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 $\left(\frac{D}{\nu}\sqrt{\frac{\tau_b}{\rho}}\right)$

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

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

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

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

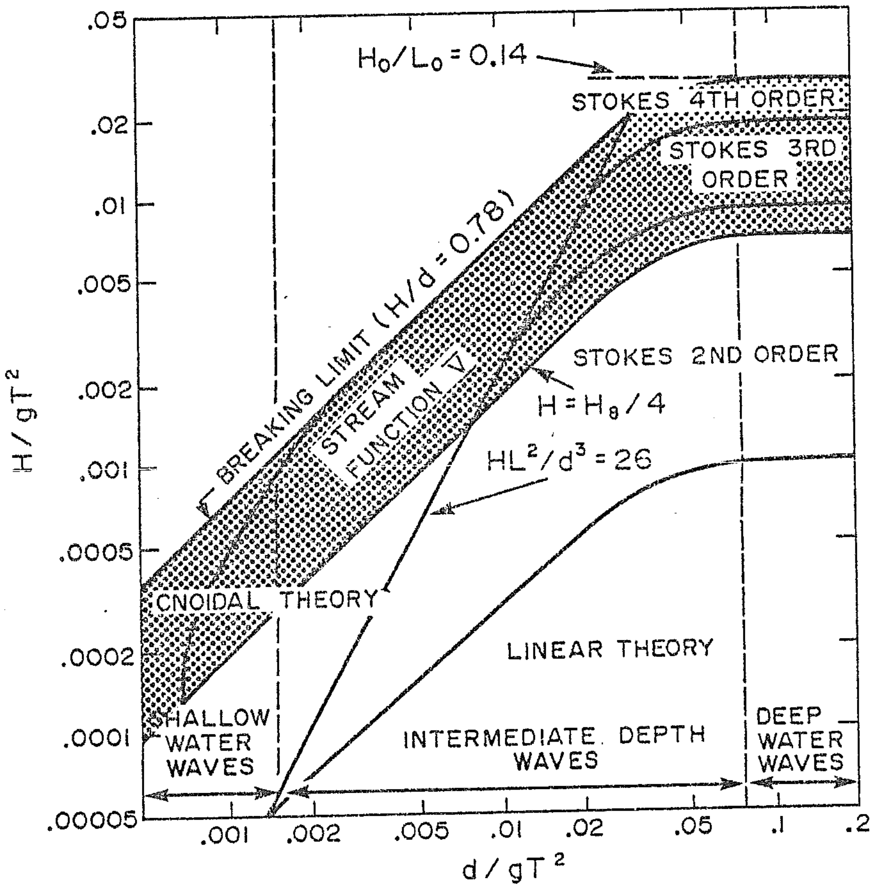

Figure 2.1. Approximate limits of validity for various wave theories (LeMéhauté, 1976).

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

$$H_b = 0.142 \; L \tanh (kd) \qquad (5)$$

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:

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

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):

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

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

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:

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

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

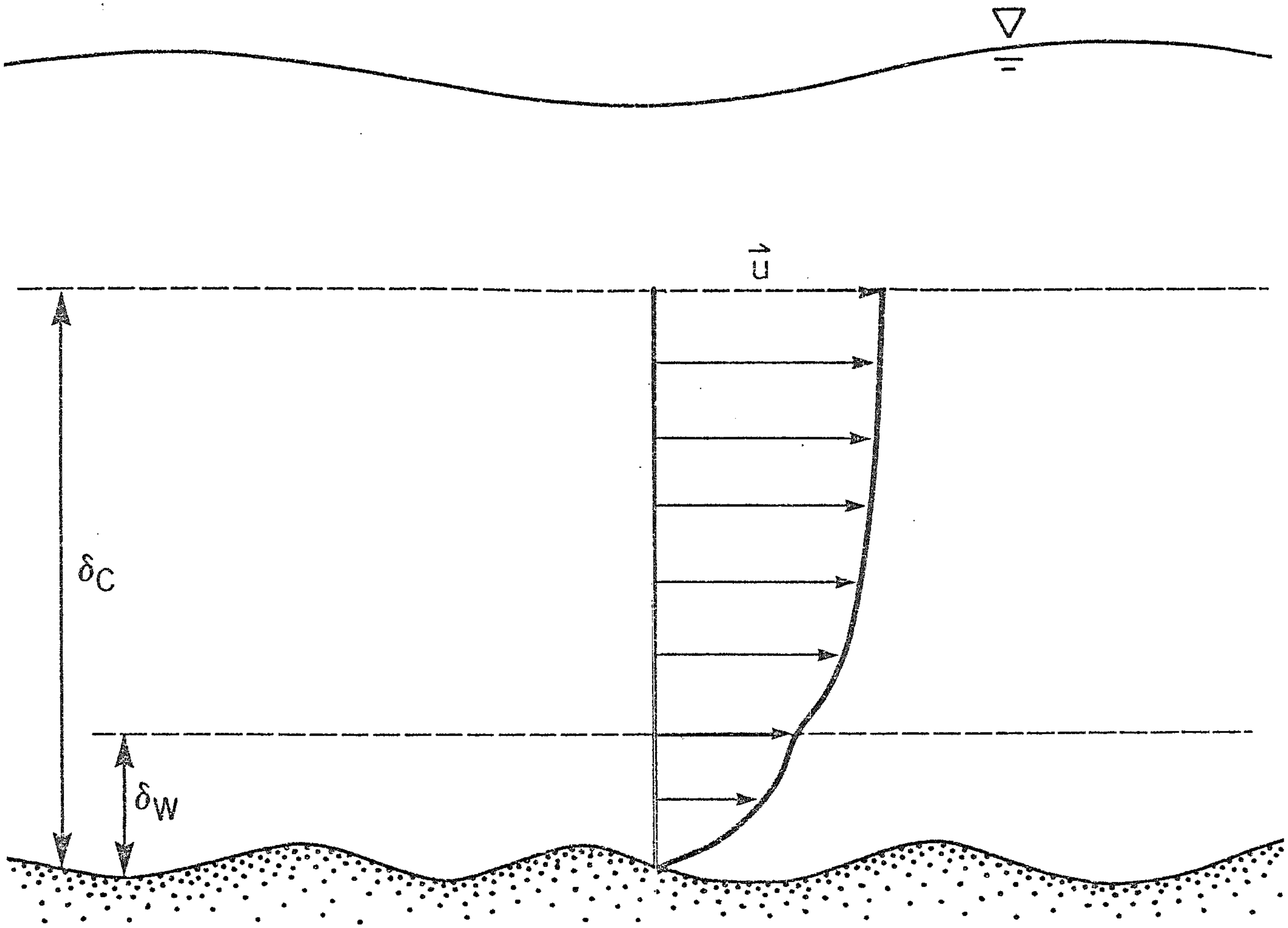

Figure 2.2. Bottom boundary layer when both waves and a steady current are present.

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; $\left|\vec{u}_z\right|/\left|\vec{u}_b\right|$ 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:

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

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

$\vec{u}_a$ 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

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

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

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

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

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

and $$u_* = \sqrt{\frac{\tau_b}{\rho}} \qquad (25)$$

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

$$g_s = K \tau_{bw} \vec{u}_c \qquad (26)$$

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

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

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

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

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	.0086	.0085	.0082	.0078	.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

$$\delta_w = 2\,\ell \tag{29}$$

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	8.26 .98 0.00	22.39 32.62 0.00	35.97 136.18 0.00	49.13 239.32 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	113.05 658.44 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	50.55 333.08 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	86.28 610.55 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 .84 0.00	19.52 1.97 0.00	31.73 8.51 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	24.15 1.75 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 59.32 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	86.49 85.67 0.00

u_a (cm/sec)
a (cm)
ϕ_b (degrees)

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 3.2. 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 6.05	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.

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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_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 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,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)
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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
        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=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
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 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)
        ZETA0=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)
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```
            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
```

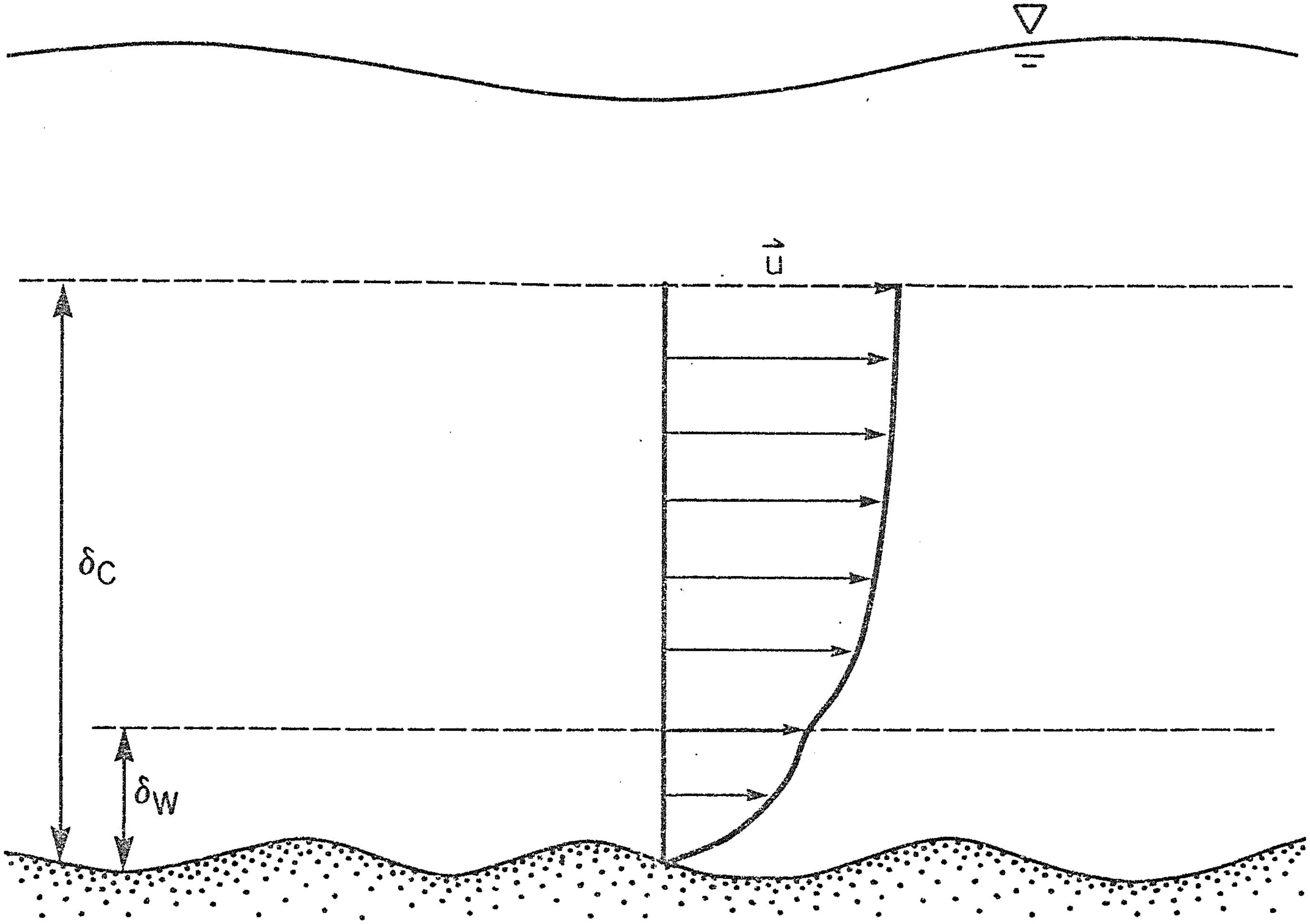
```
PRINT 115,SEDDIR,SED
      WRITE(7,115) SEDDIR,SED
 115  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
     @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
     @G12.4,' CM**2/SEC')
C
      IF (UA .NE. 0.0) THEN
C
        IF (OPT .EQ. 1) THEN
          PRINT 125
     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


∇
$\vec{u}$
δ_C
δ_W