x(t) = |\vec{v}_r(t)| \cos\theta \tag{33.a}$$

$$v_y(t) = |\vec{v}_r(t)| \sin\theta \tag{33.b}$$

where the magnitude of the resultant velocity vector is defined as

$$|\vec{v}_r(t)| = \sqrt{(v_x(t))^2 + (v_y(t))^2} \tag{33.c}$$

and $\theta = \tan^{-1}(v_y(t)/v_x(t))$ (33.d)

The sediment transport rate vector $\vec{q}(t)$ is assumed to be in the same direction as the resultant velocity vector $\vec{v}_r(t)$. The x-component $q_x(t)$ and y-component $q_y(t)$ of the sediment transport rate vector are determined using equations (33.a) and (33.b) as

$$q_x(t) = |\vec{q}(t)| \cos\theta = |q(t)| \, (v_x(t)/|\vec{v}_r(t)|) \tag{34.a}$$

$$q_y(t) = |\vec{q}(t)| \sin\theta = |q(t)| \, (v_y(t)/|\vec{v}_r(t)|) \tag{34.b}$$

The magnitude of the sediment transport rate vector in equation (24.b) is

$$|\vec{q}(t)| = |\vec{v}_r(t)| \, DC\left(\sqrt{\frac{2}{f_{wc}}}\right)^n \left[\frac{|\vec{v}_r(t)|}{A_{gr}\sqrt{(s-1)gD}} \left(\sqrt{\frac{f_{wc}}{2}}\right)^n \left(\frac{1}{5.75 \log \alpha d/D}\right)^{1-n} - 1\right]^m \tag{35}$$

The expressions for $q_x(t)$ and $q_y(t)$ are derived by substitution of (33.c) and (35) into (34.a) and (34.b) to obtain

$$q_x(t) = DC\left(\sqrt{\frac{2}{f_{wc}}}\right)^n \left\{ v_x(t) \left[\frac{\sqrt{(v_x(t)^2+(v_y(t)^2}}{A_{gr}\sqrt{(s-1)gD}} \left(\sqrt{\frac{f_{wc}}{2}}\right)^n \left(\frac{1}{5.75 \log \alpha d/D}\right)^{1-n} -1 \right]^m \right\} \tag{36.a}$$

$$q_y(t) = DC\left(\sqrt{\frac{2}{f_{wc}}}\right)^n \left\{ v_y(t) \left[\frac{\sqrt{(v_x(t)^2+(v_y(t)^2}}{A_{gr}\sqrt{(s-1)gD}} \left(\sqrt{\frac{f_{wc}}{2}}\right)^n \left(\frac{1}{5.75 \log \alpha d/D}\right)^{1-n} -1 \right]^m \right\} \tag{36.b}$$

Two time-independent parameters c_1 (called "CONST" in SED1DF) and c_2 (called "COEFF" in SED1DF) can be defined as

$$c_1 = DC\left(\sqrt{\frac{2}{f_{wc}}}\right)^n \tag{37.a}$$

$$c_2 = \left(\frac{1}{A_{gr}\sqrt{(s-1)gD}}\right)\left(\sqrt{\frac{f_{wc}}{2}}\right)^n \left(\frac{1}{5.75 \log \alpha d/D}\right)^{1-n} -1 \Big]^m \tag{37.b}$$

Integration of $q_x(t)$ and $q_y(t)$ over the wave period T to obtain the time-integrated sediment transport rates Q_x and Q_y can be expressed as

$$Q_x = \int_0^T q_x(t)dt = 2c_1\int_0^{T/2} v_x(t)\ [c_2\sqrt{(v_x(t))^2 + (v_y(t))^2}-1]^m\ dt \tag{38.a}$$

$$Q_y = \int_0^T q_y(t)dt = 2c_1\int_0^{T/2} v_y(t)\ [c_2\sqrt{(v_x(t))^2 + (v_y(t))^2}-1]^m\ dt \tag{38.b}$$

The two time-varying functions to be integrated are defined as external functions "F7" and "F8" in SED1DF and are expressed as

$$f_7(t) = v_x(t)\ \left[c_2\sqrt{(v_x(t))^2 + (v_y(t))^2} - 1\right]^m \tag{39.a}$$

$$f_8(t) = v_y(t)\ \left[c_2\sqrt{(v_x(t))^2 + (v_y(t))^2} - 1\right]^m \tag{39.b}$$

The time-integration of $f_7(t)$ and $f_8(t)$ is performed using the IMSL (International Mathematical and Statistical Library) routine DCADRE. The x- and y-components of the time-integrated sediment transport rates at the crest (called "SEDXC" and "SEDYC") and at the trough (called "SEDXT" and "SEDYT") of the wave are determined by selecting appropriate limits for the integration, based on the times during a wave cycle when the respective critical velocities for bedload and suspended load transport are exceeded. These procedures and the remaining calculations follow the approach used for the other four options.

3.2.3 Threshold Values

The threshold values for the Ackers-White option are calculated in subroutine THRESH. For fine sediments ($D_{gr} \leq 1$), a message is printed to indicate that the theory is not applicable. For coarse ($D_{gr} > 60$) and transitional ($1 < D_{gr} \leq 60$) sizes of sediment, the critical values for bedload transport are computed according to formulas listed in the previous section. If the wavelength is less than twice the water depth, then the waves have virtually no influence on the bottom velocities and equations (1), (2.b) and (3.b) for the current only case are applied. Otherwise, equations (1), (12) and (13) for the waves and current case are used. Since the Ackers-White formula does not specify a critical velocity for initial sediment movement, equations (27), (28), (30), (31) and (32) are applied. The threshold velocity for suspended load transport was calculated according to the procedures established for the other four options.

3.3 Program Checks

3.3.1 Manual Checks

The Ackers-White option was used to compute sediment transport rates for current speeds of 0, 50 and 100 cm/sec and grain sizes of 0.2 and 0.4 mm, with waves of 8 m height and 12 sec period. Additional calculations were performed for these two grain sizes with a current speed of 100 cm/sec and calm wave conditions. The resulting time-averaged net sediment transport rates are shown in Table 3.1 with the input data for each run. Intermediate variables used in the calculation were checked manually, as described in Appendix E.1 for the current only case and Appendix E.2 for the waves and current case. The results are summarized in Tables 3.2 and 3.3, respectively.

3.3.2 Comparison of SED1DE and SED1DF

The SED1DF model was used to compute sediment transport rates based on the four previous sediment transport formulas of Engelund and Hansen (1967), Einstein and Brown (1950), Bagnold (1963) and Yalin (1963). The calculations were performed for a current speed of 100 cm/sec, and a grain size of 0.4 mm, with waves of 8 m height and 12 sec period. These computations were then repeated using the SED1DE model. The results summarized in Table 3.4 indicate that the values computed by SED1DF using the four previous sediment transport formulas are identical to those computed by SED1DE for all four runs.

However, during this test, the execution of Run No. 3 was terminated due to an infinite value in one of the subroutines when the Bagnold formula was selected in the original SED1DE model. This infinite value was produced because the bottom roughness was specified as zero in the user input. The bottom roughness is checked for a zero input value and set equal to the grain diameter for the case of currents only, but this step is not included for the case of waves and currents. This oversight was corrected during the development of the Ackers-White option, and the SED1DF model did not terminate execution when the Bagnold formula was selected. When a similar revision was made to subroutine FRICFAC in an intermediate test program TSED1D, the computed sediment transport rate using Bagnolds's formula was identical to that calcuated using the SED1DF model. The computed results using the SED1DF model, the original SED1DE model and the TSED1D test program are documented in Appendix E.3.

TABLE 3.1

SUMMARY OF COMPUTER RUNS FOR ACKERS-WHITE OPTION

	Waves and Current Cases (Runs 1 - 6)						Current Only Cases (Runs 7 - 8)	
Run Number*	1	2	3	4	5	6	7	8
Input								
Grain Size (mm)	0.2	0.2	0.2	0.4	0.4	0.4	0.2	0.4
Current Speed (cm/sec)	0.0	50.0	100.0	0.0	50.0	100.0	100.0	100.0
Wave Height (m)	8.0	8.0	8.0	8.0	8.0	8.0	0.0	0.0
Wave Period (sec)	12.0	12.0	12.0	12.0	12.0	12.0	0.0	0.0
Output								
Time-averaged net sediment transport rate (cm^3/sec/cm)	0.0	13.82	40.21	0.0	2.857	7.863	1.479	0.6111

100 g/cm/s.

10 kg/m/s.

*Input Data for All Runs

Water depth (m)	20.0
Wave Direction (deg)	0.0
Current Direction (deg)	0.0
Height above bottom (cm)	100.0
Fluid Density (gm/cm^3	1.025
Sediment density (gm/cm^3)	2.65
Bottom Roughness (cm)	0.0

TABLE 3.2

SUMMARY OF MANUAL CHECKS FOR CURRENT ONLY

Variable	Run No. 7		Run No. 8	
	Computer Program	Manual Check	Computer Program	Manual Check
D_{gr}	4.26	4.26	8.52	8.52
n	6.47	0.648	4.79	0.479
m	3.61	3.61	2.47	2.47
A_{gr}	0.251	0.251	0.219	0.219
C	7.48×10^{-3}	7.48×10^{-3}	1.84×10^{-2}	1.84×10^{-2}
v (cm/sec)	5.48	5.48	5.48	5.48
F_{gr}	0.785	0.784	0.512	0.511
G_{gr}	0.113	0.113	3.80×10^{-2}	3.74×10^{-2}
X	1.91×10^{-5}	1.92×10^{-5}	7.90×10^{-6}	7.79×10^{-6}
$q(cm^3/sec/cm)$	1.48	1.48	0.611	0.601

TABLE 3.3

SUMMARY OF MANUAL CHECKS FOR WAVES AND CURRENT

Variable	Run No. 2		Run No. 3		Run No. 5		Run No. 6	
	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check
D_{gr}	4.26	4.26	4.26	4.26	8.52	8.52	8.52	8.52
R_{gr}	2.50	2.50	2.50	2.50	6.17	6.17	6.17	6.17
A_{gr}	0.285	0.284	0.285	0.284	0.248	0.248	0.248	0.248
n	0.647	0.648	0.647	0.648	0.479	0.479	0.479	0.479
m	3.61	3.61	3.61	3.61	2.47	2.47	2.47	2.47
C	7.48×10^{-3}	7.48×10^{-3}	7.48×10^{-3}	7.48×10^{-3}	1.84×10^{-2}	1.84×10^{-2}	1.84×10^{-2}	1.84×10^{-2}
COEFF	2.52×10^{-2}	2.51×10^{-2}	2.48×10^{-2}	2.48×10^{-2}	2.00×10^{-2}	2.00×10^{-2}	1.98×10^{-2}	1.97×10^{-2}
CONST	1.07×10^{-3}	1.08×10^{-3}	1.09×10^{-3}	1.09×10^{-3}	3.05×10^{-3}	3.05×10^{-3}	3.09×10^{-3}	3.09×10^{-3}

TABLE 3.4

COMPARISON OF SED1DE and SED1DF

Sediment Transport Formula	Time Averaged Net Sediment Transport (cm^3/sec/cm)			
	Run No.*	SED1DE	Run No.*	SED1DF
Engelund-Hansen	1	3.131	1	3.131
Einstein-Brown	2	54.27	2	54.27
Bagnold	3	3.148 **	3	3.148
Yalin	4	5.644	4	5.644

*Input Data for All Runs

Water Depth (m)	20.
Current Speed (cm/sec)	100.
Current Direction (deg)	0.
Height Above Bottom (cm)	100.
Wave Height (m)	8.
Wave Period (sec)	12.
Wave Direction (deg)	0.
Grain Size (mm)	0.4
Sediment Density (gm/cm^3)	2.65
Bottom Roughness (cm)	0.
Fluid Density (gm/cm^3)	1.025
Bagnold Coefficient of Proportionality (for Run No. 3 only)	0.5

** Execution was terminated due to an infinite value in subroutine TRANSPO when the input bottom roughness was zero. Subroutine FRICFAC was modified to set the bottom roughness equal to the grain diameter for the waves and current case. The computed value was then 3.148.

The Bagnold coefficient of proportionality specified by the user is not printed in the output file by SED1DE or SED1DF. It is suggested that SED1DF should be modified to include this parameter in the output file for future reference when the Bagnold formula is being used.

APPENDIX A

VENTURE SITE CURRENT METER DATA

From: Seadata Model 621 Current Meter, Serial #01
Sampling: January 14, 1985, 1800 hrs GMT to
February 20, 1986, 1200 hrs GMT.
At: 43°57'37"N
59°40'04"W
Water Depth: 32.0 m
Instrument Depth: 31.5 m
Data Units: cm/s
Sampling Rate: 1 Hz for 1024 s. every 3 hours

AVERAGE CURRENTS - FILE T621AV

YEAR	MONTH	DAY	HOUR	MEAN X-CURRENT	MEAN Y-CURRENT	RMS OF X-CURRENT	RMS OF Y-CURRENT
85	1	14	18	-1.79	-3.57	8.41	10.05
85	1	14	21	-5.66	-4.20	9.44	9.89
85	1	15	0	-3.28	-4.32	8.78	10.61
85	1	15	3	3.59	4.55	8.23	9.22
85	1	15	6	7.23	1.79	9.62	6.95
85	1	15	9	1.69	-3.68	6.60	8.94
85	1	15	12	-1.45	-3.25	6.60	8.70
85	1	15	15	-1.21	.05	9.51	9.05
85	1	15	18	0.00	-.52	12.57	18.88
85	1	15	21	-2.36	-2.24	12.24	25.44
85	1	16	0	-1.70	-2.43	14.90	24.47
85	1	16	3	14.09	11.67	27.85	35.16
85	1	16	6	16.39	9.02	25.07	26.21
85	1	16	9	6.29	.71	16.98	20.67
85	1	16	12	-4.99	-6.06	16.50	26.11
85	1	16	15	-4.38	-.25	17.45	28.12
85	1	16	18	-4.21	1.53	17.29	22.03
85	1	16	21	-5.10	-3.71	18.81	27.01
85	1	17	0	-12.52	-5.91	20.74	21.28
85	1	17	3	-4.45	-.98	19.41	22.13
85	1	17	6	4.56	8.84	19.17	28.00
85	1	17	9	7.77	3.93	16.29	21.07
85	1	17	12	-1.44	-1.37	18.19	25.01
85	1	17	15	-3.56	-3.16	17.20	21.94
85	1	17	18	-1.74	-2.18	14.42	17.85
85	1	17	21	-3.19	-5.76	10.31	13.72
85	1	18	0	-12.62	-8.54	16.61	15.76
85	1	18	3	-8.91	-2.18	13.50	12.52
85	1	18	6	3.63	4.42	8.74	10.10
85	1	18	9	14.34	9.02	16.44	11.89
85	1	18	12	7.53	-.06	10.23	7.25
85	1	18	15	-2.60	-5.43	6.41	9.04
85	1	18	18	-9.21	-7.28	10.48	9.17
85	1	18	21	-15.47	-11.14	16.20	12.25
85	1	19	0	-22.52	-10.77	23.02	13.46
85	1	19	3	-13.99	-4.77	16.09	20.75
85	1	19	6	.07	6.07	7.70	17.74
85	1	19	9	9.37	9.99	12.21	15.36
85	1	19	12	8.31	1.29	11.83	15.59
85	1	19	15	-2.98	-4.76	9.29	17.26
85	1	19	18	-7.11	-4.62	11.51	19.44
85	1	19	21	-9.23	-7.45	13.63	17.91
85	1	20	0	-15.78	-14.01	18.46	21.16
85	1	20	3	-15.83	-8.54	18.08	16.37
85	1	20	6	-5.97	1.51	9.46	12.20
85	1	20	9	8.93	12.05	11.44	16.62
85	1	20	12	14.54	5.49	16.20	10.86
85	1	20	15	3.55	-2.85	18.21	20.05
85	1	20	18	-3.32	-2.03	23.45	26.47
85	1	20	21	-2.74	-.93	22.82	26.26
85	1	21	0	-8.22	-9.19	22.02	26.26
85	1	21	3	-15.53	-11.11	23.30	23.50
85	1	21	6	-3.63	.67	14.93	20.04

AVERAGE CURRENT DATA CONTINUED

85	1	21	9	19.19	16.09	25.06	27.02
85	1	21	12	16.37	8.80	23.50	23.36
85	1	21	15	8.70	-2.58	22.61	35.93
85	1	21	18	.66	-2.81	26.07	38.54
85	1	21	21	-2.71	-.11	35.64	42.04
85	1	22	0	-2.85	-3.43	25.75	36.82
85	1	22	3	-4.49	-2.71	27.25	31.82
85	1	22	6	-3.36	1.82	26.22	31.60
85	1	22	9	15.36	15.95	26.69	32.86
85	1	22	12	25.05	14.26	34.32	28.83
85	1	22	15	5.23	.77	25.40	32.21
85	1	22	18	-2.44	-2.31	24.17	32.20
85	1	22	21	-2.00	-1.81	19.94	26.99
85	1	23	0	-3.39	-3.15	25.75	28.28
85	1	23	3	-7.35	-6.28	25.96	32.18
85	1	23	6	-5.90	-2.73	29.65	32.15
85	1	23	9	2.88	7.48	23.09	26.00
85	1	23	12	15.21	12.72	27.76	29.07
85	1	23	15	8.77	.94	23.56	24.97
85	1	23	18	-1.77	-3.15	20.05	23.80
85	1	23	21	-2.27	.64	21.05	21.68
85	1	24	0	-2.10	-.18	20.81	22.49
85	1	24	3	-10.64	-8.32	20.93	19.98
85	1	24	6	-13.06	-2.98	19.63	18.45
85	1	24	9	-1.10	1.21	16.40	19.08
85	1	24	12	7.04	6.93	17.53	19.52
85	1	24	15	6.31	-.29	14.91	18.88
85	1	24	18	-2.62	-3.79	14.35	17.71
85	1	24	21	-5.51	-4.61	14.76	17.65
85	1	25	0	-6.10	-5.49	13.14	15.60
85	1	25	3	-9.26	-10.32	14.69	18.24
85	1	25	6	-9.83	-7.78	14.47	14.62
85	1	25	9	-1.88	-1.58	9.95	13.18
85	1	25	12	4.13	3.56	9.18	10.02
85	1	25	15	5.03	-.07	8.95	8.54
85	1	25	18	-2.72	-4.28	8.36	10.58
85	1	25	21	-7.32	-5.99	11.07	10.93
85	1	26	0	-3.37	-3.17	7.72	8.62
85	1	26	3	-3.17	-5.14	7.18	8.78
85	1	26	6	-5.97	-7.22	9.43	11.05
85	1	26	9	-3.26	-2.81	7.04	8.19
85	1	26	12	.69	1.55	5.89	7.72
85	1	26	15	2.19	-1.34	6.56	7.94
85	1	26	18	-3.81	-5.63	7.27	10.72
85	1	26	21	-3.75	-4.07	8.35	11.89
85	1	27	0	-4.96	-1.36	8.92	10.88
85	1	27	3	-7.03	-3.56	10.70	11.04
85	1	27	6	-13.02	-8.65	15.99	13.39
85	1	27	9	-10.77	-6.28	14.33	11.36
85	1	27	12	-5.25	-2.02	10.17	9.05
85	1	27	15	-1.00	-1.70	7.55	7.14
85	1	27	18	-3.24	-6.30	7.22	10.66
85	1	27	21	-2.63	-3.66	7.78	11.35
85	1	28	0	2.17	2.18	11.75	15.50

AVERAGE CURRENT DATA CONTINUED

85	1	28	3	6.30	1.17	13.47	13.89
85	1	28	6	-2.36	-1.95	12.02	15.28
85	1	28	9	-2.41	-3.72	11.53	14.42
85	1	28	12	-.75	-.39	10.97	14.03
85	1	28	15	1.47	.43	11.37	12.18
85	1	28	18	-1.18	-5.67	9.95	13.50
85	1	28	21	-2.29	-3.30	11.13	13.19
85	1	29	0	-.80	.24	12.31	11.99
85	1	29	3	4.81	2.89	11.05	11.32
85	1	29	6	-1.92	-2.55	8.92	9.36
85	1	29	9	-3.42	-3.80	10.50	10.52
85	1	29	12	-3.79	-1.66	9.92	9.51
85	1	29	15	-3.03	.00	7.85	7.88
85	1	29	18	-3.75	-3.19	7.63	8.48
85	1	29	21	-6.56	-5.61	9.26	8.70
85	1	30	0	-7.10	-4.19	9.46	7.60
85	1	30	3	-1.20	-.82	6.13	6.23
85	1	30	6	-.32	-.23	5.17	5.86
85	1	30	9	-.15	.23	4.92	4.78
85	1	30	12	-1.02	-1.06	5.53	5.53
85	1	30	15	-1.63	-.70	5.13	5.39
85	1	30	18	-5.19	-5.95	7.17	7.52
85	1	30	21	-11.81	-8.48	13.17	9.86
85	1	31	0	-14.61	-4.25	15.62	6.09
85	1	31	3	-5.67	2.72	8.06	5.66
85	1	31	6	-.95	.97	5.36	5.05
85	1	31	9	-.49	-.46	5.47	5.17
85	1	31	12	-2.80	-2.52	6.00	5.06
85	1	31	15	-4.89	-2.48	6.61	5.39
85	1	31	18	-5.00	-3.60	7.02	5.74
85	1	31	21	-7.70	-5.86	8.86	7.39
85	2	1	0	-12.17	-7.63	13.07	8.68
85	2	1	3	-5.31	.61	6.64	4.09
85	2	1	6	1.18	4.15	4.44	5.72
85	2	1	9	9.48	5.80	10.25	7.11
85	2	1	12	7.09	.51	8.19	3.61
85	2	1	15	2.18	-1.93	4.16	4.31
85	2	1	18	-2.01	-4.56	4.17	5.98
85	2	1	21	-7.57	-9.80	8.33	10.47
85	2	2	0	-14.77	-10.97	15.36	11.88
85	2	2	3	-8.64	-1.92	9.36	3.60
85	2	2	6	2.93	5.58	4.07	6.49
85	2	2	9	10.06	5.10	10.68	6.12
85	2	2	12	6.65	-1.98	7.28	3.27
85	2	2	15	-1.18	-4.14	3.59	5.12
85	2	2	18	-6.25	-5.91	7.40	6.89
85	2	2	21	-11.00	-7.35	12.17	8.75
85	2	3	0	-20.67	-14.88	22.53	16.90
85	2	3	3	-17.65	-8.82	20.99	15.91
85	2	3	6	-.35	7.33	11.70	15.22
85	2	3	9	12.33	13.72	17.36	19.60
85	2	3	12	9.57	5.78	15.79	14.88
85	2	3	15	-1.44	-1.95	11.99	13.83
85	2	3	18	-10.59	-7.04	14.45	11.44

AVERAGE CURRENT DATA CONTINUED

85	2	3	21	-17.48	-11.70	19.82	14.24
85	2	4	0	-26.26	-17.86	27.93	19.49
85	2	4	3	-23.71	-11.10	25.39	13.13
85	2	4	6	-6.57	-.78	9.87	6.53
85	2	4	9	5.51	5.83	8.77	8.16
85	2	4	12	10.95	1.56	12.96	5.56
85	2	4	15	1.20	-9.47	6.92	10.78
85	2	4	18	-4.98	-6.15	7.98	8.34
85	2	4	21	-8.37	-9.29	10.16	11.13
85	2	5	0	-19.65	-10.95	20.71	12.39
85	2	5	3	-21.63	-12.03	22.68	13.43
85	2	5	6	-10.70	-.50	12.22	4.80
85	2	5	9	2.11	9.39	5.47	10.78
85	2	5	12	7.47	7.58	9.55	8.81
85	2	5	15	-.38	-4.70	6.09	6.41
85	2	5	18	-3.57	-5.48	7.71	6.72
85	2	5	21	-2.97	-2.86	6.41	4.70
85	2	6	0	-3.76	-7.33	6.28	8.26
85	2	6	3	-20.28	-12.54	21.30	13.57
85	2	6	6	-12.45	-2.76	14.15	4.88
85	2	6	9	2.57	10.08	5.69	11.12
85	2	6	12	8.08	10.89	9.27	11.56
85	2	6	15	-.19	-4.64	3.69	5.27
85	2	6	18	-7.62	-8.43	8.31	8.98
85	2	6	21	-4.44	-1.30	5.17	2.68
85	2	7	0	-4.94	-5.42	5.54	5.87
85	2	7	3	-18.74	-10.91	19.09	11.34
85	2	7	6	-16.29	-5.81	16.73	7.24
85	2	7	9	-4.30	7.38	7.43	13.03
85	2	7	12	12.38	10.47	14.47	15.39
85	2	7	15	6.71	-2.53	10.09	9.41
85	2	7	18	-2.31	-4.40	7.79	10.98
85	2	7	21	-1.05	-1.97	6.88	9.96
85	2	8	0	-3.28	-3.29	7.72	9.41
85	2	8	3	-15.20	-9.82	16.80	13.11
85	2	8	6	-14.55	-8.14	16.59	11.82
85	2	8	9	-2.54	3.95	7.02	8.77
85	2	8	12	8.16	11.01	10.50	13.03
85	2	8	15	2.07	-2.07	7.29	7.12
85	2	8	18	-4.86	-8.01	8.66	10.82
85	2	8	21	-5.42	-1.69	8.57	7.22
85	2	9	0	1.12	2.37	11.14	13.94
85	2	9	3	-2.50	-4.09	12.74	16.34
85	2	9	6	-8.07	-6.68	16.66	17.18
85	2	9	9	-2.62	-2.11	15.39	16.61
85	2	9	12	2.67	6.28	12.58	14.84
85	2	9	15	2.44	-.71	9.99	10.68
85	2	9	18	-3.78	-6.89	10.58	14.12
85	2	9	21	-7.77	-4.22	13.86	14.93
85	2	10	0	-3.55	1.40	11.00	12.63
85	2	10	3	-2.25	-2.77	9.16	11.69
85	2	10	6	-8.76	-8.12	14.17	15.37
85	2	10	9	-8.67	-4.18	13.72	11.76
85	2	10	12	-.30	3.97	10.06	12.44

AVERAGE CURRENT DATA CONTINUED

85	2	10	15	1.86	.98	10.10	11.48
85	2	10	18	-3.91	-5.09	9.40	11.40
85	2	10	21	-10.32	-7.69	13.11	11.67
85	2	11	0	-8.16	-1.32	11.13	7.80
85	2	11	3	-1.72	-.17	6.88	6.76
85	2	11	6	-1.96	-7.97	5.67	10.15
85	2	11	9	-7.56	-7.54	9.42	9.54
85	2	11	12	-5.97	-1.47	7.87	5.57
85	2	11	15	-4.25	-1.79	6.63	5.50
85	2	11	18	-12.14	-9.19	13.11	10.54
85	2	11	21	-14.55	-8.49	15.65	9.72
85	2	12	0	-5.26	2.39	7.50	5.26
85	2	12	3	5.05	7.70	8.39	9.02
85	2	12	6	2.93	-.78	6.61	3.56
85	2	12	9	-1.35	-4.45	5.24	5.81
85	2	12	12	-4.38	-3.71	7.15	5.35
85	2	12	15	-1.01	-.09	4.97	3.63
85	2	12	18	-5.37	-7.11	7.45	8.02
85	2	12	21	-12.86	-10.90	13.44	11.49
85	2	13	0	-14.93	-6.06	15.61	6.94
85	2	13	3	-.93	7.69	4.39	8.47
85	2	13	6	4.00	2.45	5.94	4.23
85	2	13	9	5.42	-.97	7.05	2.98
85	2	13	12	-.18	-3.43	3.89	4.65
85	2	13	15	-.85	-2.80	4.23	3.91
85	2	13	18	-4.38	-7.00	5.96	7.74
85	2	13	21	-13.46	-11.59	14.12	12.39
85	2	14	0	-14.57	-7.96	15.52	9.05
85	2	14	3	-1.73	5.58	6.50	8.76
85	2	14	6	9.09	9.87	13.46	15.25
85	2	14	9	12.20	5.59	20.94	22.35
85	2	14	12	6.04	1.62	20.45	33.32
85	2	14	15	-3.08	-1.82	21.43	42.72
85	2	14	18	-3.91	-3.41	18.86	30.12
85	2	14	21	-10.48	-8.79	18.87	29.56
85	2	15	0	-18.35	-11.31	24.24	30.57
85	2	15	3	-5.71	.50	17.42	25.93
85	2	15	6	4.79	9.03	13.07	23.82
85	2	15	9	14.88	9.82	18.62	20.40
85	2	15	12	6.86	1.18	13.10	18.35
85	2	15	15	-2.61	-2.37	9.31	18.00
85	2	15	18	-7.32	-5.10	12.32	16.46
85	2	15	21	-13.72	-11.55	16.59	17.62
85	2	16	0	-21.04	-14.31	22.73	19.11
85	2	16	3	-11.66	-2.86	13.87	12.04
85	2	16	6	2.37	7.78	7.62	13.57
85	2	16	9	3.14	6.02	7.97	11.68
85	2	16	12	6.46	.13	9.21	9.72
85	2	16	15	-3.38	-4.01	7.80	12.24
85	2	16	18	-6.78	-2.95	9.30	10.90
85	2	16	21	-13.83	-10.11	15.25	14.33
85	2	17	0	-18.69	-11.44	20.09	14.88
85	2	17	3	-12.09	-5.20	13.92	14.03
85	2	17	6	-1.61	4.06	6.67	12.09

AVERAGE CURRENT DATA CONTINUED

85	2	17	9	10.90	11.22	13.36	15.01
85	2	17	12	7.01	.41	9.55	10.05
85	2	17	15	-4.98	-3.58	7.85	11.18
85	2	17	18	-8.59	-6.25	10.64	10.57
85	2	17	21	-12.02	-8.48	13.21	10.87
85	2	18	0	-18.26	-11.19	19.11	13.15
85	2	18	3	-16.69	-7.96	17.53	11.36
85	2	18	6	-4.66	2.46	7.51	8.56
85	2	18	9	7.59	9.81	9.47	13.07
85	2	18	12	5.08	2.55	8.20	9.31
85	2	18	15	-2.84	-2.58	6.43	8.27
85	2	18	18	-2.98	-2.09	7.34	8.28
85	2	18	21	-2.39	-1.89	7.02	8.46
85	2	19	0	-6.82	-7.19	9.19	10.51
85	2	19	3	-16.48	-8.53	17.63	11.36
85	2	19	6	-8.94	-.82	12.06	8.54
85	2	19	9	1.61	6.92	8.44	11.41
85	2	19	12	6.79	4.48	12.46	12.64
85	2	19	15	-2.21	-1.86	10.04	11.31
85	2	19	18	-2.33	-2.16	8.48	10.00
85	2	19	21	-1.43	-.03	6.76	8.12
85	2	20	0	-2.32	-5.24	5.89	7.78
85	2	20	3	-5.93	-8.66	8.09	11.11
85	2	20	6	-5.00	-4.14	7.44	8.32
85	2	20	9	-.09	.89	4.99	8.63
85	2	20	12	4.51	4.57	10.20	17.12

SAMPLE BURST DATA

Burst data is for January 17th, 1985 Hour 0

Data is sequential in X-Y pairs at 1 Hz.

```
85   1 17   0  256
R -13.99 -19.50 -26.79 -31.11 -35.42 -33.04 -31.85 -24.26
R -26.94 -10.86 -13.39    .30  -1.49   8.48   7.44  14.14
R  14.59   9.23  13.69   2.83   1.64  -4.61 -13.39 -14.73
R -25.90 -21.88 -35.42 -21.58 -36.91 -16.52 -28.43  -6.70
R -17.41   1.93  -8.48   8.48  -1.49  14.88  10.72  21.88
R  20.69  25.00  25.90  17.26  21.73   1.34   4.46 -13.99
R -15.03 -29.02 -36.76 -37.65 -51.35 -43.90 -52.83 -33.34
R -39.74 -15.03 -15.78   4.76   3.42  22.62  20.69  34.08
R  33.78  34.68  23.81  25.90   1.34   1.64 -11.16 -16.37
R -11.61 -27.24 -16.22 -37.36 -27.24 -41.08 -31.40 -35.42
R -33.49 -27.24 -32.74 -18.90 -26.19  -7.59 -13.25   4.61
R   1.19  21.28  19.35  29.62  35.27  37.06  35.57  30.36
R  22.47   8.33  -1.64 -16.37 -23.81 -43.46 -45.24 -59.23
R -64.14 -70.25 -64.29 -57.75 -50.01 -36.31 -25.60  -7.74
R  -4.76  15.18   8.04  29.47  25.30  36.76  32.89  38.84
R  22.62  29.02   4.46   6.40 -18.90 -10.86 -32.44 -19.79
R -32.15 -32.74 -33.78 -31.25 -25.30 -32.30 -14.73 -29.77
R  -7.59 -26.34   -.74 -23.51   1.93 -16.82    .74 -12.95
R  -5.66  -1.93 -16.82  14.59 -20.98  27.68 -23.22  34.23
R -21.13  30.51 -20.24  14.14 -19.35  -3.87 -20.84 -26.49
R -27.09 -49.86 -27.53 -60.57 -26.49 -59.98 -20.09 -49.41
R -11.16 -28.13 -11.46  -6.10  -5.21  22.62   -.60  39.74
R   -.30  45.69  -2.68  43.31 -12.80  23.66 -19.94   1.64
R -28.87 -17.71 -33.19 -31.55 -40.63 -43.90 -38.10 -51.94
R -29.32 -41.67 -21.28 -24.26  -8.48  -5.36   1.19  12.65
R   6.70  25.90   6.85  25.90  -1.64  17.26 -10.27  -1.19
R -18.16 -12.06 -19.05 -16.82 -16.97 -13.39 -18.90  -9.97
R -24.41 -12.50 -31.40 -15.48 -38.25 -19.20 -34.08 -14.29
R -16.67  -5.95   3.27   4.46  12.06  13.69  11.46  10.57
R    .45  -3.42 -12.95 -15.48 -24.11 -21.58 -30.51 -21.58
R -32.89 -14.73 -30.51  -4.46 -25.30   1.04 -17.41   3.13
R -11.91   0.00  -9.67  -8.93 -12.20 -18.90 -12.80 -24.71
R -11.31 -25.00 -12.65 -16.82 -14.73  -5.06 -15.33   5.21
R -14.59  15.78 -13.99  19.20 -13.84  14.59 -16.22   3.13
R -20.54 -11.31 -24.11 -26.19 -25.90 -37.21 -24.56 -37.65
R -17.56 -25.15  -8.33  -8.04  -2.53   5.36  -5.51  13.39
R -12.80  15.03 -19.65  13.69 -21.28   9.67 -18.01   6.40
R -11.01   -.15  -6.25  -8.33  -5.51 -18.31  -6.55 -25.00
R  -7.59 -22.32  -9.38 -11.01  -9.52   2.38 -14.88   9.23
R -21.58   8.48 -26.34   5.21 -25.75   2.53 -21.73  -2.53
R -17.56  -6.99 -10.27  -5.95  -2.83  -2.38   3.13   -.15
R   4.61   1.34   -.15   2.68 -10.27   2.08 -20.98  -1.34
R -26.19  -5.36 -26.34  -6.85 -22.77 -10.27 -17.86 -12.06
R -15.63 -15.03 -14.59 -15.92 -15.48 -15.78 -16.82 -12.35
R -16.97  -4.02 -15.33   5.36 -11.16  14.73  -5.66  20.98
R  -2.23  19.50  -1.64  11.46  -5.66   -.15 -16.07 -14.59
R -25.30 -27.68 -34.08 -40.03 -36.76 -41.23 -30.21 -34.38
R -18.90 -19.20 -11.16  -5.66  -7.74   3.42 -10.27   9.23
R -13.84  10.57 -15.18   8.63 -12.50   4.17 -11.76  -2.98
R -12.95 -11.16 -19.94 -17.41 -25.90 -22.03 -32.00 -26.34
R -38.10 -27.68 -37.95 -23.81 -28.28 -16.07 -12.50  -4.91
R   9.52   7.59  19.94  13.54  14.73  12.65  -1.93   3.87
```

SAMPLE BURST DATA CONTINUED

```
R -22.03  -6.85 -37.21 -17.41 -41.37 -23.37 -35.42 -21.58
R -23.37 -16.97  -9.52 -10.27  -1.64  -4.02    .15   2.23
R  -1.34   8.33  -6.25  12.80 -11.01  10.72 -10.86   6.85
R -10.42  -1.93  -9.97 -10.42  -9.97 -16.82 -10.12 -18.01
R  -9.38 -16.22  -9.67 -13.99 -10.86 -12.95 -14.29 -12.80
R -17.41 -13.54 -18.31 -14.44 -18.16 -10.42 -15.03  -2.98
R -12.95   4.76 -13.84  12.06 -12.80  14.44 -10.72  12.20
R  -9.23   6.40  -7.44  -4.76  -6.99 -16.52 -10.72 -26.49
R -16.07 -35.27 -24.26 -36.17 -25.90 -30.36 -24.41 -16.22
R -15.18  -1.49 -10.57  13.10  -8.78  21.13  -9.38  20.39
R -15.03  14.44 -16.67   9.08 -12.50   -.15  -6.40  -7.44
R  -4.32 -18.16  -6.99 -25.45 -11.31 -29.02 -15.03 -25.75
R -13.39 -16.52 -11.46  -8.19 -13.25  -1.49 -18.75   2.53
R -24.41   4.91 -28.43   5.06 -29.62   3.57 -25.30   1.93
R -16.82   3.27  -7.59   5.21    .60   6.10   4.17   3.87
R    .30  -3.72  -9.08 -16.07 -21.58 -27.24 -27.98 -28.43
R -23.37 -21.88 -13.25 -10.27  -6.70   2.23 -11.01   6.25
R -23.22   3.27 -31.55  -1.34 -33.93   -.15 -29.02  -1.79
R -11.31   7.59   5.95  12.95  14.44   7.74  10.42  -7.44
R  -4.02 -20.09 -18.01 -25.30 -26.34 -21.13 -29.02 -12.50
R -26.64  -3.87 -23.51   6.85 -20.39   9.97 -16.97   7.14
R -14.29  -1.49 -12.35 -10.72 -12.95 -19.94 -17.56 -17.12
R -12.06 -11.31  -4.32  -5.06   3.72   2.23   6.10   5.51
R  -3.72   2.68 -19.35  -2.38 -33.93  -9.23 -43.46  -8.93
R -44.65  -6.70 -36.02  -4.17 -21.28  -4.17  -8.78  -5.36
R  -1.64  -9.38   1.04 -11.46   4.32  -8.93   6.85  -1.93
R   4.32   3.87  -5.66   5.51 -19.05   0.00 -31.85  -7.29
R -43.90 -17.71 -45.99 -29.32 -41.23 -34.97 -29.32 -34.38
R -15.48 -25.60  -3.57 -10.86   1.49   3.42   1.79  14.29
R   1.04  16.97  -5.66  16.22 -14.44  11.76 -20.69   1.49
R -22.62  -9.82 -22.03 -16.97 -15.78 -20.54 -10.72 -17.26
R  -7.59 -18.45  -8.63 -20.54 -11.91 -21.73 -17.12 -19.35
R -21.73 -12.95 -20.39  -2.53 -16.67   8.63 -13.54  18.60
R  -8.78  27.83  -8.19  28.43  -9.38  18.01 -10.72   2.98
R -16.37 -13.99 -20.84 -30.21 -19.35 -41.97 -22.77 -43.46
R -23.96 -32.59 -22.77 -18.75 -15.18  -3.57  -8.19  11.01
R    .89  24.26   2.83  29.32   7.89  26.64  -1.34  17.26
R -14.73   4.32 -27.09 -12.95 -35.72 -23.96 -34.08 -32.59
R -28.57 -28.57 -20.54 -20.39  -6.99  -7.59   7.74   3.57
R  20.24   4.46  26.64   3.72  22.47   4.76   7.89   3.13
R -11.01  -2.38 -25.15  -5.80 -34.83 -11.76 -41.52  -9.52
R -38.40  -5.95 -26.19  -1.34 -11.46   1.49   3.27    .74
R  12.80  -4.02  16.37 -13.10  12.65 -28.72   7.74 -30.36
R  -2.38 -24.85 -13.69 -18.31 -20.69 -10.27 -24.56  -2.53
R -26.49   6.70 -22.92  11.16  -9.23  20.09    .30  24.56
R   9.52  18.60   6.25   5.51  -8.04 -10.57 -20.69 -23.51
R -29.02 -32.89 -30.06 -30.36 -19.79 -19.35  -3.13  -4.32
R   8.19   9.38  12.65  11.31   5.95   8.04  -5.06   0.00
R -17.12  -8.48 -25.15 -16.22 -25.45 -14.29 -18.16  -5.95
R  -6.85   4.76   4.17  14.29  12.50  19.05  13.25  13.39
R   2.53  -2.08 -15.78 -21.28 -32.89 -34.97 -41.97 -42.42
R -41.97 -37.65 -32.15 -25.15 -16.67  -7.44  -5.06   6.25
R  -1.19  16.07    .89  18.45   3.27  15.18   5.51  12.80
R   6.85   7.89   2.08  -1.93  -6.25  -9.38 -10.72 -14.59
```

SAMPLE BURST DATA CONTINUED

```
R -14.29 -18.90 -15.92 -19.35 -15.03 -15.33 -15.78 -10.42
R -18.45  -7.14 -18.01  -2.23 -14.14   1.79  -6.70   4.32
R    .74   4.02   2.98  -3.13    .15 -13.10  -3.42 -19.65
R -12.06 -21.58 -18.75 -19.20 -16.97 -11.76 -13.54  -4.61
R  -8.78    .15  -7.89   5.36  -8.48  10.12  -8.04  11.76
R  -8.33   8.63  -9.23   1.49 -12.20  -5.80 -15.18 -13.69
R -14.59 -19.35 -12.65 -17.71  -8.33 -12.80  -5.36  -9.52
R  -6.99  -9.08 -13.54 -11.16 -18.90 -10.42 -20.09  -5.66
R -16.82   2.38  -9.82  12.95  -2.23  21.28   2.83  21.28
R   5.21  11.16  -4.46  -7.29 -16.37 -20.98 -23.07 -32.30
R -25.30 -36.91 -24.26 -28.43 -18.60 -16.37 -12.20  -5.51
R  -7.14   2.53  -4.17   6.55  -1.19  10.27   -.15   9.82
R  -4.32   3.87 -12.20  -3.57 -20.98 -12.20 -32.00 -15.03
R -35.12 -15.63 -32.15 -18.60 -22.47 -15.33  -6.70 -11.46
R   4.32  -6.85   7.44  -5.36   3.27  -2.98  -6.70   1.34
R -17.71   8.04 -27.68  11.01 -34.83  12.20 -33.04   9.38
R -28.87   2.83 -22.62  -8.04 -22.47 -24.26 -18.90 -33.93
R -12.50 -34.38  -2.38 -23.51   9.23 -13.69  15.33   1.64
R   9.52  18.75  -2.98  24.56 -20.84  23.37 -40.03   8.63
R -49.41  -7.59 -54.77 -21.28 -43.16 -26.34 -23.66 -25.60
R  -4.91 -18.45   7.44 -10.12  14.88  -5.21   2.83    .89
R  -8.48   4.61 -18.01   -.45 -26.19  -5.66 -29.17 -11.46
R -25.45 -10.27 -17.26  -8.19  -9.67  -8.48  -7.14 -10.86
R -10.12 -15.78 -12.80 -18.90 -14.29 -16.07 -12.35  -5.21
R  -8.78   7.89  -2.83  19.35    .45  22.03  -1.93  14.73
R -11.46  -1.93 -22.47 -20.69 -29.91 -38.55 -34.08 -46.14
R -27.24 -41.37 -12.80 -27.09  -4.61  -5.66    .45  14.29
R   -.74  22.47  -4.91  20.69  -3.87  14.14  -3.42   1.79
R  -9.82 -13.39 -19.05 -23.22 -18.45 -28.57 -14.29 -22.47
R  -8.04  -8.19  -2.38   3.72  -3.72  11.61  -8.19  11.46
R -12.80   6.40 -15.03  -3.13 -14.59 -14.88  -9.97 -23.37
R  -6.25 -25.45  -1.64 -21.88   -.74 -15.92   -.89  -6.40
R  -1.79   6.40   1.79  17.56   3.57  24.71  -1.64  22.03
R  -5.36  12.06 -12.35  -9.08 -26.34 -30.81 -33.34 -45.84
R -32.74 -46.73 -27.09 -33.93 -12.50 -11.31   8.33  14.88
R  22.77  36.02  30.81  48.52  29.02  44.80  10.72  20.09
R -20.69  -8.19 -33.34 -33.64 -48.07 -54.02 -59.83 -66.97
R -53.28 -61.32 -40.03 -42.42 -17.41 -15.18   7.59  14.29
R  19.65  40.33  37.50  64.74  38.55  71.29  29.02  46.73
R   6.70  12.06 -23.81 -14.88 -34.38 -40.78 -41.97 -56.70
R -45.54 -60.42 -38.25 -51.49 -20.24 -23.81   1.64   9.82
R  21.13  33.64  30.06  53.73  30.66  42.56  20.84  21.73
R   -.15  -3.87 -17.71 -20.24 -26.64 -34.08 -38.40 -35.72
R -44.50 -37.21 -42.12 -26.64 -32.74 -10.12 -13.69   8.93
R   8.19  24.26  30.96  37.21  45.99  35.87  34.08  22.32
R  11.76  -3.57 -12.80 -25.45 -32.30 -42.42 -50.45 -55.07
R -51.64 -44.05 -40.18 -24.85 -23.37  -2.98 -10.86  16.67
R  -1.34  33.34  19.79  37.21  24.41  39.74  28.87  22.77
R  31.25  10.42  20.39    .74   6.25  -9.23  -7.29 -23.81
R -19.05 -34.83 -32.15 -37.21 -38.55 -37.21 -42.56 -34.23
R -28.13 -19.94 -10.12    .60  11.16  18.31  25.15  28.28
R  36.17  30.51  31.85  18.60  13.84  -1.19  -5.66 -17.86
R -24.11 -29.77 -37.36 -32.89 -41.23 -28.87 -33.64 -19.35
R -21.28  -6.55  -6.40   2.23   3.13  11.31  11.61  18.31
```

SAMPLE BURST DATA CONTINUED

```
R  15.78  17.71  14.73  17.26  12.06   1.79  -1.34 -13.10
R -15.78 -22.32 -26.49 -28.28 -32.00 -27.83 -23.07 -26.64
R -16.07 -17.71  -8.78  -8.63   -.89    .89    .30   7.29
R  -2.38  12.35  -5.06  13.54  -6.25  13.54  -5.80  11.76
R  -7.14   3.72 -11.46  -8.48 -16.37 -20.98 -17.56 -29.91
R -16.07 -29.77 -12.50 -23.37 -11.76 -15.63 -17.12  -8.48
R -23.37  -1.79 -25.15   4.32 -20.84   7.14  -9.67  10.72
R  -1.93  12.06   3.13   7.14   2.68  -5.06  -5.95 -16.52
R -17.86 -25.60 -30.96 -30.36 -36.46 -27.09 -33.78 -15.92
R -22.47   1.64 -12.06  20.54   -.60  33.64   4.46  38.10
R  -8.33  20.54 -20.84  -9.67 -23.66 -40.33 -20.09 -57.60
R -18.31 -60.57  -8.93 -42.27  -6.55 -19.79  -4.17   3.13
R  -9.82  26.64  -8.93  37.21 -18.31  42.12 -15.92  35.57
R -19.50  14.44 -16.37   -.89 -10.86 -12.35  -8.48 -25.75
R  -6.99 -35.42    .30 -35.57  -2.53 -33.19  -7.89 -24.85
R -15.03 -11.31 -22.77   2.68 -28.43  13.39 -25.45  20.54
R -16.07  31.55  -8.63  31.55  -1.19  23.81   2.53   6.40
R    .60 -16.97  -9.23 -39.89 -21.43 -56.26 -30.21 -62.95
R -37.65 -56.11 -37.80 -35.12 -33.34  -5.80 -21.88  24.11
R  -9.52  42.42   -.89  52.83  -7.89  42.56 -11.91  19.20
R -17.12 -10.27 -21.73 -33.64 -13.69 -48.37  -3.72 -49.71
R  -3.13 -38.70  -4.91 -25.15 -17.71 -18.90 -38.70 -10.42
R -51.20  -8.19 -48.37  -5.95 -33.34   1.19 -10.57   7.59
R  12.50  18.45  24.41  21.88  23.66  18.90  14.29   3.13
R  -6.70 -14.73 -26.04 -27.83 -38.55 -40.18 -46.88 -47.63
R -55.51 -47.03 -48.37 -38.99 -31.11 -23.22  -9.38  -2.98
R   7.89  13.10  12.65  22.18  19.50  26.34  17.56  26.49
R   7.59  11.31  -4.46  -2.23 -15.92  -6.55 -17.41  -7.44
R -17.71  -7.44 -17.71  -9.52 -22.77 -13.84 -24.11 -18.75
R -23.66 -21.43 -21.13 -14.88 -12.20  -2.38    .15   9.97
R   9.97  19.05  17.71  21.88  17.71  18.16  16.07   5.21
R   5.80  -6.85  -9.97 -20.54 -29.02 -29.17 -40.63 -32.89
R -41.52 -25.90 -35.57 -10.42 -17.56   2.08  -1.34  13.99
R   8.04  19.65  12.95  18.90  10.86   3.42  -1.79 -11.61
R -12.50 -24.26 -20.54 -29.47 -21.43 -26.49 -17.71 -17.86
R  -9.82   1.93  -6.55  16.82  -3.72  22.62  -5.51  20.69
R  -7.44   9.67 -13.84  -6.40 -19.05 -22.47 -21.13 -33.93
R -20.84 -33.93 -15.33 -28.43  -7.44 -17.26  -1.19  -1.93
R   0.00  15.92  -7.29  26.64 -11.01  28.87 -15.03  23.96
R -18.75  12.35 -20.24  -2.98 -16.67 -18.45 -13.25 -34.68
R -19.05 -42.56 -27.53 -40.93 -32.00 -32.74 -28.87 -15.33
R -19.05   1.79  -6.55  18.60   7.59  26.34  13.39  27.98
R  11.91  17.41  -4.46  -5.80 -19.20 -28.57 -36.02 -45.69
R -44.05 -48.37 -40.48 -36.91 -26.94 -19.94 -11.46   1.64
R  -4.46  14.73  -4.76  22.77  -7.29   7.44 -10.86  14.88
R -14.29   8.33 -12.20  -2.23  -5.66  -8.63   -.60 -16.37
R   -.74 -19.79  -5.51 -18.90 -14.44 -15.78 -24.85 -16.07
R -34.83 -17.86 -38.25 -16.37 -34.53 -10.12 -24.41  -1.79
R -10.86   7.44   1.04  13.39  11.61  11.61  15.63   7.59
R   8.63   -.15  -3.13 -12.50 -15.78 -18.60 -27.68 -19.65
R -33.19 -15.92 -35.27 -12.35 -31.70  -4.17 -23.22    .30
R -13.54    .30  -8.48  -3.27  -8.19  -9.67 -11.91 -16.52
R -11.01 -17.86  -5.36 -11.76   2.83   -.30   8.04   7.29
R   5.36  10.12  -3.13   5.21 -13.25  -3.13 -22.47  -9.82
```

SAMPLE BURST DATA CONTINUED

```
R -27.38 -15.92 -26.79 -15.48 -21.73 -11.31 -13.99  -5.51
R  -6.55  -1.19  -3.42    .45  -2.98    .74  -2.83   1.19
R  -2.53   2.83   -.60   3.13   1.04    .60  -1.19  -6.10
R  -6.40 -13.99 -13.10 -20.39 -18.60 -22.32 -19.65 -18.45
R -17.71  -9.38 -12.20    .89  -6.85   9.23  -5.51  13.10
R  -7.89  11.31  -9.23   5.95 -12.20  -1.49 -10.12  -8.33
R  -5.66 -13.10  -3.57 -15.92  -7.14 -16.22 -14.29 -14.59
R -21.28 -12.06 -28.57  -8.19 -30.21  -5.06 -26.34  -2.38
R -17.71  -1.79  -6.40   2.38   2.68   9.38   9.08  16.07
R  10.72  15.18   5.36   4.02  -9.52 -13.99 -29.47 -28.43
R -44.20 -42.86 -53.28 -43.31 -46.14 -30.36 -30.51  -9.52
R -12.80   6.85  -2.68  18.31   6.10  22.32  15.18  26.64
R  17.41  14.73   8.93    .89  -7.29 -12.06 -19.20 -26.49
R -29.91 -33.93 -31.70 -35.57 -27.68 -31.25 -20.39 -17.86
R -10.42    .15  -6.70  13.54  -4.17  23.81   1.19  26.79
R  -6.25  23.07 -12.80  10.86 -19.20  -3.87 -27.98 -20.54
R -30.21 -36.17 -24.41 -40.93 -20.98 -33.78 -13.54 -20.09
R  -9.38  -1.04 -10.12  10.27 -11.76  17.56 -12.65  16.37
R -13.25   9.52 -16.07   1.34 -18.31  -6.55 -19.20 -11.31
R -16.22 -10.86 -13.69  -9.82  -7.74  -9.38  -3.13  -9.97
R  -3.57 -12.20  -7.74 -15.03 -16.07 -14.59 -21.58 -15.48
R -22.77 -10.12 -21.28  -4.02 -21.58   3.42 -23.51   5.80
R -21.88   5.66 -17.41   5.06 -12.06   4.76 -10.27   3.13
R -10.86  -3.72 -15.92 -10.42 -19.50 -18.75 -22.18 -24.71
R -19.20 -20.39 -10.72 -13.39  -6.25  -5.06  -6.99  -1.49
R -12.80  -2.38 -18.45  -3.42 -23.37  -2.53 -26.94   0.00
R -28.87   1.34 -27.09   -.30 -22.77  -2.38 -17.71  -4.32
R -13.84  -7.74 -11.16 -13.10  -8.33 -15.18  -5.66 -14.29
R  -3.57 -10.42  -4.02  -4.76  -8.33   -.45 -17.12   -.30
R -26.64   -.60 -36.31  -2.53 -43.01  -3.13 -41.37  -4.76
R -31.40  -2.83 -14.88  -3.87   2.53  -5.95  11.76  -9.08
R  12.20 -16.07  11.01 -21.43   2.83 -23.51  -6.25 -20.98
R -14.44 -16.52 -32.44 -11.31 -45.69   -.74 -50.45   1.34
R -45.39    .30 -31.55   9.82 -11.91   4.32   7.14   1.93
R  24.56  -2.83  29.62 -12.50  23.66 -15.92   4.32 -19.50
R -13.10 -22.62 -30.36 -26.04 -41.08 -23.22 -43.01 -16.97
R -34.38  -6.40 -20.69   3.72 -11.46   9.67  -5.06  10.27
R  -4.17  -1.04  -3.13 -11.46  -4.91 -18.01  -4.32 -18.31
R  -3.13 -12.06  -4.02  -5.21  -6.55   -.45 -10.27   -.89
R -14.88  -5.51 -19.35 -14.44 -25.15 -23.96 -26.94 -31.85
R -26.19 -35.42 -16.67 -26.94  -2.83  -8.33   7.74  16.07
R  11.76  30.21  10.86  33.04   -.89  25.75 -14.44   8.04
```

APPENDIX B

PROGRAM FOR ZERO CROSSING ANALYSIS

PROGRAM FOR ZERO CROSSING ANALYSIS

```
      PROGRAM XZERO
      DIMENSION X(1100),Y(1100),VELI(1100,2),ICRS(500),IMAX(500),
     &        RMAX(500),DIST(500)
      CHARACTER*12 HEAD,HEAD1
      CHARACTER*1 A
      DATA PI /3.1415926535897/
      DATA YBRNG /328./
      DATA Z /50./
      DATA GD /0.030/
      DATA KB /0.030/
      DATA ICRS,IMAX /1000*0/
      DATA RMAX,DIST /1000*0./
      DATA X,Y,VELI /4400*0./
      DATA RHOS /2.65/
      DATA RHOW /1.025/
      OPEN (5,FILE='T621MD1')
      OPEN (7,FILE='T621AV')
      OPEN (8,FILE='TAPE8')
      OPEN (9,FILE='TAPE9')
      REWIND 5
      REWIND 7
      REWIND 8
      REWIND 9
       SUMX1=0.
       SUMX2=0.
       SUMX3=0.
       SUMX4=0.
       SUMY1=0.
       SUMY2=0.
       SUMY3=0.
       SUMY4=0.
5      CONTINUE
C
C  READ HEADERS AND AVERAGE CURRENT DATA
C
      READ(5,10,END=999)HEAD,N
        PRINT  10, HEAD,N
10    FORMAT(A12,I4)
      READ(7,11)HEAD1,UX,UY,RMSX,RMSY
11    FORMAT(A12,4F7.2)
      IF(HEAD.NE.HEAD1)PRINT*,'ERROR  HEADERS NOT THE SAME'
C
C
C READ INSTANTANEOUS VELOCITY DATA (SAMPLED AT 1 SECOND INTERVALS)
C
C
        N1=N
       K=-4
      DO 100 I=1,N
        K=K+4
         READ(5,12)A,(X(J),Y(J),J=1+K,4+K)
12      FORMAT(A1,8F7.2)
        IF(A.NE.'R')THEN
```

```
            K=K-4
            N1=N1-1
         ENDIF
100     CONTINUE
         N=N1
C
C GET AVERAGE CURRENT DIRECTION
C
       CALL BEARNG (UX,UY,YBRNG,ANS)
         CDIR=ANS*180./PI
         UZ=SQRT(UX*UX+UY*UY)
         WRITE(8,22)HEAD,N,UZ,CDIR
22       FORMAT(A12,I4,2F7.2)
C
C
C  CALCULATE THE INSTANTANEOUS VELOCITY DIRECTION
C
C        SUM99=0.
         SUM2=0.
         OLDSN=1.0
         J=0
         IMAX(1)=0
         RMAX(1)=-999.
       CALL BEARNG ( X(1),Y(1),YBRNG,VELI(1,2) )
        VELI(1,2)=VELI(1,2)*180./PI
         BETA=ABS(CDIR-VELI(1,2))
          IF(BETA.GT.180.)BETA=360.-BETA
          IF(BETA.GT.90.)OLDSN=-1.0
        VELI(1,1)= OLDSN * SQRT( X(1)*X(1) + Y(1)*Y(1) )
                WRITE(8,23)VELI(1,1),VELI(1,2)
       DO 300 I=2,N*4
         SIGN=1.0
       CALL BEARNG ( X(I),Y(I),YBRNG,VELI(I,2) )
        VELI(I,2)=VELI(I,2)*180./PI
         BETA=ABS(CDIR-VELI(I,2))
          IF(BETA.GT.180.)BETA=360.-BETA
          IF(BETA.GT.90.)SIGN=-1.0
        VELI(I,1)= SIGN * SQRT( X(I)*X(I) + Y(I)*Y(I) )
C
C  FLAG A ZERO CROSSING
C
          IF(SIGN.NE.OLDSN)THEN
            J=J+1
            ICRS(J)=I
C
C
C   FIND THE MAX OR MIN VALUE BETWEEN CURRENT AND PREVIOUS ZERO CROSS
C
C
              IF(J.EQ.1)GOTO 299
            RMAX(J)=0.
            DIST(J)=0.
          DO 250 JJ=ICRS(J-1),ICRS(J)-1
            IF(ABS(VELI(JJ,1)).GT.RMAX(J))THEN
```

```
                    RMAX(J)=ABS(VELI(JJ,1))
                    IMAX(J)=JJ
          ENDIF
          DIST(J)=DIST(J)+OLDSN*VELI(JJ,1)
250     CONTINUE
           RMAX(J)=RMAX(J)*OLDSN -UZ
        ENDIF
299      OLDSN=SIGN
C
C
C
C
C        SUM99=SUM99+VELI(I,1)
        IF(I.EQ.ICRS(J))THEN
              WRITE(8,24)VELI(I,1),VELI(I,2),J,ICRS(J),IMAX(J),RMAX(J)
     &  ,DIST(J)
24            FORMAT(2F7.2,3I5,2F7.2)
        ELSE
              WRITE(8,23)VELI(I,1),VELI(I,2)
23            FORMAT(2F7.2)
        ENDIF
300   CONTINUE
C
C
*****************************************************************
C
C  OUTPUT WAVE CHARACTERISTICS
C
C
      JMAX=J
       JSTART=2
       IF(RMAX(2).GT.0.)JSTART=3
       ICNT=1
       RBUF=JMAX/2.
       IF((RBUF-IFIX(RBUF)).GT.0.001)ICNT=0
       IF(JSTART.EQ.2.AND.ICNT.EQ.0)K1=1
       IF(JSTART.EQ.2.AND.ICNT.EQ.1)K1=2
       IF(JSTART.EQ.3.AND.ICNT.EQ.0)K1=3
       IF(JSTART.EQ.3.AND.ICNT.EQ.1)K1=4
        GOTO(40,41,42,43) K1
40      KMAX=(JMAX-1)/2
41      KMAX=(JMAX-2)/2
        JMAX=JMAX-1
42      KMAX=(JMAX-3)/2
        JMAX=JMAX-1
43      KMAX=(JMAX-2)/2
        WRITE(9,22)HEAD,KMAX,UZ,CDIR
        K=0
```

```
        DO 500 J=JSTART,JMAX,2
          K=K+1
C         PRINT*,'NOW ON THE ',K,' TH  WAVE'
          IT1=ICRS(J-1)
          IT2=ICRS(J+1)
          PER=FLOAT(IT2-IT1)
          AB=(DIST(J)+DIST(J+1))/2.
          UB=(RMAX(J+1)-RMAX(J))/2.
C
C CALCULATE AVERAGE AVE DIRECTION FROM THE DIRECTIONS THAT THE
C MAX POSITIVE VELOCITIES OF THE WAVE HAVE
C    NOTE: AN ERROR OF A FEW DEGREES MAY OCURR DUE TO THE FACT
C        THAT THE SAMPLING RATE WAS ONLY 1 HZ AND
C        BECAUSE THE WAVE VECTOR IS INFLUENCED BY THE
C        BACKGROUND CURRENT VECTOR (BUT MUCH LESS SO THAN FOR THE
C        RELATIVELY WEAKER VECTOR OF THE WAVE TROUGH).
C
        WDIR = VELI(IMAX(J+1),2)
C
            WRITE(9,25)K,ICRS(J-1),PER,UB,AB,FCW,IFLAG
C  REPEAT FOR THE NEXT BURST OF DATA
C
       GOTO 5
C
C
998    PRINT*,' READ ERROR ON FILE 5'



       S T O P
999    PRINT*,' END OF DATA IN T621MD1'


       REWIND 5
       REWIND 7
       REWIND 8
       REWIND 9
       CLOSE (5)
       CLOSE (7)
       CLOSE (8)
       CLOSE (9)
       S T O P
       END
```

```
      SUBROUTINE BEARNG (UX,UY,YBRNG,ALPHA)
*
*  SUBROUTINE TO RETURN THETA IN DEGREES TRUE FROM X AND Y VELOCITIES
* AT THE VENTURE ESRF SEDIMENT TRACER SITE.
*
      DATA PI /3.1415926535897/
      IF (UX .EQ. 0. .AND. UY .EQ. 0) THEN
*       CALL BELL
        PRINT*,' ZERO CURRENT DIRECTION UNDEFINED'
        ALPHA = -999.0*PI/180.
        RETURN
      END IF
      ALPHA = ATAN2(UY,UX)
      IF (ALPHA .LT. 0.0) ALPHA = ALPHA + 2.0*PI
C     PRINT*, ALPHA* 180./PI
      ALPHA = PI/2. - ALPHA
      IF (ALPHA .LT. 0.0) ALPHA = 2*PI + ALPHA
*
*  NOW ADD 360-YBRNG  DEGREES BECAUSE THE Y AXIS IS AT YBRNG DEGREES
C  TRUE.
C23456789012345678901234567890123456789012345678901234567890123456789012
*
      ALPHA = ALPHA - (360.-YBRNG)*PI/180.
      IF (ALPHA .LT. 0.0) ALPHA = ALPHA + 2.0*PI
      RETURN
      END
C***********************************************************************
C***********************************************************************
```

APPENDIX C

PROGRAMS TO CALCULATE SEDIMENT TRANSPORT QUANTITIES

PROGRAMS TO CALCULATE SEDIMENT TRANSPORT QUANTITIES

```
       PROGRAM ROSESED
       DIMENSION X(1100),Y(1100),VELI(1100,2),ICRS(500),IMAX(500),
     &         RMAX(500),DIST(500),SUM(4,8),SM(4,8)
     &       ,SED(4)
       CHARACTER*12 HEAD,HEAD1
       CHARACTER*1 A
       DATA PI /3.1415926535897/
       DATA YBRNG /328./
       DATA Z /50./
       DATA GD /0.040/
C      DATA KB /0.030/
       DATA ICRS,IMAX /1000*0/
       DATA RMAX,DIST /1000*0./
       DATA X,Y,VELI /4400*0./
       DATA RHOS /2.65/
       DATA RHOW /1.025/
       OPEN (5,FILE='T621MD1')
       OPEN (7,FILE='T621AV')
       OPEN (8,FILE='TAPE8')
       OPEN (9,FILE='TAPE9')
       REWIND 5
       REWIND 7
       REWIND 8
       REWIND 9
        ROUGH=100.*GD/100.
         KB=ROUGH*100.
        FFF=0.
        VVV=0.
        KKK=0
          DO 4 JJJ=1,8
          DO 4 III=1,4
            SUM(III,JJJ)=0.
4        CONTINUE
5        CONTINUE
C   READ HEADERS AND AVERAGE CURRENT DATA
C
       READ(5,10,END=999)HEAD,N
         PRINT  10, HEAD,N
10     FORMAT(A12,I4)
       READ(7,11)HEAD1,UX,UY,RMSX,RMSY
11     FORMAT(A12,4F7.2)
       IF(HEAD.NE.HEAD1)PRINT*,'ERROR  HEADERS NOT THE SAME'
C
C
C READ INSTANTANEOUS VELOCITY DATA (SAMPLED AT 1 SECOND INTERVALS)
C
C
         N1=N
        K=-4
       DO 100 I=1,N
         K=K+4
          READ(5,12)A,(X(J),Y(J),J=1+K,4+K)
```

```
               IF(JKJK.EQ.0)THEN
                  JKJK=JKJK+1
                  J=0
               ENDIF
              J=J+1
              ICRS(J)=I
C
C
C   FIND THE MAX OR MIN VALUE BETWEEN CURRENT AND PREVIOUS ZERO CROSS
C
C
                IF(J.EQ.1)THEN
                    ANGMAX=ANGMAX+180.
                    IF(ANGMAX.GT.360.)ANGMAX=ANGMAX-360.
                      GOTO 299
                ENDIF
              RMAX(J)=0.
              DIST(J)=0.
            DO 250 JJ=ICRS(J-1),ICRS(J)-1
              IF(ABS(VELI(JJ,1)).GT.RMAX(J))THEN
                        RMAX(J)=ABS(VELI(JJ,1))
                        IMAX(J)=JJ
              ENDIF
              DIST(J)=DIST(J)+OLDSN*VELI(JJ,1)
250         CONTINUE
               RMAX(J)=VELI(IMAX(J),1)
               ANGMAX=VELI(IMAX(J),2)+180.
                    IF(ANGMAX.GT.360.)ANGMAX=ANGMAX-360.
            ENDIF
299          OLDSN=SIGN
C
C
C
C
            IF(I.EQ.ICRS(J))THEN
                  WRITE(8,24)VELI(I,1),VELI(I,2),J,ICRS(J),IMAX(J),RMAX(J)
     &   ,DIST(J)
24                FORMAT(2F7.2,3I5,2F7.2)
            ELSE
                  WRITE(8,23)VELI(I,1),VELI(I,2)
23                FORMAT(2F7.2)
            ENDIF
300       CONTINUE
C
C
******************************************************************
C
C  GET NUMBER OF WAVES
C
C
         JMAX=J
          JSTART=2
          IF(RMAX(2).GT.0.)JSTART=3
          ICNT=1
```

```
        RBUF=JMAX/2.
        IF((RBUF-IFIX(RBUF)).GT.0.001)ICNT=0
        IF(JSTART.EQ.2.AND.ICNT.EQ.0)K1=1
        IF(JSTART.EQ.2.AND.ICNT.EQ.1)K1=2
        IF(JSTART.EQ.3.AND.ICNT.EQ.0)K1=3
        IF(JSTART.EQ.3.AND.ICNT.EQ.1)K1=4
         GOTO(40,41,42,43) K1
40       KMAX=(JMAX-1)/2
41       KMAX=(JMAX-2)/2
         JMAX=JMAX-1
42       KMAX=(JMAX-3)/2
         JMAX=JMAX-1
43       KMAX=(JMAX-2)/2
         WRITE(9,22)HEAD,KMAX,UZ,CDIR
         K=0
C
C
C CALCULATE AVERAGE FRICTION FACTOR AND CRITICAL VELOCITY FOR THE BURST
C
C
          FCWAV=0.
          VCBAV=0.
        DO 500 J=JSTART,JMAX,2
          K=K+1
C         PRINT*,'NOW ON THE ',K,' TH  WAVE'
          IT1=ICRS(J-1)
          IT2=ICRS(J+1)
          PER=FLOAT(IT2-IT1)
          AB=(DIST(J)+DIST(J+1))/2.
          UB=(RMAX(J+1)-RMAX(J))/2.
C
C CALCULATE AVERAGE WAVE DIRECTION FROM THE DIRECTIONS THAT THE
C MAX POSITIVE VELOCITIES OF THE WAVE HAVE
C    NOTE: AN ERROR OF A FEW DEGREES MAY OCURR DUE TO THE FACT
C        THAT THE SAMPLING RATE WAS ONLY 1 HZ
C
        WDIR = VELI(IMAX(J+1),2)
C
C
      CALL FRCFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
C
C        PHIB=ABS(CDIR-WDIR)
C             IF(PHIB.GT.360.)PHIB=PHIB-360.
C        PHIB=PHIB*PI/180.
C       A22=AB/ROUGH
C       IF(A22.LE.1.57)THEN
C             FCW=0.28
C         ELSE
C             R1=ROUGH/AB
C             FCW=EXP(5.213*(R1**0.194)-5.977)
C       ENDIF
      CALL THRESH(UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
         FCWAV=FCWAV+FCW
```

```
12       FORMAT(A1,8F7.2)
         IF(A.NE.'R')THEN
            K=K-4
            N1=N1-1
         ENDIF
100     CONTINUE
         N=N1
C
C GET AVERAGE CURRENT DIRECTION
C
       CALL BEARNG (UX,UY,YBRNG,ANS)
         CDIR=ANS*180./PI
         UZ=SQRT(UX*UX+UY*UY)
C
C
C  INITIALIZE UA TO UZ IF USING JONSSON (1966)
C
C        UA=UZ
         WRITE(8,22)HEAD,N,UZ,CDIR
22       FORMAT(A12,I4,2F7.2)
C
C
C  CALCULATE THE INSTANTANEOUS VELOCITY DIRECTION
C
         OLDSN=1.0
         J=1
        ICRS(1)=0
          JKJK=0
         ANGMAX=CDIR
         RMAX(1)=-999.
       CALL BEARNG ( X(1)-UX,Y(1)-UY,YBRNG,VELI(1,2) )
        VELI(1,2)=VELI(1,2)*180./PI
         BETA=ABS(CDIR-VELI(1,2))
          IF(BETA.GT.180.)BETA=360.-BETA
          IF(BETA.GT.90.)OLDSN=-1.0
       VELI(1,1)=OLDSN*SQRT((X(1)-UX)*(X(1)-UX)+(Y(1)-UY)*(Y(1)-UY))
                WRITE(8,23)VELI(1,1),VELI(1,2)
         SIGN=OLDSN
       DO 300 I=2,N*4
C        SIGN=1.0
       CALL BEARNG ( X(I)-UX,Y(I)-UY,YBRNG,VELI(I,2) )
        VELI(I,2)=VELI(I,2)*180./PI
C
C
         BETA=ABS(ANGMAX-VELI(I,2))
          IF(BETA.GT.180.)BETA=360.-BETA
          IF(BETA.GT.90. .AND. I.GT.ICRS(J)+2)THEN
                  SIGN=-1.0*OLDSN
          ENDIF
       VELI(I,1)=SIGN*SQRT((X(I)-UX)*(X(I)-UX)+(Y(I)-UY)*(Y(I)-UY))
C
C  FLAG A ZERO CROSSING
C
          IF(SIGN.NE.OLDSN)THEN
```

```
         VCBAV=VCBAV+VCB
500     CONTINUE
            FCW=FCWAV/K
            VCB=VCBAV/K
            WRITE(9,88)HEAD,K,FCW,VCB
            PRINT   88, HEAD,K,FCW,VCB
88       FORMAT( A12,I5,F8.6,F8.1)
        PRINT*,'KMAX= ',KMAX,'K= ',K
C
C
C   CALCULATE SEDIMENT TRANSPORT ASSUMING THAT EACH INSTANTANEOUS
C   VELOCITY SAMPLED CAN BE TREATED AS PURE CURRENT WITH
C   THE FRICTION FACTOR CALCULATED FROM THE CASE OF COMBINED WAVES
C   AND CURRENTS (GRANT AND MADSEN, 1979).
C
C
          DO 44 JJJ=1,8
          DO 44 III=1,4
            SM(III,JJJ)=0.
44        CONTINUE
       DO 450 KK=1,N*4
         UA=SQRT(X(KK)*X(KK)+Y(KK)*Y(KK))
        IF(UA.GT.VCB)THEN
             CALL TRNSPO(UA,VCB,GD,FCW,RHOS,RHOW,
     &                  SED(1),SED(2),SED(3),SED(4))
       CALL BEARNG ( X(KK),Y(KK),YBRNG,RANG)
        RANG=RANG*180./PI
          DO 45 III=1,4
              IF(RANG.GT.337.5.OR.RANG.LE.22.5)THEN
                   JJJ=1
                ELSE
                   JJJ=IFIX((RANG+22.5)/45.)+1
              ENDIF
C         PRINT*,RANG,JJJ
           SM(III,JJJ)=SM(III,JJJ)+SED(III)
45       CONTINUE
        ENDIF
450     CONTINUE
C           WRITE(9,25)K,ICRS(J-1),PER,UB,AB,FCW,IFLAG
25              FORMAT(2I5,3F7.2,F7.6,I2)
C
C  REPEAT FOR THE NEXT BURST OF DATA AND SUM SEDIMENT TRANSPORT
C
          DO 47 JJJ=1,8
          DO 46 III=1,4
            SUM(III,JJJ)=SUM(III,JJJ)+SM(III,JJJ)
46       CONTINUE
C
          WRITE(9,*)(SM(K,JJJ),K=1,4)
C
47        CONTINUE
         KKK=KKK+1
         FFF=FFF+FCW
         VVV=VVV+VCB
```

```
       GOTO 5
C
C
998    PRINT*,' READ ERROR ON FILE 5'
              WRITE(9,35)
35      FORMAT(' THE 8 GRAND TOTALS FOR THE 4 OPTIONS ARE:')
36      FORMAT(4F8.1)
        SED1X=0.
        SED2X=0.
        SED3X=0.
        SED4X=0.
        SED1Y=0.
        SED2Y=0.
        SED3Y=0.
        SED4Y=0.
               DO 49 JJJ=1,8
                     WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
        SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
49             CONTINUE
         SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
         CALL BEARNG(SED1X,SED1Y,0.,ANS1)
         ANS1=ANS1*180./PI
         SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
         CALL BEARNG(SED2X,SED2Y,0.,ANS2)
         ANS2=ANS2*180./PI
         SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
         CALL BEARNG(SED3X,SED3Y,0.,ANS3)
         ANS3=ANS3*180./PI
         SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
         CALL BEARNG(SED4X,SED4Y,0.,ANS4)
         ANS4=ANS4*180./PI
           WRITE(9,37)SEDD1*0.01,ANS1
           WRITE(9,37)SEDD2*0.01,ANS2
           WRITE(9,37)SEDD3*0.01,ANS3
           WRITE(9,37)SEDD4*0.01,ANS4
37        FORMAT(2F8.1)
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
       S T O P
999    PRINT*,' END OF DATA IN T621MD1'
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
              WRITE(9,35)
        SED1X=0.
        SED2X=0.
```

```
        SED3X=0.
        SED4X=0.
        SED1Y=0.
        SED2Y=0.
        SED3Y=0.
        SED4Y=0.
               DO 50 JJJ=1,8
                     WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
        SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
50             CONTINUE
         SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
         CALL BEARNG(SED1X,SED1Y,0.,ANS1)
         ANS1=ANS1*180./PI
         SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
         CALL BEARNG(SED2X,SED2Y,0.,ANS2)
         ANS2=ANS2*180./PI
         SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
         CALL BEARNG(SED3X,SED3Y,0.,ANS3)
         ANS3=ANS3*180./PI
         SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
         CALL BEARNG(SED4X,SED4Y,0.,ANS4)
         ANS4=ANS4*180./PI
           WRITE(9,37)SEDD1*0.01,ANS1
           WRITE(9,37)SEDD2*0.01,ANS2
           WRITE(9,37)SEDD3*0.01,ANS3
           WRITE(9,37)SEDD4*0.01,ANS4
       REWIND 5
       REWIND 7
       REWIND 8
       REWIND 9
       CLOSE (5)
       CLOSE (7)
       CLOSE (8)
       CLOSE (9)
       S T O P
       END
      SUBROUTINE BEARNG (UX,UY,YBRNG,ALPHA)
*
*  SUBROUTINE TO RETURN THETA IN DEGREES TRUE FROM X AND Y VELOCITIES
* AT THE VENTURE ESRF SEDIMENT TRACER SITE.
*
      DATA PI /3.1415926535897/
      IF (UX .EQ. 0. .AND. UY .EQ. 0) THEN
*       CALL BELL
        PRINT*,' ZERO CURRENT DIRECTION UNDEFINED'
        ALPHA = -999.0*PI/180.
        RETURN
```

```
      END IF
      ALPHA = ATAN2(UY,UX)
      IF (ALPHA .LT. 0.0) ALPHA = ALPHA + 2.0*PI
C     PRINT*, ALPHA* 180./PI
      ALPHA = PI/2. - ALPHA
      IF (ALPHA .LT. 0.0) ALPHA = 2*PI + ALPHA
*
*  NOW ADD 360-YBRNG  DEGREES BECAUSE THE Y AXIS IS AT YBRNG DEGREES
C  TRUE.
C23456789012345678901234567890123456789012345678901234567890123456789012
*
      ALPHA = ALPHA - (360.-YBRNG)*PI/180.
      IF (ALPHA .LT. 0.0) ALPHA = ALPHA + 2.0*PI
      RETURN
      END
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRCFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      REAL KB,KBC
C
C  THIS SUBROUTINE CONTROLS THE CALCUATION OF THE BOTTOM FRICTION
C  FACTOR FOR VARIOUS WAVE AND CURRENT CONDITIONS.  ALTHOUGH THERE
C  IS NO NET SEDIMENT TRANSPORT IN THE ABSENCE OF A CURRENT, BED
C  MOBILITY AND BEDFORM GENERATION MUST STILL BE CONSIDERED.
C
C  INPUT VARIABLES:
C
C         UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C         CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH)
C         Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (CM)
C         WDIR = WAVE DIRECTION (AZIMUTH)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         KBC = APPARENT BOTTOM ROUGHNESS (CM)
C         FCW= BOTTOM FRICTION FACTOR
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)
C                  NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED
C                  OUTSIDE THE WAVE BOUNDARY LAYER.
C
C  INTERMEDIATE VARIABLES:
C
C         FBAD = BOTTOM FRICTION FACTOR INCLUDING FORM DRAG
```

```
C          UBAD = CURRENT SPEED NEGLECTING FORM DRAG (CM/SEC)
C          PHIBAD = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS, WITHIN
C                   WAVE B.L. AND NEGLECTING FORM DRAG (RADIANS)
C          RATIO = UA/UB;  DETERMINES VALIDITY OF EQUATION OF MOTION
C                  USED BY GRANT AND MADSEN (1979)
C
C
C  WAVES AND CURRENT CASE (CHECK FOR VALIDITY OF METHOD)
C
        PHI100=AMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
     @  360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
        IF (KB .EQ. 0.0) THEN
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBC,FCW,UA,PHIB,U100)
        ELSE
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FBAD,UA,PHIB,U100)
          CALL CHECK(U100,UA,UB,PHIB,FBAD)
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBCBAD,FCW,UBAD,PHIBAD,
     @    UBD100)
        ENDIF
        RATIO=UA/UB
        IF (RATIO .GT. 1.0) PRINT 15
C       IF (RATIO .GT. 1.0) WRITE(9,15)
  15    FORMAT( ' ***WARNING*** ',/,' UA/UB > 1.0',5X,'GRANT AND',
     @ ' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
C
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FCW,UA,PHIB,U100)
      REAL K,KB,KBC,L
      EXTERNAL FUN1,FUN2
      COMMON /FUNCTS/U,GY
C
C  THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND
C  CURRENT CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1979).  THIS
C  METHOD IS NOT VALID FOR UA/UB > 1.0 (APPROXIMATELY) DUE TO THE REL-
C  ATIVE IMPORTANCE OF THE CONVECTIVE ACCELERATION TERMS IN THE EQUATION
C  OF MOTION.
C
C  INPUT VARIABLES:
C
C          UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C          PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                   ABOVE SEABED (RADIANS)  (NB:  PHI100 = PHIZ)
C          UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C          AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C          PER = WAVE PERIOD (SEC)
C          KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C          FCW = BOTTOM FRICTION FACTOR FOR THE COMBINED CASE
```

```
C          UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C          U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C          PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                 WAVE BOUNDARY LAYER (RADIANS)
C
C   INTERMEDIATE VARIABLES:
C
C          PHIC = CALCULATED ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
C                 AT 1 M. ABOVE SEABED (RADIANS) - SHOULD CONVERGE TO
C                 PHI100.
C          UC = CALCULATED CURRENT VELOCITY AT 1 M. ABOVE SEABED (CM/SEC)
C          A2 = INITIAL ESTIMATE OF WAVE BOUNDARY LAYER THICKNESS, AFTER
C               SMITH (1977) (CM)
C          ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2
C          KBC = APPARENT BOTTOM ROUGHNESS (CM)
C          K = FACTOR USED IN COMPUTATION OF BOTTOM SHEAR STRESS
C          A = FACTOR RELATING MEAN SHEAR STRESS COMPONENT IN WAVE
C              DIRECTION TO RHO*UB**2*FRW/2
C          B = FACTOR RELATING MEAN SHEAR STRESS COMPONENT NORMAL TO WAVE
C              DIRECTION TO RHO*UB**2*FCW/2
C          V2 = FACTOR RELATING MAGNITUDE OF MEAN SHEAR STRESS TO
C               RHO*UB**2*FCW/2
C          L = WAVE BOUNDARY LAYER LENGTH SCALE (CM)
C          U = RATIO OF CURRENT TO WAVE VELOCITIES IN WAVE DIRECTION
C          V = RATIO OF CURRENT TO WAVE VELOCITIES NORMAL TO WAVE
C               DIRECTION
C          IT = ITERATION COUNTER
C          UA0,UC0,UA1,UDIF,DIF ARE VARIABLES USED TO ESTIMATE A NEW
C          VALUE FOR UA
C          PHIB0,PHIC0,PHIB1,PHIDIF,DIF ARE VARIABLES USED TO ESTIMATE A
C          NEW VALUE FOR PHIB
C
C   INITIALIZE ITERATION PARAMETERS
C
      UA0=0.0
      UC0=0.0
      UDIF=UZ/4.
      PHIB0=0.0
      PHIC0=0.0
      PHIDIF=PHI100/4.
      BEST=2.0
      IT=1
C
C   INITIAL ESTIMATE OF FCW (JONSSON,1966), A2 (SMITH, 1977), UA AND PHIB
C
      PI=2.*ASIN(1.)
      FCW1=EXP(5.213*(KB/AB)**0.194-5.977)
      FCW=AMIN1(FCW1,0.28)
      A2=0.4*AB*SQRT(FCW/2.)
      UA=UZ*ALOG(30.*A2/KB)/ALOG(30.*Z/KB)
      PHIB=PHI100
C
C   ITERATION LOOP:  FIRST, DETERMINE MAGNITUDE AND DIRECTION OF MEAN
C   SHEAR STRESS FOR ESTIMATED UA AND PHIB.
```

```
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
 100  ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      U=UA*COS(PHIB)/UB
      GY=UA*SIN(PHIB)/UB
C
      A=2.*DCADRE(FUN1,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
C     IF (IER .GT. 0) WRITE(9,5) IER
   5  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN1')
      B=2.*DCADRE(FUN2,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
C     IF (IER .GT. 0) WRITE(9,15) IER
  15  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN2')
C
      V2=SQRT(A*A+B*B)/(2.*PI)
      PHIC=ATAN2(B,A)
C
C  THE EQUATION FOR THE BOTTOM FRICTION FACTOR IS TRANSCENDENTAL AND
C  THUS MUST BE SOLVED ITERATIVELY.  THREE ITERATIONS WERE FOUND
C  SUFFICIENT TO OBTAIN A REASONABLE VALUE (MARTEC, 1983).
C  NOTE:  MMKELO IS AN IMSL SUBROUTINE TO COMPUTE KELVIN FUNCTIONS OF
C  ORDER ZERO.  THE IMSL LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS
C  PROGRAM.
C
      DO 30 I=1,3
      L=0.4*AB*SQRT(FCW*ALPHA/2.)
      ZETA0=KB/(30.*L)
      CALL MMKELO(2.*SQRT(ZETA0),DUMMY1,DUMMY2,XKER,XKEI,IER)
      IF (IER .GT. 0) PRINT 25,IER
  25  FORMAT(///,' ***MMKELO ERROR*** ',I3)
      K=1./(2.*SQRT(ZETA0)*SQRT(XKER**2+XKEI**2))
      C=V2/(2.*ALPHA**0.25)
      FCW=ABS(0.097*K*SQRT(KB/AB)/(SQRT(ALPHA**1.5/4.-(C*SIN(PHI100))
     @**2)-C*COS(PHI100)))**(4./3.)
  30  CONTINUE
C
C  CALCULATE APPARENT BOTTOM ROUGHNESS AND RESULTING CURRENT VELOCITY
C  AT HEIGHT Z (CM) ABOVE SEABED
C
      KBC=KB*(24.*(AB/KB)*SQRT(ALPHA*FCW/2.))**(1.-SQRT(V2/ALPHA))
      UC=UB*SQRT(V2*FCW/2.)*ALOG(30.*Z/KBC)/0.4
C
C  CHECK CONVERGENCE OF UC TO UZ AND PHIC TO PHI100.  THE ERROR LIMIT
C  HAS BEEN SET TO 0.01 (OR 1.0 PERCENT).
C
      IF (PHI100 .NE. 0.0) THEN
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(1.0-PHIC/PHI100))
      ELSE
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(PHIC-PHI100))
      ENDIF
      IF (ERR .LT. BEST) THEN
        BEST=ERR
        IF (BEST .LT. 0.01) GO TO 999
        BFCW=FCW
```

```
        BUA=UA
        BPHIB=PHIB
      ELSE IF (IT .EQ. 50) THEN
        FCW=BFCW
        UA=BUA
        PHIB=BPHIB
        PRINT 35,UZ,PHI100,UB,PER,KB,BEST
C       WRITE(9,35) UZ,PHI100,UB,PER,KB,BEST
  35    FORMAT(///,' ***WARNING*** ',/,' FOR UZ=',F8.2,', PHI100=',
     @  F7.4,', UB=',F8.2,', PER=',F6.2,/,' AND KB=',F7.3,', THE BEST',
     @  ' ESTIMATE AFTER 50 ITERATIONS HAS',/,' AN ERROR OF',F5.2)
        GO TO 999
      ENDIF
C
C  INCREMENT ITERATION COUNTER AND MAKE NEW ESTIMATE OF UA AND PHIB.
C
      IT=IT+1
      UA1=UA
      DIF=(UZ-UC)*(UA-UA0)/(UC-UC0)
      IF (DIF .LT. -UA) DIF=UA*UA/DIF
      DIF=SIGN(AMIN1(ABS(DIF),ABS(UDIF)),DIF)
      UDIF=DIF*2.
      UA=UA+DIF
      UA0=UA1
      UC0=UC
C
      IF (PHIC .NE. 0.0) THEN
        PHIB1=PHIB
        IF (PHIC .NE. PHIC0) THEN
          DIF=(PHI100-PHIC)*(PHIB-PHIB0)/(PHIC-PHIC0)
          DIF=SIGN(AMIN1(ABS(DIF),ABS(PHIDIF)),DIF)
          PHIDIF=DIF*2.
          PHIB=PHIB+DIF
        ELSE
          PHIB=PHI100
        ENDIF
        PHIB0=PHIB1
        PHIC0=PHIC
      ELSE
        PHIB=0.
      ENDIF
C
C  REPEAT ITERATION; RETURN TO MAIN PROGRAM WHEN ERROR LIMIT OR
C  ITERATION COUNT IS SATISFIED.
C
      GO TO 100
 999  DELTAW=2.*L
      IF (DELTAW .GT. Z) THEN
        PRINT 55
C       WRITE(9,55)
  55    FORMAT(' ***WARNING***',/,' DELTAW > Z',5X,'GRANT AND',
     @' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
      ENDIF
      IF (DELTAW .GT. 100) THEN
```

```
        U100=UB*V2*SQRT(FCW/(2.*ALPHA))*ALOG(3000./KB)/0.4
      ELSE
        U100=UB*SQRT(V2*FCW/2.)*ALOG(3000./KBC)/0.4
      ENDIF
      RETURN
      END
C************************************************************************
C************************************************************************
      FUNCTION FUN1(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN1=GX*SQRT(GX**2+GY**2)
      RETURN
      END
C************************************************************************
C************************************************************************
      FUNCTION FUN2(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN2=GY*SQRT(GX**2+GY**2)
      RETURN
      END
C************************************************************************
C************************************************************************
C************************************************************************
C************************************************************************
      SUBROUTINE CHECK(U100,UA,UB,PHIB,FBAD)
C
C  THIS SUBROUTINE CHECKS TO SEE IF THE TOTAL BOTTOM STRESS (INCLUDING
C  FORM DRAG), CALCULATED USING GRANT AND MADSEN'S METHOD, IS AT LEAST
C  AS LARGE AS THAT CALCULATED USING STERNBERG'S METHOD.  IF NOT, THE
C  VELOCITY UA DEFAULTS TO A NEW VALUE SUCH THAT THE TWO STRESSES ARE
C  EQUAL.
C
      ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      FSC=6.0E-03
      RATIO=FBAD*ALPHA*UB**2/(FSC*U100**2)
      IF (RATIO .LT. 1.0) THEN
        ALPHA=ALPHA/RATIO
        UA=(SQRT(COS(PHIB)**2+(ALPHA-1.0))-COS(PHIB))*UB
      ENDIF
      RETURN
      END
C************************************************************************
C************************************************************************
      SUBROUTINE THRESH(UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
C
C  THIS SUBROUTINE CALCULATES THE THRESHOLD FLUID VELOCITY FOR SEDIMENT
C  TRANSPORT FOR BOTH BEDLOAD AND SUSPENDED LOAD.  THE CRITICAL STRESSES
C  ARE FROM MARTEC (1982).  THE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS
C  BASED ON THE WORK OF MILLER ET AL. (1977); THE CRITICAL STRESS FOR
C  SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966), WHERE THE
C  PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971).
C
```

```
C  INPUT VARIABLES:
C
C          UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C          PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                 WAVE BOUNDARY LAYER (RADIANS)
C          UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C          FCW = BOTTOM FRICTION FACTOR
C          GD = SEDIMENT GRAIN SIZE (CM)
C          RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C          RHOW = FLUID DENSITY (GRAMS/CM**3)
C
C  OUTPUT VARIABLES:
C
C          VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C                TRANSPORT (CM/SEC)
C          VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C                LOAD TRANSPORT (CM/SEC)
C
C  INTERMEDIATE VARIABLES:
C
C          ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2.
C          DRHO = SEDIMENT DENSITY - FLUID DENSITY (GRAMS/CM**3)
C          VISC = DYNAMIC VISCOSITY OF THE FLUID (GRAMS/CM*SEC)
C          G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C          RE = GRAIN REYNOLDS NUMBER
C          FALL = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS
C                 ET AL. (1971) (CM/SEC)
C          TCB = CRITICAL BOTTOM STRESS FOR INITIATION OF BEDLOAD
C                TRANSPORT (DYNES/CM**2)
C          TCS = CRITICAL BOTTOM STRESS FOR INITIATION OF SUSPENDED LOAD
C                TRANSPORT (DYNES/CM**2)
C
C  INITIALIZE CONSTANTS
C
      G= 981.
      VISC=13.E-3
      DRHO=RHOS-RHOW
C
C  CALCULATE THRESHOLD VELOCITY FOR BEDLOAD TRANSPORT, VCB
C
      IF (UB .EQ. 0.0) THEN
        RE=GD*UA*SQRT(FCW/2.)*RHOW/VISC
      ELSE
        ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
        TAUB=RHOW/2.*FCW*ALPHA*UB**2
        RE=GD*SQRT(TAUB*RHOW)/VISC
      ENDIF
      IF (RE .EQ. 0.0) THEN
        TCB=9.99E99
      ELSE
        TCB=0.04*DRHO*G*GD
        IF (RE .LT. 10.0) TCB=TCB*2.4/RE**0.33
      ENDIF
      VCB=SQRT(2.*TCB/(RHOW*FCW))
```

```
C
C  CALCULATE THRESHOLD VELOCITY FOR SUSPENDED LOAD TRANSPORT, VCS
C
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TCS=0.64*RHOW*FALL**2
      VCS=SQRT(2.*TCS/(RHOW*FCW))
C
      RETURN
       END
***************************************************************
*************************************************************
C************************************************************************
C************************************************************************
C************************************************************************
      SUBROUTINE TRNSPO(UA,VCB,GD,FCW,RHOS,RHOW,SED1,SED2,SED3,SED4)
C
C  THIS SUBROUTINE CALCULATES THE INSTANTANEOUS SEDIMENT TRANSPORT
C  BY A CHOICE OF METHODS.
C
C  INPUT VARIABLES:
C
C          UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C          VCB = CRITICAL VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT
C                 (FROM ROUTINE THRESH)
C          GD = SEDIMENT GRAIN SIZE (CM)
C          FCW = BOTTOM FRICTION FACTOR
C          RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C          RHOW = FLUID DENSITY (GRAMS/CM**3)
C          IOPT = OPTION NUMBER FOR TYPE OF TRANSPORT
C
C  OUTPUT VARIABLES:
C
C          SED = TIME-AVERAGED NET SEDIMENT TRANSPORT AS VOLUME OF SEDIMENT
C        SOLIDS TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME (CM**2/SEC)
C                NOTE:  THIS IS NOT THE SAME AS VOLUME OF SOIL TRANSPORTED!
C
      G=981.
      VISC=13.E-3
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TAUCRB=RHOW*FCW/2.*VCB**2
       TAU0=RHOW*FCW/2.*UA*UA
      SED=0.0
C
C
C
C
C
C THE VARIOUS OPTIONS FOR TRANSPORT FORMULAE ARE:
C        '    1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
```

```
C        '   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
C        '   3 - MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION',/,
C        '   4 - YALIN (1963) BEDLOAD EQUATION',/,
C      WRITE(9,*)UA,TAU0,RHOW,GD,DGAMMA
            SED1=0.05*UA**2*SQRT(TAU0**3*RHOW)/(GD*DGAMMA**2)
            SED2=40.0*FALL*GD*(TAU0/(DGAMMA*GD))**3
            BETA=1.73E-05
            IF (GD .LE. 0.031) BETA=7.22E-05
            SED3=BETA/RHOS*(UA-VCB)**3
            USTAR=SQRT(FCW/2.)*UA
            S=(UA/VCB)**2-1.0
            A=2.45*(RHOW/RHOS)**0.4*SQRT(TAUCRB/(G*DRHO*GD))
            SED4=0.635*GD*USTAR*S*(1.0-ALOG(1.0+A*S)/(A*S))
             RETURN
C
C
C************************************************************************
C************************************************************************
      END
```

```
       PROGRAM RSSDBIK
       DIMENSION X(1100),Y(1100),VELI(1100,2),ICRS(500),IMAX(500),
     &        RMAX(500),DIST(500),SUM(4,8),SM(4,8)
     &      ,SED(4)
       CHARACTER*12 HEAD,HEAD1
       CHARACTER*1 A
       DATA PI /3.1415926535897/
       DATA YBRNG /328./
       DATA Z /50./
       DATA GD /0.030/
C      DATA KB /0.030/
       DATA ICRS,IMAX /1000*0/
       DATA RMAX,DIST /1000*0./
       DATA X,Y,VELI /4400*0./
       DATA RHOS /2.65/
       DATA RHOW /1.025/
       OPEN (5,FILE='T621MD1')
       OPEN (7,FILE='T621AV')
       OPEN (8,FILE='TAPE8')
       OPEN (9,FILE='TAPE9')
       REWIND 5
       REWIND 7
       REWIND 8
       REWIND 9
        ROUGH=200.*GD/100.
         KB=ROUGH*100.
        FFF=0.
        VVV=0.
        KKK=0
          DO 4 JJJ=1,8
          DO 4 III=1,4
            SUM(III,JJJ)=0.
4        CONTINUE
5        CONTINUE
C  READ HEADERS AND AVERAGE CURRENT DATA
C
       READ(5,10,END=999)HEAD,N
         PRINT  10, HEAD,N
10     FORMAT(A12,I4)
       READ(7,11)HEAD1,UX,UY,RMSX,RMSY
11     FORMAT(A12,4F7.2)
       IF(HEAD.NE.HEAD1)PRINT*,'ERROR  HEADERS NOT THE SAME'
C
C
C READ INSTANTANEOUS VELOCITY DATA (SAMPLED AT 1 SECOND INTERVALS)
C
C
         N1=N
        K=-4
       DO 100 I=1,N
         K=K+4
          READ(5,12)A,(X(J),Y(J),J=1+K,4+K)
12       FORMAT(A1,8F7.2)
```

```
          IF(A.NE.'R')THEN
             K=K-4
             N1=N1-1
          ENDIF
100      CONTINUE
          N=N1
C
C GET AVERAGE CURRENT DIRECTION
C
        CALL BEARNG (UX,UY,YBRNG,ANS)
          CDIR=ANS*180./PI
          UZ=SQRT(UX*UX+UY*UY)
C
C
C  INITIALIZE UA TO UZ
C
          UA=UZ
          WRITE(8,22)HEAD,N,UZ,CDIR
22        FORMAT(A12,I4,2F7.2)
C
C
C  CALCULATE THE INSTANTANEOUS VELOCITY DIRECTION
C
          OLDSN=1.0
          J=1
         ICRS(1)=0
           JKJK=0
          ANGMAX=CDIR
          RMAX(1)=-999.
        CALL BEARNG ( X(1)-UX,Y(1)-UY,YBRNG,VELI(1,2) )
         VELI(1,2)=VELI(1,2)*180./PI
          BETA=ABS(CDIR-VELI(1,2))
           IF(BETA.GT.180.)BETA=360.-BETA
           IF(BETA.GT.90.)OLDSN=-1.0
        VELI(1,1)=OLDSN*SQRT((X(1)-UX)*(X(1)-UX)+(Y(1)-UY)*(Y(1)-UY))
                 WRITE(8,23)VELI(1,1),VELI(1,2)
          SIGN=OLDSN
        DO 300 I=2,N*4
C         SIGN=1.0
        CALL BEARNG ( X(I)-UX,Y(I)-UY,YBRNG,VELI(I,2) )
         VELI(I,2)=VELI(I,2)*180./PI
C
C
          BETA=ABS(ANGMAX-VELI(I,2))
           IF(BETA.GT.180.)BETA=360.-BETA
           IF(BETA.GT.90. .AND. I.GT.ICRS(J)+2)THEN
                   SIGN=-1.0*OLDSN
           ENDIF
        VELI(I,1)=SIGN*SQRT((X(I)-UX)*(X(I)-UX)+(Y(I)-UY)*(Y(I)-UY))
C
C  FLAG A ZERO CROSSING
C
           IF(SIGN.NE.OLDSN)THEN
              IF(JKJK.EQ.0)THEN
```

```
                JKJK=JKJK+1
                J=0
             ENDIF
            J=J+1
            ICRS(J)=I
C
C
C    FIND THE MAX OR MIN VALUE BETWEEN CURRENT AND PREVIOUS ZERO CROSS
C
C
              IF(J.EQ.1)THEN
                  ANGMAX=ANGMAX+180.
                  IF(ANGMAX.GT.360.)ANGMAX=ANGMAX-360.
                    GOTO 299
              ENDIF
            RMAX(J)=0.
            DIST(J)=0.
          DO 250 JJ=ICRS(J-1),ICRS(J)-1
            IF(ABS(VELI(JJ,1)).GT.RMAX(J))THEN
                      RMAX(J)=ABS(VELI(JJ,1))
                      IMAX(J)=JJ
            ENDIF
            DIST(J)=DIST(J)+OLDSN*VELI(JJ,1)
250       CONTINUE
             RMAX(J)=VELI(IMAX(J),1)
             ANGMAX=VELI(IMAX(J),2)+180.
                  IF(ANGMAX.GT.360.)ANGMAX=ANGMAX-360.
          ENDIF
299        OLDSN=SIGN
C
C
C
C
          IF(I.EQ.ICRS(J))THEN
               WRITE(8,24)VELI(I,1),VELI(I,2),J,ICRS(J),IMAX(J),RMAX(J)
     &   ,DIST(J)
24             FORMAT(2F7.2,3I5,2F7.2)
          ELSE
               WRITE(8,23)VELI(I,1),VELI(I,2)
23             FORMAT(2F7.2)
          ENDIF
300     CONTINUE
C
C
*****************************************************************
C
C   GET NUMBER OF WAVES
C
C
       JMAX=J
        JSTART=2
        IF(RMAX(2).GT.0.)JSTART=3
        ICNT=1
        RBUF=JMAX/2.
```

```
        IF((RBUF-IFIX(RBUF)).GT.0.001)ICNT=0
        IF(JSTART.EQ.2.AND.ICNT.EQ.0)K1=1
        IF(JSTART.EQ.2.AND.ICNT.EQ.1)K1=2
        IF(JSTART.EQ.3.AND.ICNT.EQ.0)K1=3
        IF(JSTART.EQ.3.AND.ICNT.EQ.1)K1=4
         GOTO(40,41,42,43) K1
40       KMAX=(JMAX-1)/2
41       KMAX=(JMAX-2)/2
         JMAX=JMAX-1
42       KMAX=(JMAX-3)/2
         JMAX=JMAX-1
43       KMAX=(JMAX-2)/2
         WRITE(9,22)HEAD,KMAX,UZ,CDIR
         K=0
C
C
C CALCULATE AVERAGE FRICTION FACTOR AND CRITICAL VELOCITY FOR THE BURST
C
C
          FCWAV=0.
          VCBAV=0.
        DO 500 J=JSTART,JMAX,2
          K=K+1
C         PRINT*,'NOW ON THE ',K,' TH  WAVE'
          IT1=ICRS(J-1)
          IT2=ICRS(J+1)
          PER=FLOAT(IT2-IT1)
          AB=(DIST(J)+DIST(J+1))/2.
          UB=(RMAX(J+1)-RMAX(J))/2.
C
C CALCULATE AVERAGE WAVE DIRECTION FROM THE DIRECTIONS THAT THE
C MAX POSITIVE VELOCITIES OF THE WAVE HAVE
C    NOTE: AN ERROR OF A FEW DEGREES MAY OCURR DUE TO THE FACT
C        THAT THE SAMPLING RATE WAS ONLY 1 HZ
C
        WDIR = VELI(IMAX(J+1),2)
         PHIB=ABS(CDIR-WDIR)
              IF(PHIB.GT.360.)PHIB=PHIB-360.
         PHIB=PHIB*PI/180.
C
C
C     CALL FRCFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
C    @PHI100,U100)
      CALL BIJKER (32.,GD,PER,UZ,UB,AB,ROUGH,FCW)
C
C       A22=AB/ROUGH
C       IF(A22.LE.1.57)THEN
C             FCW=0.28
C         ELSE
C             R1=ROUGH/AB
C             FCW=EXP(5.213*(R1**0.194)-5.977)
C       ENDIF
      CALL THRESH(UA,PHIB,UB,FCW,GD,RHOS,RHOW,VCB,VCS)
         FCWAV=FCWAV+FCW
```

```
         VCBAV=VCBAV+VCB
500     CONTINUE
            FCW=FCWAV/K
            VCB=VCBAV/K
            WRITE(9,88)HEAD,K,FCW,VCB
            PRINT   88, HEAD,K,FCW,VCB
88       FORMAT( A12,I5,F8.6,F8.1)
        PRINT*,'KMAX= ',KMAX,'K= ',K
C
C
C   CALCULATE SEDIMENT TRANSPORT ASSUMING THAT EACH INSTANTANEOUS
C   VELOCITY SAMPLED CAN BE TREATED AS PURE CURRENT WITH
C   THE FRICTION FACTOR CALCULATED FROM THE CASE OF COMBINED WAVES
C   AND CURRENTS (GRANT AND MADSEN, 1979).
C
C
          DO 44 JJJ=1,8
          DO 44 III=1,4
            SM(III,JJJ)=0.
44        CONTINUE
       DO 450 KK=1,N*4
         UA=SQRT(X(KK)*X(KK)+Y(KK)*Y(KK))
        IF(UA.GT.VCB)THEN
             CALL TRNSPO(UA,VCB,GD,FCW,RHOS,RHOW,
     &                     SED(1),SED(2),SED(3),SED(4))
       CALL BEARNG ( X(KK),Y(KK),YBRNG,RANG)
        RANG=RANG*180./PI
          DO 45 III=1,4
              IF(RANG.GT.337.5.OR.RANG.LE.22.5)THEN
                   JJJ=1
                ELSE
                   JJJ=IFIX((RANG+22.5)/45.)+1
              ENDIF
C         PRINT*,RANG,JJJ
           SM(III,JJJ)=SM(III,JJJ)+SED(III)
45       CONTINUE
        ENDIF
450     CONTINUE
C           WRITE(9,25)K,ICRS(J-1),PER,UB,AB,FCW,IFLAG
25              FORMAT(2I5,3F7.2,F7.6,I2)
C
C  REPEAT FOR THE NEXT BURST OF DATA AND SUM SEDIMENT TRANSPORT
C
          DO 47 JJJ=1,8
          DO 46 III=1,4
            SUM(III,JJJ)=SUM(III,JJJ)+SM(III,JJJ)
46       CONTINUE
C
          WRITE(9,*)(SM(K,JJJ),K=1,4)
C
47        CONTINUE
         KKK=KKK+1
         FFF=FFF+FCW
         VVV=VVV+VCB
```

```
       GOTO 5
C
C
998    PRINT*,' READ ERROR ON FILE 5'
              WRITE(9,35)
35      FORMAT(' THE 8 GRAND TOTALS FOR THE 4 OPTIONS ARE:')
36      FORMAT(4F8.1)
        SED1X=0.
        SED2X=0.
        SED3X=0.
        SED4X=0.
        SED1Y=0.
        SED2Y=0.
        SED3Y=0.
        SED4Y=0.
               DO 49 JJJ=1,8
                     WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
        SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
49             CONTINUE
         SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
         CALL BEARNG(SED1X,SED1Y,0.,ANS1)
         ANS1=ANS1*180./PI
         SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
         CALL BEARNG(SED2X,SED2Y,0.,ANS2)
         ANS2=ANS2*180./PI
         SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
         CALL BEARNG(SED3X,SED3Y,0.,ANS3)
         ANS3=ANS3*180./PI
         SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
         CALL BEARNG(SED4X,SED4Y,0.,ANS4)
         ANS4=ANS4*180./PI
           WRITE(9,37)SEDD1*0.01,ANS1
           WRITE(9,37)SEDD2*0.01,ANS2
           WRITE(9,37)SEDD3*0.01,ANS3
           WRITE(9,37)SEDD4*0.01,ANS4
37        FORMAT(2F8.1)
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
         WRITE(9,*)FFF,VVV
       S T O P
999    PRINT*,' END OF DATA IN T621MD1'
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
              WRITE(9,35)
        SED1X=0.
```

```
         SED2X=0.
         SED3X=0.
         SED4X=0.
         SED1Y=0.
         SED2Y=0.
         SED3Y=0.
         SED4Y=0.
                DO 50 JJJ=1,8
                      WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
         SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
         SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
         SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
         SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
         SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
         SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
         SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
         SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
50              CONTINUE
          SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
          CALL BEARNG(SED1X,SED1Y,0.,ANS1)
          ANS1=ANS1*180./PI
          SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
          CALL BEARNG(SED2X,SED2Y,0.,ANS2)
          ANS2=ANS2*180./PI
          SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
          CALL BEARNG(SED3X,SED3Y,0.,ANS3)
          ANS3=ANS3*180./PI
          SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
          CALL BEARNG(SED4X,SED4Y,0.,ANS4)
          ANS4=ANS4*180./PI
            WRITE(9,37)SEDD1*0.01,ANS1
            WRITE(9,37)SEDD2*0.01,ANS2
            WRITE(9,37)SEDD3*0.01,ANS3
            WRITE(9,37)SEDD4*0.01,ANS4
        REWIND 5
        REWIND 7
        REWIND 8
        REWIND 9
        CLOSE (5)
        CLOSE (7)
        CLOSE (8)
        CLOSE (9)
        S T O P
        END
C************************************************************************
      SUBROUTINE BIJKER (D,W1,T,Z,UB,A0,ROUGH,F1)
**
C
C  INPUT VARIABLES
C
C  D=WATER DEPTH (M)
C  W1=GRAIN SIZE (CM)
C  W=GRAIN SIZE (M)
         W=W1/100.
```

```
C  Z=NEAR BED MEAN CURRENT (M/S)
C  T=WAVE PERIOD
C  UB=MAX WAVE INDUCED ORBITAL VELOCITY (M/S)
C  A0=WAVE ORBITAL DIAMETER (M)
C
C  OUTPUT VARIABLES
C
C  F=FRICTION FACTOR
C    C = THE CHEZY COEFFICIENT OF ROUGHNESS USED IN THE EVALUATION
C      OF BED STRESS IN THE BIJKER METHOD
C  TC=PURE CURRENT STRESS (N/M**2)
C  E=MODIFIED FRICTION FACTOR
C  TCW=COMBINED WAVE/CURRENT STRESS (N/M**2)
C  USCW=COMBINED FLOW FRICTION VELOCITY (M/S)
C  USCW1=COMBINED EQUIVALENT U(100) (M/S)
C
C
C ROUGHNESS=100 TO 300*W FROM MUIR-WOOD & FLEMING (1981)
C                              (IE AFTER MOGRIDGE-KAMPHUIS (1972)
C
C        ROUGH=100.*W
        C=18.0*(LOG(12.0*D/ROUGH)/2.3)
C
C  F IS THE WAVE INDUCED FRICTION FACTOR AFTER JONSSON
C
        A2=A0/ROUGH
        IF(A2.LE.1.57)THEN
              F=0.28
          ELSE
              R1=ROUGH/A0
              F=EXP(5.213*(R1**0.194)-5.977)
        ENDIF
C       E=C*(SQRT(F/19.62))
        E=0.0575*C
        X=E*(UB/Z)**2.0
C       TC=0.003*1026.0*Z**2.0
          TC=1026.0*9.81*Z*Z/(C*C)
        TCW=(1.+0.5*X)*TC
        USCW=SQRT(TCW/1026.)
        USCW1=(TCW/(0.003*1026.))**0.5
        UCW=USCW/0.4
        UCW=UCW*(LOG(30./W))
        F1=2.0*TCW/(1026.0*(Z+UB)**2.0)
        RETURN
        END
```

```
       PROGRAM CRUDE
       DIMENSION X(1100),Y(1100),VELI(1100,2),ICRS(500),IMAX(500),
     &         RMAX(500),DIST(500),SUM(4,8),SM(4,8)
     &       ,SED(4)
       CHARACTER*12 HEAD,HEAD1
       CHARACTER*1 A
       DATA PI /3.1415926535897/
       DATA YBRNG /328./
       DATA Z /50./
       DATA GD /0.030/
C      DATA KB /0.030/
       DATA ICRS,IMAX /1000*0/
       DATA RMAX,DIST /1000*0./
       DATA X,Y,VELI /4400*0./
       DATA RHOS /2.65/
       DATA RHOW /1.025/
       OPEN (5,FILE='T621MD1')
       OPEN (7,FILE='T621AV')
       OPEN (8,FILE='TAPE8')
       OPEN (9,FILE='TAPE9')
       REWIND 5
       REWIND 7
       REWIND 8
       REWIND 9
        FFF=0.
        KMAX=0
        VVV=0.
        KKK=0
          DO 4 JJJ=1,8
          DO 4 III=1,4
            SUM(III,JJJ)=0.
4        CONTINUE
5        CONTINUE
C  READ HEADERS AND AVERAGE CURRENT DATA
C
       READ(5,10,END=999)HEAD,N
C        PRINT  10, HEAD,N
10     FORMAT(A12,I4)
       READ(7,11)HEAD1,UX,UY,RMSX,RMSY
11     FORMAT(A12,4F7.2)
       IF(HEAD.NE.HEAD1)PRINT*,'ERROR  HEADERS NOT THE SAME'
C
C
C READ INSTANTANEOUS VELOCITY DATA (SAMPLED AT 1 SECOND INTERVALS)
C
C
         N1=N
        K=-4
       DO 100 I=1,N
         K=K+4
          READ(5,12)A,(X(J),Y(J),J=1+K,4+K)
12       FORMAT(A1,8F7.2)
         IF(A.NE.'R')THEN
```

```
            K=K-4
            N1=N1-1
         ENDIF
100     CONTINUE
         N=N1
C
C GET AVERAGE CURRENT DIRECTION
C
       CALL BEARNG (UX,UY,YBRNG,ANS)
         CDIR=ANS*180./PI
         UZ=SQRT(UX*UX+UY*UY)
C
C
C  INITIALIZE UA TO UZ
         UA=UZ
         WRITE(9,22)HEAD,KMAX,UZ,CDIR
22       FORMAT(A12,I4,2F7.2)
         K=0
C
C
C CALCULATE AVERAGE FRICTION FACTOR AND CRITICAL VELOCITY FOR THE BURST
C
C
          FCWAV=0.
          VCBAV=0.
            FCW=0.05
            VCB=8.6
            WRITE(9,88)HEAD,K,FCW,VCB
C           PRINT   88, HEAD,K,FCW,VCB
88       FORMAT( A12,I5,F8.6,F8.1)
C       PRINT*,'KMAX= ',KMAX,'K= ',K
C
C
C   CALCULATE SEDIMENT TRANSPORT ASSUMING THAT EACH INSTANTANEOUS
C   VELOCITY SAMPLED CAN BE TREATED AS PURE CURRENT WITH
C   THE FRICTION FACTOR CALCULATED FROM THE CASE OF COMBINED WAVES
C   AND CURRENTS (GRANT AND MADSEN, 1979).
C
C
          DO 44 JJJ=1,8
          DO 44 III=1,4
            SM(III,JJJ)=0.
44        CONTINUE
       DO 450 KK=1,N*4
         UA=SQRT(X(KK)*X(KK)+Y(KK)*Y(KK))
        IF(UA.GT.VCB)THEN
             CALL TRNSPO(UA,VCB,GD,FCW,RHOS,RHOW,
     &                  SED(1),SED(2),SED(3),SED(4))
       CALL BEARNG ( X(KK),Y(KK),YBRNG,RANG)
        RANG=RANG*180./PI
          DO 45 III=1,4
              IF(RANG.GT.337.5.OR.RANG.LE.22.5)THEN
                   JJJ=1
                ELSE
```

```
                   JJJ=IFIX((RANG+22.5)/45.)+1
              ENDIF
C         PRINT*,RANG,JJJ
           SM(III,JJJ)=SM(III,JJJ)+SED(III)
45       CONTINUE
        ENDIF
450     CONTINUE
C           WRITE(9,25)K,ICRS(J-1),PER,UB,AB,FCW,IFLAG
25              FORMAT(2I5,3F7.2,F7.6,I2)
C
C  REPEAT FOR THE NEXT BURST OF DATA AND SUM SEDIMENT TRANSPORT
C
          DO 47 JJJ=1,8
          DO 46 III=1,4
            SUM(III,JJJ)=SUM(III,JJJ)+SM(III,JJJ)
46       CONTINUE
C
          WRITE(9,*)(SM(K,JJJ),K=1,4)
C
47        CONTINUE
         KKK=KKK+1
         FFF=FFF+FCW
         VVV=VVV+VCB
       GOTO 5
C
C
998    PRINT*,' READ ERROR ON FILE 5'
              WRITE(9,35)
35      FORMAT(' THE 8 GRAND TOTALS FOR THE 4 OPTIONS ARE:')
36      FORMAT(4F8.1)
        SED1X=0.
        SED2X=0.
        SED3X=0.
        SED4X=0.
        SED1Y=0.
        SED2Y=0.
        SED3Y=0.
        SED4Y=0.
               DO 49 JJJ=1,8
                     WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
        SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
49             CONTINUE
         SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
         CALL BEARNG(SED1X,SED1Y,0.,ANS1)
         ANS1=ANS1*180./PI
         SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
         CALL BEARNG(SED2X,SED2Y,0.,ANS2)
```

```
         ANS2=ANS2*180./PI
         SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
         CALL BEARNG(SED3X,SED3Y,0.,ANS3)
         ANS3=ANS3*180./PI
         SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
         CALL BEARNG(SED4X,SED4Y,0.,ANS4)
         ANS4=ANS4*180./PI
           WRITE(9,37)SEDD1*0.01,ANS1
           WRITE(9,37)SEDD2*0.01,ANS2
           WRITE(9,37)SEDD3*0.01,ANS3
           WRITE(9,37)SEDD4*0.01,ANS4
37        FORMAT(2F8.1)
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
         WRITE(9,*)FFF,VVV
       S T O P
999    PRINT*,' END OF DATA IN T621MD1'
         FFF=FFF/KKK
         VVV=VVV/KKK
         PRINT*,'FCWAV= ',FFF,'VCBAV= ',VVV
              WRITE(9,35)
        SED1X=0.
        SED2X=0.
        SED3X=0.
        SED4X=0.
        SED1Y=0.
        SED2Y=0.
        SED3Y=0.
        SED4Y=0.
               DO 50 JJJ=1,8
                     WRITE(9,36)(SUM(K,JJJ)*0.01,K=1,4)
        SED1X=SED1X+SUM(1,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED1Y=SED1Y+SUM(1,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED2X=SED2X+SUM(2,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED2Y=SED2Y+SUM(2,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED3X=SED3X+SUM(3,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED3Y=SED3Y+SUM(3,JJJ)*COS(PI*(JJJ-1)*45./180.)
        SED4X=SED4X+SUM(4,JJJ)*SIN(PI*(JJJ-1)*45./180.)
        SED4Y=SED4Y+SUM(4,JJJ)*COS(PI*(JJJ-1)*45./180.)
50             CONTINUE
         SEDD1=SQRT(SED1X*SED1X+SED1Y*SED1Y)
         CALL BEARNG(SED1X,SED1Y,0.,ANS1)
         ANS1=ANS1*180./PI
         SEDD2=SQRT(SED2X*SED2X+SED2Y*SED2Y)
         CALL BEARNG(SED2X,SED2Y,0.,ANS2)
         ANS2=ANS2*180./PI
         SEDD3=SQRT(SED3X*SED3X+SED3Y*SED3Y)
         CALL BEARNG(SED3X,SED3Y,0.,ANS3)
         ANS3=ANS3*180./PI
         SEDD4=SQRT(SED4X*SED4X+SED4Y*SED4Y)
         CALL BEARNG(SED4X,SED4Y,0.,ANS4)
         ANS4=ANS4*180./PI
           WRITE(9,37)SEDD1*0.01,ANS1
```

```
          WRITE(9,37)SEDD2*0.01,ANS2
          WRITE(9,37)SEDD3*0.01,ANS3
          WRITE(9,37)SEDD4*0.01,ANS4
      REWIND 5
      REWIND 7
      REWIND 8
      REWIND 9
      CLOSE (5)
      CLOSE (7)
      CLOSE (8)
      CLOSE (9)
      S T O P
      END
```

APPENDIX D

PROGRAM LISTINGS FOR SED1DF

APPENDIX D - PROGRAM LISTING FOR SED1DF

A program listing for SED1DF is presented after page D.2. The parameter OPT that was used in SED1DE was changed to IOPT in SED1DF. This minor change is transparent to the user and is not specifically identified in the listing. However, the insertion of new lines or the modification of existing lines is indicated by the code "AW" in the identification field of these statements.

The major modifications made to incorporate the Ackers-White option into the model are contained in subroutines TRANSPO and THRESH and are described in Section 3.2. Other minor revisions include the following:

1) The statements used to read the input value of IOPT were moved to subroutine READIN.
2) The water depth D is converted from meters to centimeters for the current only case in subroutine OSCILL.
3) The bed roughness KB is set equal to the grain diameter GD when an input value of KB = 0 is specified for the waves and current case in subroutine FRICFAC.
4) The computed sediment transport rate is identified as that of the Ackers-White option when printed out in the subroutine OUTOUT.
5) The call statements, subroutine statements, type statements, and specification statements were revised to include the additional parameters used in the Ackers-White option.
6) Addtional comment statements were inserted to indicate the available options and define the additional parameters used in the Ackers-White option.

The code "INTVR" identifies the write statements used to print intermediate variables in the Ackers-White formula for manual checking (see Appendices E.1 and E.2). The code "DEBUG" was added to the write statements used to compare SED1DE and SED1DF for the case when execution of SED1DE was terminated due to an infinite value in subroutine TRANSPO (see Appendix E.3). These INTVR and DEBUG statements can be reactivated at any time (by replacing the "C" in column 1 with a blank) or can be deleted, without affecting the program execution.

```
      PROGRAM SED1DF(INPUT,OUTPUT,TAPE7)
      REAL KB,KBC
C
C  THIS PROGRAM CALCULATES SEDIMENT TRANSPORT UNDER A VARIETY OF WAVE
C  AND CURRENT CONDITIONS FOR HORIZONTAL BEDS ONLY.  A CHOICE OF
C  TRANSPORT FORMULAE IS AVAILABLE TO THE USER, HOWEVER, IT MUST BE
C  REMEMBERED THAT NONE OF THESE FORMULAE HAVE BEEN CALIBRATED FOR
C  COMBINED WAVE AND CURRENT CONDITIONS.
C  THE AVAILABLE OPTIONS ARE:                                           AW
C  IOPT = 1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION                AW
C          2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION                   AW
C          3 - BAGNOLD (1963) TOTAL LOAD EQUATION                       AW
C          4 - YALIN (1963) BEDLOAD EQUATION                            AW
C          5 - ACKERS-WHITE TOTAL LOAD EQUATION                         AW
C
C  THIS VERSION ALLOWS THE VELOCITY TO BE INPUT AT ANY LEVEL WITHIN
C  THE BOTTOM LOGARITHMIC LAYER AND CONSIDERS THE AUTOSUSPENSION
C  PHENOMENON.  AS WELL, THIS VERSION HAS BEEN CHANGED SO THAT THE
C  VELOCITY USED IN BOTTOM STRESS CALCULATIONS, UA, DEFAULTS TO A
C  VALUE CORRESPONDING TO THE PURE CURRENT CASE ONLY WHEN THE TOTAL
C  BOTTOM STRESS IS LESS THAN THAT FOR A CURRENT ALONE.
C
C
      PRINT 5
      WRITE(7,5)
  5   FORMAT(/,T11,'SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL',
     @/,'                      SHELF CONDITIONS',//,
C    @T11,'VERSION ACKERS AND WHITE (MAR. 85)          MARTEC LTD.',///,AW
     @T11,'THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED',/,
     @T11,'AND THEIR LIMITATIONS',//)
   1  CALL READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW,         AW
     .            QI,IOPT)                                              AW
      IF (QI .EQ. 1.0) GO TO 10
      CALL INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW)
C
C  CHANGE GRAIN SIZE FROM MM TO CM
C
      GD=GD*0.10
C
C  DO CALCULATIONS AND PRINT RESULTS
C
      CALL OSCIL(HT,PER,D,UB,AB,WL)
      CALL FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      CALL THRESH(U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,WL,D,VCB,VCS,DGR,    AW
     .            AGR,RGR,IOPT)                                         AW
      CALL TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,TS1,
     @TS2,TB1S,TB2S)
      CALL TRANSPO(D,UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,RHOW,    AW
     @VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR,IOPT,
     @TB1S,TB2S,DGR,AGR,RGR)                                            AW
      CALL OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,TB2,
     @PERBED,PERSUSP,SED,SEDDIR,IOPT)
```

```
      CALL BEDFORM(U100,UB,GD,KBC)
C
C  GIVE USER THE OPTION OF DOING ANOTHER RUN
C
   10 PRINT 15
   15 FORMAT(///,' ENTER 1 TO DO ANOTHER RUN, 0 TO STOP')
      READ*, IND
      IF (IND .EQ. 1) GO TO 1
      STOP
      END
      SUBROUTINE READIN(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,        AW
     .                 RHOW,QI,IOPT)                                    AW
      REAL KB
C
C  THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING
C  SED1D.
C
C  OUTPUT VARIABLES:
C
C         IRUN = RUN NUMBER
C         D = WATER DEPTH (M)
C         UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C         Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (CM)
C         CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH, DEG.)
C         HT = WAVE HEIGHT (M)
C         PER = WAVE PERIOD (SEC)
C         WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C         GD = SEDIMENT GRAIN SIZE (MM)
C         KB = BOTTOM ROUGHNESS (CM)
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY ( GRAMS/CM**3)
C         QI = QUIT INDEX
C         IOPT = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA         AW
C
      PRINT 15
   15 FORMAT('IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE',/,
     @T11,'TO ANY OF THE FOLLOWING QUESTIONS')
C
C  INITIALIZE QUIT INDEX TO 0
C
      QI=0.0
C
C  ENTER DATA
C
      PRINT 25
   25 FORMAT(//,' ENTER RUN NUMBER (1 - 9999)')
      READ*, IRUN
C
      PRINT 35
   35 FORMAT(//,' ENTER WATER DEPTH (M)')
      READ*, D
      IF ( D .EQ. -99.) GO TO 998
C
```

```
      PRINT 45
  45  FORMAT(//,' ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE SEABED',
     @/,' (CM/SEC, DEGREES TRUE, CM)')
      READ*, UZ,CDIR,Z
      IF (UZ .EQ. -99. .OR. CDIR .EQ. -99. .OR. Z .EQ. -99.) GO TO 998
C
      PRINT 55
  55  FORMAT(//,' ENTER WAVE HEIGHT, PERIOD AND DIRECTION',/,
     @' (METRES,SECONDS,DEGREES TRUE)')
      READ*, HT,PER,WDIR
      IF (HT .EQ. -99. .OR. PER .EQ. -99. .OR. WDIR .EQ. -99.) GO TO 998
C
      PRINT 65
  65  FORMAT(//,' ENTER SEDIMENT GRAIN SIZE AND SEDIMENT DENSITY',/,
     @' (MM, GRAMS/CUBIC CM)')
      READ*, GD,RHOS
      IF (GD .EQ. -99. .OR. RHOS .EQ. -99.) GO TO 998
C
      PRINT 75
  75  FORMAT(//,' ENTER BOTTOM ROUGHNESS HEIGHT (CM)')
      READ*, KB
      IF (KB .EQ. -99.) GO TO 998
C
      PRINT 85
  85  FORMAT(//,' ENTER FLUID DENSITY (GRAMS/CUBIC CM)')
      READ*, RHOW
      IF (RHOW .EQ. -99) GO TO 998
C
  90    PRINT 95                                                        AW
  95    FORMAT (//,' CHOOSE BETWEEN:',/,                                AW
     @  '   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,          AW
     @  '   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,              AW
     @  '   3 - BAGNOLD (1963) TOTAL LOAD EQUATION',/,                  AW
     @  '   4 - YALIN (1963) BEDLOAD EQUATION',/,                       AW
     @  '   5 - ACKERS-WHITE TOTAL LOAD EQUATION',/,                    AW
     @  ' ENTER 1,2,3,4 OR 5')                                          AW
        READ*,IOPT                                                      AW
      IF (IOPT .LT. 1 .OR. IOPT .GT. 5) GO TO 90                        AW
        IF (IOPT .EQ. -99) GO TO 998
C
      GO TO 999
 998  QI=1.0
 999  RETURN
      END
      SUBROUTINE INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,KB,RHOS,RHOW)
      REAL KB
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE INPUT PARAMETERS FROM
C  SUBROUTINE READIN
C
C     PRINT 15, IRUN
      WRITE(7,15) IRUN
  15  FORMAT(////,T21,'RUN NUMBER ',I4,////,T4,'INPUT DATA:',//)
```

```
C
C     PRINT 25, D,UZ,CDIR,Z
      WRITE(7,25) D,UZ,CDIR,Z
  25  FORMAT(T11,'WATER DEPTH =',F7.2,' M',/,T11,'CURRENT SPEED =',F7.2,
     @' CM/SEC',/,T11,'CURRENT DIRECTION =',F7.2,' DEGREES TRUE',/,
     @T11,'HEIGHT ABOVE BED =',F7.2,' CM')
C
C     PRINT 35, HT,PER,WDIR
      WRITE(7,35) HT,PER,WDIR
  35  FORMAT(T11,'WAVE HEIGHT =',F7.2,' M',/,T11,'WAVE PERIOD =',F6.2,
     @' SEC',/,T11,'WAVE DIRECTION =',F7.2,' DEGREES TRUE',/)
C
C     PRINT 45, GD,RHOS
      WRITE(7,45) GD,RHOS
  45  FORMAT(T11,'SEDIMENT GRAIN SIZE =',F6.2,' MM',/,T11,
     @'SEDIMENT DENSITY =',F5.2,' GRAMS/CUBIC CM',/)
C
C     PRINT 55, KB,RHOW
      WRITE(7,55) KB,RHOW
  55  FORMAT(T11,'BOTTOM ROUGHNESS HEIGHT =',F7.2,' CM',//,T11,
     @'FLUID DENSITY =',F5.2,' GRAMS/CUBIC CM',///)
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE OSCIL(HT,PER,D,UB,AB,WL)
      REAL KD,KOO,K
C
C  THIS SUBROUTINE CALCULATES WAVE-INDUCED BOTTOM PARTICLE VELOCITY
C  AND DISPLACEMENT USING LINEAR WAVE THEORY.  A CHECK IS ALSO MADE
C  FOR WAVE BREAKING.
C
C  INPUT VARIABLES:
C         HT = WAVE HEIGHT (M)
C         PER = WAVE PERIOD (SEC)
C         D = WATER DEPTH (M)
C
C  OUTPUT VARIABLES:
C
C         UB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE VELOCITY (CM/SEC)
C         AB = MAX. WAVE-INDUCED BOTTOM HORIZ. PARTICLE DISPLACEMENT(CM)
C         WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C
C  INTERMEDIATE VARIABLES:
C
C         G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C         C = CONVERSION FACTOR TO CGS UNITS
C         W = WAVE ANGULAR FREQUENCY (RAD/SEC)
C         K = WAVE NUMBER (RAD/CM)
C         KD = K*D
```

```
C         HB = BREAKING WAVE HT. FOR GIVEN WAVE PERIOD, WATER DEPTH (CM)
C
      IF (HT .EQ. 0.0) THEN
        UB=0.0
        AB=0.0
        WL=0.0
C       CHANGE DEPTH TO CM FOR ACKERS-WHITE FORMULA FOR CURRENTS ALONE  AW
        D=100.*D                                                        AW
C
C  CALCULATE WAVELENGTH BY NEWTON-RAPHSON SOLUTION OF LWT DISPERSION
C  EQUATION.
C
      ELSE
      G=981.
      PI=2.*ASIN(1.)
      C=100.
      HT=HT*C
      D=D*C
      W=2.*PI/PER
      KD0=W**2*D/G
      KD=KD0
  20  CONTINUE
      DKD=(1./TANH(KD)-KD/KD0)/(1./KD0+1./SINH(KD)**2)
      KD=KD+DKD
      IF (ABS(DKD) .GE. 1.0E-4) GO TO 20
      WL=2.*PI*D/KD
C
C  NEXT CHECK FOR BREAKING WAVES USING THE MICHE (1944) CRITERION
C
      HB=0.142*WL*TANH(KD)
      IF (HT .GE. HB) THEN
      PRINT 25
      WRITE(7,25)
  25  FORMAT(///,' ***WARNING***',/,' THIS CASE CORRESPONDS TO BREAKING',
     @' WAVE CONDITIONS WHERE',/,' LINEAR WAVE THEORY IS NOT VALID')
      ENDIF
C
C  CALCULATE WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND DISPLACEMENT
C
      UB=PI*HT/(PER*SINH(KD))
      AB=UB/W
      ENDIF
C
      RETURN
      END

C************************************************************************
C************************************************************************
C************************************************************************
C************************************************************************
      SUBROUTINE FRICFAC(UZ,CDIR,Z,WDIR,UB,AB,PER,GD,KB,KBC,FCW,UA,PHIB,
     @PHI100,U100)
      REAL KB,KBC
```

```
C
C  THIS SUBROUTINE CONTROLS THE CALCUATION OF THE BOTTOM FRICTION
C  FACTOR FOR VARIOUS WAVE AND CURRENT CONDITIONS.  ALTHOUGH THERE
C  IS NO NET SEDIMENT TRANSPORT IN THE ABSENCE OF A CURRENT, BED
C  MOBILITY AND BEDFORM GENERATION MUST STILL BE CONSIDERED.
C
C  INPUT VARIABLES:
C
C        UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C        CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH)
C        Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (CM)
C        WDIR = WAVE DIRECTION (AZIMUTH)
C        UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C        AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C        PER = WAVE PERIOD (SEC)
C        GD = SEDIMENT GRAIN SIZE (CM)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C        KBC = APPARENT BOTTOM ROUGHNESS (CM)
C        FCW= BOTTOM FRICTION FACTOR
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C        PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C               WAVE BOUNDARY LAYER (RADIANS)
C        PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                 ABOVE SEABED (RADIANS)
C                 NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED
C                 OUTSIDE THE WAVE BOUNDARY LAYER.
C
C  INTERMEDIATE VARIABLES:
C
C        FBAD = BOTTOM FRICTION FACTOR INCLUDING FORM DRAG
C        UBAD = CURRENT SPEED NEGLECTING FORM DRAG (CM/SEC)
C        PHIBAD = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS, WITHIN
C                 WAVE B.L. AND NEGLECTING FORM DRAG (RADIANS)
C        RATIO = UA/UB;  DETERMINES VALIDITY OF EQUATION OF MOTION
C                USED BY GRANT AND MADSEN (1979)
C
C  PURE CURRENT CASE
C
      IF (UB .EQ. 0.0) THEN
        CALL FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
        PHIB=0.0
        PHI100=0.0
        KBC=KB
C
C  WAVES AND CURRENT CASE (CHECK FOR VALIDITY OF METHOD)
C
      ELSE IF (UZ .NE. 0.0) THEN
        PHI100=AMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
     @  360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
```

```
        IF (KB .EQ. 0.0) THEN
C ----------------------------------------------------------------      AW
C THIS STATEMENT WAS ADDED TO PREVENT THE EXECUTION FROM TERMINATING    AW
C WHEN USING BAGNOLD'S FORMULA WITH AN INPUT VALUE OF KB = 0 FOR        AW
C THE WAVES AND CURRENT CASE                                            AW
          KB = GD                                                       AW
C ----------------------------------------------------------------      AW
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBC,FCW,UA,PHIB,U100)
        ELSE
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FBAD,UA,PHIB,U100)
          CALL CHECK(U100,UA,UB,PHIB,FBAD)
          CALL FRIC2(UZ,Z,PHI100,UB,AB,PER,GD,KBCBAD,FCW,UBAD,PHIBAD,
     @    UBAD100)
        ENDIF
        RATIO=UA/UB
*       IF (RATIO .GT. 1.0) PRINT 15
        IF (RATIO .GT. 1.0) WRITE(7,15)
  15    FORMAT(///,' ***WARNING*** ',/,' UA/UB > 1.0',5X,'GRANT AND',
     @ ' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
C
C  PURE WAVES CASE
C
      ELSE
        CALL FRIC3(UB,AB,PER,GD,KB,FCW)
        UA=0.0
        U100=0.0
        PHIB=0.0
        PHI100=0.0
        KBC=KB
      ENDIF
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC1(UZ,Z,GD,KB,FCW,UA,U100)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  CURRENT CASE.  A CONSTANT FRICTION FACTOR IS ASSUMED, BASED ON THE
C  WORK OF STERNBERG (1971).  THIS IS MOST LIKELY INADEQUATE AND WILL
C  BE REVISED IN THE FUTURE.
C
C  INPUT VARIABLES:
C
C        UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C        GD = SEDIMENT GRAIN SIZE (CM)
C        KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
```

```
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         FCW = BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C
      FCW=6.0E-3
      IF(KB .EQ. 0.0) KB=GD
      U100=UZ*ALOG(3000./KB)/ALOG(30.*Z/KB)
      UA=U100
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************

      SUBROUTINE FRIC2(UZ,Z,PHI100,UB,AB,PER,KB,KBC,FCW,UA,PHIB,U100)
      REAL K,KB,KBC,L
      EXTERNAL FUN1,FUN2
      COMMON /FUNCTS/U,GY
C
C  THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND
C  CURRENT CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1979).  THIS
C  METHOD IS NOT VALID FOR UA/UB > 1.0 (APPROXIMATELY) DUE TO THE REL-
C  ATIVE IMPORTANCE OF THE CONVECTIVE ACCELERATION TERMS IN THE EQUATION
C  OF MOTION.
C
C  INPUT VARIABLES:
C
C         UZ = CURRENT SPEED AT HEIGHT Z (CM) ABOVE SEABED (CM/SEC)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)  (NB:  PHI100 = PHIZ)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         FCW = BOTTOM FRICTION FACTOR FOR THE COMBINED CASE
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C
C  INTERMEDIATE VARIABLES:
C
C         PHIC = CALCULATED ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
C                AT 1 M. ABOVE SEABED (RADIANS) - SHOULD CONVERGE TO
C                PHI100.
C         UC = CALCULATED CURRENT VELOCITY AT 1 M. ABOVE SEABED (CM/SEC)
C         A2 = INITIAL ESTIMATE OF WAVE BOUNDARY LAYER THICKNESS, AFTER
C              SMITH (1977) (CM)
C         ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2
```

```
C         KBC = APPARENT BOTTOM ROUGHNESS (CM)
C         K = FACTOR USED IN COMPUTATION OF BOTTOM SHEAR STRESS
C         A = FACTOR RELATING MEAN SHEAR STRESS COMPONENT IN WAVE
C             DIRECTION TO RHO*UB**2*FRW/2
C         B = FACTOR RELATING MEAN SHEAR STRESS COMPONENT NORMAL TO WAVE
C             DIRECTION TO RHO*UB**2*FCW/2
C         V2 = FACTOR RELATING MAGNITUDE OF MEAN SHEAR STRESS TO
C              RHO*UB**2*FCW/2
C         L = WAVE BOUNDARY LAYER LENGTH SCALE (CM)
C         U = RATIO OF CURRENT TO WAVE VELOCITIES IN WAVE DIRECTION
C         V = RATIO OF CURRENT TO WAVE VELOCITIES NORMAL TO WAVE
C              DIRECTION
C         IT = ITERATION COUNTER
C         UA0,UC0,UA1,UDIF,DIF ARE VARIABLES USED TO ESTIMATE A NEW
C         VALUE FOR UA
C         PHIB0,PHIC0,PHIB1,PHIDIF,DIF ARE VARIABLES USED TO ESTIMATE A
C         NEW VALUE FOR PHIB
C
C  INITIALIZE ITERATION PARAMETERS
C
      UA0=0.0
      UC0=0.0
      UDIF=UZ/4.
      PHIB0=0.0
      PHIC0=0.0
      PHIDIF=PHI100/4.
      BEST=2.0
      IT=1
C
C  INITIAL ESTIMATE OF FCW (JONSSON,1966), A2 (SMITH, 1977), UA AND PHIB
C
      PI=2.*ASIN(1.)
      FCW1=EXP(5.213*(KB/AB)**0.194-5.977)
      FCW=AMIN1(FCW1,0.28)
      A2=0.4*AB*SQRT(FCW/2.)
      UA=UZ*ALOG(30.*A2/KB)/ALOG(30.*Z/KB)
      PHIB=PHI100
C
C  ITERATION LOOP:  FIRST, DETERMINE MAGNITUDE AND DIRECTION OF MEAN
C  SHEAR STRESS FOR ESTIMATED UA AND PHIB.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
 100  ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      U=UA*COS(PHIB)/UB
      GY=UA*SIN(PHIB)/UB
C
      A=2.*DCADRE(FUN1,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) WRITE(7,5) IER
   5  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN1')
      B=2.*DCADRE(FUN2,-PI/2.,PI/2.,0.0,0.01,ERROR,IER)
      IF (IER .GT. 0) WRITE(7,15) IER
  15  FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION FUN2')
```

```
C
      V2=SQRT(A*A+B*B)/(2.*PI)
      PHIC=ATAN2(B,A)
C
C  THE EQUATION FOR THE BOTTOM FRICTION FACTOR IS TRANSCENDENTAL AND
C  THUS MUST BE SOLVED ITERATIVELY.  THREE ITERATIONS WERE FOUND
C  SUFFICIENT TO OBTAIN A REASONABLE VALUE (MARTEC, 1983).
C  NOTE:  MMKEL0 IS AN IMSL SUBROUTINE TO COMPUTE KELVIN FUNCTIONS OF
C  ORDER ZERO.  THE IMSL LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS
C  PROGRAM.
C
      DO 30 I=1,3
      L=0.4*AB*SQRT(FCW*ALPHA/2.)
      ZETA0=KB/(30.*L)
      CALL MMKEL0(2.*SQRT(ZETA0),DUMMY1,DUMMY2,XKER,XKEI,IER)
      IF (IER .GT. 0) WRITE(7,25) IER
  25  FORMAT(///,' ***MMKEL0 ERROR*** ',I3)
      K=1./(2.*SQRT(ZETA0)*SQRT(XKER**2+XKEI**2))
      C=V2/(2.*ALPHA**0.25)
      FCW=ABS(0.097*K*SQRT(KB/AB)/(SQRT(ALPHA**1.5/4.-(C*SIN(PHI100))
     @**2)-C*COS(PHI100)))**(4./3.)
  30  CONTINUE
C
C  CALCULATE APPARENT BOTTOM ROUGHNESS AND RESULTING CURRENT VELOCITY
C  AT HEIGHT Z (CM) ABOVE SEABED
C
      KBC=KB*(24.*(AB/KB)*SQRT(ALPHA*FCW/2.))**(1.-SQRT(V2/ALPHA))
      UC=UB*SQRT(V2*FCW/2.)*ALOG(30.*Z/KBC)/0.4
C
C  CHECK CONVERGENCE OF UC TO UZ AND PHIC TO PHI100.  THE ERROR LIMIT
C  HAS BEEN SET TO 0.01 (OR 1.0 PERCENT).
C
      IF (PHI100 .NE. 0.0) THEN
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(1.0-PHIC/PHI100))
      ELSE
        ERR=AMAX1(ABS(1.0-UC/UZ),ABS(PHIC-PHI100))
      ENDIF
      IF (ERR .LT. BEST) THEN
        BEST=ERR
        IF (BEST .LT. 0.01) GO TO 999
        BFCW=FCW
        BUA=UA
        BPHIB=PHIB
      ELSE IF (IT .EQ. 50) THEN
        FCW=BFCW
        UA=BUA
        PHIB=BPHIB
        PRINT 35,UZ,PHI100,UB,PER,KB,BEST
        WRITE(7,35) UZ,PHI100,UB,PER,KB,BEST
  35    FORMAT(///,' ***WARNING*** ',/,' FOR UZ=',F8.2,', PHI100=',
     @  F7.4,', UB=',F8.2,', PER=',F6.2,/,' AND KB=',F7.3,', THE BEST',
     @  ' ESTIMATE AFTER 50 ITERATIONS HAS',/,' AN ERROR OF',F5.2)
        GO TO 999
```

```
      ENDIF
C
C  INCREMENT ITERATION COUNTER AND MAKE NEW ESTIMATE OF UA AND PHIB.
C
      IT=IT+1
      UA1=UA
      DIF=(UZ-UC)*(UA-UA0)/(UC-UC0)
      IF (DIF .LT. -UA) DIF=UA*UA/DIF
      DIF=SIGN(AMIN1(ABS(DIF),ABS(UDIF)),DIF)
      UDIF=DIF*2.
      UA=UA+DIF
      UA0=UA1
      UC0=UC
C
      IF (PHIC .NE. 0.0) THEN
        PHIB1=PHIB
        IF (PHIC .NE. PHIC0) THEN
          DIF=(PHI100-PHIC)*(PHIB-PHIB0)/(PHIC-PHIC0)
          DIF=SIGN(AMIN1(ABS(DIF),ABS(PHIDIF)),DIF)
          PHIDIF=DIF*2.
          PHIB=PHIB+DIF
        ELSE
          PHIB=PHI100
        ENDIF
        PHIB0=PHIB1
        PHIC0=PHIC
      ELSE
        PHIB=0.
      ENDIF
C
C  REPEAT ITERATION; RETURN TO MAIN PROGRAM WHEN ERROR LIMIT OR
C  ITERATION COUNT IS SATISFIED.
C
      GO TO 100
 999  DELTAW=2.*L
      IF (DELTAW .GT. Z) THEN
        PRINT 55
        WRITE(7,55)
  55    FORMAT(///,' ***WARNING***',/,' DELTAW > Z',5X,'GRANT AND',
     @' MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
      ENDIF
      IF (DELTAW .GT. 100) THEN
        U100=UB*V2*SQRT(FCW/(2.*ALPHA))*ALOG(3000./KB)/0.4
      ELSE
        U100=UB*SQRT(V2*FCW/2.)*ALOG(3000./KBC)/0.4
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN1(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
```

```
      FUN1=GX*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION FUN2(X)
      COMMON /FUNCTS/U,GY
      GX=SIN(X)+U
      FUN2=GY*SQRT(GX**2+GY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE FRIC3(UB,AB,PER,GD,KB,FCW)
      REAL KB
C
C  THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE
C  WAVE CONDITION USING THE METHOD OF JONSSON (1966) AS MODIFIED BY
C  NIELSEN (197?).  THE BOTTOM ROUGHNESS IS TAKEN AS THE GRAIN DIAMETER
C  AS IN GRANT AND MADSEN (1976).
C
C  INPUT VARIABLES:
C
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (CM)
C         PER = WAVE PERIOD (SEC)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C
C  OUTPUT VARIABLES:
C
C         FCW = BOTTOM FRICTION FACTOR FOR THE PURE WAVE CASE
C
      FCW=AMIN1(EXP(5.213*(GD/AB)**0.194-5.977),0.28)
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE THRESH(U100,UA,PHIB,UB,FCW,GD,RHOS,RHOW,WL,D,VCB,VCS,  AW
     .                  DGR,AGR,RGR,IOPT)                               AW
C
C  THIS SUBROUTINE CALCULATES THE THRESHOLD FLUID VELOCITY FOR SEDIMENT
C  TRANSPORT FOR BOTH BEDLOAD AND SUSPENDED LOAD.  THE CRITICAL STRESSES
C  ARE FROM MARTEC (1982).  THE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS
C  BASED ON THE WORK OF MILLER ET AL. (1977); THE CRITICAL STRESS FOR
C  SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966), WHERE THE
C  PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971).
C
C  INPUT VARIABLES:
```

```
C
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         FCW = BOTTOM FRICTION FACTOR
C         GD = SEDIMENT GRAIN SIZE (CM)
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY (GRAMS/CM**3)
C         WL = WAVELENGTH (CM)                                          AW
C         D = WATER DEPTH (CM)                                          AW
C         IOPT = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA         AW
C
C  OUTPUT VARIABLES:
C
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C         AGR = CRITICAL MOBILITY NUMBER USED IN ACKERS-WHITE FORMULA   AW
C         DGR = DIMENSIONLESS GRAIN DIAMETER IN ACKERS-WHITE FORMULA    AW
C         RGR = REYNOLDS NUMBER AS A FUNCTION OF DGR, AS GIVEN BY       AW
C               SWART AND FLEMING (1980)                                AW
C
C  INTERMEDIATE VARIABLES:
C
C         ALPHA = FACTOR RELATING MAX. SHEAR STRESS TO RHO*UB**2*FCW/2.
C         DRHO = SEDIMENT DENSITY - FLUID DENSITY (GRAMS/CM**3)
C         VISC = DYNAMIC VISCOSITY OF THE FLUID (GRAMS/CM*SEC)
C         G = ACCELERATION DUE TO GRAVITY (CM/SEC**2)
C         RE = GRAIN REYNOLDS NUMBER
C         FALL = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS
C                ET AL. (1971) (CM/SEC)
C         TCB = CRITICAL BOTTOM STRESS FOR INITIATION OF BEDLOAD
C               TRANSPORT (DYNES/CM**2)
C         TCS = CRITICAL BOTTOM STRESS FOR INITIATION OF SUSPENDED LOAD
C               TRANSPORT (DYNES/CM**2)
C         DS = DIFFERENCE BETWEEN SPECIFIC GRAVITY OF SEDIMENT AND      AW
C              WATER                                                    AW
C         VISK = KINEMATIC VISCOSITY OF FLUID (CM**2/SEC)               AW
C
C  INITIALIZE CONSTANTS
C
      REAL N
      G= 981.
      VISC=13.E-3
      DRHO=RHOS-RHOW
C
C  CALCULATE THRESHOLD VELOCITY FOR BEDLOAD TRANSPORT, VCB
C
      IF (IOPT .NE. 5) THEN                                             AW
C     MODIFIED SHIELDS CURVE (MILLER ET AL., 1977)                      AW
        IF (UB .EQ. 0.0) THEN
```

```
          RE=GD*UA*SQRT(FCW/2.)*RHOW/VISC
        ELSE
          ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          TAUB=RHOW/2.*FCW*ALPHA*UB**2
          RE=GD*SQRT(TAUB*RHOW)/VISC
        ENDIF
        IF (RE .EQ. 0.0) THEN
          TCB=9.99E99
        ELSE
          TCB=0.04*DRHO*G*GD
          IF (RE .LT. 10.0) TCB=TCB*2.4/RE**0.33
        ENDIF
        VCB=SQRT(2.*TCB/(RHOW*FCW))
      ELSE IF (IOPT .EQ. 5) THEN                                        AW
C     ACKERS-WHITE CRITERIA                                             AW
        DS = DRHO/RHOW                                                  AW
        VISK = VISC/RHOW                                                AW
        DGR = GD*(G*DS/VISK**2)**(1./3.)                                AW
        IF (DGR .LE. 1.) THEN                                           AW
        PRINT 5                                                         AW
        STOP                                                            AW
   5    FORMAT ('FINE SEDIMENT - THEORY NOT APPLICABLE')                AW
        ENDIF                                                           AW
        IF (WL .LT. 2.*D) THEN                                          AW
C     CURRENTS ONLY (ACKERS AND WHITE,1973)                             AW
          IF (DGR .GT. 60.) THEN                                        AW
            AGR = 0.17                                                  AW
            GO TO 10                                                    AW
          ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN                 AW
            AGR = (0.23/SQRT(DGR)) + 0.14                               AW
            GO TO 10                                                    AW
          ENDIF                                                         AW
        ELSE                                                            AW
C     WAVES AND CURRENTS (SWART AND FLEMING,1980)                       AW
          RGR = 10.**(0.092*(ALOG10(DGR)**2)+1.158*ALOG10(DGR)-0.367)   AW
          AGR = RGR*(DGR)**(-1.5)                                       AW
          GO TO 10                                                      AW
        ENDIF                                                           AW
  10    CONTINUE                                                        AW
          TCB = RHOW*G*GD*DS*AGR**2                                     AW
                  [illegible]                                           AW
      IF (DGR.GT.60) THEN                                               AW
      N = 0.                                                            AW
      ELSE IF (DGR.GT.1. .AND. DGR.LE.60.) THEN                         AW
      N = 1.0 - 0.56*ALOG10(DGR)                                        AW
      ELSE                                                              AW
      PRINT 135                                                         AW
  135 FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')                 AW
      STOP                                                              AW
      ENDIF                                                             AW
      VST = AGR*SQRT(G*GD*DS)*                                          AW
     .      (SQRT(FCW/2.)*5.75*ALOG10(10.*D/GD))**(1.-N)                AW
      VCB = VST/SQRT(FCW/2.)                                            AW
```

```
C THE FOLLOWING WRITE STATEMENTS ARE USED TO PRINT OUT INTERMEDIATE     AW
C VARIABLES USED IN THE ACKERS-WHITE FORMULA FOR MANUAL CHECKING        AW
C     PRINT 45,DGR,N,AGR,VCB                                            AW
C     WRITE(7,45) DGR,N,AGR,VCB                                         AW
C  45 FORMAT (//' INTERMEDIATE VARIABLES FOR ACKERS-WHITE FORMULA:'/    AW
C    .        ' DGR = ',E10.3,T20,'N = ',E10.3,T40,'AGR = ',E10.3/      AW
C    .        ' VCB = ',E10.3)                                          AW
      ENDIF                                                             AW
C
C  CALCULATE THRESHOLD VELOCITY FOR SUSPENDED LOAD TRANSPORT, VCS
C
C FOR THE ACKERS-WHITE OPTION, A TOTAL LOAD EQUATION IS USED.  SET VCS  AW
C EQUAL TO VCB FOR THIS OPTION                                          AW
      IF (IOPT .EQ. 5) THEN                                             AW
      VCS = VCB                                                         AW
      ELSE                                                              AW
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TCS=0.64*RHOW*FALL**2
      VCS=SQRT(2.*TCS/(RHOW*FCW))
      ENDIF                                                             AW
C
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE CHECK(U100,UA,UB,PHIB,FBAD)
C
C  THIS SUBROUTINE CHECKS TO SEE IF THE TOTAL BOTTOM STRESS (INCLUDING
C  FORM DRAG), CALCULATED USING GRANT AND MADSEN'S METHOD, IS AT LEAST
C  AS LARGE AS THAT CALCULATED USING STERNBERG'S METHOD.  IF NOT, THE
C  VELOCITY UA DEFAULTS TO A NEW VALUE SUCH THAT THE TWO STRESSES ARE
C  EQUAL.
C
      ALPHA=1.+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
      FSC=6.0E-03
      RATIO=FBAD*ALPHA*UB**2/(FSC*U100**2)
      IF (RATIO .LT. 1.0) THEN
        ALPHA=ALPHA/RATIO
        UA=(SQRT(COS(PHIB)**2+(ALPHA-1.0))-COS(PHIB))*UB
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
C***********************************************************************
C***********************************************************************
      SUBROUTINE TIMING(UA,PHIB,UB,PER,VCB,VCS,PERBED,PERSUSP,TB1,TB2,
     @TS1,TS2,TB1S,TB2S)
C
C  THIS SUBROUTINE CALCULATES THE DURATION OF SEDIMENT TRANSPORT PHASES
```

```
C  (NO TRANSPORT, BEDLOAD TRANSPORT, SUSPENDED LOAD TRANSPORT) BY
C  CALCULATING WHEN THE RESPECTIVE CRITICAL VELOCITIES ARE EXCEEDED.
C
C  INPUT VARIABLES:
C
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C        PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C               WAVE BOUNDARY LAYER (RADIANS)
C        UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C        PER = WAVE PERIOD (SEC)
C        VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C              TRANSPORT (CM/SEC)
C        VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C              LOAD TRANSPORT (CM/SEC)
C
C  OUTPUT VARIABLES:
C
C        TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C              LOAD TRANSPORT CEASES (SEC)
C        TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C              TRANSPORT CEASES (SEC)
C        TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C              LOAD TRANSPORT RECOMMENCES (SEC)
C        TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C              TRANSPORT RECOMMENCES (SEC)
C        PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C        PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                  PHASE
C
C  INTERMEDIATE VARIABLES:
C
C        XS1 = COS(W*TS1), WHERE W IS THE WAVE ANGULAR FREQUENCY
C        XB1 = COS(W*TB1),           .                .
C        XS2 = COS(W*TS2),           .                .
C        XB2 = COS(W*TB2),           .                .
C        B = -B/2A, AS IN EQ'N. FOR ROOTS OF A QUADRATIC EQUATION
C        B24AC = (B**2-4*A*C)/(2*A)**2, AS IN QUADRATIC EQ'N. SOLUTION
C
C  FIRST, SET DEFAULT VALUES TO ZERO
C
      PI=2.*ASIN(1.)
      TB1=0.0                                                          AW
      TS1=0.0
      TS2=0.0
      TB2=0.0
      PERSUSP=0.0
      PERBED=0.0
      TB1S=0.0
      TB2S=0.0
      S=1.0E-10
C
C  CONSIDER PURE CURRENT CASE
C
```

```
      IF (UB .EQ. 0.0) THEN
        IF (UA .GE. VCS) PERSUSP=100.
        IF (UA .GE. VCB .AND. UA .LT. VCS) PERBED=100.
        RETURN
C
C  CONSIDER PURE WAVE CASE
C
      ELSE IF (UA .EQ. 0.0) THEN
          IF (VCS .LT. UB) THEN
            TS1=PER/(2.*PI)*ACOS(VCS/UB)
            TS2=PER/2.-TS1
            PERSUSP=400.*TS1/PER
          ENDIF
          IF (VCB .LT. VCS .AND. VCB .LT. UB) THEN
            TB1=PER/(2.*PI)*ACOS(VCB/UB)
            TB2=PER/2.-TB1
            PERBED=400.*(TB1-TS1)/PER
          ENDIF
C
        RETURN
C
C  CONSIDER COMBINATION OF WAVES AND A CURRENT.  FIRST CALCULATE TIMES
C  FOR SUSPENDED LOAD, THEN BEDLOAD (SEE FLOWCHART IN USER'S GUIDE)
C
      ELSE
        B24ACS=(VCS**2-(UA*SIN(PHIB))**2)/(UB**2)
        IF (B24ACS .LE. 0.0) THEN
          TS1=PER/2.
          PERSUSP=100.0
          PERBED=0.0
          RETURN
        ELSE
          B=-UA*COS(PHIB)/UB
          XS1=B+SQRT(B24ACS)
C
          IF (XS1 .GE. 1.0) THEN
            PERSUSP=0.0
            GO TO 50
          ELSE IF (XS1 .LE. -1.0) THEN
            TS1=PER/2.
            PERSUSP=100.0
            PERBED=0.0
            RETURN
          ELSE
            TS1=PER/(2.*PI)*ACOS(XS1)
          ENDIF
C
          XS2=B-SQRT(B24ACS)
C
          IF (XS2 .LE. -1.0) THEN
            PERSUSP=200.*TS1/PER
          ELSE
            TS2=PER/(2.*PI)*ACOS(XS2)
```

```
            PERSUSP=(2.*(TS1-TS2)+PER)/PER*100.
          ENDIF
C
        ENDIF
C
C  CALCULATE TIMES FOR BEDLOAD ONLY IF VCB < VCS
C
  50    IF (VCB .LT. VCS) THEN
        B24ACB=(VCB**2-(UA*SIN(PHIB))**2)/(UB**2)
        B24ACBS=(VCB**2*(S+1)-(UA*SIN(PHIB))**2)/(UB**2)
C
       IF (B24ACB .LE. 0.0) THEN
          TB1=PER/2.
          TB1S=PER/2.
          PERBED=100.-PERSUSP
          RETURN
        ELSE
          B=-UA*COS(PHIB)/UB
          XB1=B+SQRT(B24ACB)
          XB1S=B+SQRT(B24ACBS)
C
          IF (XB1 .GE. 1.0) THEN
            PERBED=0.0
            RETURN
          ELSE IF (XB1 .LE. -1.0) THEN
            TB1=PER/2.
            TB1S=PER/2.
            PERBED=100.-PERSUSP
            RETURN
          ELSE
          TB1=PER/(2.*PI)*ACOS(XB1)
          TB1S=PER/(2.*PI)*ACOS(XB1S)
          ENDIF
C
          XB2=B-SQRT(B24ACB)
          XB2S=B-SQRT(B24ACBS)
C
          IF (XB2 .LE. -1.0) THEN
            PERBED=200.*TB1/PER-PERSUSP
          ELSE
            TB2=PER/(2.*PI)*ACOS(XB2)
            TB2S=PER/(2.*PI)*ACOS(XB2S)
            PERBED=(2.*(TB1-TB2)+PER)/PER*100.-PERSUSP
          ENDIF
C
        ENDIF
        ENDIF
C
      ENDIF
      RETURN
      END
C***********************************************************************
C***********************************************************************
```

```
C**********************************************************************
C**********************************************************************
      SUBROUTINE TRANSPO(D,UA,PHIB,U100,PHI100,UB,PER,GD,KB,FCW,RHOS,   AW
     @RHOW,VCB,VCS,TB1,TB2,TS1,TS2,PERBED,PERSUSP,WDIR,CDIR,SED,SEDDIR, AW
     @IOPT,TB1S,TB2S,DGR,AGR,RGR)                                       AW
      REAL K,KB,L,M,N                                                   AW
      EXTERNAL F1,F2,F3,F4,F5,F6,F7,F8                                  AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                               AW
C
C  THIS SUBROUTINE CALCULATES THE TIME-AVERAGED NET SEDIMENT TRANSPORT
C  BY A CHOICE OF METHODS.  FOR THE PURE WAVE CASE THERE IS NO NET
C  TRANSPORT SINCE TRANSPORT DURING THE WAVE CREST IS EQUAL AND OPPOSITE
C  TO THAT DURING THE WAVE TROUGH (DUE TO THE USE OF LWT).  FOR THE PURE
C  CURRENT AND MIXED CONDITIONS, THE USER MAKES A CHOICE BETWEEN TRANS-
C  PORT FORMULAE, HOWEVER IF SUSPENDED LOAD TRANSPORT IS SIGNIFICANT IT
C  IS RECOMMENDED THAT A TOTAL LOAD FORMULA BE USED.
C
C  INPUT VARIABLES:
C
C         D = WATER DEPTH (CM)                                          AW
C         UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (CM/SEC)
C         PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C                WAVE BOUNDARY LAYER (RADIANS)
C         U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (CM/SEC)
C         PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M.
C                  ABOVE SEABED (RADIANS)
C         UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C         PER = WAVE PERIOD (SEC)
C         WL = WAVELENGTH FROM LWT DISPERSION EQUATION (CM)
C         GD = SEDIMENT GRAIN SIZE (CM)
C         KB = BOTTOM ROUGHNESS (CM)
C         FCW = BOTTOM FRICTION FACTOR
C         RHOS = SEDIMENT DENSITY (GRAMS/CM**3)
C         RHOW = FLUID DENSITY (GRAMS/CM**3)
C         VCB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD
C               TRANSPORT (CM/SEC)
C         VCS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED
C               LOAD TRANSPORT (CM/SEC)
C         TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT CEASES (SEC)
C         TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD
C               TRANSPORT RECOMMENCES (SEC)
C         TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT CEASES (SEC)
C         TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED
C               LOAD TRANSPORT RECOMMENCES (SEC)
C         PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C         PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT
C                   PHASE
C         WDIR = WAVE DIRECTION (AZIMUTH, DEGREES)
C         CDIR = CURRENT DIRECTION (AZIMUTH, DEGREES)
C         AGR = CRITICAL MOBILITY NUMBER IN ACKERS-WHITE FORMULA        AW
C         DGR = DIMENSIONLESS GRAIN DIAMETER IN ACKERS-WHITE FORMULA    AW
```

```
C         RGR = REYNOLDS NUMBER AS A FUNCTION OF DGR, AS GIVEN          AW
C         IOPT = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA         AW
C
C  OUTPUT VARIABLES:
C
C         SED = TIME-AVERAGED NET SEDIMENT TRANSPORT AS VOLUME OF SEDIMENT
C               TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME (CM**2/SEC)
C               NOTE:  THIS IS NOT THE SAME AS VOLUME OF SOIL TRANSPORTED!
C         SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH, DEGREES)
C
C  INTERMEDIATE VARIABLES:                                              AW
C                                                                       AW
C         C = COEFFICIENT IN ACKERS-WHITE FORMULA                       AW
C         DS = DIFFERENCE BETWEEN SPECIFIC GRAVITY OF SEDIMENT AND      AW
C              WATER                                                    AW
C         FGR = SEDIMENT MOBILITY NUMBER, AS DEFINED BY ACKERS AND      AW
C               WHITE (1973)                                            AW
C         GGR = DIMENSIONLESS SEDIMENT TRANSPORT RATE, AS DEFINED BY    AW
C               ACKERS AND WHITE (1973)                                 AW
C         M = EXPONENT IN ACKERS-WHITE FORMULA                          AW
C         N = TRANSITION EXPONENT IN ACKERS-WHITE FORMULA               AW
C               BY SWART AND FLEMING (1980)                             AW
C         S = SPECIFIC GRAVITY OF WATER                                 AW
C         VST = SHEAR VELOCITY (CM/SEC)                                 AW
C         X = SEDIMENT LOAD, EXPRESSED AS CONCENTRATION BY WEIGHT       AW
      G=981.
      VISC=13.E-3
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*(0.015476+
     @0.099205*GD)))/(RHOW*(0.011607+0.074405*GD))
      TAUCRB=RHOW*FCW/2.*VCB**2
      TAUCRS=RHOW*FCW/2.*VCS**2
      UAX=UA*COS(PHIB)
      UAY=UA*SIN(PHIB)
      W=2.*PI/PER
      VCBB=VCB
      UBB=UB
      SED=0.0
      SEDDIR=0.0
      VC=0.0
C
C
C     PRINT 15,PERBED,PERSUSP
C     WRITE(7,15) PERBED,PERSUSP
  15  FORMAT(///,' PERCENT TIME SPENT AS BEDLOAD =',F7.2,/,
     @' PERCENT TIME SPENT IN SUSPENSION =',F7.2)
C
C  FOR THE PURE WAVE CASE NO NET TRANSPORT OCCURS
C
      IF (UA .EQ. 0.0) THEN
        SED=0.0
```

```
        SEDDIR=0.0
C
C  NO INTEGRATION IS REQUIRED FOR THE PURE CURRENT CASE.  WHEN TRANSPORT
C  IS AS SUSPENDED LOAD, THE TOTAL TRANSPORT FORMULA OF ENGELUND AND
C  HANSEN (1967) IS USED.  WHEN TRANSPORT IS AS BEDLOAD, THE USER HAS
C  A CHOICE OF FORMULAE.
C
      ELSE IF (UB .EQ. 0.0) THEN
        TAU0=RHOW*FCW/2.*UA**2
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
        ELSE IF (PERBED .EQ. 0.0 .AND. IOPT .NE. 5) THEN                AW
           PRINT 25
           WRITE (7,25)
  25      FORMAT(/,' SEDIMENT TRANSPORT WILL BE CALCULATED USING THE',/,
     @    ' ENGELUND-HANSEN TOTAL LOAD FORMULA')
          V=U100
          SED=0.05*V**2*SQRT(TAU0**3*RHOW)/(GD*DGAMMA**2)
          SEDDIR=CDIR
        ELSE
  30      CONTINUE
          IF (IOPT .EQ. 1) THEN
            V=U100
            SED=0.05*V**2*SQRT(TAU0**3*RHOW)/(GD*DGAMMA**2)
          ELSE IF (IOPT .EQ. 2) THEN
            SED=40.0*FALL*GD*(TAU0/(DGAMMA*GD))**3
          ELSE IF (IOPT .EQ. 3) THEN
            BETA=1.73E-05
            IF (GD .LE. 0.031) BETA=7.22E-05
            SED=BETA/RHOS*(U100-VCB)**3
          ELSE IF (IOPT .EQ. 4) THEN
            USTAR=SQRT(FCW/2.)*UA
            S=(UA/VCB)**2-1.0
            A=2.45*(RHOW/RHOS)**0.4*SQRT(TAUCRB/(G*DRHO*GD))
            SED=0.635*GD*USTAR*S*(1.0-ALOG(1.0+A*S)/(A*S))
          ELSE IF (IOPT .EQ. 5) THEN                                    AW
            S = RHOS/RHOW                                               AW
            DS = DGAMMA/(RHOW*G)                                        AW
            IF (DGR .GT. 60.) THEN                                      AW
              N = 0.                                                    AW
              M = 1.50                                                  AW
              C = 0.025                                                 AW
            ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN               AW
              N = 1.00 - 0.56*ALOG10(DGR)                               AW
              M = (9.66/DGR) + 1.34                                     AW
              C = 10.**(2.86*ALOG10(DGR)-(ALOG10(DGR))**2-3.53)         AW
            ELSE                                                        AW
              PRINT 35                                                  AW
  35          FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')         AW
              STOP                                                      AW
            ENDIF                                                       AW
            VST = SQRT(FCW/2.)*UA                                       AW
```

```
            FGR = (VST**N/SQRT(G*GD*DS))*                               AW
     .            (UA/(5.75*ALOG10(10.*D/GD)))**(1.-N)                  AW
            IF (FGR .LT. AGR) THEN                                      AW
              PRINT 36                                                  AW
              PRINT 37                                                  AW
              PRINT 38                                                  AW
36    FORMAT(' ACKERS-WHITE MOBILITY NUMBER "FGR" IS LESS THAN "AGR"')  AW
37    FORMAT(' AGR = THE CRITICAL MOBILITY NUMBER ')                    AW
38    FORMAT(' THAT IS CALCULATED IN THRESH FOR THE ACKERS-WHITE CASE') AW
              CDIR=0.                                                   AW
            GGR = 0.                                                    AW
            X = 0.                                                      AW
            SED = 0.                                                    AW
            GO TO 40                                                    AW
            ELSE                                                        AW
            GGR = C*((FGR/AGR)-1.)**M                                   AW
            X = (S*GD*GGR/D)*(U100/VST)**N                              AW
            SED = U100*GD*GGR*(U100/VST)**N                             AW
            ENDIF                                                       AW
  40        CONTINUE                                                    AW
C THE FOLLOWING WRITE STATEMENTS ARE USED TO PRINT OUT INTERMEDIATE      INTVR
C VARIABLES USED IN THE ACKERS-WHITE FORMULA FOR MANUAL CHECKING        INTVR
C     PRINT 45,DGR,N,M,AGR,C,VST,FGR,GGR,X,SED                          INTVR
C     WRITE(7,45) DGR,N,M,AGR,C,VST,FGR,GGR,X,SED                       INTVR
C  45 FORMAT (//' INTERMEDIATE VARIABLES FOR ACKERS-WHITE FORMULA:'/    INTVR
C    .        ' DGR = ',E10.3,T20,'N = ',E10.3,T40,'M = ',E10.3/        INTVR
C    .        ' AGR = ',E10.3,T20,'C = ',E10.3,T40,'VST = ',E10.3/      INTVR
C    .        ' FGR = ',E10.3,T20,'GGR = ',E10.3,T40,'X = ',E10.3/      INTVR
C    .        ' SED = ',E10.3)                                          INTVR
          ENDIF                                                         AW
C
         SEDDIR=CDIR
        ENDIF
C
C  THE COMBINED WAVE AND CURRENT CASE REQUIRES INTEGRATION OF THE
C  INSTANTANEOUS TRANSPORT OVER THE WAVE PERIOD.  THE USE OF LWT ALLOWS
C  INTEGRATION TO BE DONE OVER ONLY HALF A WAVE CYCLE.  BAGNOLD'S METHOD
C  DOES NOT REQUIRE INTEGRATION.
C  THE X- AND Y- COMPONENTS OF TRANSPORT ARE CONSIDERED SEPARATELY,
C  WHERE THE X-COMPONENT IS PARALLEL TO THE WAVE DIRECTION AND THE
C  Y-COMPONENT IS NORMAL TO THE WAVE DIRECTION.
C  NOTE:  DCADRE IS AN IMSL SUBROUTINE FOR INTEGRATION.  THE IMSL
C  LIBRARY MUST BE ATTACHED BEFORE RUNNING THIS PROGRAM.
C
      ELSE
        IF (TB1 .EQ. 0.0 .AND. TS1 .EQ. 0.0) THEN
          SED=0.0
          SEDDIR=0.0
          GO TO 999
        ENDIF
        SEDXC=0.0
        SEDXT=0.0
        SEDYC=0.0
```

```fortran
        SEDYT=0.0
  50    CONTINUE
        IF (IOPT .EQ. 1) THEN
          V=U100
          CONST=0.0177*FCW**1.5*(V*RHOW/DGAMMA)**2/GD
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F1,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
  65        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F1')
            SEDYC=2.*CONST*DCADRE(F2,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
  75        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F2')
          ELSE
            SEDXC=2.*CONST*DCADRE(F1,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYC=2.*CONST*DCADRE(F2,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ENDIF
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F1,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYT=2.*CONST*DCADRE(F2,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ELSE IF (TS2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F1,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,65) IER
            SEDYT=2.*CONST*DCADRE(F2,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,75) IER
          ENDIF
C
C
        ELSE IF (IOPT .EQ. 2) THEN
          CONST=5.*FALL*GD*(FCW*RHOW/(GD*DGAMMA))**3
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F3,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,85) IER
  85        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F3')
            SEDYC=2.*CONST*DCADRE(F4,0.0,TB1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,95) IER
  95        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F4')
          ELSE
            SEDXC=2.*CONST*DCADRE(F3,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,85) IER
            SEDYC=2.*CONST*DCADRE(F4,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,95) IER
          ENDIF
C
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F3,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,85) IER
            SEDYT=2.*CONST*DCADRE(F4,TB2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,95) IER
          ELSE IF (TS2 .NE. 0.0) THEN
```

```
            SEDXT=2.*CONST*DCADRE(F3,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,85) IER
            SEDYT=2.*CONST*DCADRE(F4,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,95) IER
          ENDIF
C
C
        ELSE IF (IOPT .EQ. 3) THEN
          ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          USTAR=SQRT(FCW*ALPHA/2.)*UB
          L=0.4*USTAR*PER/(2.*PI)
          ZETA0=KB/(30.*L)
          CALL MMKEL0(2.*SQRT(ZETA0),DUMMY1,DUMMY2,XKER,XKEI,IER)
C THE FOLLOWING WRITE STATEMENTS ARE USED TO PRINT VARIABLES USED IN    DEBUG
C CALCULATING TAU0. (EXECUTION TERMINATED WHEN USING BAGNOLD'S FORMULA  DEBUG
C WITH KB = 0 FOR WAVES AND CURRENTS)                                   DEBUG
C     PRINT 1000, UA,UB,PHIB,ALPHA,FCW,USTAR,PER,L,KB,ZETA0,            DEBUG
C    .           RHOW,XKER,XKEI                                         DEBUG
C     WRITE (7,1000) UA,UB,PHIB,ALPHA,FCW,USTAR,PER,L,KB,ZETA0,         DEBUG
C    .               RHOW,XKER,XKEI                                     DEBUG
C1000 FORMAT (///' CHECK OF VALUES USED TO CALCULATE TAU0:'/            DEBUG
C    .        ' UA = ',E12.3,T25,'UB = ',E12.3,T50,'PHIB = ',E12.3/     DEBUG
C    .        ' ALPHA = ',E12.3,T25,'FCW = ',E12.3,T50,'USTAR = ',E12.3/DEBUG
C    .        ' PER = ',E12.3,T25,'L = ',E12.3,T50,'KB = ',E12.3/       DEBUG
C    .        ' ZETA0 = ',E12.3,T25,'RHOW = ',E12.3,T50,'XKER = ',E12.3/DEBUG
C    .        ' XKEI = ',E12.3)                                         DEBUG
          TAU0W=0.2*RHOW*USTAR*UB/SQRT(XKER**2+XKEI**2)
           PRINT 105
 105      FORMAT(//,' BAGNOLD''S METHOD REQUIRES A COEFFICIENT OF ',
     @    'PROPORTIONALITY, K',/,' WHICH RANGES BETWEEN 0.0 AND 1.0',/,
     @    ' PLEASE ENTER A VALUE FOR K')
          READ*, K
          SED=K*TAU0W*UA/DGAMMA
          SEDDIR=CDIR
C
C
        ELSE IF (IOPT .EQ. 4) THEN
          ALPHA=1.0+(UA/UB)**2+2.*(UA/UB)*COS(PHIB)
          USTAR=SQRT(FCW*ALPHA/2.)*UB
          A=2.45*SQRT(TAUCRB/DGAMMA/GD)*(RHOW/RHOS)**0.4
          CONST=0.635*GD*USTAR
          IF (TB1 .NE. 0.0) THEN
            SEDXC=2.*CONST*DCADRE(F5,0.0,TB1S,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
 115        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F5')
            SEDYC=2.*CONST*DCADRE(F6,0.0,TB1S,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
 125        FORMAT(///,' ***DCADRE ERROR*** ',I3,' WITH FUNCTION F6')
          ELSE
            SEDXC=2.*CONST*DCADRE(F5,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYC=2.*CONST*DCADRE(F6,0.0,TS1,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
```

```
          ENDIF
C
          IF (TB2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F5,TB2S,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYT=2.*CONST*DCADRE(F6,TB2S,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
          ELSE IF (TS2 .NE. 0.0) THEN
            SEDXT=2.*CONST*DCADRE(F5,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,115) IER
            SEDYT=2.*CONST*DCADRE(F6,TS2,PER/2.,0.01,0.0,ER,IER)
            IF (IER .GT. 0) WRITE(7,125) IER
          ENDIF
C
C
        ELSE IF (IOPT .EQ. 5) THEN                                      AW
          DS = DGAMMA/(RHOW*G)                                          AW
          IF (DGR .GT. 60.) THEN                                        AW
            N = 0.                                                      AW
            M = 1.50                                                    AW
            C = 0.025                                                   AW
          ELSE IF (DGR .GT. 1. .AND. DGR .LE. 60.) THEN                 AW
            N = 1.0 - 0.56*ALOG10(DGR)                                  AW
            M = (9.66/DGR) + 1.34                                       AW
            C = 10.**(2.86*ALOG10(DGR) - (ALOG10(DGR))**2 - 3.53)       AW
          ELSE                                                          AW
            PRINT 135                                                   AW
 135        FORMAT (' FINE SEDIMENT - THEORY NOT APPLICABLE')           AW
            STOP                                                        AW
          ENDIF                                                         AW
          COEFF = (1./(AGR*SQRT(DS*G*GD)))*                             AW
     .            (SQRT(FCW/2.))**N*                                    AW
     .            (1./(5.75*ALOG10(10.*D/GD)))**(1.-N)                  AW
          CONST = GD*C*(SQRT(2./FCW))**N                                AW
C THE FOLLOWING WRITE STATEMENTS ARE USED TO PRINT OUT INTERMEDIATE     INTVR
C VARIABLES USED IN THE ACKERS-WHITE FORMULA FOR MANUAL CHECKING        INTVR
C     PRINT 138,UAX,UAY,UBB,W,DGR,RGR,AGR,N,M,C,COEFF,CONST             INTVR
C     WRITE(7,138) UAX,UAY,UBB,W,DGR,RGR,AGR,N,M,C,COEFF,CONST          INTVR
C 138 FORMAT (///' INTERMEDIATE VARIABLES FOR ACKERS-WHITE FORMULA:'/   INTVR
C    .        ' UAX = ',E10.3,T20,'UAY = ',E10.3,T40,'UBB = ',E10.3,/   INTVR
C    .        ' W = ',E10.3,T20,'DGR = ',E10.3,T40,'RGR = ',E10.3,/     INTVR
C    .        ' AGR = ',E10.3,T20,'N = ',E10.3,T40,'M = ',E10.3,/       INTVR
C    .        ' C = ',E10.3,T20,'COEFF = ',E10.3,T40,'CONST = ',E10.3)  INTVR
          IF (TB1 .NE. 0.) THEN                                         AW
            SEDXC = 2.*CONST*DCADRE(F7,0.0,TB1,0.01,0.0,ER,IER)         AW
            IF (IER .GT. 0) WRITE (7,145) IER                           AW
 145        FORMAT (///,' DCADRE ERROR*** ',I3,' WITH FUNCTION F7')     AW
            SEDYC = 2.*CONST*DCADRE(F8,0.0,TB1,0.01,0.0,ER,IER)         AW
            IF (IER .GT. 0) WRITE (7,155) IER                           AW
 155        FORMAT (///,' DCADRE ERROR*** ',I3,' WITH FUNCTION F8')     AW
          ELSE                                                          AW
            SEDXC = 2.*CONST*DCADRE(F7,0.0,TS1,0.01,0.0,ER,IER)         AW
            IF (IER .GT. 0) WRITE (7,135) IER                           AW
```

```
            SEDYC = 2.*CONST*DCADRE(F8,0.0,TS1,0.01,0.0,ER,IER)         AW
            IF (IER .GT. 0) WRITE (7,145) IER                           AW
          ENDIF                                                         AW
C                                                                       AW
          IF (TB2 .NE. 0.0) THEN                                        AW
            SEDXT = 2.*CONST*DCADRE(F7,TB2,PER/2.,0.01,0.0,ER,IER)      AW
            IF (IER .GT. 0) WRITE (7,135) IER                           AW
            SEDYT = 2.*CONST*DCADRE(F8,TB2,PER/2.,0.01,0.0,ER,IER)      AW
            IF (IER .GT. 0.0) WRITE (7,145) IER                         AW
          ELSE IF (TS2 .NE. 0.) THEN                                    AW
            SEDXT = 2.*CONST*DCADRE(F7,TS2,PER/2.,0.01,0.0,ER,IER)      AW
            IF (IER .GT. 0) WRITE (7,135) IER                           AW
            SEDYT = 2.*CONST*DCADRE(F8,TS2,PER/2.,0.01,0.0,ER,IER)      AW
            IF (IER .GT. 0) WRITE (7,145) IER                           AW
          ENDIF                                                         AW
        ENDIF
C
C
C
C
        IF (IOPT .NE. 3) THEN
          SEDX=(SEDXC+SEDXT)/PER
          SEDY=(SEDYC+SEDYT)/PER
          SED=SQRT(SEDX**2+SEDY**2)
C IF SEDX=0 AND SEDY=0 THEN ATAN2 IS NOT DEFINED. SET SEDDIR EQUAL TO   AW
C A FLAG (10.**9.) AND PRINT APPROPRIATE MESSAGE IN OUTOUT              AW
      IF (SEDX.EQ.0. .AND. SEDY.EQ.0.) THEN                             AW
      SEDDIR = 10.**9.                                                  AW
      GO TO 998                                                         AW
      ENDIF                                                             AW
          PHIS=ATAN2(SEDY,SEDX)
          DIF=SIGN((PHI100-PHIS)*180./PI,CDIR-WDIR)
          CWDIF=ABS(CDIR-WDIR)
          IF(CWDIF .LE. 90.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 180.0 .AND. CWDIF .GT. 90.0) SEDDIR=CDIR+DIF
          IF (CWDIF .LE. 270.0 .AND. CWDIF .GT. 180.0) SEDDIR=CDIR-DIF
          IF (CWDIF .LE. 360.0 .AND. CWDIF .GT. 270.0) SEDDIR=CDIR+DIF
          IF (SEDDIR .LT. 0.0) SEDDIR=SEDDIR+360.0
          IF (SEDDIR .GE. 360.0) SEDDIR=SEDDIR-360.0
  998   CONTINUE                                                        AW
        ENDIF
      ENDIF
  999 RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F1(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F1=UX*(UX**2+UY**2)
      RETURN
      END
```

```
C***********************************************************************
C***********************************************************************
      FUNCTION F2(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F2=UY*(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F3(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F3=UX*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F4(X)
      COMMON UAX,UAY,UBB,W
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      F4=UY*(UX**2+UY**2)**2.5
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F5(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F5=S*(1.-ALOG(1.+A*S)/(A*S))*UX/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F6(X)
      COMMON UAX,UAY,UBB,W,A,VCBB
      UX=UAX+UBB*COS(W*X)
      UY=UAY
      S=(UX**2+UY**2)/VCBB**2-1.0
      F6=S*(1.-ALOG(1.+A*S)/(A*S))*UY/SQRT(UX**2+UY**2)
      RETURN
      END
C***********************************************************************
C***********************************************************************
      FUNCTION F7(X)                                                    AW
      REAL M                                                            AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                               AW
      UX = UAX + UBB*COS(W*X)                                           AW
```

```
      UY = UAY                                                          AW
C IF FGR(T) IS LESS THAN AGR (I.E., IF FGR(T)/AGR IS LESS THAN 1)       AW
C THEN THE SEDIMENT MOBILITY IS BELOW CRITICAL SEDIMENT MOBILITY        AW
C AND THERE IS NO SEDIMENT TRANSPORT AT THIS TIME STEP (I.E., F7=0)     AW
      IF (COEFF*SQRT(UX**2+UY**2) .LT. 1.) THEN                         AW
      F7 = 0.                                                           AW
      ELSE                                                              AW
C OTHERWISE, THE SEDIMENT TRANSPORT AT THIS TIME STEP IS CALCULATED     AW
C ACCORDING TO THE ACKERS-WHITE EQUATION.                               AW
      F7 = UX*(COEFF*SQRT(UX**2+UY**2) - 1.)**M                         AW
      ENDIF                                                             AW
      RETURN                                                            AW
      END                                                               AW
C***********************************************************************AW
C***********************************************************************AW
      FUNCTION F8(X)                                                    AW
      REAL M                                                            AW
      COMMON UAX,UAY,UBB,W,A,VCBB,COEFF,M                               AW
      UX = UAX + UBB*COS(W*X)                                           AW
      UY = UAY                                                          AW
C IF FGR(T) IS LESS THAN AGR (I.E., IF FGR(T)/AGR IS LESS THAN 1)       AW
C THEN THE SEDIMENT MOBILITY IS BELOW CRITICAL SEDIMENT MOBILITY        AW
C AND THERE IS NO SEDIMENT TRANSPORT AT THIS TIME STEP (I.E., F8=0)     AW
      IF (COEFF*SQRT(UX**2+UY**2) .LT. 1.) THEN                         AW
      F8 = 0.                                                           AW
      ELSE                                                              AW
C OTHERWISE, THE SEDIMENT TRANSPORT AT THIS TIME STEP IS CALCULATED     AW
C ACCORDING TO THE ACKERS-WHITE EQUATION                                AW
      F8 = UY*(COEFF*SQRT(UX**2+UY**2) - 1.)**M                         AW
      ENDIF                                                             AW
      RETURN                                                            AW
      END                                                               AW
      SUBROUTINE OUTOUT(UB,AB,WL,FCW,UA,U100,PHIB,VCB,VCS,TS1,TB1,TS2,
     @TB2,PERBED,PERSUSP,SED,SEDDIR,IOPT)
C
C  THIS SUBROUTINE PRINTS THE VALUES OF THE OUTPUT PARAMETERS FROM ALL
C  SUBROUTINES
C
      PRINT 15
      WRITE(7,15)
  15  FORMAT(///,T4,'RESULTS:',//)
C
      PRINT 25,UB,AB,WL/100.
      WRITE(7,25) UB,AB,WL/100.
  25  FORMAT(T11,'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'VELOCITY, FROM LINEAR WAVE THEORY',T56,'=',F7.2,' CM/SEC',/,T11,
     @'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'DISPLACEMENT, FROM LINEAR WAVE THEORY',T56,'=',F8.2,' CM',/,T11,
     @'WAVELENGTH, FROM LWT DISPERSION EQUATION =',F7.2,' M',/)
C
      PRINT 35,FCW
      WRITE(7,35) FCW
  35  FORMAT(T11,'BOTTOM FRICTION FACTOR =',F7.4)
```

```
      IF (UB .EQ. 0.0) THEN
        PRINT 45
        WRITE(7,45)
  45    FORMAT(T11,'(STERNBERG, 1971)')
      ELSE IF (UA .EQ. 0.0) THEN
        PRINT 55
        WRITE(7,55)
  55    FORMAT(T11,'(JONSSON, 1966)')
      ELSE
        PRINT 65
        WRITE(7,65)
  65    FORMAT(T11,'(GRANT AND MADSEN, 1979)')
      ENDIF
C
      PRINT 75,U100,UA,PHIB*90./ASIN(1.)
      WRITE(7,75) U100,UA,PHIB*90./ASIN(1.)
  75  FORMAT(T11,'CURRENT SPEED 1 M. ABOVE SEABED',T53,'=',F7.2,
     @' CM/SEC',/,T11,'CURRENT SPEED TO BE USED IN BOTTOM STRESS',/,T11,
     @'CALCULATIONS',T53,'=',F7.2,' CM/SEC',/,T11,
     @'ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS',/,T11,
     @'WITHIN WAVE BOUNDARY LAYER',T53,'=',F7.2,' DEGREES',/,T11,
     @'NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY',/)
C
      PRINT 85,VCB,VCS
      WRITE(7,85) VCB,VCS
  85  FORMAT(T11,'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'BEDLOAD TRANSPORT',T53,'=',F7.2,' CM/SEC',/,T11,
     @'CRITICAL FLUID VELOCITY FOR INITIATION OF',/,T11,
     @'SUSPENDED LOAD TRANSPORT',T53,'=',F7.2,' CM/SEC')                AW
C IF USING ACKERS-WHITE OPTION, PRINT A MESSAGE TO INFORM THE USER THAT AW
C THESE CRITICAL VELOCITIES ARE NOT CALCULATED FROM THE SHIELDS CURVE   AW
C BUT ARE CALCULATED FROM THE ACKERS-WHITE CRITICAL MOBILITY CRITERIA   AW
      IF (IOPT .EQ. 5) THEN                                             AW
      PRINT 86                                                          AW
      WRITE (7,86)                                                      AW
   86 FORMAT (T11,'NOTE: CRITICAL VELOCITY FOR BEDLOAD TRANSPORT IS'/   AW
     .        T17,'NOT CALCULATED FROM THE SHIELDS CURVE, BUT IS'/      AW
     .        T17,'CALCULATED FROM ACKERS-WHITE CRITICAL MOBILITY'/     AW
     .        T17,'CRITERIA.  CRITICAL VELOCITY FOR SUSPENDED LOAD'/    AW
     .        T17,'TRANSPORT IS SET EQUAL TO THE CRITICAL VELOCITY'/    AW
     .        T17,'FOR BEDLOAD BECAUSE THIS VELOCITY IS NOT USED '/     AW
     .        T17,'FOR THE ACKERS-WHITE TOTAL LOAD EQUATION'/)          AW
      ENDIF                                                             AW
C
      PRINT 95,TS1,TB1,TS2,TB2
      WRITE(7,95) TS1,TB1,TS2,TB2
  95  FORMAT(T11,'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT RECOMMENCES       =',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
```

```
     @'BEDLOAD TRANSPORT RECOMMENCES             =',F6.2,' SEC',/)
C
      PRINT 105,PERBED,PERSUSP
      WRITE(7,105) PERBED,PERSUSP
 105  FORMAT(T11,'PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =',F7.2,/,
     @T11,'PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =',F7.2,/)
C
C IF SEDDIR IS SET TO A FLAG (10.**9.), THEN SEDX=0 AND SEDY=0 AND      AW
C THE DIRECTION OF NET SEDIMENT TRANSPORT HAS NO MEANING. PRINT AN      AW
C APPROPRIATE MESSAGE IN THE OUTPUT LISTING                             AW
      IF (SEDDIR.EQ.10.**9.) THEN                                       AW
      PRINT 114,SED                                                     AW
      WRITE (7,114) SED                                                 AW
  114 FORMAT (T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT = ',G12.4,      AW
     .        ' CM**2/SEC'/T11,'NOTE:DIRECTION OF NET SEDIMENT',        AW
     .        ' TRANSPORT'/T17,'HAS NO MEANING, SINCE SEDX=0 AND',      AW
     .        ' SEDY=0.')                                               AW
      ELSE                                                              AW
C OTHERWISE, PRINT VALUES OF SEDDIR AND SED                             AW
      PRINT 115,SEDDIR,SED
      WRITE(7,115) SEDDIR,SED
 115  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
      ENDIF                                                             AW
C
      IF (UA .NE. 0.0) THEN
C
        IF (IOPT .EQ. 1) THEN
          PRINT 125
          WRITE(7,125)
 125      FORMAT(T11,'(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)')
        ELSE IF (IOPT .EQ. 2) THEN
          PRINT 135
          WRITE(7,135)
 135      FORMAT(T11,'(EINSTEIN-BROWN (1950) BEDLOAD EQUATION)')
        ELSE IF (IOPT .EQ. 4) THEN
          PRINT 145
          WRITE(7,145)
 145      FORMAT(T11,'(YALIN (1963) BEDLOAD EQUATION)')
        ELSE IF (IOPT .EQ. 5) THEN                                      AW
          PRINT 185                                                     AW
          WRITE (7,185)                                                 AW
 185      FORMAT (T11,'(ACKERS-WHITE TOTAL LOAD EQUATION)')             AW
        ELSE IF (UB .EQ. 0.0) THEN
          PRINT 155
          WRITE(7,155)
 155      FORMAT(T11,'(MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION)')
        ELSE
          PRINT 165
          WRITE(7,165)
 165      FORMAT(T11,'(BAGNOLD (1963) TOTAL LOAD EQUATION)')
        ENDIF
```

```
C
      ENDIF
C
      PRINT 175
      WRITE(7,175)
 175  FORMAT(T11,'NOTE:  THIS IS SEDIMENT VOLUME TRANSPORT RATE RATHER
     @THAN',/,T18,'SOIL VOLUME TRANSPORT RATE',/)
C
      RETURN
      END
      SUBROUTINE BEDFORM(U100,UB,GD,KBC)
      REAL KBC
C
C  THIS SUBROUTINE PRINTS OUT THE EXPECTED TYPE OF BEDFORM FOR THE GIVEN
C  FLOW CONDITIONS (PURE WAVE OR PURE CURRENT CONDITIONS ONLY).  THE
C  BEDFORM TYPE IS ONLY APPROXIMATE SINCE IT IS BASED ON A VELOCITY
C  MEASUREMENT ONLY.  THE LIMITS ARE FROM C. L. AMOS, IN PROGRESS.
C
C  INPUT VARIABLES:
C
C           U100 = CURRENT SPEED AT 1 M. ABOVE SEABED ( CM/SEC)
C           UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (CM/SEC)
C           GD = SEDIMENT GRAIN SIZE (CM)
C           KBC = APPARENT BOTTOM ROUGHNESS (CM)
C
      IF (KBC .EQ. 0.0) KBC=GD
C
C  SET UP FORMAT STATEMENTS
C
      PRINT 15
      WRITE(7,15)
  15  FORMAT(//,T11,'EXPECTED BEDFORMS ARE (C. L. AMOS):',/)
  25  FORMAT(T21,'WAVE RIPPLES')
  35  FORMAT(T21,'WAVE-INDUCED FLAT BED')
  355 FORMAT(T21,'WAVE RIPPLES OR WAVE-INDUCED FLAT BED')
  45  FORMAT(T21,'CURRENT RIPPLES')
  55  FORMAT(T21,'FLAT BED (LOWER)')
  65  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES')
  75  FORMAT(T21,'FLAT BED (LOWER) OR 2-D MEGARIPPLES OR SAND WAVES')
  85  FORMAT(T21,'2-D MEGARIPPLES')
  95  FORMAT(T21,'2-D MEGARIPPLES OR SAND WAVES')
 105  FORMAT(T21,'SAND WAVES')
 115  FORMAT(T21,'SAND WAVES OR 3-D MEGARIPPLES')
 125  FORMAT(T21,'3-D MEGARIPPLES')
 135  FORMAT(T21,'FLAT BED (UPPER) AND SAND RIBBONS')
 145  FORMAT(T21,'SEDIMENT IN SUSPENSION')
 155  FORMAT(T21,'NO TRANSPORT')
 165  FORMAT(T21,'BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS')
C
C  VERY COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      IF (GD .LE. 0.2 .AND. GD .GT. 0.1) THEN
```

```
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 30.0) PRINT 155
          IF (UB .LT. 30.0) WRITE(7,155)
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) PRINT 25
          IF (UB .GE. 30.0 .AND. UB .LT. 100.0) WRITE(7,25)
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) PRINT 355
          IF (UB .GE. 100.0 .AND. UB .LT. 200.0) WRITE(7,355)
          IF (UB .GE. 200.0) PRINT 35
          IF (UB .GE. 200.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 40.0) PRINT 155
          IF (U100 .LT. 40.0) WRITE(7,155)
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) PRINT 95
          IF (U100 .GE. 40.0 .AND. U100 .LE. 45.0) WRITE(7,95)
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) PRINT 75
          IF (U100 .GE. 45.0 .AND. U100 .LE. 50.0) WRITE(7,75)
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) PRINT 95
          IF (U100 .GE. 50.0 .AND. U100 .LE. 60.0) WRITE(7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) PRINT 105
          IF (U100 .GE. 60.0 .AND. U100 .LE. 100.0) WRITE(7,105)
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) PRINT 135
          IF (U100 .GE. 100.0 .AND. U100 .LE. 295.0) WRITE(7,135)
          IF (U100 .GE. 295.0) PRINT 145
          IF (U100 .GE. 295.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  COARSE SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.1 .AND. GD .GT. 0.05) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 20.0) PRINT 155
          IF (UB .LT. 20.0) WRITE(7,155)
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) PRINT 25
          IF (UB .GE. 20.0 .AND. UB .LT. 90.0) WRITE(7,25)
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) PRINT 355
          IF (UB .GE. 90.0 .AND. UB .LT. 125.0) WRITE(7,355)
          IF (UB .GE. 125.0) PRINT 35
          IF (UB .GE. 125.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 25.0) PRINT 155
```

```
          IF (U100 .LT. 25.0) WRITE(7,155)
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) PRINT 45
          IF (U100 .GE. 25.0 .AND. U100 .LT. 35.0) WRITE(7,45)
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) PRINT 55
          IF (U100 .GE. 35.0 .AND. U100 .LT. 40.0) WRITE(7,55)
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) PRINT 65
          IF (U100 .GE. 40.0 .AND. U100 .LT. 45.0) WRITE(7,65)
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) PRINT 85
          IF (U100 .GE. 45.0 .AND. U100 .LT. 50.0) WRITE(7,85)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) PRINT 95
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE(7,95)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) PRINT 115
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE(7,115)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) PRINT 125
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) WRITE(7,125)
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) PRINT 135
          IF (U100 .GE. 150.0 .AND. U100 .LT. 240.0) WRITE(7,135)
          IF (U100 .GE. 240.0) PRINT 145
          IF (U100 .GE. 240.0) WRITE(7,145)
C
C  COMBINED WAVES AND CURRENT CASE
C
        ELSE
          PRINT 165
          WRITE(7,165)
        ENDIF
C
C  MEDIUM SAND
C  FIRST, DO PURE WAVE CASE
C
      ELSE IF (GD .LE. 0.05 .AND. GD .GT. 0.025) THEN
        IF (U100 .EQ. 0.0) THEN
          IF (UB .LT. 13.0) PRINT 155
          IF (UB .LT. 13.0) WRITE(7,155)
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) PRINT 25
          IF (UB .GE. 13.0 .AND. UB .LT. 80.0) WRITE(7,25)
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) PRINT 355
          IF (UB .GE. 80.0 .AND. UB .LT. 100.0) WRITE(7,355)
          IF (UB .GE. 100.0) PRINT 35
          IF (UB .GE. 100.0) WRITE(7,35)
C
C  PURE CURRENT CASE
C
        ELSE IF (UB .EQ. 0.0) THEN
          IF (U100 .LT. 20.0) PRINT 155
          IF (U100 .LT. 20.0) WRITE(7,155)
          IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) PRINT 45
          IF (U100 .GE. 20.0 .AND. U100 .LT. 50.0) WRITE(7,45)
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) PRINT 85
          IF (U100 .GE. 50.0 .AND. U100 .LT. 60.0) WRITE(7,85)
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) PRINT 115
          IF (U100 .GE. 60.0 .AND. U100 .LT. 100.0) WRITE(7,115)
          IF (U100 .GE. 100.0 .AND. U100 .LT. 150.0) PRINT 125
```

APPENDIX E

SAMPLE CALCULATIONS

APPENDIX E - SAMPLE CALCULATIONS

E.1 Manual Calculations for Current Only

A sample calculation for Run No. 7 of Table 3.2 is presented below.

Input Data:

water depth, $d = 20.0$ m $= 2000$ cm
current speed, $V = 100$ cm/sec
grain size, $D = 0.2$ mm $= 0.02$ cm
fluid density, $\rho = 1.025$ gm/cm^3
sediment density $\rho_s = 2.65$ gm/cm^3

Assumptions

dynamic viscosity, $\mu = 13 \times 10^{-3}$ gm/cm sec
kinematic viscosity, $\nu = \mu/\rho = 1.27 \times 10^{-2}$ cm^2/sec
acceleration due to gravity, $g = 981$ cm/sec^2
relative sediment density, $s = \rho_s/\rho = 2.59$
coefficient in rough-turbulent equation, $\alpha = 10$

Intermediate Variables

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

$$= 0.02\left[\frac{(981)(2.59-1)}{(1.27\times 10^{-2})^2}\right]^{1/3}$$

$$= 4.26 \text{ (transitional size of sediment, } 1 < D_{gr} \leq 60)$$

$$n = 1.00 - 0.56 \log D_{gr}$$

$$= 1.00 - 0.56 \log 4.26$$

$$= 0.648$$

$$m = \frac{9.66}{D_{gr}} + 1.34$$

$$= \frac{9.66}{4.26} + 1.34$$

$$= 3.61$$

$$A_{gr} = \frac{0.23}{\sqrt{D_{gr}}} + 0.14$$

$$= \frac{0.23}{\sqrt{4.26}} + 0.14$$

$$= 0.251$$

$$C = 10^{2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53}$$

$$= 10^{2.86 \log 4.26 - (\log 4.26)^2 - 3.53}$$

$$= 10^{-2.13}$$

$$= 7.48 \times 10^{-3}$$

$$v_{*fg} = \sqrt{\frac{\tau_{fg}}{\rho}}$$

$$= \sqrt{\frac{(f/2)\rho V^2}{\rho}}$$

$$= \sqrt{\frac{f}{2}}\, V \text{ where } f = 0.0060 \text{ (Sternberg, 1972)}$$

$$= \sqrt{\frac{0.0060}{2}}\,(100)$$

$$= 5.48 \text{ cm/sec}$$

$$F_{gr} = \frac{(v_{*fg})^n}{\sqrt{gD(s-1)}} \left[\frac{V}{5.75 \log \alpha d/D}\right]^{1-n}$$

$$= \frac{(5.48)^{0.648}}{\sqrt{(981)(0.02)(2.59-1)}} \left[\frac{100}{5.75 \log[(10)(2000)/(0.02)]}\right]^{0.352}$$

$$= 0.784$$

$$G_{gr} = C\left(\frac{F_{gr}}{A_{gr}} - 1\right)^m$$

$$= (7.48 \times 10^{-3}) \left(\frac{0.784}{0.251} - 1\right)^{3.61}$$

$$= 0.113$$

$$x = \frac{s\ D}{d}\ G_{gr}\left(\frac{V}{v_{*fg}}\right)^n$$

$$= \frac{(2.59)(0.02)}{(2000)} (0.113)\left(\frac{100}{5.48}\right)^{0.648}$$

$$= 1.92 \times 10^{-5}$$

Sediment Transport Rate:

$$q = VD\ G_{gr}\left(\frac{V}{v_{*fg}}\right)^n$$

$$= (100)(0.02)(0.113)\left(\frac{100}{5.48}\right)^{0.648}$$

$$= 1.48\ \text{cm}^3/\text{sec/cm}$$

E.2 Manual Calculations for Waves and Current

A sample calculation for Run No. 3 of Table 3.3 is presented below.

Input Data:

water depth, $d = 20.0$ m = 2000 cm
current speed, $V = 100$ cm/sec
grain size, $D = 0.2$ mm = 0.02 cm
fluid density, $\rho = 1.025$ gm/cm^3
sediment density $\rho_s = 2.65$ gm/cm^3

Assumptions

dynamic viscosity, $\mu = 13 \times 10^{-3}$ gm/cm sec
kinematic viscosity, $\nu = \mu/\rho = 1.27 \times 10^{-2}$ cm^2/sec
acceleration due to gravity, $g = 981$ cm/sec^2
relative sediment density, $s = \rho_s/\rho = 2.59$
coefficient in rough-turbulent equation, =10

Intermediate Variables

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3}$$

$$= 0.02\left[\frac{(981)(2.59 - 1)}{(1.27 \times 10^{-2})^2}\right]^{1/3}$$

$$= 4.26 \text{ (transitional size of sediment, } 1<D_{gr}\leq 60)$$

$$R_{gr} = 10^{0.092 (\log D_{gr})^2 + 1.158 \log D_{gr} - 0.367}$$

$$= 10^{0.092 (\log 4.26)^2 + 1.158 \log 4.26 - 0.367}$$

$$= 10^{0.398}$$

$$= 2.50$$

$$A_{gr} = R_{gr}\, D_{gr}^{-1.5}$$

$$= (2.50)(4.26)^{-1.5}$$

$$= 0.284$$

$$n = 1.00 - 0.56 \log D_{gr}$$

$$= 1.00 - 0.56 \log 4.26$$

$$= 0.648$$

$$m = \frac{9.66}{D_{gr}} + 1.34$$

$$= \frac{9.66}{4.26} + 1.34$$

$$= 3.61$$

$$C = 10^{2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53}$$

$$= 10^{2.86 \log 4.26 - (\log 4.26)^2 - 3.53}$$

$$= 10^{-2.126}$$

$$= 7.48 \times 10^{-3}$$

$$\text{COEFF} = \left(\frac{1}{A_{gr}\sqrt{(s-1)gD}}\right)\left(\sqrt{\frac{f_{wc}}{2}}\right)^{n}\left(\frac{1}{5.75 \log \alpha d/D}\right)^{1-n}$$

where $f_{wc} = 0.0043$ from output file for Run No. 3

$$= \left(\frac{1}{0.284 \sqrt{(2.59 - 1)(981)(0.02)}} \right) \left(\sqrt{\frac{0.0043}{2}} \right)^{0.648}$$

$$\left(\frac{1}{5.75 \log [(10)(2000)/(0.02)]} \right)^{0.352}$$

$$= 2.48 \times 10^{-2}$$

$$\text{CONST} = DC \left(\sqrt{\frac{2}{f_{wc}}} \right)^{n}$$

$$= (0.02)(7.48 \times 10^{-3}) \left(\sqrt{\frac{2}{0.0043}} \right)^{0.648}$$

$$= 1.09 \times 10^{-3}$$

E.3 Computed Results for SED1DF, SED1DE and TSED1D

A comparison of the computed results for SED1DF model, the original SED1DE model and the TSED1D test program is shown in Table E.1 for the Bagnold option. Using SED1DE, the input value of bed roughness KB=0 produces a zero value for ZETAO and a large value for XKER, which causes the execution to terminate when computing TAUO in the following step. When KB is reset to the grain diameter in test program TSED1D, the results are identical to those for SED1DF.

It is suggested that the user be aware of this problem should the original SED1DE model be used in future work.

TABLE E.1

COMPUTED RESULTS FOR SED1DF, SED1DE AND TSED1D

Parameter	SED1DF***	SED1DE	TSED1D***
UA	0.600E + 02	0.600E + 02	0.600E + 02
UB	0.227E + 03	0.227E + 03	0.227E + 03
PHIB	0.000E + 00	0.000E + 00	0.000E + 00
ALPHA	0.160E + 01	0.160E + 01	0.160E + 01
FCW	0.502E - 02	0.502E - 02	0.502E - 02
USTAR	0.144E + 02	0.144E + 02	0.144E + 02
PER	0.120E + 02	0.120E + 02	0.120E + 02
L	0.110E + 02	0.110E + 02	0.110E + 02
KB	0.400E - 01	0.000E + 00**	0.400E - 01
ZETA0	0.121E - 03	0.000E + 00	0.121E - 03
RHOW	0.103E + 01	0.103E + 01	0.103E + 01
XKER	0.393E + 01	0.127E + 323 *	0.393E + 01
XKEI	-0.785E + 00	-0.785E + 00	-0.785E + 00

* Large value for XKER causes execution to terminate when computing TAU0 in the following step.

** Input value of KB=0 produces zero value for ZETA0 and large value for XKER

*** After setting KB=GD (grain diameter), the results for TSED1D are identical to those for SED1DF

APPENDIX F

ACKERS-WHITE ADDENDUM TO DAVIDSON AND AMOS (1985)

APPENDIX F - ACKERS-WHITE ADDENDUM TO DAVIDSON AND AMOS (1985)

The following material was prepared for insertion following the first paragraph on page 18 of Davidson and Amos (1985):

(v) The Ackers-White (1973) total load equation for the pure current case where:

$$g_s = V\,D\,C\left(\frac{F_{gr}}{A_{gr}} - 1\right)^m \left(\frac{V}{v_{\bullet fg}}\right)^n$$

$$D_{gr} = D\left(\frac{g(s-1)}{\nu^2}\right)^{1/3}$$

for $D_{gr} > 0$: $n = 0$

$A_{gr} = 0.17$

$m = 1.50$

$C = 0.025$

for $1 < D_{gr} \leq 60$: $n = 1.00 - 0.56 \log D_{gr}$

$$A_{gr} = \frac{0.23}{\sqrt{D_{gr}}} + 0.14$$

$$m = \frac{9.66}{\sqrt{D_{gr}}} + 1.34$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53$$

$v_{\bullet fg}$ = shear velocity for fine sediment

$$F_{gr} = \frac{(v_{\bullet fg})^n}{\sqrt{gD(s-1)}}\left[\frac{V}{5.75 \log \alpha d/D}\right]^{1-n}$$

α = 10 = empirical coefficient in rough-turbulent equation

and the adapted Ackers-White total load equation developed by Swart and Lenhoff (see Swart and Fleming, 1980) for the mixed flow case, where

$$g_s = uDCE_f \left[\frac{F_{gr}}{A_{gr}} - 1\right]^m$$

$$E_f = \left[\frac{\frac{P_{fg}}{\rho}}{(v_{*fg})^3}\right]^n \left[\frac{\frac{P_{cg}}{\rho}}{(v_{*cg})^2 u}\right]^{1-n}$$

$P_{fg} = u\,\tau_{fg}$

$P_{cg} = u\,\tau_{cg}$

τ_{fg} = shear stress for fine grains

τ_{cg} = shear stress for coarse grains

$A_{gr} = R_{gr} D_{gr}^{-1.5}$

$\log R_{gr} = 0.092(\log D_{gr})^2 + 1.158 \log D_{gr} - 0.367$

The Ackers-White formula is applicable to coarse sediment with grain diameters in excess of 2.5 mm and to transitional sizes of sediment with grain diameters in excess of 0.04 mm, ranging up to 2.5 mm. The theory is not applicable to fine sediments with grain diameters less than or equal to 0.04 mm, since these materials would, in general, exhibit cohesive properties. The initiation of sediment movement criteria is based on a sediment mobility number and the analysis of experiments with established motion of sediment, rather than the commonly used Shields curve, but the results are comparable in the range $4 < D_{gr} < 60$.

The following references are to be inserted in the list of references beginning on page 33 of Davidson and Amos (1985):

ACKERS, P. and W.R. WHITE. 1973. Sediment transport; new approach and analysis. J. Hydraul. Div., Proc. ASCE, 99, No. HY11, p. 2041-2060.

SWART, D.H. and C.A. FLEMING. 1980. Longshore water and sediment movement. Proc. 17th Coastal Engrg. Conf., p. 1275-1294.

The following symbols are to be inserted in the list of symbols beginning on page iii of Davidson and Amos (1985):

A_{gr} - value of F_{gr} at nominal initial motion

C - coefficient in sediment transport function

D_{gr} - dimensionless grain size

E_f - sediment transport efficiency

F_{gr} - sediment mobility number

m - exponent in sediment transport function

n - transition exponent depending on sediment size

P_{cg} - stream power for coarse sediment

P_{fg} - stream power for fine sediment

R_{gr} - Reynolds number based on mean shear stress at incipient motion

s - specific gravity of sediment

v_{*cg} - shear velocity for coarse sediment

v_{*fg} - shear velocity for fine sediment

α - coefficient in rough-turbulent equation

τ_{cg} - shear stress for coarse grains

τ_{fg} - shear stress for fine grains

The definition of the symbol V in the list of symbols should be modified to read:

V - mean flow velocity used in Engelund-Hansen method and Ackers-White method for calculating sediment transport.

REFERENCES

ACKERS, P. 1972. Sediment Transport in Channels: An Alternative Approach. Report INT 102, Hydraulics Research Station, Wallingford, England.

ACKERS, P. and W.R. WHITE. 1973. Sediment transport: new approach and analysis. J. Hydraul. Div., Proc. ASCE, Vol. 99, No. HY11, pp. 2041-2060.

AMOS, C.L. 1986. Extension of the Environmental Studies Revolving Fund Sediment Tracer Experiment, Atlantic Geoscience Centre Report (in preparation).

BAGNOLD, R.A. 1963. Mechanics of marine sedimentation. In: The Sea, M.H. Hill (ed.) Publ. Wiley-Interscience, New York, N.Y.: 507-582.

BIJKER, E.W. 1968. Littoral Drift as Function of Waves and Currents, Proceedings of the 11th International Conference on Coastal Engineering, pp. 415-434.

BROWN, C.B. 1950. In Rouse H., ed., Engineering Hydraulics, Publ. John Wiley and Sons, N.Y.: 1039 pp.

BROWN, C.B. 1950. Sediment transportation. In: Engineering Hydraulics. H. Rouse (ed.), John Wiley and Sons, New York, N.Y. pp. 769-857.

DAVIDSON, S.H. and C.L. AMOS. 1985. A re-evaluation of SED1D and SED2D: Sediment transport models for the Continental Shelf. Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia.

ENGELUND, F. and E. HANSEN. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen, Denmark.

GRANT, W.D. and GLENN, S.M. 1983. Continental Shelf Bottom Boundary Layer Model. Final Report to American Gas Association, 3 Vol.

GRANT, W.D. and O.S. MADSEN. 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res., 84(4): 1797-1808.

GRASS, A.J. 1970. Initial instability of fine bed sand. J. Hydraul. Div., Proc. ASCE, Vol. 96, No. HY3, pp. 619-632.

HUNTLEY, D.A., T.M. CHRISS and D.G. HAZEN. 1986. Seabed stresses in combined wave and steady flow conditions of the Nova Scotia continental shelf; field measurements and an assessment of predictability. Unpublished Report Submitted to Geol. Surv. Canada, Dartmouth, N.S. 49 p.

JONSSON, E.G. 1966. Wave boundary layers and friction factors. Proc. Coastal Eng. Conf. 10th,: 127-148.

MARTEC LIMITED. 1982. Sediment transport on a continental shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-1-M571, 91 pp.

REFERENCES

MARTEC LIMITED. 1983. A 2-D sediment transport model for continental shelves. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-2-M777, 63 pp.

MARTEC LIMITED. 1984. SED1D: A Sediment Transport Model for the Continental Shelf. Unpublished report submitted to the Geological Survey of Canada. DSS Contract 10SC.23420-3-M753.

MILLER, M.C., J.N. McCAVE and P.D. KOMAR. 1977. Threshold of sediment motion under unidirectional currents. Sedimentology, 24: 507-527.

NEILL, C.R. 1967. Mean velocity criterion for scour of coarse uniform bed-material. Proc. 12th Conf. Int. Assoc. Hydraul. Res., Vol. 3, pp. 46-54.

NIELSON, P. 1979. Some basic concepts of wave sediment transport. Inst. Hydrodynamics and Hydaulic Eng., Tech. Univ. of Denmark, Sed. Paper 20.

SEACONSULT MARINE RESEARCH LTD. 1985. Field Measurements of Sediment Transport on the Scotian Shelf. Volume 1 The Radio-Isotope Experiment. Submitted to ESRF/COGLA, Ottawa.

STERNBERG, R.W. 1972. Predicting initial motion and bedload transport of sediment particles in the shallow marine environment. In: Shelf Sediment Transport, Process and Pattern, D.J.P. Swift, D.B. Duane and O.H. Pilkey (eds.), Publ. Dowden, Hutchinson & Ross, Inc. 61-83.

SWART, D.H. and C.A. FLEMING. 1980. Longshore water and sediment movement. Proc. 17th Coastal Engrg. Conf., pp. 1275-1294.

WHITE, S.J. 1970. Plain bed thresholds for fine grained sediments. Nature, Vol. 228, No. 5267, pp. 152-153.

WILLIS, D.H. 1978. Sediment load under waves and currents. Proc. 16th Coastal Engrg. Conf., pp. 1626-1637.

YALIN, M.S. 1963. An expression for bedload transportation. J. Hydraul. Div., Proc. ASCE, Vol. 89, HY3, pp. 221-250.

UPGRADING OF AGC
SEDIMENT TRANSPORT MODEL

by

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March 31, 1987

Dr. Carl Amos
Atlantic Geoscience Centre
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, N.S.
B2Y 4A2

Dear Carl:

Please find enclosed two copies of the final report entitled "Upgrading of AGC Sediment Transport Model" under contract 23420-6-M887/01-OAE.

The report details the work carried out on the project, and specfically includes the following:

1. Incorporation of the Smith (1977) and Smith and McLean (1977) theories of sediment transport into SED1DF. The upgraded program is now given a new name: SED1DG.

2. An IBM-PC compatible version of the program is also produced and the following are provided in the enclosed diskette:

   Fortran Source Code
   Compiled Code
   Executable Code
   INSTALL.BAT

   To install the program on your PC, simply type, "A:INSTALL" at the C prompt.

3. An operator's manual is given in Appendix A of the report and sample runs and checkings in Appendix B and C.

We have enjoyed working on this project and look forward to further work with you and AGC. If you have any questions, please do not hesitate to contact Ron or myself. Thank you.

Yours truly,

MARTEC LIMITED

Ray

Dr. Ray Han

TO TRANSFER SED1DG FROM DISKETTE TO HARD DISK:

1. Insert diskette into Drive A:
2. Type A:INSTALL
   to create a directory /SEDTR and copy SED1DG.FOR, SED1DG.EXE, and SED1DG.OBJ to this directory.
3. When installation is complete remove diskette - you will be in C:/SEDTR.
4. To run SED1DG, type SED1DG and enter responses to prompts.
5. As a test run, the following responses can be used:

0	(No printing of values for manual checking)
1	(Interactive input)
TEST.OUT	(Filename for output)
1	(Run. No.)
20	(Water depth)
20 0 100	(Current speed, direction, height)
1 6 0	(Wave height, period, direction)
0.8 2.65 1.0	(Sediment grain size, density, fraction)
0	(Bottom roughness height)
1.025	(Fluid density)
1	(Engelund-Hansen formula)
2	(Smith method)
0	(To stop)

Results are saved in file TEST.OUT.

TABLE OF CONTENTS

1.0 INTRODUCTION

The sediment transport model of the Atlantic Geosciences Centre (AGC) has been modified to implement the theory and methodology of Smith (1977) to predict sediment transport under combined wave/current flows when currents dominate. Additional modifications were made to the input and output subroutines to upgrade the model as requested by AGC. During the program development, the calculations of the bottom friction factor and the suspended sediment transport were checked against longhand computations. As a further check, the upgraded model SED1DG was used to compute sediment transport rates by the Grant and Madsen (1979) method for wave/current flows when waves dominate. The results were then compared with results from the previous version SED1DF to ensure that the modifications did not alter the existing program logic. As a final check the friction factors and sediment transport computed using the Smith method were compared with those computed using the Grant and Madsen method for a wave-dominated flow condition.

The operational upgrade of the model has been developed to run on the BIO Cyber and on IBM compatible microcomputers. However, the Smith method requires the computation of Kelvin functions of arbitrary order and the evaluation of Fourier coefficients to obtain suspended sediment transport. Library subroutines that perform these calculations are not available on microcomputers or on the BIO Cyber. Consequently, subroutines were developed to perform these calculations and were include in the source code of SED1DG. During the program development, these subroutines were checked against tabulated values of the Kelvin functions (where available) and against Fourier coefficients for simple functions to verify the accuracy of the computations.

A discussion of the computation of Kelvin functions and Fourier coefficients and the documentation of the program checks is presented in Section 2.0. The theoretical background, description of the source code and documentation of the program checks for the Smith method are presented in Section 3.0. A user's manual for program SED1DG is provided in Appendix A and the manual checking of the calculations is described in Appendices B and C.

2.0 COMPUTATION OF MATHEMATICAL FUNCTIONS

2.1 Calculation of Kelvin Functions of Arbitrary Order

Kelvin functions are defined in terms of Bessels and Modified Bessels functions as follows:

$$\begin{aligned}\operatorname{ber}_\nu x+i\operatorname{bei}_\nu x&=J_\nu(xe^{3\pi i/4})=e^{\nu\pi i}J_\nu(xe^{-\pi i/4})\\&=e^{\frac{1}{2}\nu\pi i}I_\nu(xe^{\pi i/4})=e^{3\nu\pi i/2}I_\nu(xe^{-3\pi i/4})\end{aligned} \tag{2.1}$$

and

$$\begin{aligned}\operatorname{ker}_\nu x+i\operatorname{kei}_\nu x&=e^{-\frac{1}{2}\nu\pi i}K_\nu(xe^{\pi i/4})\\&=\tfrac{1}{2}\pi iH_\nu^{(1)}(xe^{3\pi i/4})=-\tfrac{1}{2}\pi ie^{-\nu\pi i}H_\nu^{(2)}(xe^{-\pi i/4})\end{aligned} \tag{2.2}$$

where ν is real, x is real and positive and n is a positive integer or zero. In general, Kelvin functions have a branch point at x=0 and individual functions with arguments $xe^{\pm\pi i}$ are complex. The branch point is absent however, in the case of ber_ν and bei_ν when ν is an integer. Further discussions and properties of these functions are given in Abramowitz and Stegun (p. 379-381). The computations of these functions of arbitrary order are conveniently divided into two categories: computation of integer-order, including the zeroth order functions, and computation of real non-zero order functions.

2.1.1 Kelvin Functions of Integer Order, Including Zero

Integer-order functions including the zeroth-order, may be computed using the following relationships:

$$\begin{aligned}\operatorname{ker}_n x = {} & \tfrac{1}{2}(\tfrac{1}{2}x)^{-n} \sum_{k=0}^{n-1} \cos\{(\tfrac{3}{4}n+\tfrac{1}{2}k)\pi\} \\ & \times \frac{(n-k-1)!}{k!} (\tfrac{1}{4}x^2)^k - \ln(\tfrac{1}{2}x) \operatorname{ber}_n x + \tfrac{1}{4}\pi \operatorname{bei}_n x \\ & + \tfrac{1}{2}(\tfrac{1}{2}x)^n \sum_{k=0}^{\infty} \cos\{(\tfrac{3}{4}n+\tfrac{1}{2}k)\pi\} \\ & \qquad \times \frac{\{\psi(k+1)+\psi(n+k+1)\}}{k!(n+k)!} (\tfrac{1}{4}x^2)^k\end{aligned} \tag{2.3a}$$

$$\begin{aligned}\operatorname{kei}_n x = {} & -\tfrac{1}{2}(\tfrac{1}{2}x)^{-n} \sum_{k=0}^{n-1} \sin\{(\tfrac{3}{4}n+\tfrac{1}{2}k)\pi\} \\ & \times \frac{(n-k-1)!}{k!} (\tfrac{1}{4}x^2)^k - \ln(\tfrac{1}{2}x) \operatorname{bei}_n x - \tfrac{1}{4}\pi \operatorname{ber}_n x \\ & + \tfrac{1}{2}(\tfrac{1}{2}x)^n \sum_{k=0}^{\infty} \sin\{(\tfrac{3}{4}n+\tfrac{1}{2}k)\pi\} \\ & \qquad \times \frac{\{\psi(k+1)+\psi(n+k+1)\}}{k!(n+k)!} (\tfrac{1}{4}x^2)^k\end{aligned} \tag{2.3b}$$

These expressions are quite straight forward and are easily programmable. It is of interest to note that the computation of integer-order functions of greater than 1 is not available in the IMSL math package.

2.1.2 Kelvin Functions of Real Non-zero Order

The computation of real non-zero order functions is considerably harder with very slow convergence rate. The equations given by Dungan Smith (Eqns. 64, p. 572) for computing ker and kei are incorrect as the arguments are now complex. They are therefore modified as follows:

by definition,

$$\mathrm{ker}_\nu x + i\,\mathrm{kei}_\nu x = \frac{\pi i}{2} H^{(1)}_\nu \left(xe^{\frac{3\pi i}{4}}\right)$$

but

$$H^{(1)}_\nu(z) = J_\nu(z) + iY_\nu\,(z)$$

$$= \{U^J_\nu(x,\psi) + U^Y_\nu(x,\psi)\} + i\,\{V^J_\nu(x,\psi) + V^Y_\nu\,(x,\psi)\}$$

where

$$U^J_\nu(x,\psi)\Big|_{\psi = \frac{3}{4}\pi} = \mathrm{ber}_\nu x$$

$$V^J_\nu(x,\psi)\Big|_{\psi = \frac{3}{4}\pi} = \mathrm{bei}_\nu x$$

and

$$U^Y_\nu(x,\psi)\Big|_{\psi = \frac{3}{4}\pi} = \frac{1}{\sin\nu\pi}\,(\mathrm{ber}_\nu x\,\cos\nu\pi - \mathrm{ber}_{-\nu} x)$$

$$V^Y_\nu(x,\psi)\Big|_{\psi = \frac{3}{4}\pi} = \frac{1}{\sin\nu\pi}\,(\mathrm{bei}_\nu x\,\cos\nu\pi - \mathrm{bei}_{-\nu} x)$$

Equating real and imaginary terms we have,

$$\mathrm{ker}_\nu x = \frac{-\pi}{2}\,\{V^J_\nu(x,\psi) + V^Y_\nu(x,\psi)\}$$

$$\mathrm{kei}_\nu x = \frac{\pi}{2}\,\{U^J_\nu(x,\psi) + U^Y_\nu(x,\psi)\}$$

and substituting for the U's and V's yields,

$$\mathrm{ker}_\nu x = \frac{\pi}{2\sin\nu\pi}\,(\mathrm{ber}_{-\nu} x - \cos\nu\pi\,\mathrm{ber}_\nu x - \sin\nu\pi\,\mathrm{bei}_\nu x)$$

$$\mathrm{kei}_\nu x = \frac{\pi}{2\sin\nu\pi}\,(\mathrm{bei}_{-\nu} x + \sin\nu\pi\,\mathrm{ber}_\nu x - \cos\nu\pi\,\mathrm{bei}_\nu x) \qquad (2.4)$$

Incidentially, the expressions given by Equations (2.4) agree with those depicted in Abramowitz and Stegun (p. 379).

2.2 Calculation of Fourier Coefficients

The Fourier coefficients in Dungan Smith's model can be evaluated using a fast Fourier transform technique. This technique is simply a very efficient procedure for organizing the computations of these coefficients defined as,

$$\alpha_k = \sum_{j=0}^{n-1} x_j \exp(i2\pi jk/n) \tag{2.5}$$

where k=0,1,..,(n-1). For example, it is quite easy to show that the direct calculation of these 2n coefficients takes approximately $(2n)^2$ multiplications and $(2n)^2$ additions. By efficient programming, the fast Fourier transform can reduce the number of operations to approximately 2nln(2n) operations. For small values of n, this change is perhaps not significant, but for large values of n (say n>1000), the saving is of at least an order of magnitude greater, and more importantly, the formerly impractical computations are now fairly easily handled.

2.2.1 Fourier Transform Algorithm

The mixed radix fast Fourier transform algorithm given here is due to Richard Singleton. It is actually based on the technique proposed by Cooley and Tukey. The dimension n of the transform is factored (if possible), and n/p elementary transform of dimension p are computed for each factor p of n. The number of complex multiplications for an elementary transform of dimension p is reduced by a 25% in this improved technique of Singleton's. Also, the algorithm includes a very efficient method for permuting the results in their normal order.

2.3 Program Checks

To assess the accuracies of the above programming, the following checks were performed. For Kelvin functions of integer-orders, the results are compared with the tabulated results of Abramowitz and Stegun, and for real-orders, an indirect check using the recurrence relationships is used.

They are,

$$f_{\nu+1}+f_{\nu-1}=-\frac{\nu\sqrt{2}}{x}(f_\nu-g_\nu)$$

$$f'_\nu=\frac{1}{2\sqrt{2}}(f_{\nu+1}+g_{\nu+1}-f_{\nu-1}-g_{\nu-1})$$

$$f'_\nu-\frac{\nu}{x}f_\nu=\frac{1}{\sqrt{2}}(f_{\nu+1}+g_{\nu+1})$$

$$f'_\nu+\frac{\nu}{x}f_\nu=-\frac{1}{\sqrt{2}}(f_{\nu-1}+g_{\nu-1})$$

where

$$\left.\begin{matrix}f_\nu=\mathrm{ber}_\nu\,x\\ g_\nu=\mathrm{bei}_\nu\,x\end{matrix}\right\}\qquad\left.\begin{matrix}f_\nu=\mathrm{bei}_\nu\,x\\ g_\nu=-\mathrm{ber}_\nu\,x\end{matrix}\right\}$$
$$\left.\begin{matrix}f_\nu=\mathrm{ker}_\nu\,x\\ g_\nu=\mathrm{kei}_\nu\,x\end{matrix}\right\}\qquad\left.\begin{matrix}f_\nu=\mathrm{kei}_\nu\,x\\ g_\nu=-\mathrm{ker}_\nu\,x\end{matrix}\right\}\tag{2.6}$$

For the fast Fourier transform, a sinusoidal function given by,

$$y_r=\frac{\sin\theta_j}{\theta_j},\qquad \theta j=j\frac{2\pi}{10}=\frac{j\pi}{5},$$
$$j=0,1,\ldots,9,\tag{2.7}$$

is used. The results of these checks show that the algorithms are correctly implemented. Further details on these assessments are now described.

2.3.1 Checks for Kelvin Functions

To check the computation of arbitrary-order, real or integer Kelvin functions, is not trivial. The reason is simply that, only the zeroth and first order Kelvin functions results are published. For integer orders >1 and for real positive or negative orders functions, published results are either extremely difficult to find or not available. Hence, the following method is used. For the algorithm generating integer orders, the zeroth and first orders are checked against Abramowitz and Stegun's table (p. 431). The results are tabulated in Table 2.1 below. For higher integer orders, the results are check if they obey the recurrence relationships. To check the algorithm generating real positive or negative orders, the computed results are check if they obey the recurrence relationships. Table 2.2 summarizes these checkings.

2.3.2 Checks for Fourier Coefficients

To check that Singleton's algorithm is correctly programmed, the following example is used. Let the data given by a sinusoidal function defined as,

$$y_r = \frac{\sin \theta_j}{\theta_j}, \qquad \theta j = j\frac{2\pi}{10} = \frac{j\pi}{5}, \qquad j = 0, 1, \ldots, 9, \tag{2.8}$$

be required. Note that for $j=0$, $y_0=1$. The results are summarized in Table 2.3, and they show that identical agreement is obtained. This is because the data obeys a sinusoidal variation.

TABLE 2.1

Comparison of Zeroth and First Orders Kelvin Functions.

		Abramowitz and Stegun (p. 431)	Computed
x = 0.7	$\mathrm{ker}_0 x$	0.56137 8274	0.56137 8268
	$\mathrm{kei}_0 x$	-0.60217 5451	-0.60217 5452
	$\mathrm{ker}_1 x$	-1.09407 2943	-1.09407 2941
	$\mathrm{kei}_1 x$	-0.59017 5251	-0.59017 5252
x = 1.3	$\mathrm{ker}_0 x$	0.12345 5395	0.12345 5389
	$\mathrm{kei}_0 x$	-0.39329 1826	-0.39329 1829
	$\mathrm{ker}_1 x$	-0.52321 5989	-0.52321 5984
	$\mathrm{kei}_1 x$	-0.06683 2622	-0.06683 2624
x = 2.7	$\mathrm{ker}_0 x$	-0.07097 3560	-0.07097 3561
	$\mathrm{kei}_0 x$	-0.08342 1858	-0.08342 1869
	$\mathrm{ker}_1 x$	-0.08580 8451	-0.08580 8442
	$\mathrm{kei}_1 x$	0.08991 5810	0.08991 5811
x = 4.00	$\mathrm{ker}_0 x$	-0.03617 8848	-0.03617 8839
	$\mathrm{kei}_0 x$	0.00219 8399	0.00219 8384
	$\mathrm{ker}_1 x$	0.00535 1296	0.00535 1309
	$\mathrm{kei}_1 x$	0.03916 6011	0.03916 6028

TABLE 2.2

Comparison of Integer Orders >1 and Real Positive or Negative Orders Kelvin Functions

Recurrence Relationship: $f_{\nu+1} + f_{\nu-1} = \frac{\nu\sqrt{2}}{x} (f_\nu - g_\nu)$ (Eqn 2.6)

	x	ν	$f_{\nu+1}$	$f_{\nu-1}$	f_ν	g_ν	L.H.S.	R.H.S.	Status
Integer Orders >1	0.3	2	207.13078	-2.47074	0.49140	22.19887	204.66004	204.66002	O.K.
	1.3	5	-67.05854	-16.56325	80.27715	64.90347	-83.62179	-83.62178	O.K.
	10.2	12	0.02968	-0.02171	0.03325	0.03804	0.007972	0.007970	O.K.
Real Orders	0.5	0.3	-2.63214	1.35987	0.44954	-1.04983	-1.27227	-1.27226	O.K.
	1.5	1.3	0.93256	-0.11020	-0.40515	0.26546	0.82236	0.82193	O.K.
	2.5	-0.5	-0.13283	0.11760	0.02650	-0.13283	0.04477	0.04507	O.K.

TABLE 2.3

Comparison of Exact and Fast Fourier Transform Results of a Sinusoidal Function.

No.	Exact	Computed	Percent Difference
1	1.000000	1.000000	0.00
2	0.935489	0.935489	0.00
3	0.756827	0.756827	0.00
4	0.504551	0.504551	0.00
5	0.233872	0.233872	0.00
6	0.000000	0.000000	0.00
7	-0.155915	-0.155915	0.00
8	-0.216236	-0.216236	0.00
9	-0.189207	-0.189207	0.00
10	-0.103943	-0.103943	0.00

REFERENCES

Abramowitz, M. and I.A. Stegun. 1964. Handbook of mathematical functions with formulas, graphs and mathematical tables. Dover, New York.

Smith, J.D. 1977. Modeling of sediment transport on continental shelves. In: The Sea, Vol. 6, Wiley-Interscience, New York.

Singleton, R.C. 1969. An algorithm for computing the mixed radix fast fourier transform. IEEE Trans. Audio Electracoustics No. 2.

3.0 UPGRADING OF SEDIMENT TRANSPORT MODEL

3.1 Theoretical Background for Smith (1977) Method

3.1.1 Boundary Shear Stress in Waves and Currents

The Smith method for computing the boundary shear stress in combined wave/current flows where currents dominate is described in the paper by Smith (1977). In order to implement this method in the AGC sediment transport model, the boundary shear stress determined by the Smith method must be converted to a wave-current friction factor that can be used in lieu of that computed by the Grant and Madsen method.

However, the paper by Smith does not give expressions for the maximum velocity and boundary shear stress under waves and currents, which are needed to compute the bottom friction factor. An expression for the time varying total velocity in the vicinity of the seabed is also not provided. Expressions for these variables that could be used in the sediment transport model and were consistent with Smith's theory were derived prior to modifying the sediment transport model. These expressions are summarized in this section and some of the equations from Smith (1977) are repeated to identify the equations in that paper that are used in SED1DG. The detailed derivations of the equations presented here are not included in this report, since this is beyond the intended scope of the work.

The equation governing uniform flow in the vicinity of the seabed due to a combination of wind waves and quasi-steady currents is

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z} K(z) \frac{\partial u}{\partial z} \qquad (3.1)$$

with the boundary conditions

$$u \rightarrow u_\infty(t) \qquad \text{as } z \rightarrow \infty \qquad (3.2a)$$

$$u \rightarrow 0 \qquad \text{as } z \rightarrow z_0 \qquad (3.2b)$$

where u is the fluid velocity, p is the pressure, ρ is the fluid density and K(z) is the kinematic eddy viscosity.

The momentum equation can be separated into two parts for the steady and unsteady components, respectively

$$0 = \frac{\partial}{\partial z} K(z) \frac{\partial u_1}{\partial z} \qquad (3.3)$$

$$\frac{\partial u_2}{\partial t} = \frac{\partial U_\infty}{\partial t} + \frac{\partial}{\partial z} K(z) \frac{\partial u_2}{\partial z} \qquad (3.4)$$

where $u = u_1 + u_2$ and $U_\infty(t)$ is the oscillatory velocity outside the boundary layer.

(a) Steady Component

When the flow consists of a steady component alone, a solution of equation (3.3) is obtained by assuming a kinematic eddy viscosity of the form

$$K(z) = k\, u_{*1}\, z \qquad (3.5)$$

where k is von Karman's constant and u_{*1} is the shear velocity for the the steady component.

The solution is

$$u_1 = \frac{u_{*1}}{k} \ln \frac{z}{z_0} \qquad (3.6)$$

where z_0 is the roughness length.

(b) Unsteady Component

When the flow consists of an unsteady component alone, a solution of equation (3.4) is obtained by assuming an eddy viscosity of the form

$$K(z) = k(u_{*2})_m \tag{3.7}$$

and $(u_{*2})_m$ is the shear velocity for the unsteady component. The solution is in terms of zero order Kelvin functions ker and kei (Bessel functions of complex argument). The solution for the velocity is

$$u_2 = U_o \Big[\cos\omega t - \frac{(\mathrm{ker}\xi)(\mathrm{ker}\xi_o) + (\mathrm{kei}\xi)(\mathrm{kei}\xi_o)}{\mathrm{ker}^2\xi_o + \mathrm{kei}^2\xi_o} \cos\omega t - \frac{(\mathrm{ker}\xi)(\mathrm{kei}\xi_o) - (\mathrm{kei}\xi)(\mathrm{ker}\xi_o)}{\mathrm{ker}^2\xi_o + \mathrm{kei}^2\xi_o} \sin\omega t\Big] \tag{3.8}$$

where

$$\xi = 2(\omega z/K_o)^{1/2} \tag{3.9a}$$

$$\xi_o = 2(\omega z_o/K_o)^{1/2} \tag{3.9b}$$

$$K_o = k(u_{*2})_m \tag{3.9c}$$

and ω is the wave frequency.

(c) Combined Flow

The eddy viscosity for each independent component is assumed to increase linearly with distance from the boundary in the region immediately above the seabed. When the flow consists of a combination of a steady and an unsteady component, the eddy viscosity produced by the shear of the combined motions is assumed to be equivalent to that based on the sum of the two shear velocities

$$K(z) = k[u_{*1} + (u_{*2})_m]z \tag{3.10}$$

Solutions to (3.3) and (3.4) can be found using the combined eddy viscosity.

The solution for the steady component of the combined flow in the vicinity of the seabed is

$$u_1 = \frac{(u_*)_1}{k} \left[1 + \frac{(u_{*2})_m}{(u_*)_1}\right]^{-1} \ln \frac{z}{z_0} \tag{3.11}$$

The solution for the unsteady component of the combined flow in the vicinity of the seabed is

$$u_2 = u_0\Big[\cos\omega t - \frac{(\mathrm{ker}\xi)(\mathrm{ker}\xi_0) + (\mathrm{kei}\xi)(\mathrm{kei}\xi_0)}{\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0} \cos\omega t$$

$$- \frac{(\mathrm{ker}\xi)(\mathrm{ker}\xi_0) - (\mathrm{kei}\xi)(\mathrm{kei}\xi_0)}{\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0} \sin\omega t\Big] \tag{3.12}$$

where

$$\xi = 2(\omega z/K_0)^{1/2} \tag{3.13a}$$

$$\xi_0 = 2(\omega z_0/K_0)^{1/2} \tag{3.13b}$$

$$K_0 = k[u_{*1} + (u_{*2})_m] \tag{3.13c}$$

The total velocity in the vicinity of the seabed is

$$u = \frac{(u_*)_1}{k} \left[1 + \frac{(u_{*2})_m}{(u_*)_1}\right]^{-1} \ln \frac{z}{z_0}$$

$$+ U_0\Big[\cos\omega t - \frac{(\mathrm{ker}\xi)(\mathrm{ker}\xi_0) + (\mathrm{kei}\xi)(\mathrm{kei}\xi_0)}{\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0} \cos\omega t$$

$$- \frac{(\mathrm{ker}\xi)(\mathrm{kei}\xi_0) - (\mathrm{kei}\xi)(\mathrm{ker}\xi_0)}{\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0} \sin\omega t\Big] \tag{3.14}$$

This velocity reaches a maximum when

$$\frac{\partial u}{\partial t} = 0 \tag{3.15}$$

or,

$$t_{max} = \frac{1}{\omega} \tan^{-1} \frac{F_2(\xi,\xi_o)}{1-F_1(\xi,\xi_o)} \tag{3.16}$$

and the maximum velocity is

$$u_{max}(z) = \frac{(u_*)_1}{k} \left[1 + \frac{(u_{*2})_m}{(u_*)_1}\right]^{-1} \ln \frac{z}{z_o}$$

$$+ U_o[\cos\omega t_{max} - F_1(\xi,\xi_o)\cos\omega t_{max} + F_2(\xi,\xi_o)\sin\omega t_{max}] \tag{3.17}$$

where

$$F_1(\xi,\xi_o) = \frac{(\mathrm{ker}\,\xi)(\mathrm{ker}\,\xi_o) + (\mathrm{kei}\,\xi)(\mathrm{kei}\,\xi_o)}{\mathrm{ker}^2\xi_o + \mathrm{kei}^2\xi_o} \tag{3.18a}$$

$$F_2(\xi,\xi_o) = -\frac{(\mathrm{ker}\,\xi)(\mathrm{kei}\,\xi_o) - (\mathrm{kei}\,\xi)(\mathrm{ker}\,\xi_o)}{\mathrm{ker}^2\xi_o + \mathrm{kei}^2\xi_o} \tag{3.18b}$$

Since the boundary shear stress is

$$\tau_b = \rho K \frac{\partial u}{\partial z}\bigg|_{z = z_o} = \rho u_*^2 \tag{3.19}$$

where

$$K = K_o z \tag{3.20}$$

Then

$$\frac{u_*^2}{K_o z_o} = \frac{\partial u_2}{\partial z}\bigg|_{z_o} \tag{3.21}$$

By differentiating u and setting $z=z_o$, the shear velocity can be written as

$$u_* = \{\frac{K_o u_{*1}}{k} [\frac{1 + u_{*2m}}{u_{*1}}]^{-1}$$

$$+ \frac{K_oU_o \xi_o}{2} \{[F'_1(\xi_o)]^2 + [F'_2(\xi_o)]^2\}^{1/2} \cos[\omega t + \tan^{-1}(\frac{F'_2(\xi_o)}{F'_1(\xi_o)})]]\}^{1/2}$$

$$(3.22)$$

where

$$F'_1\,(\xi_0) = \frac{(\mathrm{ker}_1\xi_0 + \mathrm{kei}_1\xi_0)\mathrm{ker}\xi_0 + (\mathrm{kei}_1\xi_0 - \mathrm{ker}_1\xi_0)\ \mathrm{kei}\xi_0}{\sqrt{2}\ (\mathrm{ker}^2\xi_0 + \mathrm{kei}_2\xi_0)} \tag{3.23a}$$

$$F'_2\,(\xi_0) = \frac{-\ (\mathrm{ker}_1\xi_0 + \mathrm{kei}_1\xi_0)\mathrm{kei}\xi_0 + (\mathrm{kei}_1\xi_0 - \mathrm{ker}_1\xi_0)\ \mathrm{kei}\xi_0}{\sqrt{2}\ (\mathrm{ker}^2\xi_0 + \mathrm{kei}_2\xi_0)} \tag{3.23b}$$

The maximum shear velocity occurs when

$$\cos\left[\omega t + \tan^{-1}\frac{F'_2(\xi_0)}{F'_1(\xi_0)}\right] = 1 \tag{3.24}$$

The maximum shear velocity is

$$(u_*)_m = \{\frac{K_0\ u_{*1}}{k}\left[1+\frac{(u_{*2})_m}{u_{*1}}\right]^{-1} + \frac{U_0K_0\xi_0}{2}\ \{[(F'_1(\xi_0)^2 + (F'_2(\xi_0)^2]\}^{1/2}\}^{1/2} \tag{3.25}$$

and the maximum boundary shear stress is

$$(\tau_b)_m = \rho\ \{\ \frac{K_0\ u_{*1}}{k}\ \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1} + \frac{K_0U_0\xi_0}{2}\ \{[F'_1(\xi_0)]^2 + [F'_2(\xi_0)]^2\}^{1/2}\ \} \tag{3.26}$$

Assuming a quadratic drag law, the friction factor is

$$f_{cw} = \frac{2(\tau_b)_m}{\rho(u)^2_m} \tag{3.27}$$

3.1.2 Suspended Sediment Transport in Waves and Currents

The Smith method for computing the suspended load transport in combined wave/current flows where currents dominate is described in the paper by Smith (1977). The concentration field of suspended sediment is computed for each of the important size and specific gravity classes of the bed material. Once the suspended sediment concentration field is determined for each sedimentary component, it can be added to all the others, multiplied by the velocity and integrated over the water depth to give the volume flux of suspended sediment.

Since the AGC sediment transport model allows the user to do multiple runs, the Smith method was implemented assuming that only one sedimentary component is present for each run. If more than one component is present then additional runs should be made and the results added together to obtain the total volume flux of suspended sediment.

The paper by Smith does not give an expression for the volume flux of sediment and does not provide details on appropriate methods of integration to be used. Since some of the parameters used in the method are not defined in the paper, certain assumptions were made based on an interpretation of the text to define these parameters. These parameters are defined in this section and some of the equations from Smith (1977) are repeated to identify the equations in that paper that are used in SED1DG. The detailed derivations of the equations summarized in this section are not included in this report, since this is beyond the intended scope of the work.

The concentration field of suspended sediment is derived from equations expressing conservation of mass for each size and specific gravity class plus an additional equation for the transporting fluid. Conservation of mass yields N equations of the form

$$\frac{\partial \epsilon_n}{\partial t} + \nabla (u_n \epsilon_n) = 0 \tag{3.28}$$

where ϵ_n is the instantaneous volume concentration of sediment in class n and U_n is the instantaneous velocity of this material. Averaging each of these equations over time, approximating the turbulent mass fluxes by gradient type diffusion and assuming the flow to be horizontally uniform yields N equations of the form

$$\frac{\partial \bar{\epsilon}_n}{\partial t} = \frac{\partial}{\partial z} \left[-\bar{w}_n \bar{\epsilon}_n + K_n \frac{\partial \bar{\epsilon}_n}{\partial z} \right] \tag{3.29}$$

where K_n is the eddy diffusion coefficient and w_n is the vertical velocity of the material. Assuming the sediment velocity equal to the fluid velocity u_w minus the settling velocity of the sediment w_n

$$u_n = u_w - w_n \tag{3.30a}$$

or

$$w_n = -W_n \tag{3.30b}$$

yields a set of equations of the form

$$\frac{\partial \bar{\epsilon}_n}{\partial t} = \frac{\partial}{\partial z} \left(w_n \bar{\epsilon}_n + K(z) \frac{\partial \bar{\epsilon}_n}{\partial z} \right) \tag{3.31}$$

Assuming an eddy viscosity

$$K = K_o \, z \tag{3.32}$$

and defining

$$d\nu = K_o \, dt \tag{3.33}$$

and

$$p_n = w_n / K_o \tag{3.34}$$

yields a set of equations

$$\frac{\partial \bar{\epsilon}_n}{\partial \nu} = \frac{\partial}{\partial z} \left[p_n \, \bar{\epsilon}_n + z \frac{\partial \bar{\epsilon}_n}{\partial z} \right] \tag{3.35}$$

A separable solution with a sinusoidal time variation can be found in terms of Kelvin functions of order p_n. When the sediment concentration at a reference level $z = z_a$ oscillates sinusoidally with time around a mean value and the boundary layer is of infinite depth, the concentration field is

$$\bar{\epsilon}_n = \bar{\epsilon}_{cn}\left[\frac{\xi_a}{\xi}\right]^{2p_n} + \left[\bar{\epsilon}_{\omega n}\frac{\xi_a}{\xi}\right]^{p_n}\left[\frac{(\mathrm{ker}_{p_n}\xi)(\mathrm{ker}_{p_n}\xi_a)+(\mathrm{kei}_{p_n}\xi)(\mathrm{kei}_{p_n}\xi_a)}{\mathrm{ker}^2{}_{p_n}\xi_a + \mathrm{kei}^2{}_{p_n}\xi_a}\cos\omega t\right.$$

$$\left. + \frac{(\mathrm{ker}_{p_n}\xi)(\mathrm{kei}_{p_n}\xi_a)-(\mathrm{kei}_{p_n}\xi)(\mathrm{ker}_{p_n}\xi_a)}{\mathrm{ker}^2{}_{p_n}\xi_a + \mathrm{kei}^2{}_{p_n}\xi_a}\right]\sin\omega t$$

$$= \bar{\epsilon}_{cn}\left[\frac{Z_a}{Z}\right]^{p_n} + \bar{\epsilon}_{\omega n}\left[\frac{Z_a}{Z}\right]^{p_n/2}\left[F_1(\xi;\xi_a,p_n)\cos\omega t + F_2(\xi;\xi_a,p_n)\sin\omega t\right]$$

(3.36)

where $\bar{\epsilon}_{cn}$ is the mean value of concentration at $z = z_a$, $\bar{\epsilon}_{\omega n}$ is the amplitude of the sinusoidal variation, ω is the frequency of this temporal oscillation, and

$$\xi = 2(\omega z/K_o)^{1/2} \tag{3.37a}$$

$$\xi_a = 2(\omega z_a/K_o)^{1/2} \tag{3.37b}$$

$$K_o = k[u_{*1} + (u_{*2})_m] \tag{3.37c}$$

the definitions for functions $F_1(\xi;\xi_a,p_n)$ and $F_2(\xi;\xi_a,p_n)$ are

$$F_1(\xi;\xi_a,p_n) = \frac{(\mathrm{ker}_{p_n}\xi)(\mathrm{ker}_{p_n}\xi_a)+(\mathrm{kei}_{p_n}\xi)(\mathrm{kei}_{p_n}\xi_a)}{\mathrm{ker}^2{}_{p_n}\xi_a + \mathrm{kei}^2{}_{p_n}\xi_a}$$

(3.38a)

$$F_2(\xi;\xi_a,p_n) = \frac{(\mathrm{kei}_{p_n}\xi)(\mathrm{kei}_{p_n}\xi_a)-(\mathrm{kei}_{p_n}\xi)(\mathrm{kei}_{p_n}\xi_a)}{\mathrm{ker}^2{}_{p_n}\xi_a + \mathrm{kei}^2{}_{p_n}\xi_a}$$

(3.38b)

The result in (3.36) can be generalized to give the suspended sediment concentration field for any size and specific gravity class not interacting with any other above $z = z_a$ as long as p_n is constant with respect to time. The generalized concentration field is

$$\bar{\epsilon}_n(z_a,t) = \left[\frac{z_a}{z}\right]^{p_n} A_o + \left[\frac{z_a}{z}\right]^{p_n/2} \Big\{ \sum_{m=1}^{\infty} A_m [F_1(\xi;\xi_a,p_n)_m \cos\omega_m t + F_2(\xi;\xi_a,p_n)_m \sin\omega_m t]$$

$$+ \sum_{m=1}^{\infty} B_m \; F_1(\xi;\xi_a,p_n)_m \sin\omega_m t + F_2(\xi;\xi_a,p_n)_m \cos\omega_m t \tag{3.39}$$

The coefficients A_o, A_m and B_m are the Fourier coefficients obtained by expressing the concentration of sediment in class n at $z = z_a$ as a Fourier series. At $z = z_a$, the concentration of sediment is

$$\bar{\epsilon}_n(z_a,t) = A_o + \sum_{m=1}^{\infty} (A_m \cos\omega_m t + B_m \sin\omega_m t) \tag{3.40}$$

Smith (1977) indicates that a means of finding $\epsilon_n(z_a,t)$ in terms of $(\tau_b/\tau_c - 1)$ is described earlier in the paper. Equation (3.40) can be written as

$$\gamma_n \left[\frac{\tau_b}{\tau_c} - 1\right] = A_o + \sum_{m=1}^{\infty} (A_m \cos\omega_m t + B_m \sin\omega_m t) \tag{3.41}$$

The constant γ_n is not defined, but it is described as "a constant times the fraction of material in class n available at the seabed for transport". In a previous discussion of the Yalin bedload equation, the concentration field at $z = z_a$ is given as

$$\epsilon_a = \gamma_Y \, S \tag{3.42}$$

and the parameter S was previously defined as the normalized excess shear stress

$$S = \frac{\tau_t}{\tau_c} - 1 \tag{3.43}$$

The parameter γ_Y is not defined, however, Yalin (1963) assumes that the number of grains lifted from the surface of the bed increases proportionally with the dimensionless excess tractive force and determines the value of the constant to be 0.635, based on experimental data. Assuming that

$$\gamma_\gamma = 0.635 \qquad (3.44)$$

and defining the fraction of material in class n as f_n, the definition of γ_n is

$$\gamma_n = f_n \gamma_\gamma \qquad (3.45)$$

The boundary shear stress is computed using the method described in Section 3.2.1 and the critical shear stress can be obtained from the Shield's diagram to determine the concentration field at $z = z_a$. A fast Fourier transform can be applied to this time function to compute the Fourier coefficients which are used in (3.39) to compute the suspended sediment concentration field.

The concentration field $\epsilon_n(z,t)$ is multiplied by the velocity field $u(z,t)$ which is computed as described in Section 3.2.1. The volume flux of suspended sediment is then determined by averaging over time and integrating from z_0 to the water surface at $z = h$.

In the SED1DG model, the integration is performed with an upper limit of $z = z_a$ since the expression for the concentration field is valid within the boundary layer. It is not clear from Smith's paper how the concentration field outside the boundary layer is evaluated. Dr. Smith was contacted and asked to clarify this point, however no reply has been received to date.

3.2 Program Modifications for Smith (1977) Method

3.2.1 Calculation of Bottom Friction Factor

Subroutine READIN was modified to allow the user to select either the Grant and Madsen or the Smith method to compute the bottom friction factor for combined wave/current flows. Subroutine FRICFAC was modified to call a new subroutine FRIC4 if the user selected the Smith option. The bottom friction factor based on the Smith method is used to compute threshold velocities and sediment transport in subroutines THRESH and TRANSPO, respectively. Subroutine OUTOUT was modified to print a message indicating that the friction factor was computed using the Smith method.

In subroutine FRIC4, the shear velocities for the unsteady and steady components alone are computed and these parameters are used to calculate the maximum shear stress and maximum velocity for the combined flow. The bottom friction factor for combined waves and currents is then computed from the quadratic drag law.

The wave-induced bottom particle velocity just above the seabed is computed in subroutine OSCILL and passed into FRIC4 as Uo, and the wave frequency is computed from the wave period. An initial guess is made for the roughness length z_0. If only skin friction is considered, an initial estimate of 1.0×10^{-3} cm is recommended by Smith (1977).

An iterative procedure described by Smith (1977) is then used to compute $(u_{*2})_m$ for the unsteady component. The dimensionless parameter $(\omega z_0/U_0)$ is computed and the value of (K_0/U_0) is found from the graph in Figure 5 of Smith (1977), which is a plot of (Ko/Uo) = $F3(\omega z_0/U_0)$. Since the function $F3(\omega z_0/U_0)$ is not provided by Smith (1977), a set of 28 points was read from the graph to define the function F3. A cubic spline interpolation is then used to determine (K_0/U_0) for the computed value of $(\omega z_0/U_0)$.

Since $K_0 = k(u_{*2})_m$, the shear velocity for the unsteady component is computed as

$$(u_{*2})_m = \frac{U_0}{K} \quad \frac{K_0}{U_0} \tag{3.46}$$

The Reynolds number is calculated as

$$R_* = \frac{(u_{*2})_m k_s}{\nu} \tag{3.47}$$

where ν is the kinematic viscosity and ks is the grain diameter. A new estimate of z_0 is found from Fig. 1 of Smith (1977), which is a plot of (z_f/k_s) as a function of R*. Although an expression is given for this function for hydraulically rough and hydraulically smooth flows, no expression is given for hydraulically transitional flows. A set of 14 data points was read from this graph and a cubic spline interpolation is used to find (z_f/k_s) for the computed value of R*. A new value of (z_0/U_0) is computed using $z_0 = z_f$ and the iteration is repeated until $((u_{*2})m/U_0)$ converges.

The calculation of u*1 for the steady component is based on the method of calculation previously used in the sediment transport model. For steady flows, a constant friction factor based on the work of Sternberg (1971) is used. Assuming a quadratic drag law, the shear velocity for the steady component is

$$u_{*1} = \sqrt{\frac{f_c}{2}}\; u_1 \tag{3.48}$$

The eddy viscosity is computed from equation (3.10) and ξ_0 is computed from equation (3.13b),using the final estimate of zo. The functions $F'_1(\xi,\xi_0)$ and $F'_2(\xi,\xi_0)$ are computed from (3.23a) and (3.23b) and the maximum boundary shear stress is computed from (3.26).

The maximum velocity for the combined flow is computed at the top of the wave boundary layer $\delta_z = \delta_w$. The thickness of the wave boundary layer is estimated as

$$\delta_w = 0.03\,(U_0)/\omega \tag{3.49}$$

by Smith (1977). The functions $F_1(\xi,\xi_0)$ and $F_2(\xi,\xi_0)$ are computed from (3.18a) and (3.18b). The time at which the maximum velocity occurs is computed from (3.16) and the maximum velocity is computed from (3.17). The wave-current friction factor is computed from (3.27) and passed back to subroutine FRICFAC.

3.2.2 Calculation of Suspended Sediment Transport

Subroutine READIN was modified to allow the user to select the Smith (1977) method for computing suspended sediment transport as a sixth option. Since this method requires the fraction of material in each sediment size and specific gravity class, a value FRACT will be entered by the user. Only one sediment class will be considered in each run and the results will be summed to obtain the total volume flux of suspended sediment. If the Smith method is not selected, a value of 1.0 should be entered in response to the prompt.

Subroutine TRANSPO was modified to call a new subroutine CONCN if the Smith method for suspended load transport is selected, and a new function F9Z was developed for use in the depth integration. Subroutine OUTOUT was modified to print a message indicating that the Smith method for suspended sediment transport was used.

In subroutine CONCN, the concentration of sediment at $z = z_a$ is computed from the boundary shear stress computed in FRIC4 and the critical velocity for suspension of sediment computed in THRESH. The Fourier coefficients are then determined from the computed values using a fast Fourier transform. The concentration field of suspended sediment is multiplied by the velocity field and a time-averaging is performed by evaluating an analytical expression for the integral of this product over the time interval when suspension of sediment occurs in a half wave cycle The result is integrated over the water depth using a Romberg integration algorithm similar to that used in the previous version of the sediment transport model to determine the volume flux of suspended sediment.

The wave-induced bottom particle velocity just above the seabed is computed in subroutine OSCILL and passed into CONCN as $U_o = U_b$, and the wave frequency is computed from the wave period. The fall velocity for the particle is calculated using the formula previously used in the sediment transport model and the critical shear stress is computed from the critical velocity calculated in THRESH.

The fall velocity is divided by the eddy viscosity coefficient K_o computed in FRIC4 to obtain the value of the parameter p_n. The reference depth z_a is specified as twice the grain diameter by Smith (1977). The parameter ξ_a is computed from (3.37b) and the parameter ξ_o is computed from (3.13b). The functions $F_1'(\xi o)$ and $F_2'(\xi o)$ are then calculated from (3.23a) and (3.23b). The boundary shear stress can be obtained from (3.22) as

$$\tau_b = \rho\{\frac{K_o u_{*1}}{k} [1 + \frac{(u_{*2})_m}{u_{*1}}]^{-1} \frac{K_o U_o \xi_o}{2} \{F'_1(\xi_o)^2 + F'_2(\xi_o)^2\}^{1/2} \cos[\omega t + \tan^{-1} \frac{F_2(\xi_o)}{F_1(\xi_o)}]] \tag{3.50}$$

The concentration of sediment at $z = z_a$ is

$$\epsilon_n(z_a,t) = \gamma_n(\frac{\tau_b}{\tau_c} - 1)$$

$$= C1 + C2 \cos(\omega t + PHASE) \tag{3.51}$$

where

$$C1 = -\gamma_n + \frac{\gamma_n}{\tau_c} \rho \, K_o \frac{u_{*1}}{k} [1 + \frac{u_{*2m}}{u_{*1}}]^{-1} \tag{3.52a}$$

$$C2 = \frac{\gamma_n}{\tau_c} \rho \frac{K_o U_o \xi_o}{2} \{F'_1(\xi_o)^2 + F'_2(\xi_o)^2\}^{1/2} \tag{3.52b}$$

$$PHASE = \tan^{-1} \frac{F'_2(\xi_o)}{F'_1(\xi_o)} \tag{3.52c}$$

The function $\epsilon_n(z_a,t)$ is evaluated at 50 time steps over a wave period and a fast Fourier transform is applied to this time function to determine the Fourier coefficients. These coefficients are used to evaluate the concentration field in the depth integration function F9Z. Subroutine CONCN calls the depth integration subroutine ROMBZ to integrate the product of the concentration field and the velocity field over the water depth from $z = z_0$ to $z = z_a$ using Romberg integration.

ROMBZ calls the function F9Z to evaluate an analytical expression for the time-averaged integral of the concentration field multiplied by the velocity field. The time-averaged integral can be written as

$$\begin{aligned}\frac{1}{T}\int_{t_1}^{t_2} u(z,t)\ \epsilon_n(z,t)\ dt = C3 + \frac{1}{T}\ &\Big\{C4 \sum_{m=1}^{\infty} [\mathrm{TRM12\ I3} + \mathrm{TRM21\ I4}] \\ &+ C5\ [D1\ I1 + D2\ I2] \\ &+ C6\ [D1(\mathrm{TRM12\ I5} + \sum_{m=2}^{\infty} \mathrm{TRM12\ I16}) + D2\ (\mathrm{TR21\ I7} + \sum_{m=2}^{\infty} \mathrm{TRM21\ I8}) \\ &+ D1(\mathrm{TR21\ I9} + \sum_{m=2}^{\infty} \mathrm{TRM21\ I10}) + D2(\mathrm{TRM12\ I9} + \sum_{m=2}^{\infty} \mathrm{TRM12\ I11})]\Big\} \Big|_{t_1}^{t_2}\end{aligned} \tag{3.53}$$

where

$$C3 = \frac{(u_{*1})}{K}\ \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1}\ \left[\ln \frac{z}{z_0}\right] \left[\frac{z_a}{z}\ \right]^{p_n}\ A_o \tag{3.54a}$$

$$C4 = \frac{(u_{*1})}{K}\ \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1}\ \left[\ln \frac{z}{z_0}\right] \left[\frac{z_a}{z}\right]^{p_n/2} \tag{3.54b}$$

$$C5 = \left[\frac{z_a}{z}\right]^{p_n}\ A_o\ U_o \tag{3.54c}$$

$$C6 = U_o\ \frac{z_a}{z}^{p_n\ /2}$$

$$D1 = 1 - F_1(\xi;\xi_o) \tag{3.54e}$$

$$D2 = F_2\ (\xi;\xi_o) \tag{3.54f}$$

$$\mathrm{TR12} = A_1\ F_1(\xi;\xi_a,p_n)_1 + B_1\ F_2(\xi;\xi_a,p_n)_1 \tag{3.54g}$$

$$TR21 = A_1\ F_2(\xi;\xi_a,p_n)_1 + B_1\ F_1(\xi;\xi_a,p_n)_1 \qquad (3.54h)$$

$$TRM12 = A_m F_1(\xi;\xi_a,p_n)_m + B_m\ F_2(\xi;\xi_a,p_n)_m \qquad (3.54i)$$

$$TRM21 = A_m F_2(\xi;\xi_a,p_n)_m + B_m\ F_1(\xi;\xi_a,p_n)_m \qquad (3.54j)$$

and the integrals to be evaluated at t_1 and t_2 are

$$I1 = (1/\omega)\sin\omega t \qquad (3.55a)$$

$$I2 = -(1/\omega)\cos\omega t \qquad (3.55b)$$

$$I3 = (1/m\omega)\sin m\omega t \qquad (3.55c)$$

$$I4 = -\ (1/m\omega)\cos m\omega t \qquad (3.55d)$$

$$I5 = (1/2)t + (1/4\omega)\sin 2\omega t \quad \text{for } m = n \qquad (3.55e)$$

$$I6 = \frac{\sin(m-1)\omega t}{2(m-1)\omega} + \frac{\sin(m+1)\omega t}{2(m+1)\omega} \quad \text{for } m^2 \neq n^2 \qquad (3.55f)$$

$$I7 = (1/2)t - (1/4\omega)\sin 2\omega t \quad \text{for } m = n \qquad (3.55g)$$

$$I8 = \frac{\sin(m-1)\omega t}{2(m-1)\omega} - \frac{\sin(m+1)\omega t}{2(m+1)\omega} \quad \text{for } m^2 \neq n^2 \qquad (3.55h)$$

$$I9 = (1/2\omega)\sin^2\omega t \quad \text{for } m = n \qquad (3.55i)$$

$$I10 = -\frac{\cos\ (m-1)\omega t}{2(m-1)\omega} - \frac{\cos(m+1)\omega t}{2(m+1)\omega} \quad \text{for } m^2 \neq n^2 \qquad (3.55j)$$

$$I11 = -\frac{\cos\ (1-m)\omega t}{2(1-m)\omega} - \frac{\cos(1+m)\omega t}{2(1+m)\omega} \quad \text{for } m^2 \neq n^2 \qquad (3.55k)$$

The functions $F_1(\xi,\xi_0)$ and $F_2(\xi,\xi_0)$ are computed from (3.18a) and (3.18b) and the functions $F_1(\xi;\xi_a,p_n)$ and $F_2(\xi;\xi_a,p_n)$ are computed from (3.38a) and (3.38b).

The function F9Z is integrated over the depth in subroutine ROMBZ and the result is passed back to subroutines CONCN and TRANSPO as the volume flux of suspended sediment. Since the time integration is performed over half a wave period, the result from ROMBZ is multiplied by a factor of two to give the sediment transport Q_x in the x-direction. The Smith theory considers only the codirectional flow case and the sediment transport in the y-direction is set equal to zero.

3.3 Additional Modifications

3.3.1 Modifications to Input

The main program and subroutine READIN were modified slightly to permit the option of batch processing for convenience during the program development phase of the work. If the batch processing option is selected, then the user enters the name of the data file to be read. The data file must contain the user responses to the prompts that are issued during the interactive sessions. Multiple runs can be included in a single data file.

In the previous version of the model SED1DF the user was requested to enter a value for Bagnold's coefficient of proportionality RK in subroutine TRANSPO. This code was moved to subroutine READIN so that all input data required for running the model would be read in this subroutine. The value of RK is passed to subroutine TRANSPO through the argument list.

Subroutine READIN was also modified to allow the user to select either the Grant and Madsen method or the Smith method for combined wave/current flows. The parameter OPT in SED1DF was changed to OPT1 in SED1DG and a new parameter OPT2 was defined to identify which of the two methods was selected. Parameter OPT2 is set equal to 1 if the Grant and Madsen method is selected and is set equal to 2 if the Smith method is selected. This parameter is passed to the other subroutines to control the selection of the computations to be performed.

Subroutine READIN was also modified to print warning statements when the grain size entered by the user is not compatible with the selected sediment transport formula. The user is given the option of either entering a different grain size or continuing with the calculations. Since the Smith method treats only the codirectional flow case, a warning message is printed when the waves and current are not in the same or opposing directions. The user must then enter a new value for the current direction which is the same as the wave direction to continue execution.

3.3.2 Modifications to Output

In the previous version of the model SED1DF, the ratio of the current speed to the maximum wave-induced bottom particle velocity was checked to determine if this ratio was greater than 1.0. A warning message was then printed to indicate that the Grant and Madsen method may not be appropriate. This section of the code was modified to perform this check and print this message only if IOPT2 = 1. If IOPT2 = 2, then the ratio is checked and if it is less than 1.0, a warning message is printed to indicate that the Smith method may not be appropriate.

Subroutine TRANSPO was modified to convert the sediment transport units from volume (cm^3/sec/cm) to mass (kg/sec/cm) in SI units. Since the volume units are useful for comparing the results of SED1DG with those from SED1DF during program development and checking, a new variable SEDM was defined for mass sediment transport. This variable is passed to subroutine OUTOUT and the sediment transport is printed in both mass and volume units in the output.

Bagnold's coefficient of proportionality RK was not printed in the output in previous versions of this model and this omission was found to be inconvenient during program checking. Subroutine OUTOUT was modified to print the value of Bagnold's coefficient RK in the output file. Subroutine OUTOUT was also modified to print a message in the output file to indicate when the Smith method was used to compute the bottom friction factor and the sediment transport.

3.4 PROGRAM CHECKS

3.4.1 Manual Checks of Bottom Friction Factor

The Smith method was used to compute bottom friction factors and time-averaged net sediment transport for current speeds of 20 and 30 cm/sec and grain sizes of 0.4 and 0.8 mm with waves of 1 m height and 6 sec period. The resulting bottom friction factors and sediment transport are shown in Table 3.1 with the input data for each run. Intermediate variables used in the calculation were checked against longhand calculations and the results are summarized in Table 3.2.

The calculation of z_0 and $(u_{*2})_m$ uses an iterative procedure, and a manual check of these calculations was performed only for Run No. 2. The iterative calculations were compared with those in SED1DG and relatively good argeement was found.

The values of z_0 and $(u_{*2})_m$ in SED1DG after the iteration converged were then used in longhand calculations of the remaining intermediate variables in all runs. The iterative calculations and the longhand calculations of the bottom friction factor for Run No. 2 are presented in Appendix B.

3.4.2 Manual Checks for Suspended Sediment Transport

The Smith method was used to compute suspended sediment transport for current speeds of 60 and 70 cm/sec and grain sizes of 0.2 and 0.3 mm with waves of 1 m height and 6 sec period. The resulting suspended sediment transport is shown in Table 3.3 with the input data for each run. Intermediate variables used in the calculation were checked against longhand calculations and the results are summarized in Table 3.4. The calculation of the suspended sediment tranport involves a calculation of the concentration of sediment at a reference level $z = z_a$ as a function

TABLE 3.1
SUMMARY OF BOTTOM FRICTION FACTOR COMPUTED BY SMITH METHOD FOR WAVES AND CURRENTS

	Run Number*			
	1	2	3	4
Input:				
Grain Size (mm)	0.4	0.4	0.8	0.8
Current Speed (cm/sec)	20.0	30.0	20.0	30.0
Output:				
Bottom Friction Factor	0.0179	0.0168	0.0193	0.0182
Time-averaged Net Sediment Transport Rate (cm^3/sec/cm) (Engelund-Hansen formula)	0.00185	0.01159	0.00092	0.00598

*Input Data for All Runs:

Water Depth (m)	20.0
Wave Height (m)	1.0
Wave Period (sec)	6.0
Wave Direction (deg)	0.0
Current Direction (deg)	0.0
Height above Bottom (cm)	100.0
Fluid Density (gm/cm^3)	1.025
Sediment Density (gm/cm^3)	2.65
Bottom Roughness (cm)	0.0

TABLE 3.2
SUMMARY OF MANUAL CHECKS OF BOTTOM FRICTION FACTOR FOR SMITH METHOD FOR WAVES AND CURRENT

					Run No.			
	Run No. 1		Run No. 2		Run No. 3		Run No.4	
Variable	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check
z_o (cm)	0.00154	*	0.00154	0.00155	0.00185	*	0.00185	*
$(u_{*2})_m$ (cm/sec)	0.9138	*	0.9138	0.9130	0.9426	*	0.9426	*
u_{*1} (cm/sec)	1.0954	1.0954	1.6432	1.6432	1.0954	1.0954	1.6432	1.6432
K_o (cm²/sec)	0.8037	0.8037	1.0228	1.0228	0.8152	0.8152	1.0343	1.0343
ξ_o	0.0897	0.0896	0.0795	0.0795	0.0974	0.0974	0.0865	0.0865
$F_1'(\xi_o)$	-4.0309	-4.0325	-4.3726	-4.3716	-3.8133	-3.8144	-4.1288	-4.1302
$F_2'(\xi_o)$	-1.1867	-1.1869	-1.2395	-1.2392	-1.1529	-1.1530	-1.2019	-1.1979
τ_{max} (gm/cm sec²)	2.9049	2.9038	4.8112	4.8107	2.9806	2.9795	4.8959	4.8951
δ_w (cm)	0.3092	0.3091	0.3092	0.3091	0.3092	0.3091	0.3092	0.3091
ξ	1.2695	1.2693	1.1254	1.1251	1.2605	1.2603	1.1191	1.1181
$F_1(\xi,\xi_o)$	0.0941	0.0941	0.1185	0.1186	0.1001	0.0983	0.1248	0.1248
$F_2(\xi,\xi_o)$	-0.1304	-0.1305	-0.1355	-0.1355	-0.1342	-0.1336	-0.1390	-0.1390
t_{max} (sec)	5.8634	5.8634	5.8543	5.8532	5.8586	5.8595	5.8496	5.8496
u_{max} (cm/sec)	17.79	17.79	23.62	23.61	17.36	17.37	22.93	22.93
f_{cw}	0.0179	0.0179	0.0168	0.0168	0.0193	0.0193	0.0182	0.0182

* Iterative calculations were manually checked only for Run No. 2 (See Appendix B)

TABLE 3.3
SUMMARY OF SUSPENDED SEDIMENT TRANSPORT COMPUTED BY SMITH METHOD FOR WAVES AND CURRENTS

	Run Number*			
	5	6	7	8
Input:				
Grain Size (mm)	0.2	0.2	0.3	0.3
Current Speed (cm/sec)	60.0	70.0	60.0	70.0
Output:				
Bottom Friction Factor	0.0148	0.0144	0.0148	0.0144
Suspended Sediment Transport (cm^3/sec/cm) (Smith formula)	1.647	2.517	1.510	3.026

*Input Data for All Runs:

Water Depth (m)	20.0
Wave Height (m)	1.0
Wave Period (sec)	6.0
Wave Direction (deg)	0.0
Current Direction (deg)	0.0
Height above Bottom (cm)	100.0
Fluid Density (gm/cm^3)	1.025
Sediment Density (gm/cm^3)	2.65
Fraction of Seabed Material	0.25
Bottom Roughness (cm)	0.0

TABLE 3.4
SUMMARY OF MANUAL CHECKS OF SUSPENDED SEDIMENT TRANSPORT FOR SMITH METHOD FOR WAVES AND CURRENT

	Run No.							
	Run No. 5		Run No. 6		Run No. 7		Run No. 8	
Variable*	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check
Tn	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159
τ_{cs} (gm/cm sec^2)	2.681	2.676	2.681	2.674	8.860	8.843	8.860	8.815
w (cm/sec)	2.022	2.022	2.022	2.022	3.675	3.675	3.675	3.675
p_n	1.2033	1.2036	1.0645	1.0648	2.1875	2.1875	1.9351	1.9532
ξ_a	0.3158	0.3158	0.2970	0.2970	0.3868	0.3868	0.3638	0.3638
ξ_o	0.0620	0.0620	0.0583	0.0583	0.0620	0.0620	0.0583	0.0583
$F_1'(\xi,\xi_o)$	-5.190	-5.191	-5.418	-5.420	-5.190	-5.191	-5.418	-5.420
$F_2'(\xi,\xi_o)$	-1.364	-1.363	-1.398	-1.398	-1.364	-1.363	-1.398	-1.398
C1	0.4967	0.4946	0.7334	0.7322	0.0396	0.0400	0.1112	0.1128
C2	0.1831	0.1837	0.2030	0.2038	0.0554	0.0554	0.0614	0.0618
PHASE	-2.8846	-2.8848	-2.8890	-2.8892	-2.8846	-2.8848	-2.8890	-2.8892
ϵ(za,0.)	0.3196	0.3169	0.5368	0.5349	-0.0140	-0.0138	0.0517	0.0530
$\epsilon(z_a, 1.224)$	0.4949	0.4887	0.7261	0.7247	0.0379	0.0382	0.1090	0.1105
$\epsilon(z_a, 2.449)$	0.6705	0.6690	0.9258	0.9254	0.0922	0.0928	0.1695	0.1714

* The remaining calculations of intermediate variables used to compute Q_x were manually checked only for Run No. 7 (See Appendix C)

of time to evaluate the Fourier coefficients. This calculation of $\epsilon(z_a,t)$ was checked only for 3 points, at $t = 0.0$, 1.224 and 2.449. The remainder of the calculation of suspended sediment transport requires a numerical integration over the water depth and a timeintegration which is performed analytically, using a summation of terms involving the Fourier coefficients. A manual check of these calculations was performed only for Run No. 7, and these calculations are presented in Appendix C.

3.4.3 Comparison of SED1DF and SED1DG

The SED1DG model was used to compute sediment transport rates based on the Grant and Madsen theory. The calculations were performed for a current speed of 100 cm/sec and a grain size of 0.4 mm, with waves of 8 m height and 12 sec period. These computations were repeated using the SED1DF model. The results summarized in Table 3.5 indicate that the values computed by SED1DG using the Grant and Madsen theory are identical to those computed by SED1DF for all runs.

3.4.4 Comparison of Smith (1977) and Grant and Madsen (1979) Methods

The previous version of the model SED1DF uses the Grant and Madsen method to compute the bottom friction factor in combined wave/current flows. Since this method is applicable to wave-dominated flows, a warning message is printed when the current speed exceeds the maximum wave-induced bottom particle velocity ($u_a/u_b > 1.0$).

When the Smith method was added to the model, the check of the velocity ratio was modified to print a warning message that the Smith method may not be appropriate then the wave-induced bottom particle velocity exceeds the current speed ($u_a/u_b < 1.0$), because this method is applicable to current-dominated flows.

TABLE 3.5

COMPARISON OF SED1DF AND SED1DG USING GRANT AND MADSEN METHOD

Run No.*	Sediment Transport Formula	Time Averaged Net Sediment Transport (cm^3/sec/cm) SED1DF	SED1DG
9	Engelund-Hansen	3.131	3.131
10	Einstein-Brown	54.27	54.27
11	Bagnold	3.148	3.148
12	Yalin	5.644	5.644
13	Ackers-White	7.863	7.863

*Input Data for All Runs:

Water Depth (m)	20.0
Wave Height (m)	8.0
Wave Period (sec)	12.0
Wave Direction (deg)	0.0
Current Speed (cm/sec)	100.0
Current Direction (deg)	0.0
Height above Bottom (cm)	100.0
Fluid Density (gm/cm^3)	1.025
Grain Size (mm)	0.4
Sediment Density (gm/cm^3)	2.65
Bottom Roughness (cm)	0.0
Bagnold Coefficient of Proportionality (for Run No. 11 only)	0.5

In reality, the transition from wave-dominated flows to current dominated flows does not occur abruptly when $u_a=u_b$. It is expected that there will be a transition range where the velocities are of the same order of magnitude and both theories may not be valid. However, since the transition is not expected to be discontinuous in nature, a practical method for dealing with wave and current velocities of comparable magnitudes may be to apply both theories beyond the limiting case of $u_a=u_b$ and interpolate between the results in the region of overlap.

As a preliminary step in examining the feasibility of such an approach, the Smith method was used to compute the friction factor and sediment transport for the case of wave-dominated flow previously treated using the Grant and Madsen method. The results are presented in Table 3.6.

The bottom friction factor computed using the Smith method was 0.0057. This value is 14% higher than the friction factor of 0.0050 computed using the Grant and Madsen method. The sediment transport predicted by the Smith method is larger than that predicted by the Grant and Madsen method for the five sediment transport formulas used in the model.

Table 3.6

COMPARISON OF SMITH AND GRANT AND MADSEN METHOD

Run No.	Sediment Transport Formula	Friction Factor		Time-averaged Net Sediment Transport (cm3/sec/cm)	
		Smith	Grant & Madsen	Smith	Grant & Madsen
14	Engelund-Hansen	0.0057	0.0050	6.977	3.131
15	Einstein-Brown	0.0057	0.0050	196.6	54.27
16	Bagnold	0.0057	0.0050	6.244	3.148
17	Yalin	0.0057	0.0050	13.64	5.644
18	Ackers-White	0.0057	0.0050	16.26	7.863

*Input Data for All Runs:

Water Depth (m)	20.0
Wave Height (m)	8.0
Wave Period (sec)	12.0
Wave Direction (deg)	0.0
Current Speed (cm/sec)	100.0
Current Direction (deg)	0.0
Height above Bottom (cm)	100.0
Fluid Density (gm/cm^3)	1.025
Grain Size (mm)	0.4
Sediment Density (gm/cm^3)	2.65
Bottom Roughness (cm)	0.0
Bagnold Coefficient of Proportionality (for Run No. 16 only)	0.5

REFERENCES

Grant, W.D. and O.S. Madsen. 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res. 84, No. (4), pp 1797-1808.

Smith, J.D. 1977. Modeling of sediment transport on continental shelves. In: The Sea, Vol. 6, Wiley-Interscience, New York.

Sternberg, R.W. 1972. Predicting initial motion and bedload transport o sediment particles in the shallow marine environment. In: Shelf Sediment Transport. D.J.P. Swift, D.B. Duane and O.H. Pilkey, eds. Dowden, Hutchinson and Ross, Stroudsburg, Pa. pp. 61-82.

Yalin, M. S. 1963. An expression for bed-load transportation. J. Hydraul. Div., Proc. ASCE, Vol. 89, No. HY3, pp. 221-250.

APPENDIX A - USER'S MANUAL

A.1 Smith Method for Bedload Transport

The SED1DG model reads input data from batch files or accepts interactive input from the terminal. The data in the batch files are in the same sequence as the data that would be entered from the terminal, but the user prompts are not displayed on the screen. Although the batch mode of operation was convenient for program development, the program will be used primarily in the interactive mode. This section presents a sample interactive session for the Smith method of computing the bottom friction factor for bedload transport.

The following pages show the prompts that are displayed on the terminal and some sample input to indicate the sequence in which the data must be entered by the user. The sample interactive session includes the output that is written to the terminal and to the output datafile specified by the user.

SAMPLE INTERACTIVE SESSION

```
PRINT VALUES FOR MANUAL CHECKING?
(ENTER 1 FOR YES, 0 FOR NO): 0

CHOOSE BETWEEN:
  1 - INTERACTIVE INPUT
  2 - BATCH INPUT (FOR PROGRAM DEVELOPMENT)
ENTER 1 OR 2: 1


ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED: test.out

IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE
         TO ANY OF THE FOLLOWING QUESTIONS


ENTER RUN NUMBER (1 - 9999): 3


ENTER WATER DEPTH (M): 20


ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE
SEABED (CM/SEC, DEGREES TRUE, CM): 20 0 100



ENTER WAVE HEIGHT, PERIOD AND DIRECTION
(METRES,SECONDS,DEGREES TRUE): 1 6 0


ENTER SEDIMENT GRAIN SIZE, SEDIMENT DENSITY
AND FRACTION OF THIS SIZE CLASS
MM, GRAMS/CUBIC CM, FRACTION: 0.8 2.65 1.0


ENTER BOTTOM ROUGHNESS HEIGHT (CM): 0


ENTER FLUID DENSITY (GRAMS/CUBIC CM): 1.025


CHOOSE BETWEEN:
  1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
  2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
  3 - BAGNOLD (1963) TOTAL LOAD EQUATION
  4 - YALIN (1963) BEDLOAD EQUATION
  5 - ACKERS-WHITE TOTAL LOAD EQUATION
ENTER 1,2,3,4 OR 5: 1
```

```
CHOOSE BETWEEN:
 1 - GRANT AND MADSEN(1977) THEORY (WAVE-DOMINATED FLOWS)
 2 - SMITH(1977) THEORY (CURRENT-DOMINATED FLOWS)
ENTER 1 OR 2: 2




         SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
                  SHELF CONDITIONS

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         THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
         AND THEIR LIMITATIONS




  RESULTS:

         MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
         VELOCITY, FROM LINEAR WAVE THEORY              =  10.79 CM/SEC
         MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
         DISPLACEMENT, FROM LINEAR WAVE THEORY          =   10.31 CM
         WAVELENGTH, FROM LWT DISPERSION EQUATION =  55.05 M

         BOTTOM FRICTION FACTOR = 0.0193
         (SMITH, 1977)
         CURRENT SPEED 1 M. ABOVE SEABED              =  20.00 CM/SEC
         CURRENT SPEED TO BE USED IN BOTTOM STRESS
         CALCULATIONS                                 =  20.00 CM/SEC
         ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
         WITHIN WAVE BOUNDARY LAYER                   =   0.00 DEGREES
         NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

         CRITICAL FLUID VELOCITY FOR INITIATION OF
         BEDLOAD TRANSPORT                            =  22.71 CM/SEC
         CRITICAL FLUID VELOCITY FOR INITIATION OF
         SUSPENDED LOAD TRANSPORT                     =  95.68 CM/SEC

         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         SUSPENDED LOAD TRANSPORT CEASES                =  0.00 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         BEDLOAD TRANSPORT CEASES                       =  1.26 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         SUSPENDED LOAD TRANSPORT RECOMMENCES           =  0.00 SEC
         TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
         BEDLOAD TRANSPORT RECOMMENCES                  =  0.00 SEC
```

```
         PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =  41.93
         PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE     0.00

         DIRECTION OF NET SEDIMENT TRANSPORT =    0.00 DEGREES TRUE
         TIME-AVERAGED NET SEDIMENT TRANSPORT =  0.9171E-03 CM**2./SEC
                                                 0.2430E-03 KG/SEC/M
         (ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)
          SMITH (1977) METHOD (FOR CURRENT-DOMINATED FLOWS)
          WAS APPLIED IN THE CALCULATION
         NOTE:  THIS IS SEDIMENT MASS TRANSPORT RATE
                RATHER THAN SOIL MASS TRANSPORT RATE


         EXPECTED BEDFORMS ARE (C. L. AMOS):

                   BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS


ENTER 1 TO DO ANOTHER RUN, 0 TO STOP: 0
```

SAMPLE OUTPUT DATAFILE

```
       SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
                SHELF CONDITIONS

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       THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
       AND THEIR LIMITATIONS




                 RUN NUMBER    3



INPUT DATA:


       WATER DEPTH =  20.00 M
       CURRENT SPEED =  20.00 CM/SEC
       CURRENT DIRECTION =   0.00 DEGREES TRUE
       HEIGHT ABOVE BED = 100.00 CM
       WAVE HEIGHT =   1.00 M
       WAVE PERIOD =  6.00 SEC
       WAVE DIRECTION =   0.00 DEGREES TRUE

       SEDIMENT GRAIN SIZE =  0.80 MM
       SEDIMENT DENSITY = 2.65 GRAMS/CUBIC CM

       BOTTOM ROUGHNESS HEIGHT =   0.00 CM

       FLUID DENSITY = 1.02 GRAMS/CUBIC CM




RESULTS:


       MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
       VELOCITY, FROM LINEAR WAVE THEORY            =  10.79 CM/SEC
       MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
       DISPLACEMENT, FROM LINEAR WAVE THEORY        =   10.31 CM
       WAVELENGTH, FROM LWT DISPERSION EQUATION =  55.05 M
```

```
BOTTOM FRICTION FACTOR = 0.0193
(SMITH, 1977)
CURRENT SPEED 1 M. ABOVE SEABED              =  20.00 CM/SEC
CURRENT SPEED TO BE USED IN BOTTOM STRESS
CALCULATIONS                                 =  20.00 CM/SEC
ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
WITHIN WAVE BOUNDARY LAYER                       0.00 DEGREES
NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

CRITICAL FLUID VELOCITY FOR INITIATION OF
BEDLOAD TRANSPORT                            =  22.71 CM/SEC
CRITICAL FLUID VELOCITY FOR INITIATION OF
SUSPENDED LOAD TRANSPORT                     =  95.68 CM/SEC

TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT CEASES               =  0.00 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT CEASES                      =  1.26 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT RECOMMENCES          =  0.00 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT RECOMMENCES                 =  0.00 SEC

PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =  41.93
PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =   0.00

DIRECTION OF NET SEDIMENT TRANSPORT =   0.00 DEGREES TRUE
TIME-AVERAGED NET SEDIMENT TRANSPORT =  0.9171E-03 CM**2./SEC
                                        0.2430E-03 KG/SEC/M
(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)
 SMITH (1977) METHOD (FOR CURRENT-DOMINATED FLOWS)
 WAS APPLIED IN THE CALCULATION
NOTE:  THIS IS SEDIMENT MASS TRANSPORT RATE
       RATHER THAN SOIL MASS TRANSPORT RATE


EXPECTED BEDFORMS ARE (C. L. AMOS):

          BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS
```

A.2 Smith Method for Suspended Load Transport

This section presents a sample interactive session for the Smith method of computing suspended load transport. The following pages show the prompts that are displayed on the terminal and some sample input to indicate the sequence in which the data must be entered by the user. The sample interactive session includes the output that is written to the terminal and to the output datafile specified by the user.

SAMPLE INTERACTIVE SESSION

```
PRINT VALUES FOR MANUAL CHECKING?
(ENTER 1 FOR YES, 0 FOR NO): 0

CHOOSE BETWEEN:
  1 - INTERACTIVE INPUT
  2 - BATCH INPUT (FOR PROGRAM DEVELOPMENT)
ENTER 1 OR 2: 1


ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED: test.out

IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE
         TO ANY OF THE FOLLOWING QUESTIONS


ENTER RUN NUMBER (1 - 9999): 7


ENTER WATER DEPTH (M): 20


ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE
SEABED (CM/SEC, DEGREES TRUE, CM): 60 0 100



ENTER WAVE HEIGHT, PERIOD AND DIRECTION
(METRES,SECONDS,DEGREES TRUE): 1 6 0


ENTER SEDIMENT GRAIN SIZE, SEDIMENT DENSITY
AND FRACTION OF THIS SIZE CLASS
MM, GRAMS/CUBIC CM, FRACTION: 0.3 2.65 0.25


ENTER BOTTOM ROUGHNESS HEIGHT (CM): 0


ENTER FLUID DENSITY (GRAMS/CUBIC CM): 1.025
```

```
CHOOSE BETWEEN:
   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
   3 - BAGNOLD (1963) TOTAL LOAD EQUATION
   4 - YALIN (1963) BEDLOAD EQUATION
   5 - ACKERS-WHITE TOTAL LOAD EQUATION
   6 - SMITH (1977) SUSPENDED LOAD (WAVES AND CURRENTS)
ENTER 1,2,3,4,5 OR 6: 6


CHOOSE BETWEEN:
 1 - GRANT AND MADSEN(1977) THEORY (WAVE-DOMINATED FLOWS)
 2 - SMITH(1977) THEORY (CURRENT-DOMINATED FLOWS)
ENTER 1 OR 2: 2




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                  SHELF CONDITIONS

         MARTEC LIMITED                       FEBRUARY, 1987


         THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
         AND THEIR LIMITATIONS


ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
BEGIN INTEGRATION OVER WATER DEPTH
DEPTH INTEGRATION: N = 0       I = 0
CALL #  1 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
CALL #  2 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  1      I =  1
CALL #  3 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX
```

```
EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  2      I =  1
CALL #  4 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  2      I =  3
CALL #  5 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  3      I =  1
CALL #  6 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


                              .
                              .
                              .


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  6      I = 59
CALL # 63 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  6      I = 61
CALL # 64 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
DEPTH INTEGRATION: N =  6      I = 63
CALL # 65 TO FUNCTION F9Z
ENTRY TO SUBROUTINE KELVNR
         This computation is time-consuming, so RELAX


EXIT FROM SUBROUTINE KELVNR
RSLT =  0.755E+00
END INTEGRATION OVER WATER DEPTH
SEDX =  0.1510E+01
SEDY =  0.0000E+00
```

```
RESULTS:


       MAX. WAVE INDUCED BOTTOM HORIZONTAL PARTICLE
       VELOCITY, FROM LINEAR WAVE THEORY            =  10.79 CM/SEC
       MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
       DISPLACEMENT, FROM LINEAR WAVE THEORY        =   10.31 CM
       WAVELENGTH, FROM LWT DISPERSION EQUATION =  55.05 M

       BOTTOM FRICTION FACTOR = 0.0148
       (SMITH, 1977)
       CURRENT SPEED 1 M. ABOVE SEABED           =  60.00 CM/SEC
       CURRENT SPEED TO BE USED IN BOTTOM STRESS
       CALCULATIONS                              =  60.00 CM/SEC
       ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
       WITHIN WAVE BOUNDARY LAYER                =   0.00 DEGREES
       NOTE:  THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

       CRITICAL FLUID VELOCITY FOR INITIATION OF
       BEDLOAD TRANSPORT                         =  15.87 CM/SEC
       CRITICAL FLUID VELOCITY FOR INITIATION OF
       SUSPENDED LOAD TRANSPORT                  =  34.14 CM/SEC

       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       SUSPENDED LOAD TRANSPORT CEASES            =  3.00 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       BEDLOAD TRANSPORT CEASES                   =  0.00 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       SUSPENDED LOAD TRANSPORT RECOMMENCES       =  0.00 SEC
       TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
       BEDLOAD TRANSPORT RECOMMENCES              =  0.00 SEC

       PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE =   0.00
       PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE = 100.00

       DIRECTION OF NET SEDIMENT TRANSPORT =   0.00 DEGREES TRUE
       TIME-AVERAGED NET SEDIMENT TRANSPORT =   1.510     CM**2./SEC
                                           0.4003     KG/SEC/M
       (SMITH (1977) SUSPENDED LOAD EQUATION)
        SMITH (1977) METHOD (FOR CURRENT-DOMINATED FLOWS)
        WAS APPLIED IN THE CALCULATION
       NOTE:  THIS IS SEDIMENT MASS TRANSPORT RATE
              RATHER THAN SOIL MASS TRANSPORT RATE


       EXPECTED BEDFORMS ARE (C. L. AMOS):

                 BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS
```

SAMPLE OUTPUT DATAFILE

```
SED1D:  A SEDIMENT TRANSPORT MODEL  FOR CONTINENTAL
         SHELF CONDITIONS

MARTEC LIMITED                        FEBRUARY [illegible]


THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED
AND THEIR LIMITATIONS





          RUN NUMBER    7



INPUT DATA:


    WATER DEPTH =  20.00 M
    CURRENT SPEED =   60.00 CM/SEC
    CURRENT DIRECTION =    0.00 DEGREES TRUE
    HEIGHT ABOVE BED = 100.00 CM
    WAVE HEIGHT =    1.00 M
    WAVE PERIOD =  6.00 SEC
    WAVE DIRECTION =    0.00 DEGREES TRUE

    SEDIMENT GRAIN SIZE =   0.30 MM
    SEDIMENT DENSITY = 2.65 GRAMS/CUBIC CM
    FRACTION OF SEABED MATERIAL =  0.25
    BOTTOM ROUGHNESS HEIGHT =    0.00 CM

    FLUID DENSITY = 1.02 GRAMS/CUBIC CM


RESULTS:


    MAX. WAVE INDUCED BOTTOM HORIZONTAL PARTICLE
    VELOCITY, FROM LINEAR WAVE THEORY               =  10.79 CM/SEC
    MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
    DISPLACEMENT, FROM LINEAR WAVE THEORY            =   10.31 CM
    WAVELENGTH, FROM LWT DISPERSION EQUATION =   55.05 M

    BOTTOM FRICTION FACTOR = 0.0148
    (SMITH, 1977)
    CURRENT SPEED 1 M. ABOVE SEABED                  60.00 CM/SEC
    CURRENT SPEED TO BE USED IN BOTTOM STRESS
    CALCULATIONS                                     60.00 CM/SEC
    ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
    WITHIN WAVE BOUNDARY LAYER              =    0.00 DEGREES
    NOTE   THIS APPLIES TO MIXED FLOW CONDITIONS ONLY
```

```
CRITICAL FLUID VELOCITY FOR INITIATION OF
BEDLOAD TRANSPORT                                  15.87 CM/SEC
CRITICAL FLUID VELOCITY FOR INITIATION OF
SUSPENDED LOAD TRANSPORT                           24.14 CM/SEC

TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT CEASES                    [illegible] SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT CEASES                           0.40 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT RECOMMENCES               0.36 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT RECOMMENCES                    . [illegible] SEC

PERCENT OF TIME IN BEDLOAD TRANSPORT PHASE .     0.00
PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE . 100.00

DIRECTION OF NET SEDIMENT TRANSPORT =   0.00 DEGREES TRUE
TIME-AVERAGED NET SEDIMENT TRANSPORT =   1.510      CM**2./SEC
                                        0.4003      KG/SEC/M
(SMITH (1977) SUSPENDED LOAD EQUATION)
 SMITH (1977) METHOD (FOR CURRENT-DOMINATED FLOWS)
 WAS APPLIED IN THE CALCULATION
NOTE:  THIS IS SEDIMENT MASS TRANSPORT RATE
       RATHER THAN SOIL MASS TRANSPORT RATE


EXPECTED BEDFORMS ARE (C. L. AMOS):

          BEDFORMS UNKNOWN FOR MIXED FLOW CONDITIONS
```

APPENDIX B SAMPLE CALCULATIONS FOR BOTTOM FRICTION FACTOR

A sample calculation for Run No. 2 of Table 3.2 is presented below.

Input Data:
water depth, $d = 20$ m $= 2000$ cm
current speed, $u_z = 30$ cm/sec
height above bed, $z = 100$ cm
wave height, $H = 1$ m $= 100$ cm
wave period, $T = 6$ sec
fluid density, $\rho_w = 1.025$ gm/cm^3
grain size, $D = 0.4$ mm $= 0.04$ cm
sediment density, $\rho_s = 2.65$ gm/cm^3
bottom roughness, $k_b = 0.0$ cm

Assumptions:
dynamic viscosity, $\mu = 13\text{x}10\text{-}3$ gm/cm sec
kinematic viscosity, $\nu = \mu/\rho_w = 1.27\text{x}10^{-2}$ cm^2/sec
acceleration due to gravity, $g = 981$ cm/sec^2
von Karman constant, $k = 0.4$

Intermediate Variables:

$\omega = 2\pi/T$

$= 1.0472$ sec^{-1}

initial estimate for $z_o = 1.0\text{x}10^{-3}$

$u_o = 10.79$ cm/sec (from subroutine OSCILL)

(a) Calculation of $(u_{*2})_m$

First Iteration:

$$(\omega z_o/u_o) = \frac{(1.0472)(1.0\times10^{-3})}{(10.79)}$$

$$= 9.71\text{x}10\text{-}5$$

The function $(K_o/u_o) = F3(\omega\ z_o/u_o)$ is not explicitly defined, however, the function is plotted in Fig. 5 of Smith (1977). Values of $(\omega z_o/u_o)$ were read on this log-log plot by converting the values to a linear measurement scale on the y-axis as shown in Figure B.1(a).

$$y = (\omega z_o/u_o) = 9.71\times10^{-5}$$

$$y = \frac{\Delta L(\log y - \log y_1)}{(\log y_2 - \log y_1)}$$

$$= \frac{39\ \log(9.71\times10^{-5}) - \log(1\times10^{-5})}{\log(1\times10^{-4}) - \log(1\times10^{-5})}$$

$$= 38.50 \text{ div (on 50 div/inch scale)}$$

This measurement was used to locate the point on the curve of (K_o/u_o) corresponding to the value of $(\omega z_o/u_o)$. A linear measurement along the x-axis was made and converted to a value of (K_o/u_o) as shown in Figure B.1(b).

$$\Delta x = 19.5 \text{ div (on 50 div/inch scale)}$$

$$(k_o/u_o) = x = 10^{[\log x_1 + \frac{\Delta x}{\Delta L}(\log x_2 - \log x_1)]}$$

$$= 10^{[\log(0.01) + \frac{19.5}{39}(\log 0.1 - \log 0.01)]}$$

$$= 0.0316$$

Since $(K_o/u_o) = k(u_{*2})_m\ /u_o$

then $(u_{*2})_m/u_o = (1/k)(K_o/u_o)$

$= (1/0.4)(0.0316)$

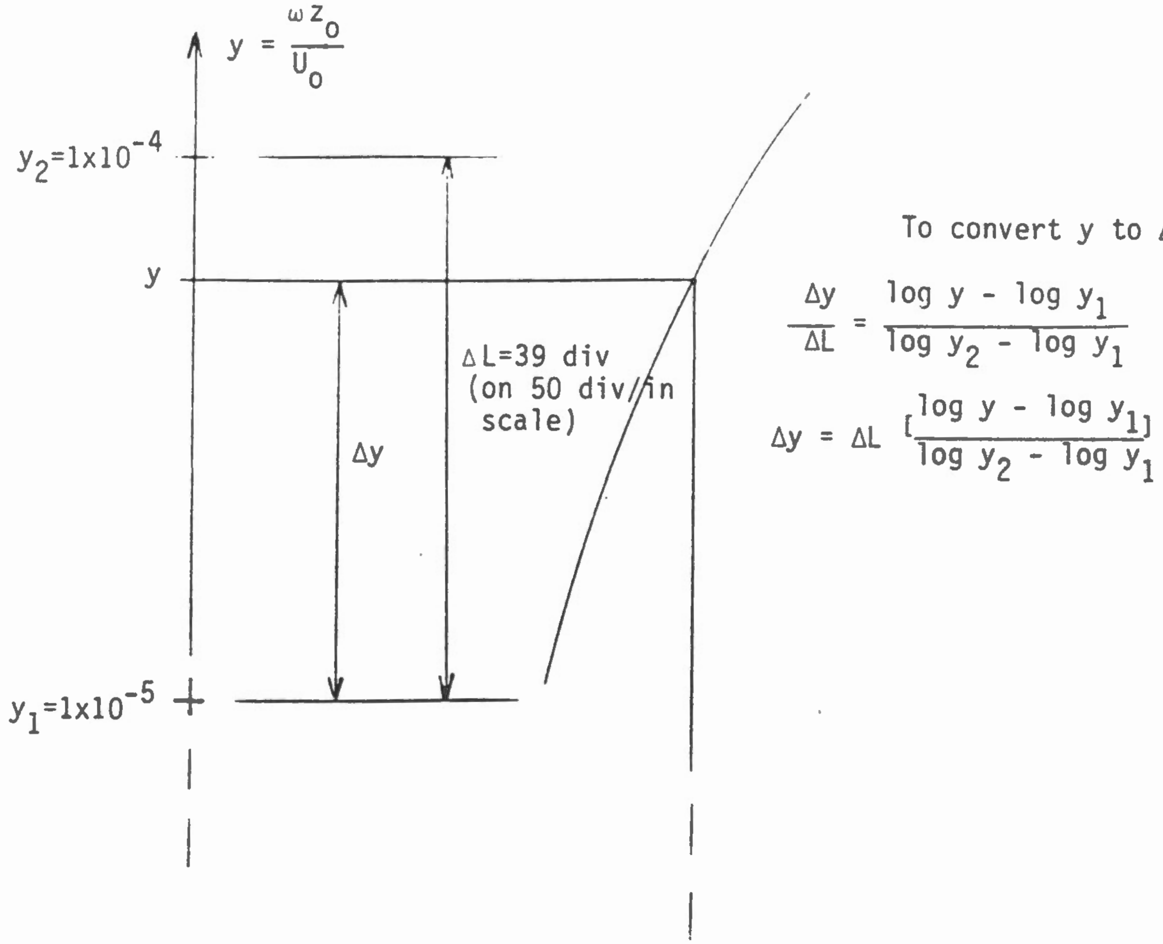
$= 0.0791$

Since this is the first iteration, set $((u_{*2})_m/u_o)_{sv}$ equal to zero

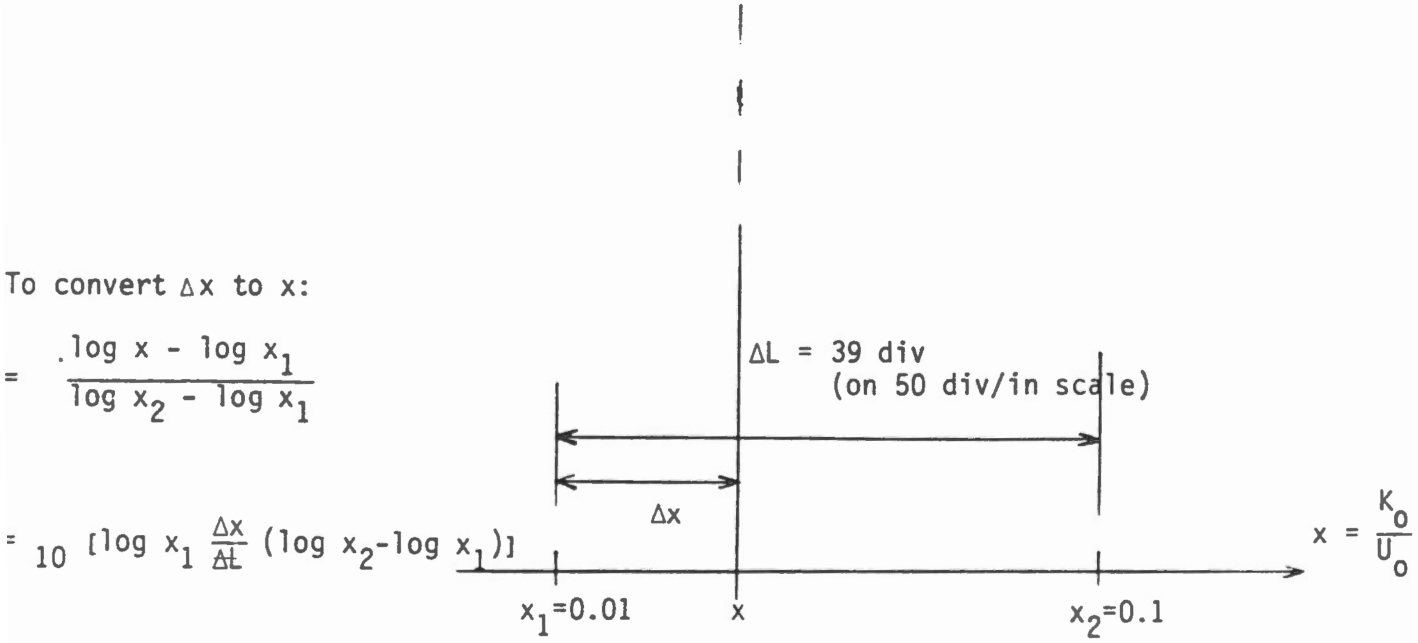
$$\text{DIFF} = \left| \frac{((u_{*2})_m/u_o) - ((u_{*2})_m/u_o)_{sv}}{((u_{*2})_m/u_o)} \right|$$

$$= \left|\frac{0.0791 - 0}{0.0791}\right|$$

$$= 1.0$$



(a) Conversion of Log to Linear Scale



(b) Conversion of Linear to Log Scale

FIGURE B.1 SCALE CONVERSION

$$(u_{*2})m = (u_o)((u_{*2})_m/u_o)$$
$$= (10.79)(0.0791)$$
$$= 0.8530 \text{ cm/sec}$$

$$R_* = (u_{*2})_m D/\nu$$
$$= (0.8530)(0.04)/(1.27\text{x}10^{-2})$$
$$= 2.6867$$

From Fig. 1 of Smith (1977), for $R_* < 3$,

$$(z_f/k_s) = (1/9)(R_*)^{-1}$$
$$= (1/9)(2.6867)^{-1}$$
$$= 0.0414$$

A new estimate for z_o is

$$z_o = (k_s)(z_f/k_s)$$
$$= (0.04)(0.0414)$$
$$= 1.65\text{x}10^{-3} \text{ cm}$$

The value of $((u_{*2})_m/u_o)$ is saved for use in checking convergence in the next iteration.

$$((u_{*2})_m/u_o)sv = 0.0791$$

A new value of $(\omega z_o/u_o)$ is computed and the calculation is repeated until the value of $((u_{*2})_m/u_o)$ converges. The results of the iterative calculations are summarized in Table B.1. Since the iteration converged rapidly and the degree of precision of the measurements on the log-log plot was very limited, Δx was estimated from the Δy values for the last 4 iterations. The computations were performed using a programmable hand calculator and the iterations were stopped when the computed value for Δy was equal to the previous value of Δy to within 1 decimal place.

The iterative calculations in SED1DG are summarized in Table B.2. The iterations were stopped when the relative difference in $((u_{*2})_m/u_o)$ was less than $1\text{x}10^{-6}$. The results of the iterative calculations agree with those of the manual calculations and the slight differences are due to inaccuracies in measurements on the log-log plot. Since the source code for performing the iterative calculation of $(u_{*2})_m$ appears to be correct, the remainder of the manual checking was based on the values computed by SED1DG.

After the iteration has converged, the intermediate variables are:

$z_o = 0.1542\text{x}10^{-2}$
$(z_f/k_s) = 0.0386$
$((u_{*2})_m/u_o) = 0.0847$
$(u_{*2})_m = 0.9138$

(b) Calculation of u_{*1}

A constant friction factor based on Sternberg (1971) is used:

$$f_c = 6\text{x}10^{-3}$$

$$\begin{aligned} k_b &= (z_o)/(z_f/k_s) \\ &= (0.001542)/(0.0386) \\ &= 0.0399 \text{ cm} \end{aligned}$$

$$u_{100} = u_z \left[\frac{\log(3000/k_b)}{\log(30\ z/k_b)}\right]$$

$$= 30 \quad \left[\frac{\log(3000/0.0399)}{\log((30)(100)/(0.0399))}\right]$$

$$\begin{aligned} &= 30 \text{ cm/sec} \\ u_a &= u_{100} \\ &= 30 \text{ cm/sec} \end{aligned}$$

$$u_{*1} = \sqrt{\frac{f_c}{2}}\ u_a$$

$$\begin{aligned} &= \sqrt{\frac{6\text{x}10^{-3}}{2}} \quad (30) \\ &= 1.6432 \text{ cm/sec} \end{aligned}$$

(c) Calculation of τ_{max}

$$\begin{aligned} K_o &= k(u^{*}_{*1} + (u_{*2})_m) \\ &= (0.4)(1.6432 + 0.9138) \\ &= 1.0228 \end{aligned}$$

$$\xi_o = 2 \left[\frac{\omega z_o}{K_o}\right]^{1/2}$$

$$= 2 \left[\frac{(1.0472)(0.1542\text{x}10^{-2})}{(1.0228)}\right]^{1/2}$$

$$= 0.0795$$

$$
\begin{aligned}
\ker(\xi_0) &= \ker(0.0795)\\
&= 2.6492\\
\mathrm{kei}(\xi_0) &= \mathrm{kei}(0.0795)\\
&= -0.7796\\
\ker_1(\xi_0) &= \ker_1(0.0795)\\
&= -8.9609\\
\mathrm{kei}_1(\xi_0) &= \mathrm{kei}_1(0.0795)\\
&= -8.7839
\end{aligned}
$$

$$F_1'(\xi_0) = \frac{(\ker_1\xi_0 + \mathrm{kei}_1\xi_0)\ker\xi_0 + (\mathrm{kei}_1\xi_0 - \ker_1\xi_0)\mathrm{kei}\,\xi_0}{\sqrt{2}\,(\ker^2\xi_0 + \mathrm{kei}^2\xi_0)}$$

$$= \frac{((-8.9609) + (-8.7839))(2.6492) + ((-8.7839)-(-8.9609))(-0.7796)}{\sqrt{2}\,((2.6492)^2 + (-0.7796)^2)}$$

$$= -\,4.3716$$

$$F_2'(\xi_0) = -\frac{(\ker_1\xi_0 + \mathrm{kei}_1\xi_0)\ker\xi_0 + (\mathrm{kei}_1\xi_0 - \ker_1\xi_0)\mathrm{kei}\,\xi_0}{\sqrt{2}\,(\ker^2\xi_0 + \mathrm{kei}^2\xi_0)}$$

$$= -\frac{((-8.9609) + (-8.7839))(-0.7796) + ((-8.7839) - (8.9609))\,(2.6492)}{\sqrt{2}\,((2.6492)^2 + (-0.7796)^2)}$$

$$= -1.2392$$

$$\tau_{max} = \rho\left\{ \frac{K_0 u_{*1}}{k}\left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1} + \frac{K_0 u_0 \xi_0}{2}\left((F_1'(\xi_0))^2 + (F_2'(\xi_0))^2 \right)^{1/2}\right\}$$

$$= 1.025\left\{\frac{(1.0228)(1.6432)}{(0.4)}\left[1 + \frac{0.9138}{1.6432}\right]^{-1} + \frac{(1.0228)(10.79)(0.0795)}{(2)}\left((-4.3716)^2 + (-1.2392)^2 \right)^{1/2}\right\}$$

$$= 4.8107 \text{ gm/cm sec}^2$$

(d) Calculation of u_{max}

Assuming u_{max} occurs at $z_w = \delta_w$

$$
\begin{aligned}
\delta_w &= 0.03(uo/\omega)\\
&= (0.03)(10.79)/(1.0472)\\
&= 0.3091\\
z_w &= \delta_w\\
&= 0.3091
\end{aligned}
$$

$$\xi = \left[\frac{2\,\omega\, z_w}{K_0}\right]^{1/2}$$

$$= 2\left[\frac{(1.0472)(0.3091)}{(1.0228)}\right]^{1/2}$$

$$= 1.1251$$

$$\ker(\xi) = \ker(1.1251)$$

$$= 0.2084$$

$$\mathrm{kei}(\xi) = \mathrm{kei}(1.1251)$$

$$= -0.4515$$

$$F_1(\xi,_0) = \frac{(\ker\xi)(\ker\xi_0) + (\mathrm{kei}\xi)(\mathrm{kei}\xi_0)}{\ker^2\xi_0 + \mathrm{kei}^2\xi_0}$$

$$= \frac{(0.2084)(2.6492) + (-0.4515)(-0.7796)}{(2.67492)^2 + (-0.7796)^2}$$

$$= 0.1186$$

$$F_2(\xi,_0) = -\frac{(\ker\xi)(\ker\xi_0) - (\mathrm{kei}\xi)(\mathrm{kei}\xi_0)}{\ker^2\xi_0 + \mathrm{kei}^2\xi_0}$$

$$= -\frac{(0.2084)(-0.7796) - (-0.4515)(2.6492)}{(2.6492)^2 + (-0.7796)^2}$$

$$= -0.1355$$

$$t_{max} = \frac{1}{\omega}\tan^{-1}\left[1 - \frac{F_2(\xi,\xi_0)}{F_1(\xi,\xi_0)}\right]$$

$$= (1/1.0472)\tan^{-1}\frac{-0.1355}{1 - 0.1186}$$

$$= (1/1.0472)\tan^{-1}\ -0.1537$$

$$= (1/1.0472)(-0.1525)$$

$$= -0.1457$$

or, for positive t_{max}, since $-\theta = 2\pi - \theta$

$$t_{max} = (1/1.0472)(2\pi - 0.1537)$$

$$= (1/1.0472)(6.1295)$$

$$= 5.8532$$

$$u_{max} = \frac{u_{*1}}{k}\left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1} \ln \frac{z_w}{z_o}$$

$$+ uo(\cos\omega t_{max} - F_1(\xi,\xi_o)\cos\omega t_{max} + F_2(\xi,\xi_o)\sin\omega t_{max})$$

$$= \frac{(1.6432)}{(0.4)}\left[1 + \frac{0.9138}{1.6432}\right]^{-1} \ln \frac{0.3091}{0.1542x10^{-2}}$$

$$+ 10.79\,[\cos(1.0472)(5.8532) - (-0.1186)\cos(1.0472)(5.8532)$$

$$+ (-0.1355)\sin(1.0472)(5.8532)]$$

$= 23.61$ cm/sec

(e) Calculation of f_{cw}

$$f_{cw} = \frac{2\tau_m}{\rho(u_m)^2}$$

$$= \frac{(2)(4.8107)}{(1.025)(23.61)^2}$$

$= 0.0168$

TABLE B.1 SUMMARY OF ITERATIVE MANUAL CALCULATIONS

Iter.	$\frac{\omega z_o}{U_o}$	Δy	Δx	$\frac{K_o}{U_o}$	$\frac{(u_{*2})_m}{U_o}$	DIFF	$(u_{*2})_m$	R_*	$\frac{z_f}{k_s}$	z_o
1	$9.71\text{x}10^{-5}$	38.49	19.50	0.0316	0.0791	1.0000	0.8530	2.6867	0.0414	$1.65\text{x}10^{-3}$
2	$1.61\text{x}10^{-4}$	8.02	21.00	0.0346	0.0864	0.0848	0.9320	2.9355	0.0379	$1.51\text{x}10^{-3}$
3	$1.47\text{x}10^{-4}$	6.52	20.50	0.0335	0.0839	0.0300	0.9049	2.8501	0.0390	$1.56\text{X}10^{-3}$
4	$1.51\text{X}10^{-4}$	7.02	20.70	0.0339	0.0849	0.0117	0.9157	2.8839	0.0385	$1.54\text{X}10^{-3}$
5	$1.50\text{X}10^{-4}$	6.82	20.60	0.0337	0.0844	0.0059	0.9103	2.8670	0.0388	$1.55\text{X}10^{-3}$
6	$1.50\text{X}10^{-4}$	6.92	20.65	0.0338	0.0846	0.0029	0.9130	2.8754	0.0386	$1.55\text{X}10^{-3}$
7	$1.50\text{X}10^{-4}$	6.87	20.65	0.0338	0.0846	0				

TABLE B.2 SUMMARY OF ITERATIVE CALCULATIONS IN THE COMPUTER PROGRAM

Iter.	$\frac{\omega z}{U_o}$	$\frac{K_o}{U_o}$	$\frac{(u_{*2})_m}{U_o}$	DIFF	$(u_{*2})_m$	R_*	z_f	$\frac{z_o}{k_a}$
1	9.70×10^{-5}	0.0314	0.0786	1.0000	0.8484	2.6757	0.0415	1.66×10^{-3}
2	1.61×10^{-4}	0.0343	0.0857	0.0833	0.9255	2.9188	0.0381	1.52×10^{-3}
3	1.48×10^{-4}	0.0338	0.0845	0.0150	0.9118	2.8757	0.0386	1.55×10^{-3}
4	1.50×10^{-4}	0.0339	0.0847	0.0026	0.9141	2.8830	0.0385	1.54×10^{-3}
5	1.50×10^{-4}	0.0339	0.0846	0.0004	0.9137	2.8817	0.0386	1.54×10^{-3}
6	1.50×10^{-4}	0.0339	0.0847	0.0001	0.9138	2.8819	0.0386	1.54×10^{-3}
7	1.50×10^{-4}	0.0339	0.0847	0.0000	0.9138	2.8819	0.0386	1.54×10^{-3}
8	1.50×10^{-4}	0.0339	0.0847	0.0000	0.9138	2.8819	0.0386	1.54×10^{-3}
9	1.50×10^{-4}	0.0339	0.0847	0.0000				

APPENDIX C SAMPLE CALCULATIONS FOR SUSPENDED SEDIMENT TRANSPORT

A sample calculation for Run No. 7 of Table 3.4 is presented below.

Input Data:
water depth, $d = 20$ m = 2000 cm
current speed, $u_z = 60$ cm/sec
height above bed, $z = 100$ cm
wave height, $H = 1$ m = 100 cm
wave period, $T = 6$ sec
fluid density, $\rho_w = 1.025$ gm/cm^3
grain size, $D = 0.3$ mm = 0.03 cm
sediment density, $\rho_s = 2.65$ gm/cm^3
fraction of seabed material $f_n = 0.250$
bottom roughness, $k_b = 0.0$ cm

Assumptions:
dynamic viscosity, $\mu = 13x10-3$ gm/cm sec
kinematic viscosity, $\nu = \mu/\rho_w = 1.27x10^{-2}$ cm^2/sec
acceleration due to gravity, $g = 981$ cm/sec^2
von Karman constant, $k = 0.4$
Yalin constant, $T\gamma = 0.635$

Intermediate Variables:
$\omega = 2\pi / T$
$= 1.0472$ sec^{-1}
$K_o = 1.6800$ (from FRIC4)
$z_o = 1.542x10^{-3}$ cm (from FRIC4)
$U_o = 10.79$ cm/sec (from OSCILL)
$u*_1 = 3.2863$ cm/sec (from FRIC4)
$(u*_2)_m = 0.9138$ cm/sec (from FRIC4)
$\gamma_n = f_n \gamma\gamma$
$= (0.250)(0.635)$
$= 0.159$
$f_{cw} = 0.0148$ (from FRIC4)
$v_{cs} = (f_{cw}/2)\ \rho_w\ v_{cs}^2$
$= (0.0148/2)(1.025)(34.14)^2$
$= 8.843$
$\Delta\rho = \rho_s - \rho_w$
$= 2.65 - 1.025$
$= 1.625$

$$w = \frac{-3\mu + [9\mu^2 + g(D/2)^2\ \rho_w\ \Delta\rho(0.015476+0.099205D)]^{1/2}}{\rho_w(0.011607+0.074405D)}$$

$$= -(3)(13x10^{-3}) +$$

$$\frac{((9)(13x10^{-3})^2+(981)(0.03/2)^2(1.025)(1.625)(0.015476+0.099205)(0.03)^{1/2}}{(1.025)\ 0.011607 + (0.074405)(0.03)}$$

$= 3.675$

$p_n = w/K_o$

$= 3.675/1.680$

$= 2.188$

$z_a = 2\ D$

$= (2)(0.03)$

$= 0.06$

$$\xi a = \left[\frac{2\ \omega z_a}{K_o}\right]^{1/2}$$

$$= 2\left[\frac{(1.0472)(0.06)}{(1.680)}\right]^{1/2}$$

$= 0.3868$

$\mathrm{ker}_{pn}\ (\xi_a) = \mathrm{ker}_{2.188}\ (0.3868)$

$= 9.088$

$\mathrm{kei}_{pn}\ (\xi_a) = \mathrm{kei}_{2.188}\ (0.3868)$

$= 17.713$

$$\xi o = 2\left[\frac{\omega z_o}{K_o}\right]^{1/2}$$

$$= 2\left[\frac{(1.0472)(1.542\mathrm{x}10^{-3})}{(1.680)}\right]^{1/2}$$

$= 0.0620$

$\mathrm{ker}(\xi_o) = \mathrm{ker}(0.0620)$

$= 2.897$

$\mathrm{kei}(\xi_o) = \mathrm{kei}(0.0620)$

$= -0.782$

$\mathrm{ker}_1(\xi_o) = \mathrm{ker}_1(0.0620)$

$= -11.462$

$\mathrm{kei}_1(\xi_o) = \mathrm{kei}_1(0.0620)$

$= -11.313$

$$F_1'(\xi_0) = \frac{(\mathrm{ker}_1\xi_0 + \mathrm{kei}_1\xi_0)\ \mathrm{ker}\xi_0 + (\mathrm{kei}_1\xi_0 - \mathrm{ker}_1\xi_0)\mathrm{kei}\ \xi_0}{\sqrt{2}\ (\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0)}$$

$$= \frac{(-11.462) + (-11.313)\ (2.897) + \ (-11.313) - (-11.462)\ (-0.782)}{\sqrt{2}\ [(2.897)^2 + (-0.782)^2]}$$

$$= -5.1906$$

$$F_2'(\xi_0) = \frac{-(\mathrm{ker}_1\xi_0 + \mathrm{kei}_1\xi_0)\ \mathrm{ker}\xi_0 + (\mathrm{kei}_1\xi_0 - \mathrm{ker}_1\xi_0)\mathrm{ker}\ \xi_0}{\sqrt{2}\ (\mathrm{ker}^2\xi_0 + \mathrm{kei}^2\xi_0)}$$

$$= \frac{-\ (-11.462) + (-11.313)\ (-0.781) + (-11.313) - (-11.462)\ (2.897)}{\sqrt{2}\ [(2.897)^2 + (-0.781)^2]}$$

$$= -1.3632$$

$$C1 = -\ \gamma_n + \frac{\gamma_n \rho}{\tau_c}\ \ \frac{K_0 u_{*1}}{k}\ \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1}$$

$$= -\ 0.159 + \frac{0.159}{8.843}\ (1.025)\ \frac{(1.680)(3.2863)}{(0.4)}\ \left[1 + \frac{0.9138}{3.2863}\right]^{-1}$$

$$= 0.0400$$

$$C2 = \frac{\gamma_n \rho}{\tau_c}\ \frac{K_0 U_0 \xi_0}{2}\ \left[F_1'(\xi_0)^2 + F_2'(\xi_0)^2\right]^{1/2}$$

$$= \frac{(0.159)}{(8.843)}\ (1.025)\ \frac{(1.680)(10.79)(0.0620)}{2}\left\{(-5.1906)^2 + (-1.3632)^2\right\}^{1/2}$$

$$= 0.0556$$

$$\mathrm{PHASE} = \tan^{-1} \frac{F_2'(\xi_0)}{F_1'(\xi_0)}$$

$$= \tan^{-1} \frac{-1.3632}{-5.1906}$$

$$= 0.2568 - \pi$$

$$= -2.8848$$

select NTIME = 50

$$DT = T/(NTIME - 1)$$

$$= (6.0)/(49)$$

$$= 0.1224$$

$$\epsilon n(z_a,t) = C1 + C2\cos(\omega t + PHASE)$$

for $t = 0.0$:

$$\epsilon_n(z_a,0.0) = (0.0400) + (0.0556)\cos[(1.0472)(0.0) + (-2.8848)]$$
$$= -0.0138$$

for $t = 1.224$:

$$\epsilon_n(z_a,1.224) = (0.0400) + (0.0556)\cos[(1.0472)(1.224) + (-2.8848)]$$
$$= 0.0382$$

for $t = 2.449$:

$$\epsilon_n(z_a,2.449) = (0.0400) + (0.0556)\cos[(1.0472)(2.449) + (-2.8848)]$$
$$= 0.0928$$

The function $\epsilon_n(z_a,t)$ is used as input to subroutine FFT, which was checked as described in Section 2.3.2. The results from FFT that will be used in the manual checking are:

$A_0 = 0.385\text{x}10^{-1}$
$A_1 = -0.266\text{x}10^{-1}$
$A_2 = 0.349\text{x}10^{-3}$

$B_0 = 0$
$B_1 = 0.865\text{x}10^{-2}$
$B_2 = -0.240\text{x}10^{-3}$

The integration over the water depth is carried out in subroutine ROMBZ. This subroutine is similar to ROMBIN and ROMB2 which are used in the previous version of the sediment transport model. ROMBZ calls the function F9Z which includes a time integration of the product of the concentration and velocity fields. ROMBZ calls F9Z once at the lower and upper limits of integration, then calls F9Z several additional times at the subintervals used in the integration routine. The manual checking of F9Z was performed only for the lower and upper limits.

For $z = z_0$:

$$C30 = \frac{u_{*1}}{k} \ln \frac{z_0}{z_0} \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1}$$

$$= \frac{3.2863}{0.4} \ln \frac{1.542\text{x}10^{-3}}{1.542\text{x}10^{-3}} \left[1 + \frac{0.9138}{3.2863}\right]^{-1}$$

$$= 0$$

$$C3 = C30 \left[\frac{z_a}{z_o}\right]^{p_n} A_o$$

$$= 0$$

$$C4 = C30 \frac{z_a}{z_o}^{p_n/2}$$

$$= 0$$

$$C5 = U_o \; A_o \left[\frac{z_a}{z_o} \right]^{p_n}$$

$$= (10.79)(0.0385) \left[\frac{0.060}{1.542\text{x}10^{-3}}\right]^{2.188}$$

$$= 1.252\text{x}10^{3}$$

$$C6 = U_o \quad \left[\frac{z_a}{z_o} \right]^{p_n/2}$$

$$= (10.79) \left[\frac{0.060}{1.542\text{x}10^{-3}} \right]^{2.188/2}$$

$$= 592.3$$

$$= 2 \left[\frac{wz}{K_o}\right]^{1/2} \Bigg|_{z = z_o}$$

$$=\xi_o$$

$$\text{ker}\xi = \text{ker}\xi_o$$

$$\text{kei}\xi = \text{kei}\xi_o$$

$$F_1(\xi,\xi_o) = \frac{\text{ker}\xi \;\; \text{ker}\xi_o + \text{kei}\xi_o \text{kei}\xi_o}{\text{ker}^2\xi_o + \text{kei}^2\xi_o}$$

$$= 1.0$$

$$F_2(\xi,\xi_o) = \frac{\text{ker}\xi \;\; \text{kei}\xi_o + \text{kei}\xi_o \; \text{ker}\xi_o}{\text{ker}^2\xi_o + \text{kei}^2\xi_o}$$

$$D1 = 1 - F_1$$

$$= 0$$

$$D2 = F_2 = 0$$

Since C3 = 0, C4 = 0, D1 = 0 and D2 = 0, then

F9Z = C3 + (1/(T2 - T1))*{C4*SUM(1) + C5*(D1*I1 + D2*I2)
+ C6*[D1*SUM(2)+D2*SUM(3)+D1*SUM(4)+D2*SUM(5)]}

= 0

For z = za:

$$C30 = \frac{u_{*1}}{k} \ln \frac{z_a}{z_o} \left[1 + \frac{(u_{*2})_m}{u_{*1}}\right]^{-1}$$

$$= \frac{3.2863}{0.4} \ln \frac{0.06}{1.542 x 10^{-3}} \left[1 + \frac{0.9138}{3.2863}\right]^{-1}$$

$$= 23.536$$

$$C3 = C30 \left[\frac{z_a}{z_a}\right]^{p_n} A_o$$

$$= (23.536)\left[\frac{0.06}{0.06}\right]^{2.188}(0.0385)$$

$$= 0.9061$$

$$C4 = C30 \left[\frac{z_a}{z_a}\right]^{p_n/2}$$

$$= (23.536)\left[\frac{0.06}{0.06}\right]^{2.188/2}$$

$$= 23.536$$

$$C5 = U_o A_o \left[\frac{z_a}{z_a}\right]^{p_n}$$

$$= (10.79)(0.0385) \left[\frac{0.06}{0.06}\right]^{2.188/2}$$

$$= 0.4154$$

$$C6 = (10.79) \left[\frac{0.06}{0.06}\right]^{2.188/2}$$

$$= 10.79$$

$$= 2 \, \frac{\omega z}{K_o}^{1/2} \Bigg|_{z = z_a}$$

$= 0.3868$

$\ker\xi = \ker(0.3868)$

$= 1.094$

$\mathrm{kei}\,\xi = \mathrm{kei}(0.3868)$

$= -0.708$

$$F_1(\xi,\xi_o) = \frac{\ker\xi \ \ker\xi_o + \mathrm{kei}\,\xi_o \ \mathrm{kei}\,\xi_o}{\ker^2\xi_o + \mathrm{kei}^2\xi_o}$$

$$= \frac{(1.094)(2.897) + (-0.708)(-0.782)}{(2.897)^2 +(-0.782)^2}$$

$= 0.4135$

$$F_2(\xi,\xi o) = \frac{-\ker\xi \ \mathrm{kei}\,\xi_o + \mathrm{kei}\,\xi_o \ \ker\xi_o}{\ker^2\xi_o + \mathrm{kei}^2\xi_o}$$

$$= - \frac{(1.094)(-0.782) - (-0.708)(2.897)}{(2.897)^2 + (-0.782)^2}$$

$= -0.1328$

$D1 = 1 - F_1$

$= 1 - 0.4135$

$= 0.5865$

$D2 = F_2$

$= -0.1328$

$\ker p_n\xi = \ker_{2.188}(0.3868)$

$= \ker_{pn}\xi a$

$\mathrm{kei}\,p_n\xi = \mathrm{kei}_{2.188}(0.3868)$

$= \mathrm{kei}_{pn}\xi a$

$$F_1(\xi;\xi_a,p_n) = \frac{\ker_{p_n}\xi \ \ker_{p_n}\xi_a + \mathrm{kei}_{p_n}\xi \ \mathrm{kei}_{p_n}\xi_a}{\ker_{p_n}{}^2\xi_a + \mathrm{kei}_{p_n}{}^2\xi_a}$$

$= 1.0$

$$F_2(\xi;\xi_a,p_n) = \frac{\ker_{p_n}\xi \ \mathrm{kei}_{p_n}\xi_a + \mathrm{kei}_{\beta_n}\xi \ \ker_{p_n}\xi_a}{\ker_{p_n}{}^2\xi_a + \mathrm{kei}_{p_n}{}^2\xi_a}$$

$A_1 = -0.266\times10^{-1}$ (from FFT)

$B_1 = 0.865\times10^{-2}$ (from FFT)

$$\begin{aligned} TR12 &= A_1\ F_1(\xi;\xi_a,p_n) + B_1\ F_2(\xi;\xi_a,p_n) \\ &= (-0.266\times10^{-1})(1.0) + (0.865\times10^{-2})(0) \\ &= -0.266\times10^{-1} \end{aligned}$$

$$\begin{aligned} TR21 &= A_1\ F_2(\xi;\xi_a,p_n) + B_1\ F_1(\xi;\xi_a,p_n) \\ &= (-0.266\times10^{-1})(0) + (0.865\times10^{-2})(1.0) \\ &= 0.865\times10^{-2} \end{aligned}$$

T1 = 0.0 (from TIMING)

T2 = 3.000 (from TIMING)

$$\begin{aligned} I1 &= \left[(1/\omega)\sin\omega\ t\right]_{0.0}^{3.0} \\ &= (1/1.0472)\ \sin(1.0472)(3.0) \\ &= 0 \end{aligned}$$

$$\begin{aligned} I2 &= \left[(-1/\omega)\cos\omega\ t\right]_{0.0}^{3.0} \\ &= (-1/1.0472)[\cos(1.0472)(3.0) - 1.0] \\ &= 1.9099 \end{aligned}$$

$$\begin{aligned} I5 &= \left[(t/2) + (1/4\omega)\sin 2\omega t\right]_{0.0}^{3.0} \\ &= (3.0/2) + \frac{1}{(4)(1.0472)}\sin(2)(1.0472)(3.0) \\ &= 1.50 \end{aligned}$$

$$\begin{aligned} I7 &= \left[(t/2) - (1/4\omega)\sin 2\omega t\right]_{0.0}^{3.0} \\ &= (3.0/2) - \frac{1}{(4)(1.0472)}\sin(2)(1.0472)(3.0) \\ &= 1.50 \end{aligned}$$

$$\begin{aligned} I9 &= \left[(1/2\omega)\sin^2\omega t\right]_{0.0}^{3.0} \\ &= \frac{1}{(2)(1.0472)}\quad [\sin(1.0472)(3.0)]^2 \\ &= 0 \end{aligned}$$

The results of the manual calculations and computer run are summarized in Table C.1.

Only the first two terms in the summations will be manually checked.

For m = 1:

$\text{TRM12} = A_1\ F_1(\xi;\xi_a,p_n) + B_1\ F_2(\xi;\xi_a,p_n)$
$= (-0.266\text{x}10^{-1})(1.0) + (0.865\text{x}10^{-2})(0)$
$= -0.266\text{x}10^{-1}$

$\text{TRM21} = A_1\ F_2(\xi;\xi_a,p_n) + B_1\ F_1(\xi;\xi_a,p_n)$
$= (-0.266\text{x}10^{-1})(0) + (0.865\text{x}10^{-2})(1.0)$
= 0.865x10-2

$\text{I3} = [(1/m\omega)\sin m\omega t]_{0.0}^{3.0}$

$= (1/1.0472)\ \sin(1)(1.0472)(3.0)$
$= 0$

$\text{I4} = [(-1/m\omega)\cos m\omega t]_{0.0}^{3.0}$

$= (-1/1.0472)\ \cos\ (1)(1.0472)(3.0) - 1.0$
$= 1.9099$

$\text{SUM}(1) = \text{SUM}(1) + \text{TRM12*I3} + \text{TRM21*I4}$
$= (-0.266\text{x}10^{-1})(0) + (0.865\text{x}10^{-2})(1.9099)$
$= 0.0165$

$\text{SUM}(2) = \text{SUM}(2) + \text{TR12*I5}$
$= (-0.266\text{x}10^{-1})(1.50)$
$= -0.0399$

$\text{SUM}(3) = \text{SUM}(3) + \text{TR21*I7}$
$= (0.865\text{x}10^{-2})(1.50)$
$= 1.30\text{x}10^{-2}$

$\text{SUM}(4) = \text{SUM}(4) + \text{TR21*I9}$
$= (0.865\text{x}10^{-2})(0)$
$= 0$

$\text{SUM}(5) = \text{SUM}(5) + \text{TR12*I9}$
$= (-0.266\text{x}10^{-1})(0)$
$= 0$

For m = 2:

$\text{TRM12} = A_2\ F_1(\xi;\xi_a,p_n) + B_2\ F_2(\xi;\xi_a,p_n)$
$= (0.349\text{x}10^{-3})(1.0) + (-0.240\text{x}10^{-3})(0)$
$= 0.349\text{x}10^{-3}$

$\text{TRM21} = A_2\ F_2(\xi;\xi_a,p_n) + B_2\ F_1(\xi;\xi_a,p_n)$
$= (0.349\text{x}10^{-3})(0) + (-0.240\text{x}10^{-3})(1.0)$
$= -0.240\text{x}10^{-3}$

$$I3 = \left[(1/m\omega)\sin m\omega t\right]_{0.0}^{3.0}$$

$$= \frac{1}{(2)(1.0472)} \quad \sin(2)(1.0472)(3.0)$$

$$= 0$$

$$I4 = \left[(-1/m\omega)\cos m\omega t\right]_{0.0}^{3.0}$$

$$= -\frac{1}{(2)(1.0472)} \quad [\cos(2)(1.0472)(3.0) - 1.0]$$

$$= 0$$

$$\begin{aligned} SUM(1) &= SUM(1) + TRM12*I3 + TRM21*I4 \\ &= (0.0165) + (0.349\text{x}10^{-3})(0) + (-0.240\text{x}10^{-3})(0) \\ &= 0.0165 \end{aligned}$$

$$I6 = \left[\frac{\sin(m-1)\omega t}{2(m-1)} + \frac{\sin(m+1)\omega t}{2(m+1)}\right]_{0.0}^{3.0}$$

$$= \left[\frac{\sin(1)(1.0472)(3.0)}{(2)(1)(1.0472)} + \frac{\sin(3)(1.0472)(3.0)}{(2)(3)(1.0472)}\right]$$

$$= 0$$

$$I8 = \left[\frac{\sin(m-1)\omega t}{2(m-1)\omega} - \frac{\sin(m+1)\omega t}{2(m+1)\omega}\right]_{0.0}^{3.0}$$

$$= \frac{\sin(1)(1.0472)(3.0)}{(2)(1)(1.0472)} - \frac{\sin(3)(1.0472)(3.0)}{(2)(3)(1.0472)}$$

$$= 0$$

$$I10 = -\left[\frac{\cos(m-1)\omega t}{2(m-1)\omega} - \frac{\cos(m+1)\omega t}{2(m+1)\omega}\right]_{0.0}^{3.0}$$

$$= -\frac{\cos(1)(1.0472)(3.0) - 1.0}{(2)(1)(1.0472)} - \frac{\cos(3)(1.0472)(3.0) - 1.0}{(2)(3)(1.0472)}$$

$$= 1.2732$$

$$I11 = \left[-\frac{\cos(1-m)\omega t}{2(1-m)\omega} - \frac{\cos(1+m)\omega t}{2(1+m)\omega}\right]_{0.0}^{3.0}$$

$$= -\frac{\cos(-1)(1.0472)(3.0) - 1.0}{(2)(-1)(1.0472)} - \frac{\cos(3)(1.0472)(3.0) - 1.0}{(2)(3)(1.0472)}$$

$$= -0.6366$$

SUM(2) = SUM(2) + TRM12*I6
= (-0.0399) + $(0.349\text{x}10^{-3})$(0)
= -0.0399

SUM(3) = SUM(3) + TRM21*I8
= $1.30\text{x}10^{-3}$ + $(-0.240\text{x}10^{-3})$(0)
= $1.30\text{x}10^{-3}$

SUM(4) = SUM(4) + TRM21*I10
= $(-0.240\text{x}10^{-3})$(1.2732)
= $3.06\text{x}10^{-4}$

SUM(5) = SUM(5) + TRM12*I11
= $(0.349\text{x}10^{-3})$(-0.6366)
= $-2.22\text{x}10^{-4}$

The terms in the summation for m=1 and m=2 for $z=z_a$ are summarized in Table C.2 for the manual and computer results.

The remaining terms in the summations are not checked, but are assumed to be correct, since the calculations in the DO loop for m = 2 are repeated for m = 3 to m = 50. When the summations are complete, the results from the program are:

SUM(1) = $0.161\text{x}10^{-1}$

SUM(2) = $-0.398\text{x}10^{-1}$

SUM(3) = $0.130\text{x}10^{-1}$

SUM(4) = $-0.375\text{x}10^{-3}$

SUM(5) = $-0.228\text{x}10^{-3}$

These values are used to check the final calculation of F9Z.

F9Z = C3 + (1/(T2-T1){C4*SUM(1) + C5*(D1*I1+D2*I2)
+ C6*[D1*SUM(2)+D2*SUM(3)+D1*SUM(4)+D2*SUM(5)]}
= (0.9061) + (1/3.0){(23.536)(0.161x10-1)
+ (0.4154)[(0.5865)(0) + (-0.1328)(1.9099)]
+(10.79)[(0.5865)(-0.398x10-1) + (-0.1328)(0.130x10-1)
+ (0.5865)(-0.375x10-3) + (-0.1328)(-0.228x10-3)]}
= 0.9292

The remainder of the depth integration is not checked, since ROMBZ uses the same algorithm that was previously used in subroutines ROMBIN and ROMB2. ROMBZ returns the value

RSLT = 0.755

Since the time integration is for half a wave cycle, the result is multiplied by a factor of two to be consistent with the sediment transport computed using the other options.

$$Q_x = 2.0*RSLT$$

$$= (2.0)(0.755)$$

$$= 1.510$$

TABLE C.1 MANUAL CALCULATIONS AND COMPUTER RESULTS FOR COMPUTATION OF FUNCTION F9Z

Intermediate Variable	For $z = z_o$ Computer Program	 Manual Check	For $z = z_a$ Computer Program	 Manual Check
C30	0.0	0.0	23.5	23.5
C3	0.0	0.0	0.907	0.906
C4	0.0	0.0	23.5	23.5
C5	0.125×10^4	0.125×10^4	0.416	0.415
C6	0.592×10^3	0.592×10^3	10.8	10.8
ξ_o	0.0620	0.0620	0.3868	0.3868
F1	1.0	1.0	0.414	0.414
F2	0.0	0.0	-0.133	0.133
D1	0.0	0.0	0.586	0.587
D2	0.0	0.0	-0.133	0.133
F9Z	0.0	0.0	0.907	0.929

TABLE C.2 SUMMARY OF TERMS IN SUMMATION FOR $z = z_a$
FOR M = 1 AND M = 2

INTERMED. VARIABLE	BEFORE SUMMATION		FOR M = 1		FOR M = 2	
	Computer Program	Manual Check	Computer Program	Manual Check	Computer Program	Manual Check
F1P	1.0	1.0				
F2P	0.0	0.0				
TR12	-0.0266	-0.0266				
TR21	$0.865\text{x}10^{-2}$	$0.865\text{x}10^{-2}$				
I1	0	0				
I2	1.91	1.91				
I5	1.50	1.50				
I7	1.50	1.50				
I9	0	0				
TRM12			-0.0266	0.0266	$0.35\text{x}10^{-3}$	$0.35\text{x}10^{-3}$
TRM21			$0.865\text{x}10^{-2}$	$865\text{x}10^{-2}$	$2.24\text{x}10^{-3}$	$0.24\text{x}10^{-3}$
I3			0	0	0	0
I4			1.91	1.91	0	0
SUM(1)			0.0165	0.0165	0.0165	0.0165
I6			*	*	0	0
I8			*	*	0	0
I10			*	*	1.27	1.27
I11			*	*	-0.637	0.637
SUM(2)			-0.0398	-0.0399	-0.0398	0.0399
SUM(3)			0.0130	0.0130	0.0130	0.0130
SUM(4)			0	0	$-0.31\text{x}10^{-3}$	$0.31\text{x}10^{-3}$
SUM(5)			0	0	$-0.22\text{x}10^{-3}$	$0.22\text{x}10^{-3}$

* Not computed for M = 1