Contract Report

SED1D: A SEDIMENT TRANSPORT MODEL FOR THE CONTINENTAL SHELF

by

Susan Davidson

Martec Ltd.

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Geological Survey of Canada

Atlantic Geoscience Centre

Bedford Institute of Oceanography

P.O. Box 1006

Dartmouth, N.S. B2Y 4A2

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Abstract

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:

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

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):

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

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

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 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; 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 x 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, bed-load 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

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

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

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

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

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

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

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

and $$u_* = \sqrt{\frac{\tau_b}{\rho}} \qquad (24)$$

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

$$g_s = K\ \tau_{bw}\ \vec{u}_{100} \qquad (25)$$

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

from $$\tau_{bw} = \frac{\rho}{2}\ f|\vec{u}_b|^2 \qquad (26)$$

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

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

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 mega-ripples	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 mega-ripples	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.

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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

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

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

$$\phi_{bo} = \phi_{100} \qquad \text{(A-2)}$$

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

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

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

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

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

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

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

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

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

$$g_x = \sin\ \theta + \frac{u_a}{u_b} \cos \phi_b \tag{A-10}$$

$$g_y = \frac{u_a}{u_b} \sin\ \phi_b \tag{A-11}$$

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

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

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

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).

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

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

$$C = \frac{V_2}{2\alpha^{1/4}} \tag{A-16}$$

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

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

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

Ker and Kei are Kelvin functions of order zero.

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

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

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.

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

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 =  30.00 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,KD0,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 MMKELO(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(///,' ***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 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
        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) 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(TAU0**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(TAU0**3*RHOW)/(GD*DGAMMA**2)
          ELSE IF (OPT .EQ. 2) THEN
            SED=40.0*FALL*GD*(TAU0/(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
```