SEDTRANS96: UPGRADE AND CALIBRATION OF THE GSC SEDIMENT TRANSPORT MODEL

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by

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LIST OF SYMBOLS

A	empirical coefficient for downcore sediment resistance
A_b	near-bed wave orbital amplitude
c	sediment concentration
C_b	volume concentration of the bottom sediment
$C_{\delta cw}$	suspended sediment concentration at the height of the wave-current boundary layer
C_{dir}	direction of mean current
C_r	wave-to-current strength ratio
c_t	time-dependent suspended sediment concentration
C_z	suspended sediment concentration at height z above the seabed
c_0	initial suspended sediment concentration
C_0	reference suspended sediment concentration at the height of bed roughness z_0
D	sediment grain diameter
E	option number of transport equation
E_m	eroded mass
E_0	empirical coefficient for minimum erosion
F	fraction of the size class in bottom sediment
f_c, f_{cs}	current friction factor
f_{cw}, f_{cws}	combined wave-current friction factor
f_w, f_{ws}	wave friction factor
g	gravitational acceleration
h	water depth
H_s	significant wave height
h_{tm}	thickness scale of the bedload layer
(k_0) k	(deep-water) wave number
K	proportionality coefficient in Bagnold transport formula
k_b	total bed roughness height
k_{bg}	sediment grain roughness height
k_{br}	ripple roughness height
k_{bt}	bedload-transport roughness height
(L_o) L	(deep-water) wave length
m	sediment mass
M	empirical coefficient in Bagnold transport formula
P_e	proportionality coefficient for erosion
P_s	probability coefficient of resuspension
q	volume rate of sediment transport
Q_b	mass bedload transport rate
$Q_{b\text{-}dir}$	direction of bedload transport
Q_m	mass bedform transport rate
(Q_{s0}) Q_s	(initial) suspended-load transport rate
r_d	deposition rate of cohesive sediments
r_e	erosion rate of cohesive sediments
R_m	ripple migration rate
S_*	dimensionless sediment parameter
$t, \Delta t$	time and time interval
T	wave period
t_b	time of bedload transport over a 1/2 wave cycle
t_s	time of suspended-load transport over a 1/2 wave cycle
u, V	mean velocity

u_b	near-bed maximum wave orbital velocity
u_{cr}	critical mean velocity
u_z	mean velocity at height z above the bottom
u_{100}	mean velocity at 1 m above the bottom
u_*	shear velocity
u_{*bf}	critical shear velocity for ripple break-off
u_{*c}, u_{*cb}, u_{*cs}	total/bedload/skin-friction current shear velocity
u_{*cr}	critical shear velocity for bedload transport
u_{*crs}	critical shear velocity for suspended-load transport
$u_{*cw}, u_{*cwb}, u_{*cws}$	total/bedload/skin-friction combined wave-current shear velocity
u_{*cwe}	ripple-enhanced combined shear velocity
u_{*up}	critical shear velocity for upper-plane bed sheet-flow
u_{*w}, u_{*wb}, u_{*ws}	total/bedload/skin-friction wave shear velocity
W_{dir}	wave propagation direction
W_s	particle settling velocity
W_{sc}	settling velocity for cohesive sediment
Y	Yalin parameter
z	height above the bottom
z_r	height of measured mean current
z_s	downcore sediment depth
z_0	bottom roughness
z_{0c}	apparent bottom roughness
$\alpha, \alpha 1, \alpha 2$	Rouse suspension parameter
β	bed slope or grain size coefficient in the modified Bagnold formula
γ_0	empirical sediment resuspension coefficient
δ_{cw}	thickness of wave-current boundary layer
η	ripple height
θ_{cr}	Shields parameter for bedload transport
θ_{cs}	skin-friction current Shields parameter
θ_{cws}	skin-friction combined Shields parameter
θ_{up}	Shields parameter for sheet-flow
θ_{ws}	skin-friction wave Shields parameter
κ	von Karman constant
λ	ripple wavelength
μ	dynamic fluid viscosity
ν	kinematic fluid viscosity
ρ	fluid density
ρ_b	sediment bulk density
ρ_s	sediment density
τ_b	bottom shear stress
τ_{cr}	critical shear stress for bedload transport
τ_{crs}	critical shear stress for suspended-load transport
τ_{cs}	skin-friction current shear stress
τ_{cwe}	ripple-enhanced combined shear stress
τ_{cws}	skin-friction combined shear stress
τ'_{cws}	effective bed shear stress
τ_d	critical deposition shear stress for cohesive sediments
τ_e	critical erosion shear stress for cohesive sediments
$\tau_e(z)$	critical erosion shear stress as a function of sediment depth
$\tau_e(0)$	critical erosion shear stress at the sediment surface

τ_{up}	critical shear stress for sheet-flow
τ_w, τ_{ws}	total/skin-friction wave shear stress
τ_y	yield stress for cohesive sediments
τ_*	normalized excess shear stress
ϕ_b	angle between wave and current in the wave-current boundary layer
ϕ_i	internal friction angle for cohesive sediment
ω	wave angular frequency

SUMMARY

The Geological Survey of Canada sediment transport model (SEDTRANS) has been upgraded significantly on the basis of new advances in both cohesive and non-cohesive sediment transport. The new version of the model, SEDTRANS96, uses the Grant and Madsen (1986) combined-flow bottom boundary layer theory to compute the bed shear stresses and predicts sediment transport rates using one of five algorithms. Critical shear stresses for bedload, suspension and sheet-flow transport tested for the combined-flow conditions are adopted in SEDTRANS96 to properly define the initiation of these transport modes. A combined-flow ripple and bed roughness predictor is included in the model to provide a time-dependent ripple predictor and to account for the effect of bedload transport on boundary layer dynamics. The vertical profiles of velocity and suspended sediment concentration are also predicted in SEDTRANS96 so that their product can be integrated through depth to compute the suspended-load transport rate. Also proposed is a scheme of effective shear stress as a function of sediment transport and bedform development stages to reflect the effects of the ripple-enhanced shear stress on the computation of sediment transport rates. Data of measured sediment transport rates over fine and medium sands collected on Sable Island Bank, the Scotian Shelf, have been used to calibrate the upgraded model. The differences between the measured and predicted sediment transport rates have been reduced to be less than a factor of 5. The model operation and result output are now menu-driven and a set of output data files are generated to provide more complete information on the boundary layer dynamics and seabed responses. The model results are also presented graphically in a series of plots by calling a computation and visualization software package MATLAB. A new computation algorithm is proposed for cohesive sediment transport in SEDTRANS96. Three states are defined for the transport of cohesive sediment transport according to the relative values of the applied shear stress and the critical shear stresses for deposition and erosion. For a given initial sediment concentration, applied bed shear stress, and the time duration of the deposition or erosion process, a finite-difference scheme is used to calculate the final erosion or deposition rate and the new sediment concentration which is multiplied by mean flow velocity and water depth to obtain the cohesive sediment transport flux.

SEDTRANS96: UPGRADE AND CALIBRATION OF THE GSC SEDIMENT TRANSPORT MODEL

1. INTRODUCTION

The processes of sediment erosion, transport and deposition essentially occur in the bottom boundary layer which forms the interface between the seabed and the water column. These processes greatly affect seabed stability, the configuration of the bottom, the dispersal of particulate material and the communities of the benthic animals. The study of boundary layer dynamics and sediment transport is important to oceanographers, coastal engineers as well as environmental managers (Grant and Madsen, 1986; Wright, 1989; Cacchione and Drake, 1990). A sediment transport model (SEDTRANS) has been developed at the Geological Survey of Canada - Atlantic (GSCA) to deal with the boundary layer dynamics and sediment transport problems on continental shelves and in coastal environments (Martec Ltd., 1984 & 1987; Davidson and Amos, 1985). SEDTRANS is a one-dimensional numerical computer model that predicts sediment transport under steady currents or combined wave-current flows. The model adopts established bottom boundary layer theories to predict bed shear stress and velocity profiles near the seabed. Sediment transport is predicted using one of five algorithms that may be selected by the user. The original model was re-evaluated, upgraded and calibrated by Li and Amos (1993, 1995) based on advances in combined-flow bottom boundary layer theory (Grant and Madsen, 1986) and available data of in situ sediment transport measurements (Amos et al., 1988). The upgraded version of the model, SEDTRANS92, has been successfully applied to predict sediment transport patterns on the Scotian Shelf (Anderson, 1995; Li et al., in press). There have been more than 50 requests of the Open File Report and paper on SEDTRANS92 and up to date there are 15 external users in various universities, institutes and companies around the world.

As stated in Li and Amos (1993), SEDTRANS92 has several shortcomings. The model relies on the measured ripple geometry input by the user and does not have a time-dependent bed roughness predictor. Several wave ripple predictors are available (Nielsen, 1981; Grant and Madsen, 1982), but none has been tested for application under combined flows. For this reason, SEDTRANS92 uses a mixed wave ripple and current ripple predictors. SEDTRANS92 is also only calibrated (with limited data) for bedload transport and it does not include a separate algorithm for the prediction of suspended load transport which is more important during storms or for fine sediment. Several recent studies have advanced our understandings on boundary layer dynamics, the development of bedforms, and their effects on shear stress partition and sand resuspension (e.g. Wiberg and Nelson, 1992; Wright, 1993; Madsen et al., 1993; van Rijn et al., 1993; Li, 1994; Vincent and Downing, 1994; Wiberg and Harris, 1994; Wright et al., 1994; van Rijn and Havinga, 1995; Li et al., 1996a). A joint project between GSCA and Pan Canadian (formerly LASMO Ltd.) was initiated in 1993 to study wave-current dynamics and seabed scouring during storms on the Scotian Shelf. Various instrumentation packages have been deployed on Sable Island Bank, Scotian Shelf, during several cruises to obtain in situ measurements on waves, currents and seabed responses under storm conditions. (Amos et al., 1994a; Zevenhuizen and Li, 1994; Li et al., 1994 and 1996b). Through the analyses of data sets so collected, the following advances have been made: (1) We have established the threshold shear stresses for various transport modes (bedload, suspension and sheetflow) under combined flows, (2) A new empirical ripple predictor has also been proposed for the combined waves and currents and (3) The new model has been further calibrated by these new data (Li and Amos, in press; Li et al., in press; Li and Amos, in review[a,b]). Due to the developments of Sea Carousel and Lab Carousel (Amos et al., 1992a & 1994b), significant advances have also been made in our understanding of cohesive sediment transport, particularly in situ measurements of cohesive sediment stability, temporal and spatial changes of cohesive sediment erodibility, and the correlation between the erodibility and sediment physical properties, biostablization/destabilization, and subaerial exposure (Mehta, 1993; Amos et al., 1996a and in press).

Because of these significant advancements in both cohesive and non-cohesive sediment transport studies, SEDTRANS92 is due for another major upgrade. The main objective of this report is thus to describe the newly upgraded and calibrated GSC sediment transport model, SEDTRANS96. The key improvements in SEDTRANS96 are (1) tested critical shear stresses for various transport modes under combined flows, (2) a time-dependent bed roughness predictor, (3) a ripple predictor for combined waves and currents, (4) predictions of bedload as well as suspended load transport, (5) effects of bed slope on the prediction of sediment transport rates, (6) upgraded algorithms for cohesive sediment transport, (7) a more rigorous calibration of the model with new field data, and (8) detailed output files and graphical displays of the key parameters. The introduction (this chapter) provides an overview of the historical development of the model, the shortcomings of the old version SEDTRANS92, and the key improvements in the upgraded version SEDTRANS96. The next chapter gives a general description of the model structure and its operation. Chapter 3 covers the main subroutines of the model and the changes made in SEDTRANS96. Available field data are used in Chapter 4 to further calibrate the model and conclusions are given in Chapter 5. The complete source codes of SEDTRANS96 are listed in Appendix 1.

2. MODEL STRUCTURE AND OPERATION

SEDTRANS96 is a one-dimensional numerical model that can be used to predict the transport rate and direction of sand or mud under either steady currents or combined waves and currents. SEDTRANS96 adopts the Grant and Madsen (1986) continental shelf bottom boundary layer theory (GM86 hereafter) to predict bed shear stress and velocity profiles in the bottom boundary layer. The model uses the algorithms of Einstein-Brown (Brown, 1950) and Yalin (1963) for bedload prediction. The methods of Engelund and Hansen (1967) and Bagnold (1963) are used to determine total load transport (bedload plus suspended load). The prediction of cohesive sediment transport adopts the method of Amos and Greenberg (1980) and Amos et al. (1996a and in press).

SEDTRANS96 is written in standard Fortran77. It can be run either interactively or in batch mode. The source codes of the model (see Appendix 1) are made modular to simplify the computational processes. This structure allows each subroutine to be modified separately without having to change the whole program. There are 11 subroutines in the program and they are given below with their main functions:

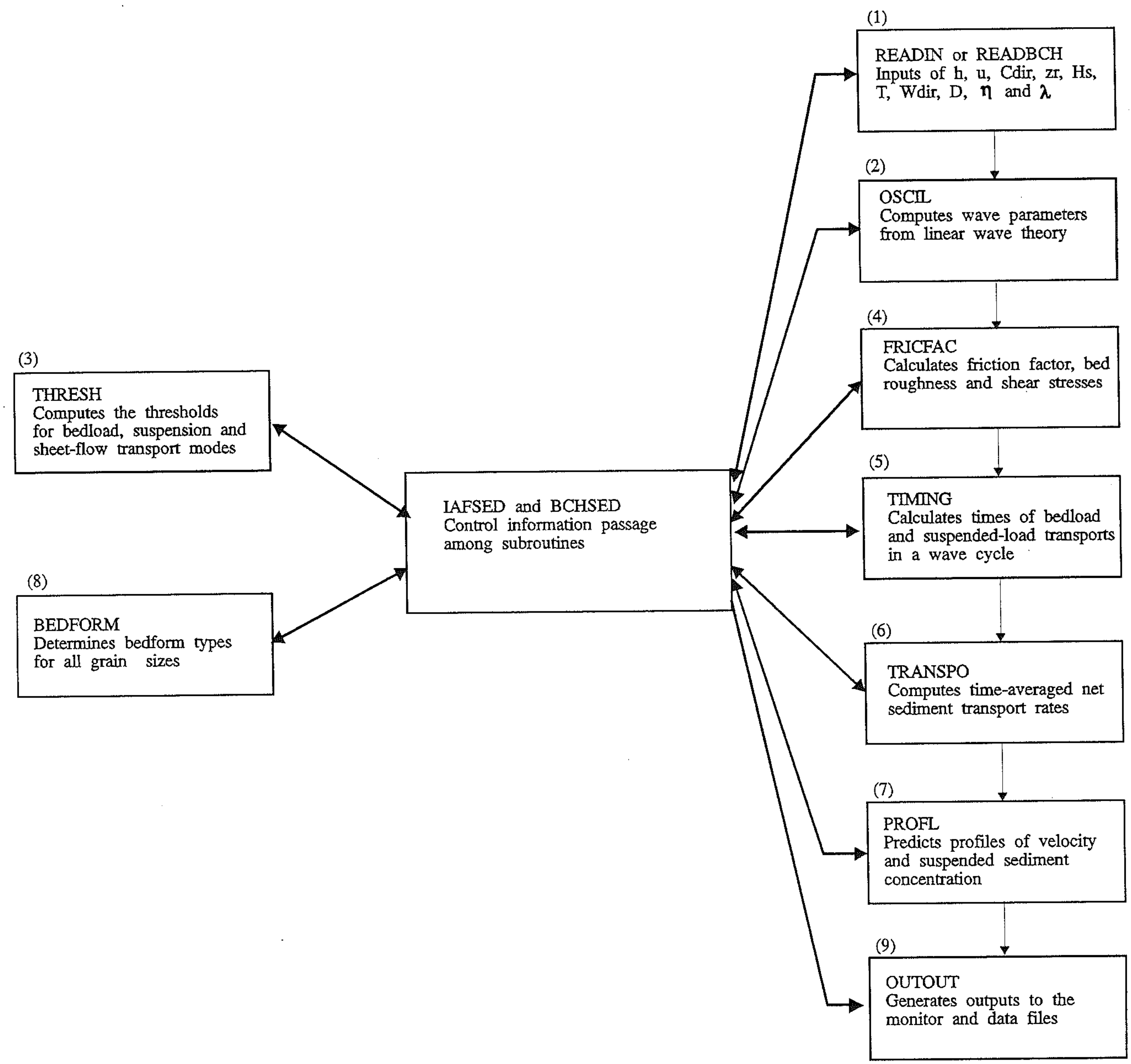
1. Main programs, IAFSED (interactive mode) and BCHSED (batch mode): control passage of information among subroutines.
2. Subroutines READIN (interactive mode) and READBCH (batch mode): read user-supplied data required to run the model.
3. Subroutine INOUT: prints the input data both to the terminal and to the output files.
4. Subroutine OSCIL: computes the required wave parameters using linear wave theory.
5. Subroutine THRESH: calculates the threshold shear stresses and shear velocities for various sediment transport modes.
6. Subroutine FRICFAC: calculates the friction factor, bedform geometry and various shear stresses required by the program.

7. Subroutine TIMING: calculates the duration of bedload and suspended load transport during a wave cycle.
8. Subroutine TRANSPO: computes the time-averaged net sediment transport according to one of five available algorithms.
9. Subroutine PROFL: predicts the profiles of mean velocity and suspended sediment concentration and integrates them to derive the suspended load transport rate and direction.
10. Subroutine BEDFORM: predicts the possible types of bedforms.
11. Subroutine OUTOUT: prints the selected output parameters from all the subroutines both to the terminal and to the output files.

The following input data of wave, current and seabed parameters are required to run SEDTRANS96: water depth h (m), mean current velocity u (m/s) and its direction C_{dir} (degree), height of current measurement above the sea bed z_r (m), significant wave height H_s (m), wave period T (s), wave propagation direction W_{dir} (degree), median sediment grain size D (m), ripple height η (m), ripple wavelength λ (m), and bed slope β (degree). For a given set of wave, current and seabed conditions, the subroutine OSCIL is first run to calculate related wave parameters (see flow-chart in Fig. 1). Subroutine THRESH is then used to determine the critical shear stresses for bedload, suspended load and upper-plane bed sheet-flow sediment transport, respectively. Friction factors, bed shear stresses and bedform geometry are predicted in subroutine FRICFAC. Based on the results from the above operations, the duration of bedload and suspended load sediment transport over a wave cycle are calculated in subroutine TIMING and net sediment transport rates are obtained in subroutine TRANSPO through integration of the instantaneous sediment transport rate. Subroutine PROFL is then run to predict the profiles of velocity and suspended sediment concentration which are integrated to obtain the rate of suspended load sediment transport. Based on near-bed velocities and shear stresses, bedform types are predicted in BEDFORM and finally the subroutine OUTOUT outputs results to the monitor and data files. The key output parameters from SEDTRANS96 include nearbed maximum wave orbital velocity u_b (m/s), wave excursion amplitude A_b (m), predicted bedform types and dimension (ripple height and length), various wave and current shear velocities, and the magnitude and direction of bedload and suspended load sediment transport.

In this latest version of SEDTRANS, several batch files are used to control the model running and result output. By typing **menu96** and pressing Enter, a menu is displayed and the user can choose

Figure 1. A flow chart showing the structure and model operation of SEDTRANS96.


(1)
READIN or READBCH
Inputs of h, u, Cdir, zr, Hs, T, Wdir, D, η and λ
(2)
OSCIL
Computes wave parameters from linear wave theory
(4)
FRICFAC
Calculates friction factor, bed roughness and shear stresses
(5)
TIMING
Calculates times of bedload and suspended-load transports in a wave cycle
(6)
TRANSPO
Computes time-averaged net sediment transport rates
(7)
PROFL
Predicts profiles of velocity and suspended sediment concentration
(9)
OUTOUT
Generates outputs to the monitor and data files
IAFSED and BCHSED
Control information passage among subroutines
(3)
THRESH
Computes the thresholds for bedload, suspension and sheet-flow transport modes
(8)
BEDFORM
Determines bedform types for all grain sizes

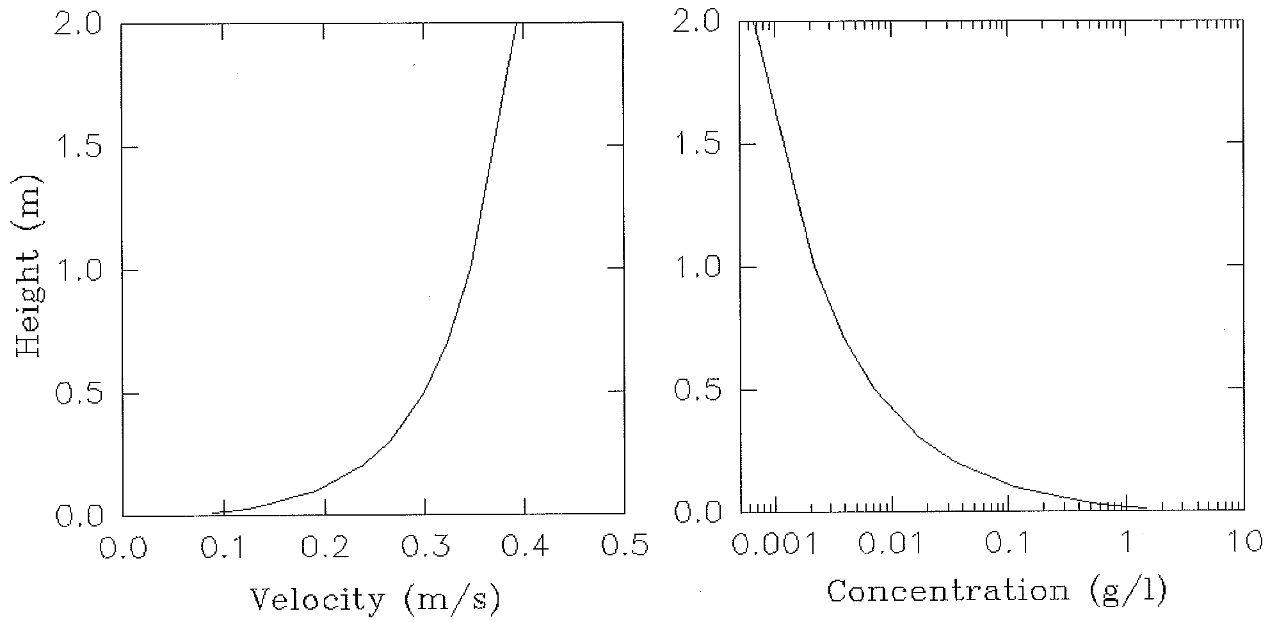
to run the model in interactive or batch mode (Appendix 2). For the interactive mode, SEDTRANS96 is started by running the executable file IAFSED. The model will prompt for each of the input parameters. The detailed output text is stored in a file specified by the user and the parameters are stored in two tabular files SEDOUTI1 and SEDOUTI2. The predicted velocity and suspended sediment concentration profiles are saved in PROFILE.DAT. An example of an interactive session of SEDTRANS96 and its output files are given in Appendix 2. For the batch mode SEDTRANS96, the model is run by executing the file BCHSED. The input data need to be prepared in advance and are stored in a file named INDATA which will be called by BCHSED. Detailed text outputs are saved in OUTDATA and the output parameters are saved to SEDOUT1.DAT and SEDOUT2.DAT in tabular format. The predicted velocity and suspended sediment concentration profiles are stored in a file named PROFILE. Examples of an INDATA file, SEDOUT1.DAT, SEDOUT2.DAT and PROFILE from running the batch-mode SEDTRANS96 can be found in Appendix 3. When the model is completed, it returns to the main menu and the user can choose to plot the results in Matlab or go back to DOS. For the interactive mode, the vertical profiles of the predicted velocity and suspended sediment concentration will be plotted and the following parameters are listed under these plots: skin-friction current (u_{*cs}), wave (u_{*ws}) and combined (u_{*cws}) shear velocities, total current (u_{*c}), wave (u_{*w}) and combined (u_{*cw}) shear velocities, mass bedload transport rate (Q_b, kg/m/s), mass suspended-load transport rate (Q_s, kg/m/s), and the direction of the bedload transport ($Q_{b\text{-}dir}$). The graphical outputs from an example interactive-mode model run are shown in Fig. 2a. For the batch-mode SEDTRANS96, the time series of the skin-friction combined shear velocity u_{*cws}, the predicted bedload transport rate Q_b, the predicted suspended-load transport rate Q_s, and the direction of the bedload transport $Q_{b\text{-}dir}$ will be plotted. An example of these plots is given in Fig. 2b.

3. THEORIES OF MAIN SUBROUTINES

The computations of SEDTRANS96 mainly occur in seven subroutines. These subroutines are: OSCIL, FRICFAC, THRESH, TIMING, TRANSPO, PROFL and BEDFORM. The theories and upgraded algorithms behind these subroutines are described in this chapter.

3.1 Subroutine OSCIL

Waves usually are described by water depth (h), wave height (H) and wave period (T). The



bt#	u_{*cs}	u_{*ws}	u_{*cws}	u_{*c}	u_{*w}	u_{*cw}	Q_b	Q_s	$Q_{b\text{-}dir}$	
1	0.0162	0.0201	0.0258	0.0271	0.0399	0.0481	0.000994		0.007549	15.3

Figure 2 The graphical outputs from SEDTRANS96: (a) predicted profiles of velocity and suspended sediment concentration and key output parameters from a sample interactive-mode run, and (b) time-series of the skin-friction combined shear velocity u_{*cws}, bedload transport rate Q_b, suspended-load transport rate Q_s and the direction of bedload transport $Q_{b\text{-}dir}$ from a sample batch-mode run.

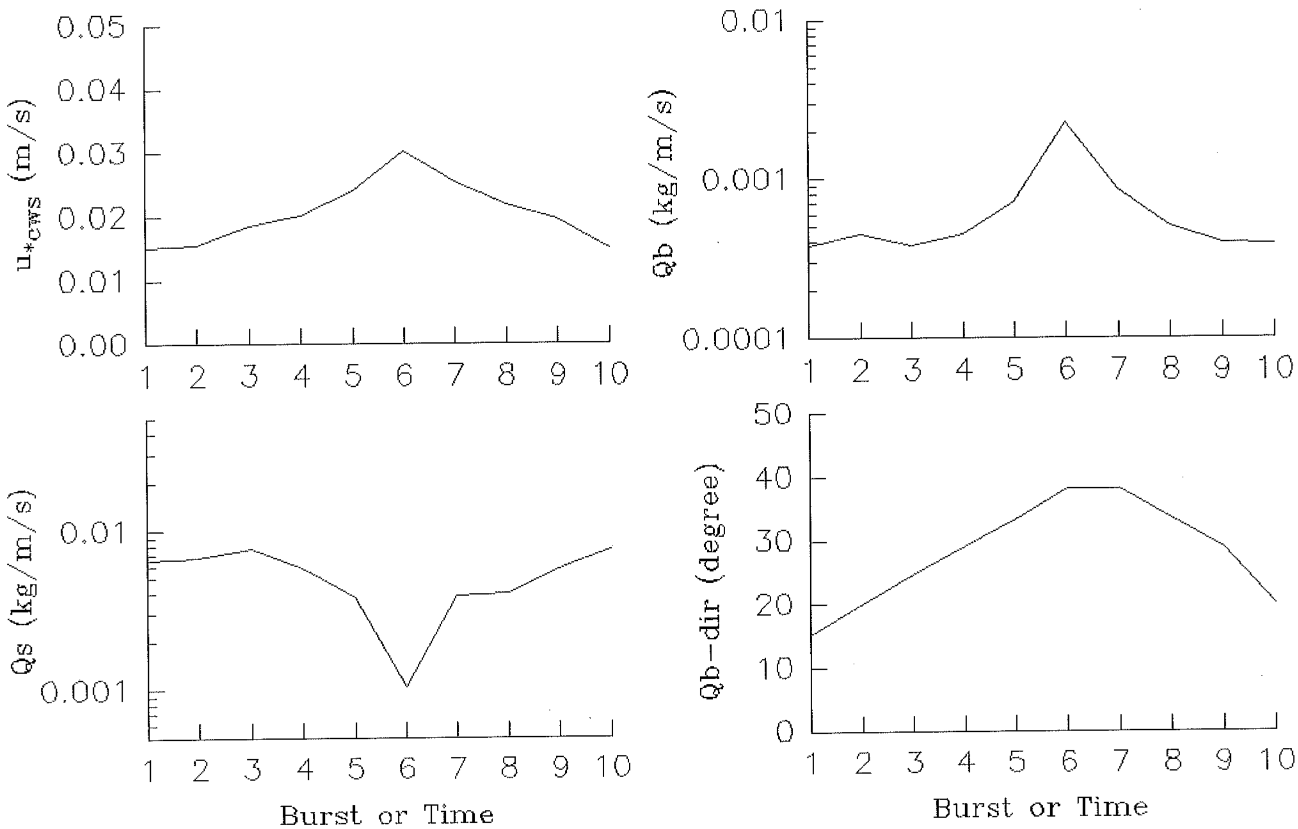

0.05
0.04
0.03
0.02
0.01
0.00
u_{*cws} (m/s)
1 2 3 4 5 6 7 8 9 10
0.01
0.001
0.0001
Qb (kg/m/s)
1 2 3 4 5 6 7 8 9 10
0.01
0.001
Qs (kg/m/s)
1 2 3 4 5 6 7 8 9 10
Burst or Time
50
40
30
20
10
0
Qb-dir (degree)
1 2 3 4 5 6 7 8 9 10
Burst or Time

Figure 2b

calculation of bottom shear stress, however, requires the maximum nearbed wave orbital velocity (u_b) and wave particle excursion amplitude (A_b) to be known. Linear wave theory is used in SEDTRANS96 to calculate u_b and A_b in subroutine OSCIL.

Waves do not affect the sea bed in the deep water case, thus u_b and A_b are assumed to be zero when the deep water criterion $h/L_o > 0.5$ is met, where $L_o = gT^2/2\pi$ is the deep-water wave length and g is the acceleration of gravity. Wave number k is computed from the linear wave dispersion equation:

$$\omega^2 = gk \tanh(kh) \qquad (1)$$

where ω is the wave angular frequency ($\omega = 2\pi/T$) and tanh is the hyperbolic tangent function. Due to the transcendental nature of equation (1), iterative calculations are required to solve for k. The Newton-Raphson method is used in this model to solve equation (1). If x_1 is assumed to be the first-estimated root to function f(x), then successive estimates can be obtained from $x_{n+1} = x_n - f(x_n)/f'(x_n)$ in which f' indicates the first derivative of function f. Equation (1) can be re-written as:

$$f(kh) = 1/\tanh(kh) - kh/k_oh = 0 \qquad (2)$$

where $k_o = \omega^2/g$ is the deep water wave number. Based on equation (2), the Newton-Raphson solution can be written as:

$$\begin{aligned}(kh)_{n+1} &= (kh)_n + f(kh)_n/f'(kh)_n \\ &= (kh)_n - [1/\tanh(kh)_n - (kh)_n/k_oh] \\ &\quad /[1/\sinh^2(kh)_n + 1/(kh)_n]\end{aligned} \qquad (3)$$

where sinh is the hyperbolic sine function. The deep water parameter k_oh is used as the first estimate of kh and a new estimate is obtained from equation (3). If this new kh is still significantly different from the first estimate, the procedure is repeated until kh converges to a steady solution. The final kh is then used in the following equation to determine wave length:

$$L = L_o \tanh(kh) \qquad (4)$$

and u_b and A_b are then calculated from the following relationships:

$$u_b = \pi H/[T^*\sinh(kh)] \qquad (5)$$

$$A_b = u_b/\omega \qquad (6)$$

3.2 Subroutine THRESH

As bed shear stress increases, sediment particles will first be entrained from their resting equilibrium positions and then go through three distinctive modes of transport, i.e. bedload, suspension and sheet-flow transport. In bedload transport, particles move by rolling and sliding in association with ripple growth. At higher shear stresses, sediments are thrown up into the water column by turbulence and the re-suspended sediments are carried downstream by the advective mean current to form suspension transport. At even higher shear stresses, ripples are washed out and sediment grains are moving in a high-concentration nearbed layer. This is defined as upper-plane bed sheet-flow transport. Accurate predictions of sediment transport rates very much depend on the establishment of the critical shear stresses for the initiation of these three transport modes.

The total-load transport method of Ackers and White (1973) uses a complex threshold criterion and thus is not included in SEDTRANS96. Other transport methods all use the modified Shields curve to determine the threshold of bedload transport. For given fluid and sediment densities (ρ and ρ_s), sediment threshold should be affected by sediment grain size and fluid viscosity only, the latter being a function of temperature. As in SEDTRANS92, the critical shear velocity u_{*cr} was adopted as the threshold criterion in SEDTRANS96. In order to avoid the iterative computation required by the Shields method, Yalin's method according to Miller et al. (1977) thus has been used in this version of the model. Figure 3 shows the Yalin diagram in which the dimensionless critical Shields parameter θ_{cr} is plotted against the Yalin parameter Y. For a given grain size D and kinematic viscosity ν, a Shields parameter can be directly obtained from Fig. 3.

It is apparent that the modified Shields curve shown in Fig. 3 can be separated into three parts based on the values of the Yalin parameter Y. Regression of these segments gives us the following relationships:

$$\log\theta_{cr} = 0.041(\log Y)^2 - 0.356\log Y - 0.977 \qquad Y < 100 \qquad (7a)$$

$$\log\theta_{cr} = 0.132\log Y - 1.804 \qquad 100 < Y \leq 3000 \qquad (7b)$$

$$\log\theta_{cr} = 0.045 \qquad Y > 3000 \qquad (7c)$$

where Y is defined as $[(\rho_s-\rho)gD^3/\rho\nu^2]^{0.5}$. Thus for given sediment grain size and fluid viscosity, the Yalin parameter is calculated and then the modified Yalin curve as described by equation (7) is used to determine the critical Shields parameter θ_{cr}. This θ_{cr} value can be used in turn to calculate the critical shear stress τ_{cr} from:

$$\tau_{cr} = \theta_{cr}(\rho_s-\rho)gD \qquad (8)$$

and the critical shear velocity u_{*cr} can be obtained from the quadratic law $\tau_{cr} = \rho u^2_{*cr}$.

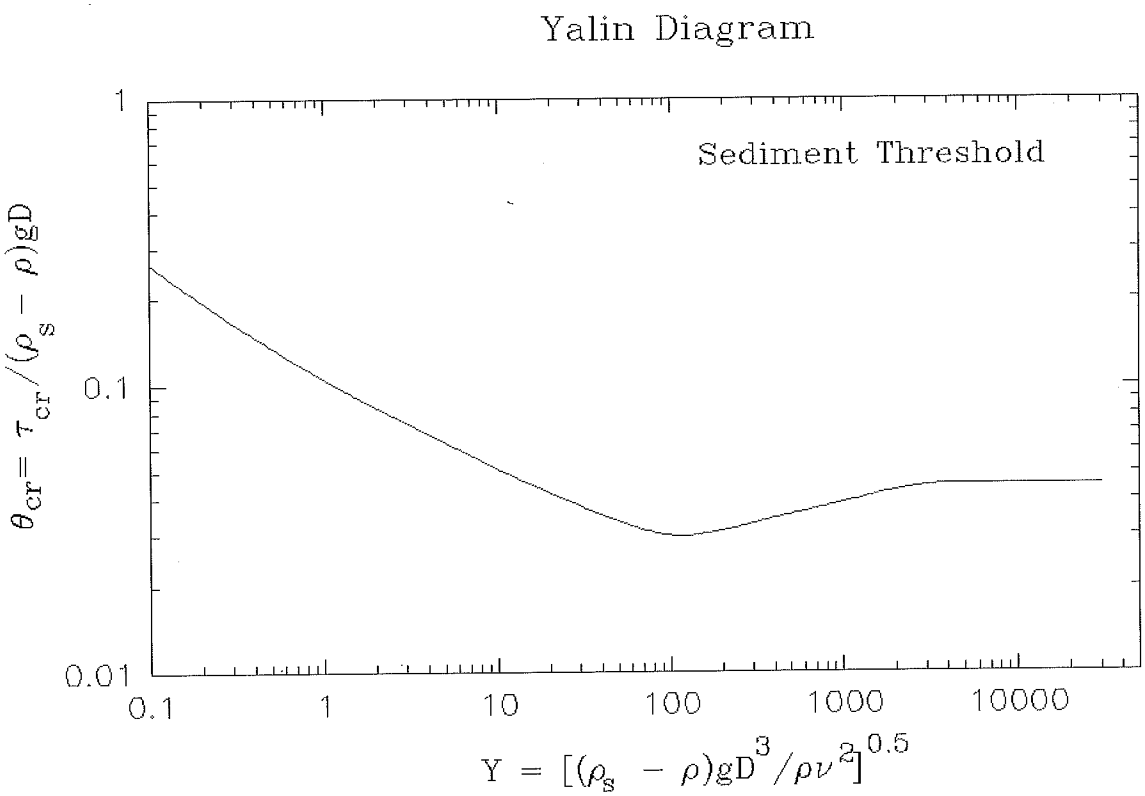


Figure 3. Shields parameter θ_{cr} plotted against the Yalin parameter Y (modified from Miller et al., 1977).

The computation of the critical shear velocity for suspension transport in SEDTRANS96 is similar as that in SEDTRANS92. Based on the work of Gibbs et al. (1971), the settling velocity W_s of a sediment grain of diameter D is first calculated from:

$$W_s = \{-3\mu + [9\mu^2 + (gD^2/4)\rho(\rho_s-\rho)(0.0155 + 0.0992D)]^{0.5} / [\rho(0.0116 + 0.0744D)] \qquad (9)$$

where μ is the dynamic viscosity. The critical shear stress for the initiation of suspended load transport, τ_{crs}, is then computed from Bagnold (1966):

$$\tau_{crs} = 0.64W_s^2 \qquad (10)$$

or converted to the critical shear velocity u_{*crs}:

$$u_{*crs} = (0.8/\rho)W_s \qquad (11)$$

SEDTRANS92 does not include the computation of the critical shear stress for upper-plane bed sheet-flow. Since seabed scouring and intensive sediment transport mostly occur under this condition, the computation of the critical shear velocity for sheet-flow is included in SEDTRANS96. Various criteria have been suggested for sheet flow under waves, but no consensus has been reached (e.g. Manohar, 1955; Komar and Miller, 1975; Dingler and Inman, 1976). Data of sheet flow under combined flows are very limited (see Hay and Bowen, 1993; Madsen et al., 1993; Dick et al., 1994). Li and Amos (in review[b]) have compiled data from previous studies and compared them to their field observations on the Scotian Shelf in attempting to derive a universal criterion. SEDTRANS96 adopts their findings to predict the critical Shields parameter for sheet-flow as:

$$\theta_{up} = 0.172D^{-0.376} \qquad (12)$$

where particle size D is in cm. The corresponding critical shear stress for sheet-flow is obtained from:

$$\tau_{up} = \rho u_{*up}^2 = \theta_{up}(\rho_s-\rho)gD \qquad (13)$$

in which u_{*up} is the critical shear velocity for sheet-flow.

Analyses of flow dynamics and sediment transport data collected from Sable Island Bank on the Scotian Shelf, however, have shown that enhanced shear stresses due to ripples and bedload transport have to be considered in order to correctly apply these threshold criteria under combined waves and currents (Li et al., in press; Li and Amos, in press). Similar findings can also be found in Kapdasli and Dyer (1986), Wilson (1988), Wiberg and Nelson (1992) and Wiberg and Harris (1994). These effects are further discussed in the sections on subroutines FRICFAC and TIMING.

3.3 Subroutine FRICFAC

The computation of the friction factor itself for either the pure wave or the steady current case is not changed in this version of the model. The steady-current skin-friction factor f_{cs} is taken to be 0.006 based on field experiments of Sternberg (1972) and Soulsby (1983). Wave friction factor f_w is calculated according to Jonsson (1966) as modified by Nielsen (1979):

$$f_w = \exp[5.213(k_b/A_b)^{0.194}-5.977] \qquad A_b/k_b > 1.7 \tag{14a}$$

$$f_w = 0.28 \qquad A_b/k_b \le 1.7 \tag{14b}$$

where k_b is the bottom roughness height. A quadratic law is used to compute the bottom shear stress τ_b. For pure waves:

$$\tau_b = 0.5\rho f_w u_b^2 \tag{15}$$

and for steady currents:

$$\tau_b = 0.5\rho f_c u_{100}^2 \tag{16}$$

where f_c is the current friction factor and u_{100} is the mean velocity at 1 m above the bottom.

One of the modifications made in SEDTRANS96 is that the height and length of bedforms under pure currents or pure waves are now predicted in subroutine FRICFAC instead of in subroutine BEDFORM so that a time-dependent bed roughness and its effects on boundary layer parameters are included. But types of bedforms are still predicted in subroutine BEDFORM. As field measurements of ripples are scarce for coarse and very coarse sands (e.g. Forbes and Boyd, 1987), bedform heights and lengths are not predicted for these sizes. Under either steady currents or pure waves, the skin-friction shear stress τ_b is compared with the critical shear stresses for bedload and sheet-flow transports τ_{cr} and τ_{up} respectively. If $\tau_b < \tau_{cr}$, sediment transport does not occur and the input values of bedform height and length will be used. If $\tau_b \ge \tau_{up}$, upper-plane bed sheet-flow occurs and ripples are completely washed out. Only when $\tau_{cr} \le \tau_b < \tau_{up}$, will bedform dimensions be estimated. The ripple length λ under steady currents is predicted according to Yalin (1964):

$$\lambda = 1000D \tag{17}$$

and that under waves is given according to Boyd et al. (1988):

$$\lambda = 557A_b(u_bA_b/\nu)^{-0.68} \tag{18}$$

The ripple height η under both conditions is predicted following Allen (1970):

$$\eta = 0.074\lambda^{1.19} \tag{19}$$

in which λ needs to be in cm.

For the wave-only case, the grain size roughness height of 2.5D is first used in place of k_b in equation 14 to calculate the skin-friction wave friction factor f_{ws}. This is used in equation 15 for the computation of skin-friction wave shear stress τ_{ws}. This stress and equations 18 and 19 are used to predict the ripple height and length. The predicted ripple dimensions are used in the following equation (Grant and Madsen, 1982) to obtain the ripple roughness height k_{br}:

$$k_{br} = 27.7\eta(\eta/\lambda) \qquad (20)$$

This new roughness height is again used in equations 14 and 15 to obtain the total wave friction factor f_w and total wave shear stress $\tau_w = \rho u_{*w}^2$, where u_{*w} is the total wave shear velocity. The bottom roughness length is calculated from $z_0 = k_{br}/30$.

For the current-only case, if the measured ripple height and length are available, they will be used in equation 20 to obtain an initial estimate of the bed roughness height k_b. Otherwise, the initial bed roughness height will be the grain roughness height 2.5D. This initial bed roughness height together with the measured mean velocity u_z at height z are used to estimate the total shear velocity u_{*c} in the von Karman-Prandtl law-of-wall equation

$$u_{*c} = \kappa u_z/\ln(30*z/k_b) \qquad (21)$$

and the initial estimate of the mean velocity at 1 m above the seabed is then obtained from

$$u_{100} = (u_{*c}/\kappa)\ln(30*100/k_b) \qquad (22)$$

where 100 in the natural log function is used assuming all other parameters are in cgs units. The mean velocity u_{100} and $f_{cs} = 0.006$ are then used in equation 16 to obtain the skin-friction current shear stress (or shear velocity u_{*cs}) $\tau_{cs} = \rho u_{*cs}^2$. If the predicted ripple height is zero (sheet-flow or $u_{*cs} < u_{*cr}$ and input ripple height equal to 0), the new bed roughness height is obtained from the von Karman-Prandtl law of wall $k_b = 30*\exp[\ln(z) - \kappa u_z/u_{*c}]$ (see equation 21). Otherwise if non-zero ripple height is predicted, the new bed roughness height will be given by equation 20. With this new estimate of bed roughness height, the above procedures are repeated until the values of u_{*cs} converge. Finally the bottom roughness length is calculated from $z_0 = k_b/30$.

Important changes are made in the computation of friction factor for combined wave-current flows. SEDTRANS92 uses the sediment grain size to predict the combined-flow skin-friction factor f_{cws} and corresponding skin-friction shear velocities. The sum of the grain roughness and the bedform roughness based on the input ripple geometry is then used to obtain a total friction factor f_{cw} and total shear velocities. The FRICFAC subroutine of SEDTRANS92 thus has two major problems. Firstly it uses the input ripple geometry to determine the bedform roughness and thus lacks a time-dependent ripple predictor. This approach has neglected the interaction between the prevailing flow dynamics and the equilibrium bedforms. Secondly the FRICFAC subroutine of SEDTRANS92 predicts the total friction factor and shear stresses using only the grain roughness plus the bedform roughness. Since the GM86 model assumes that the total bed roughness is composed of grain roughness, bedform (ripple) roughness and bedload roughness when sediment is in transport, the effect of bedload roughness on the total friction factor and shear stresses is not accounted for in SEDTRANS92. These problems are solved in SEDTRANS96 by including a time-dependent ripple predictor and calculations of bedload roughness in FRICFAC. The calculation of the combined-flow friction factor f_{cw} and various shear stresses in SEDTRANS96 follows the GM86 model. The basic theory and procedures of this method are described below:

Step 1 The Initial Estimate of f_{cw} An arbitrary value is first assumed for the relative strength ratio of wave to current C_r. The friction factor f_{cw} can then be obtained by iteration from:

$$1/(4f_{cw}^{0.5}) + \log[1/(4f_{cw}^{0.5})\} = \log(C_r u_b/\omega z_0) + 0.14(4f_{cw}^{0.5}) - 1.65 \quad (23)$$

where $z_0 = k_b/30$ is the bottom roughness. For skin-friction factor, k_b is equal to the grain roughness height $k_{bg} = 2.5D$. For the computation of bedload shear stresses (see below for explanation), the sum of the grain and bedload roughness heights ($k_{bg} + k_{bt}$) is used in equation 23. For the total friction factor and shear stresses, the complete total bed roughness height ($k_b = k_{bg} + k_{br} + k_{bt}$) will be used.

Step 2 Estimating u_{*c}, u_{*w} and u_{*cw} The maximum wave shear velocity u_{*w} is calculated using C_r and f_{cw} from above:

$$u_{*w} = (C_r f_{cw} u_b^2/2)^{0.5} \quad (24)$$

and the shear velocity due to combined waves and currents is obtained from:

$$u_{*cw} = u_{*w} C_r^{0.5} \quad (25)$$

The equations governing the near-bed velocity profiles will be:

$$u_z = (u_{*c}/\kappa)(u_{*c}/u_{*cw})\ln(z/z_0) \qquad z \le \delta_{cw} \quad (26a)$$

$$u_z = (u_{*c}/\kappa)\ln(z/z_{0c}) \qquad z \ge \delta_{cw} \quad (26b)$$

where u_{*c} is the current shear velocity, κ is the von Karman constant (= 0.4), z_{0c} is the apparent bed roughness experienced by the current in the presence of waves, and $\delta_{cw} = 2\kappa u_{*cw}/\nu$ is the thickness of the wave-current boundary layer. By matching the current of the outer layer ($z \ge \delta_{cw}$) and that of the wave boundary layer ($z \leq \delta_{cw}$) at the height of δ_{cw}, current shear velocity u_{*c} can be computed from the following:

$$u_z = (u_{*c}/\kappa)[(u_{*c}/u_{*cw})\ln(\delta_{cw}/z_0) + \ln(z/\delta_{cw})] \quad (27)$$

where u_z is the measured mean flow velocity at the height z above the bottom.

Step 3 Iteration and Final Estimates Results from step 2 are used to compute a new value of C_r from:

$$C_r = [1+2(u_{*c}/u_{*w})^2\cos\phi_b + (u_{*c}/u_{*w})^4]^{0.5} \quad (28)$$

where ϕ_b is the angle between wave and current in the boundary layer. This new C_r is then used to repeat steps 1 to 3 until a convergence of C_r is achieved and the final values of f_{cw}, u_{*c}, u_{*w}, u_{*cw} and δ_{cw} are determined.

Step 4 u_{100} Calculation The procedures described above are repeated three times in the subroutine FRICFAC of SEDTRANS96 in order to obtain various friction factors and shear velocities. The grain roughness height $k_{bg} = 2.5D$ is first used to obtain the skin-friction factor and shear velocities (u_{*cs}, u_{*ws} and u_{*cws}). The skin-friction combined shear velocity u_{*cws} is used to compute the bedload roughness height k_{bt} (see discussion below). The sum of the grain roughness height and bedload roughness height is used in the second repeat of steps 1 to 3 to obtain the (transport-related) bedload friction factor and bedload shear velocities (u_{*cb}, u_{*wb} and u_{*cwb}). The skin-friction and bedload shear velocities are then used in a combined-flow ripple model proposed by Li and Amos (in press) to obtain ripple height and length which are used to obtain the ripple roughness height k_{br} (see discussion below). The ripple roughness height is added to the grain roughness height and bedload roughness height to derive the total roughness height $k_b = k_{bg} + k_{br} + k_{bt}$. Finally, this total roughness height is used in steps 1 to 3 for the third time to derive the total friction factor and total bed shear velocities (u_{*c}, u_{*w} and u_{*cw}) which eventually determine the vertical profiles of velocity and suspended sediment concentration. Based on parameters calculated using the total roughness, apparent bed roughness z_{0c} is obtained as:

$$z_{0c} = \delta_{cw} * \exp[-(u_{*c}/u_{*cw})\ln(\delta_{cw}/z_0)] \quad (29)$$

where z_0 now is the total bottom roughness defined as $k_b/30$. The mean velocity 1 m above the sea bed finally is computed from:

$$u_{100} = (u_{*c}/\kappa)\ln(1/z_{0c}) \quad (30a)$$

for $\delta_{cw} \leq 1$ m or from:

$$u_{100} = (u_{*c}/\kappa)(u_{*c}/u_{*cw})\ln(30*1/z_0) \qquad (30b)$$

for $\delta_{cw} > 1$ m.

Recent studies by Wilson (1988 and 1989), Wiberg and Harris (1994) and Li and Amos (in press) have shown that the friction factor at high-transport stages depends on the thickness of the bedload layer and that the transport-related shear stress due to the combined grain and bedload roughness should be used for predicting ripple geometry and thresholds of sand suspension and sheet flow transport. Based on the wave tunnel experiment of Sawamoto and Yamashita (1986) and field observations on Sable Island Bank of Li et al. (in press), SEDTRANS96 uses the skin-friction combined shear velocity u_{*cws} in the following equations to compute the thickness scale of the bedload layer h_{tm} and the bedload roughness height k_{bt}:

$$h_{tm} = 2.9D(\theta_{cws} - \theta_{cr})^{0.75} \qquad (31)$$

$$k_{bt} = 180h_{tm} \qquad (32)$$

There is very little data on ripples under combined waves and currents, and their prediction is just beginning to be dealt with (Amos et al., 1988; Li et al., 1996a; Li and Amos, in press). Laboratory and field measurements of wave ripples have been used to derive several wave-ripple predictors and the most widely used among these are the Nielsen (1981) and Grant and Madsen (1982) methods. However, recent field measurements of combined-flow ripples have shown that these wave-ripple predictors are not applicable to combined waves and currents (e.g., Osborne and Vincent, 1993; Li et al., 1996a). SEDTRANS96 uses the combined-flow ripple predictor proposed by Li and Amos (in press) based on their field observations of ripples on the Scotian Shelf. The ripple predictor of Li and Amos separates ripples into five categories: no transport, ripples in weak-transport range, ripples in equilibrium range, ripples in break-off range, and upper-plane bed sheet-flow. For $u_{*cws} < u_{*cr}$, the presence of pre-existing ripples will cause bed shear stress to increase from ripple trough to crest (Wiberg and Nelson, 1992; Li, 1994). This enhanced skin-friction shear velocity at the ripple crest, u_{*cwe}, determines when bedload transport and hence ripple movement will start (Li et al., in press). The ripple-enhanced shear velocity is calculated according to Nielsen (1986):

$$u_{*cwe} = u_{*cws}/(1 - \pi\eta/\lambda) \qquad (33)$$

where η and λ are the ripple height and length respectively. If ripple-enhanced shear velocity u_{*cwe} is still less than the critical shear velocity u_{*cr}, there is no sediment transport and the input ripple height and length will be used as the predicted ripple dimension. At high transport stages when bedload shear velocity becomes higher than the critical shear velocity for sheet-flow ($u_{*cwb} \geq u_{*up}$), ripples are completely washed out and upper-plane bed will be predicted (both η and λ will be zero). When the average skin-friction combined shear velocity is less than the critical shear velocity ($u_{*cws} < u_{*cr}$) but ripple-enhanced shear velocity u_{*cwe} is larger than u_{*cr}, localized sediment transport occurs close to the ripple crest and ripples in this weak-transport range will be predicted from:

$$\eta/D = 19.6(u_{*cws}/u_{*cr}) + 20.9 \qquad (34a)$$

$$\eta/\lambda = 0.12 \qquad (34b)$$

When the skin-friction combined shear velocity u_{*cws} is greater than the critical shear velocity u_{*cr} but the bedload shear velocity u_{*cwb} is smaller than the ripple break-off shear velocity u_{*bf}, overall bedload transport will occur and ripples will be in the equilibrium range:

$$\eta/D = 27.14(u_{*cwb}/u_{*cr}) + 16.36 \qquad (35a)$$

$$\eta/\lambda = 0.15 \qquad (35b)$$

for wave-dominant ripples ($u_{*ws}/u_{*cs} \geq 1.25$) and

$$\eta/D = 22.15(u_{*cwb}/u_{*cr}) + 6.38 \qquad (36a)$$

$$\eta/\lambda = 0.12 \qquad (36b)$$

for current-dominant or combined wave-current ripples ($u_{*ws}/u_{*cs} < 1.25$). The break-off shear velocity u_{*bf} is the critical shear velocity beyond which significant sand by-passing occurs and ripple steepness η/λ starts to decrease from its maximum value obtained in the equilibrium range. This break-off criterion is defined as $u_{*bf} = 1.34S_*^{0.3}u_{*cr}$ according to Grant and Madsen (1982) and $S_* = (D/4\nu)[(\rho_s - \rho)gD/\rho]^{0.5}$ is a dimensionless sediment parameter. The last category of ripples is the break-off ripple under the conditions of $u_{*bf} \leq u_{*cwb} < u_{*up}$ and their geometry is predicted from:

$$\lambda = 535D \qquad (37a)$$

$$\eta/\lambda = 0.15(u_{*up} - u_{*cwb})/(u_{*up} - u_{*bf}) \qquad (37b)$$

Equation 37 predicts that ripple length is constant in the break-off range and that the ripple steepness has the maximum value of 0.15 at $u_{*cwb} = u_{*bf}$ and decreases towards 0 as u_{*cwb} approaches the upper-plane bed criterion u_{*up}.

SEDTRANS92 included the method of Smith (1977) for predicting combined-flow friction factors under current-dominant conditions. However, several uncertain assumptions were made in using the Smith method and the predicted friction factors and sediment transport rates were found to be incompatible with those based on the Grant and Madsen method (Martec Ltd., 1987). A recent study by Xu et al. (1994) has also shown that the Grant and Madsen (1986) method could also be applied to a current-dominant situation. For these reasons, the Smith (1977) method is not included in SEDTRANS96.

3.4 Subroutine TIMING

The computation of the duration of sediment transport phases (no transport, bedload transport, and suspended load transport) for steady currents only is not changed in SEDTRANS96. Sediment is always transported in suspended load if current shear velocity u_{*cs} exceeds the critical suspended load shear velocity u_{*crs}. Otherwise, if $u_{*cr} \leq u_{*cs} < u_{*crs}$, then bedload transport always exists.

For the pure wave or combined-flow cases, SEDTRANS92 vectorially adds the wave and current shear velocities to obtain an instantaneous combined shear velocity and this combined shear velocity is compared against the critical shear velocities to compute the transport durations of various transport phases in a wave cycle. According to Madsen (personal communication, 1993), however, shear velocity is just an expression of the bed shear stress in units of velocity . For vector addition, the shear stresses should be used instead of shear velocities. Thus SEDTRANS96 has been improved by using bed shear stresses for the computation of transport duration under wave or combined-flow conditions. For the pure wave case, the time of bedload transport in 1/2 wave cycle t_b or that of suspended-load transport t_s can be found by solving the following two equations respectively:

$$|\tau_{ws} \cos(\omega t_b)| = \tau_{cr} \qquad (38a)$$

$$|\tau_{ws} \cos(\omega t_s)| = \tau_{crs} \qquad (38a)$$

where $\tau_{ws} = \rho u_{*ws}^2$ is the maximum skin-friction wave shear stress near the seabed. The value of t_b or t_s is multiplied by 2 to obtain the total transport time in a complete wave cycle.

The time computation for the combined wave and current flows is somewhat more complex. Assuming that skin-friction current shear stress τ_{cs} is separated from the wave shear stress τ_{ws} at an angle ϕ_b in the wave-current boundary layer (Fig. 4), the instantaneous combined shear stress τ_{cws} is given by:

$$\tau_{cws}^2 = [\tau_{ws}\cos(\omega t_b) + \tau_{cs}\cos(\phi_b)]^2 + [\tau_{cs}\sin(\phi_b)]^2$$

and the initiation of bedload transport then requires this total shear stress to be equal to the critical shear stress τ_{cr}:

$$[\tau_{ws}\cos(\omega t_b) + \tau_{cs}\cos(\phi_b)]^2 + [\tau_{cs}\sin(\phi_b)]^2 = \tau_{cr}^2 \qquad (39)$$

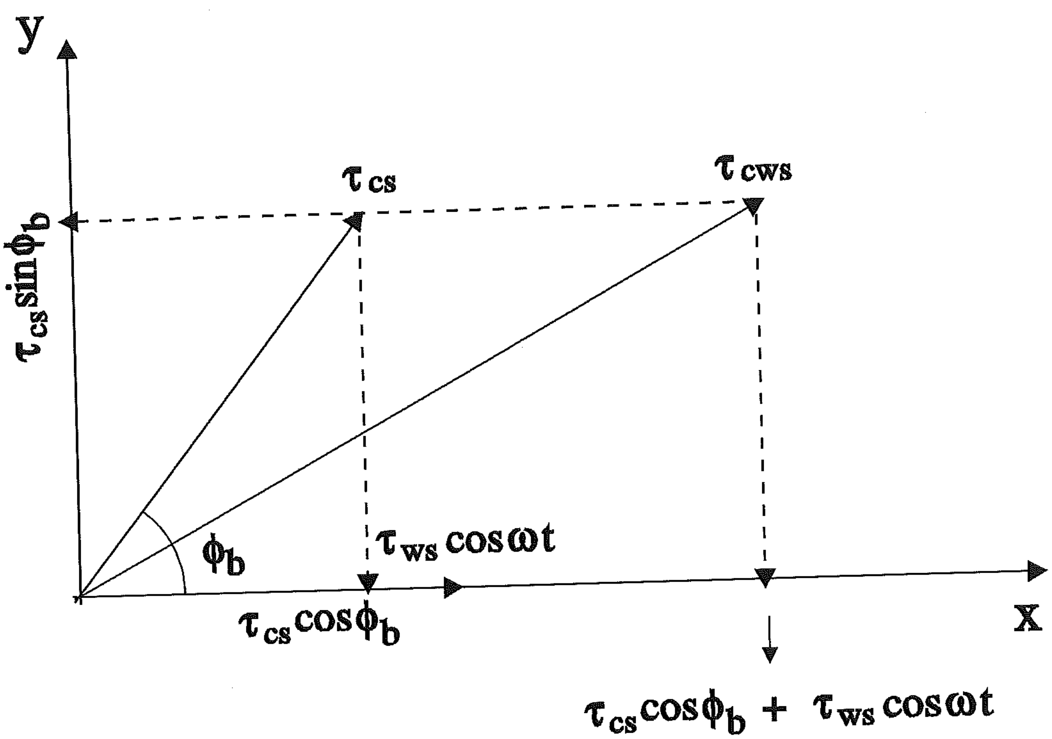


Figure 4 A schematic diagram showing the vectorial relationship between the current shear stress (τ_{cs}) and instantaneous wave shear stress ($\tau_{ws}\cos\omega t$) separated by an angle ϕ_b.

The solution of time t_b to equation (39) is:

$$\cos(\omega t_b) = -(\tau_{cs}/\tau_{ws})\cos(\phi_b) \pm \{[\tau_{cr}^2 - (\tau_{cs}\sin\phi_b)^2]/\tau_{ws}^2\}^{0.5} \quad (40)$$

The plus and minus signs in this equation represent passages of wave crests and troughs respectively. Several special cases exist that do not require solving equation 40 for t_b. If we use B to represent the square root portion on the right-hand side of equation (40), then for $B \leq 0$ [i.e. when the y-component of the current stress $\tau_{cs}\sin(\phi_b)$ is always larger than or equal to τ_{cr}], bedload transport occurs all the time. Under the wave crest, for $\cos(\omega t_b)$ to be ≥ 1, t_b must be zero (since $\omega = 2\pi/T$ cannot be zero), thus indicating that no bedload transport takes place through the wave cycle. For $\cos(\omega t_b) \leq -1$, t_b must be equal to the half of the wave period. Thus it represents the second situation in which bedload transport exists through the entire wave cycle. Finally, only if $-1 < \cos(\omega t_b) < 1$, then equation (40) is solved to obtain the time in which bedload transport occurs in 1/2 wave cycle.

The same procedures are repeated using τ_{crs} so that times for suspended-load transport may be calculated. The percent of time spent in each transport phase is calculated according to the following method:

if τ_{crs} is exceeded all the time, suspended load transport = 100% and bedload transport = 0%;

if τ_{crs} is never exceeded and τ_{cr} always exceeded, bedload = 100% and suspended load transport = 0%;

if both τ_{crs} and τ_{cr} are exceeded sometimes, the time percent of suspended load transport = 100(suspended-load transport time/wave period), and the bedload transport percent = 100(bedload transport time - suspended-load transport time)/wave period.

It should be pointed out here that the average skin-friction shear stresses are traditionally used in the above method to determine the bedload and suspended-load transport times for combined flows. As stated in section 3.3, however, recent studies have shown that shear stresses enhanced due to the presence of ripples and the bedload transport layer need to be used in order to correctly compute the sediment transport times. This is further discussed in section 4 where new field data are used for model calibration.

3.5 Subroutine TRANSPO

The instantaneous sediment transport is integrated through a wave cycle in this subroutine to obtain the net time-averaged transport rate. There were seven options in SEDTRANS92 for the calculation of sediment transport rates. Due to reasons stated in sections 3.2 and 3.3, the algorithms of Ackers and White (1973) and Smith (1977) have been eliminated in this version of the model. The remaining available transport formulae in SEDTRANS96 are the Engelund-Hansen (1967) total load equation, the Einstein-Brown (Brown, 1950) bedload equation, the Bagnold (1963) total load equation, the Yalin (1963) bedload equation and the method for cohesive sediment transport modified according to Amos and Greenberg (1980) and Amos et al. (1992b, 1996a and in press).

Three key improvements are made in SEDTRANS96. Firstly the wave and current shear stresses, instead of shear velocities, are used in the vector addition to obtain the total shear stress for the calculation of sediment transport rates (see discussion in 3.4). SEDTRANS92 uses the decomposed wave-parallel and wave-normal components of shear velocity to compute sediment transport rates in these two directions and then vectorially adds these transport components to obtain the total sediment transport rate. Since sediment transport rate is proportional to the third or higher power of shear velocity, using the decomposed shear velocities can significantly under-predict sediment transport rates compared with that using the total shear velocity. Thus the second improvement in SEDTRANS96 is that the vectorially-added instantaneous combined shear stress is used in the computation of sediment transport rates. The third important change in SEDTRANS96 is that the effect of bed slope is now included in the predicted sediment transport rate.

Integration is not required for the steady current case since the transport rate will be constant with time for the sampling period. The symmetry of the linear wave theory also dictates that no net sediment transport will occur for the pure wave case. For combined waves and current, SEDTRANS96 decomposes the skin-friction current shear stress τ_{cs} into the x (wave-parallel) and y (wave-normal) components based on the angle between waves and current ϕ_b (see Fig. 4). The x-component of the current shear stress is added to the instantaneous skin-friction wave shear stress τ_{ws} to obtain the total shear stress in the x direction. This summarized x-component shear stress and the y-component current shear stress are then vectorially added to get the instantaneous combined shear stress τ_{cws}:

$$\tau_{cws} = \{(\tau_{cs}\sin\phi_b)^2 + [\tau_{cs}\cos\phi_b + \tau_{ws}\cos(\omega t)]^2\}^{0.5}$$

This vectorially-added instantaneous combined shear stress is used to compute the sediment transport rate in various formulae and this is numerically integrated through the entire wave cycle to obtain the time-average net sediment transport rate (kg/m/s). Each of the five chosen sediment transport formulae is briefly described below.

3.5.1 Engelund-Hansen Total Load Equation

The original Engelund-Hansen (Engelund and Hansen, 1967) equation states:

$$q = 0.05V^2(\rho\tau_b^3)^{0.5}/D(\Delta\rho g)^2 \tag{41}$$

where q is the volume rate of sediment transport per unit width of bed, V is the mean velocity, τ_b is the bottom shear stress and $\Delta\rho$ is equal to $(\rho_s-\rho)$. This equation was based on unidirectional flume experiment data and was derived for dune-covered beds with mean grain sizes larger than 0.15 mm. For continental shelf conditions, the mean velocity V is replaced by the current velocity at 1 m above the bed (u_{100}) and τ_b is converted to the corresponding shear velocity u_*. The modified Engelund-Hansen equation reads:

$$q = 0.05u_{100}^2\rho^2u_*^3/D(\Delta\rho g)^2 \tag{42}$$

3.5.2 Einstein-Brown Bedload Equation

The Einstein-Brown (Brown, 1950) bedload equation was also obtained from flume experiments under unidirectional flow over well-sorted sediment. With shear stress being converted to shear velocity, this equation can be written as:

$$q = 40W_sD(\rho/\Delta\rho gD)^3u_*^5|u_*| \tag{43}$$

This equation has been tested by Madsen and Grant (1976) using wave-flume data. The equation was found to agree reasonably well with available data when skin friction only was used. The applicable grain size range for the Einstein-Brown equation is 0.3 mm to 29 mm.

3.5.3 Bagnold Total Load Equation

Bagnold (1963) assumed that waves cause sediments to be suspended, but it is the steady currents that cause net sediment transport since wave orbits are closed. Therefore no integration is required in the Bagnold method and the transport direction is assumed to be that of the steady current.

The Bagnold equation is given below:

$$q = K\tau_{cws}u_{100}/(\rho_s-\rho)g \quad (44)$$

where τ_{cws} is the maximum skin-friction combined shear stress, and K is the proportionality coefficient and is described by the following empirical equation according to Sternberg (1972):

$$K = M \exp[0.7(\tau_{cws} - \tau_{cr})/\tau_{cr}]$$

where the empirical coefficient M has a value of 0.005.

When there are pure currents only, the Bagnold's bedload equation modified by Gadd et al. (1978) is used:

$$q = (\beta/\rho_s)(u_{100} - u_{cr})^3 \quad (45)$$

where the critical velocity for the initiation of bedload transport u_{cr} is obtained from $\tau_{cr} = 0.5\rho f_{cs}u_{cr}^2$. Coefficient β (with units of kg s^2 m^{-4}) is a function of grain size. Gadd et al. analyzed data from several flume experiments and suggested that β ranges from 1.73 to 7.22 x 10^{-3} for grain sizes of 0.18 mm to 0.45 mm. Though data from Sea Carousel experiments (Amos et al., 1993) suggest a constant β (1.73 x 10^{-3}) for different grain sizes, no final conclusion is reached yet.

3.5.4 Yalin Bedload Equation

Based on analyses of the trajectory of the grain motion and Einstein's (1950) saltation concept, Yalin (1963) obtained the following bedload equation:

$$q = 0.635Du_*[\tau_* - (1/a)\ln(1 + a\tau_*)] \quad (46)$$

where $\tau_* = (\tau_b/\tau_{cr})^2 - 1$ is the normalized excess shear stress and a is equal to $2.45(\rho/\rho_s)^{0.4}(\tau_{cr}/\Delta\rho gD)^{0.5}$. The constant 0.635 was again based on data from unidirectional flume experiments. Since an assumption was made that the bed roughness exceeds the thickness of the viscous sublayer, this equation is generally limited to sediment grains of 0.2 mm or coarser.

3.5.5 Cohesive Sediment Transport

Cohesive sediments are different from non-cohesive sediments in two essential ways: aggregation and consolidation. Fine particles of cohesive sediments tend to form large, low density aggregates due to their surface ionic charges. Consequently the settling velocity of muddy sediments is a function of concentration, salinity and flow shearing. After deposition, cohesive sediments will consolidate leading to a progressive increase in density and shear resistance with time and down-core depth. Due to our limited understanding of the erosion, deposition and consolidation processes of cohesive sediments, modelling cohesive sediment transport is still in its early stage. The cohesive sediment transport method in the earlier versions of the model was based on Amos and Greenberg (1980). Significant progresses have been made in recent few years in in situ measurements of cohesive sediment stability, temporal and spatial changes of cohesive sediment erodibility, and the correlation between the erodibility and sediment physical/biological properties (e.g. Mehta and Hayter, 1989; Amos, et al., 1992b; Mehta, 1993; and Amos et al., 1996a and in press). Based on these advances, we propose new algorithms for cohesive sediment transport in SEDTRANS96 and this new method is described below.

The key parameters controlling cohesive sediment transport are the applied bed shear stress τ_b, the critical shear stress for deposition τ_d and the critical shear stress for erosion τ_e. τ_d defines the critical stress value so that deposition will occur only when τ_b is less than τ_d. Similarly, τ_e defines the critical stress value so that mud erosion will begin only when τ_b is greater than τ_e. Depending on various relationships among these three parameters, cohesive sediment transport can be separated into three states: depositional, stable, and erosional.

State 1: Depositional. When the applied bed shear stress τ_b is less than the critical shear stress for deposition τ_d, there is no erosion and only deposition occurs. The mass deposition rate r_d (kg m^{-2} s^{-1}) is given by:

$$r_d = \partial m/\partial t = c_t W_{sc}(1-\tau_b/\tau_d)(1-P_s) \qquad (47)$$

where $\partial m/\partial t$ is the change in mass m with time t, c_t is the time-dependent mass suspended sediment concentration, W_{sc} is the settling velocity of cohesive sediments, and P_s is a dimensionless probability coefficient of resuspension in the depositional state (ranging from 0 to 0.2 with a default value of 0). Assuming a uniform concentration through the entire water depth h, the decrease of sediment concentration with time, c_t, is described by

$$c_t = c_0 - (r_d \Delta t)/h \qquad (48)$$

where c_0 is the initial sediment concentration and Δt is the time duration of the deposition process. The deposition duration Δt is divided into 5 minute steps and equations 47 and 48 are used to calculate the time-dependent r_d and c_t for each step which are numerically integrated to obtain the final deposition rate and sediment concentration (c) at the end of Δt. If c_t drops below the minimum value of 0.1 mg/l during the integration, the subroutine will stop and the time when the cohesive sediment concentration reaches the practical zero value will be determined.

State 2: Stable state. If the condition of $\tau_d < \tau_b < \tau_e$ is met, there will be no deposition or erosion and stable state exists. The final sediment concentration c will be equal to the initial concentration c_0.

State 3: Erosional. When the applied shear stress τ_b is higher than the critical shear stress for erosion τ_e, sediment erosion will occur and the mass erosion rate r_e (kg m^{-2} s^{-1}) is defined as

$$r_e = \partial m/\partial t = E_0 \exp[P_e(\tau_b - \tau_e(z))^{0.5}] \qquad (49)$$

where $E_0 = 0.000051$ is an empirical coefficient for minimum erosion, P_e is the proportionality coefficient for erosion (default value 1.62) and $\tau_e(z)$ is the critical shear stress for erosion as a function of erosion depth z_s. Recent studies by Amos et al. (1992b; 1996a and in press) have found that $\tau_e(z)$ increases as sediment is eroded away and its variation with downcore depth z_s can be given as:

$$\tau_e(z) = \tau_e(0) + A(\rho_b - \rho) g z_s \tan\phi_i \qquad (50)$$

in which $\tau_e(0)$ is the critical erosion stress at the sediment surface, A is an empirical coefficient for downcore sediment resistance, ρ_b is the bulk sediment density, and ϕ_i is the internal friction angle of cohesive sediment. In principle, both ρ_b and ϕ_i will change with downcore depth to cause the observed increase of τ_e with z_s. The dependence of ρ_b and ϕ_i on z_s is also site and mud-type specific. An ideal approach would be to specify the downcore variations of ρ_b and ϕ_i for the study site and use equation 50 to obtain a downcore profile of $\tau_e(z)$. Given our very limited measurements of ρ_b and ϕ_i with downcore depth, however, it is impossible at the present to do so. Thus for modelling purposes, we have assumed that ρ_b and ϕ_i would be constant with the downcore depth and that an arbitrary value is assigned to the empirical coefficient A to generate a reasonable downcore profile of $\tau_e(z)$. Field and laboratory measurements of $\tau_e(z)$ have shown that $\tau_e(z)$ generally increases 2 to 4 times as the erosion depth reaches about 4-5 mm (Amos, et al., 1996a,b). A conservative value of A = 0.01 has been taken in SEDTRANS96 for the prediction of $\tau_e(z)$ to mimic this general trend.

With erosion rate being calculated from equation 49, the eroded mass E_m (kg m^{-2}) in the given time interval Δt is computed from

$$E_m = r_e \Delta t \qquad (51)$$

The erosion depth and the new concentration due to this erosion will be

$$z_s = E_m/\rho_b \qquad (52)$$

$$c_t = c_0 - (r_e \Delta t)/h \qquad (53)$$

As for state 1, SEDTRANS96 again divides Δt into 5 minute steps and equations 49 through 53 are used to calculate the time-dependent r_e and c_t for each step which are numerically integrated to obtain the final erosion rate and sediment concentration (c) at the end of Δt. If τ_b is found to be smaller than τ_e at a certain erosion depth z_s during the integration, the model will stop and the time when the erosion process ceases will be given.

For all three states described above, the final step of the method is to compute the starting (Q_{s0}, kg m^{-1} s^{-1}) and ending (Q_s) sediment transport rates of the time duration Δt. Again for these computations, we have assumed a uniform vertical concentration and the mean velocity at 1 m above the sea bed u_{100} is used to represent the depth-averaged mean velocity. The starting sediment transport rate will be

$$Q_{s0} = c_0 h u_{100} \qquad (54)$$

and the final sediment transport rate will be

$$Q_s = c h u_{100} \qquad (55)$$

All the key parameters used in the above method must be input as known values, except the bed shear stress τ_b. The cohesive sediment settling velocity W_{sc} cannot be predicted by the method used for non-cohesive sediments given in section 3.2 because of aggregation and flocculation. W_{sc} is mainly a function of concentration and turbulence, and is less dependent on salinity. Cited settling velocities range from 0.005 mm/s to 3 mm/s. Graphs of W_{sc} can be found in Owen (1970) and Ross (1988). However, field or laboratory measurements are recommended for each particular site to obtain W_{sc}. Different measurement techniques have been described by Amos and Mosher (1985), McCave and Gross (1991), Kineke et al. (1989), Hill et al. (1994) and Syvitski et al. (1995). As is the case for the settling velocity, there are also no known ways to predict the critical deposition shear stress τ_d, the critical erosion shear stress τ_e, and the downcore variation of ρ_b (and hence τ_e). Measurements have to be done for specific site and mud type. The values of τ_d and τ_e depend on mineralogy, degree of consolidation and benthic biological activities. Amos and Greenberg (1980) used τ_d = 1 dynes/cm^2 and τ_e = 2.5 dynes/cm^2 for the Bay of Fundy muds. In-situ measurements by Gust and Morris (1989) also suggest a τ_e value of 2 dynes/cm^2 for Puget Sound mud. Recent in-situ and laboratory measurements by Amos et al. (in press) show that τ_d of the mud deposits in Humber estuary, UK, ranges from 0.3 to

3.2 dynes/cm^2 while the values of τ_e are from 1.1 to 9.5 dynes/cm^2. Physical and rheological properties have also been found to be related to τ_e. For instance, Mimura (1989) shows that τ_e can be calculated from the yield stress τ_y of cohesive sediments as $\tau_e = 0.79\tau_y^{0.94}$ and Amos et al. (1996a) show that τ_e can be related to ρ_b through $\tau_e = 0.0007\rho_b - 0.47$ (ρ_b in kg m^{-3} to give τ_e in pascal). It should be pointed out that laboratory measurements inevitably will disturb the original texture, chemistry and biological conditions of the cohesive sediments. In situ measurements using benthic flumes are therefore recommended (Young and Southard, 1978; Amos, et al., 1992a).

3.6 Subroutine PROFL

Another main improvement in SEDTRANS96 is the inclusion of the predictions of the velocity and suspended sediment concentration (ssc) profiles which enable us to calculate the rates of suspended load transport. These computations are dealt with in a new subroutine PROFL.

For the wave-only case, there is no steady current present and thus no velocity profile will be predicted. Though the suspended-load transport will be zero for this situation due to the absence of current advection, sand can still be resuspended into the water column when the skin-friction wave shear velocity is higher than the critical shear velocity for suspension u_{*crs}. The mean suspended sediment concentration C_z at the height z is given by the Rouse (1937) equation:

$$C_z = C_0\,(z/z_0)^{-\alpha} \qquad (56)$$

where C_0 is the reference sediment concentration at the height of bed roughness z_0 and the Rouse suspension parameter $\alpha = 0.74W_s/\kappa u_{*w}$ in which W_s is the particle settling velocity and u_{*w} is the total wave shear stress. Based on Smith and McLean (1977), the reference concentration C_0 can be calculated from:

$$C_0 = \gamma_0 C_b \tau_* \qquad (57)$$

where $C_b = 0.65$ is the volume concentration of bottom sediment, $\tau_* = (\tau_{ws} - \tau_{cr})/\tau_{cr}$ again is the normalized excess shear stress, and γ_0 is the empirical sediment resuspension coefficient. A wide range of γ_0 values has been suggested in the past (Smith and McLean, 1977; Kachel and Smith, 1986; Hill et al., 1988; Drake and Cacchione, 1989). Recent studies by Vincent et al. (1991), Vincent and Downing (1994) and Li et al. (1996a) have shown that sand resuspension is strongly controlled by the development of bedforms. Their studies show that the value of γ_0 initially increases with the excess shear stress as ripples grow in the equilibrium range and that when ripples enter the break-off range γ_0

will decrease with the excess shear stress as ripples deteriorate at these high-transport stages. Thus based on the results of these recent studies, SEDTRANS96 uses the following equations for the predictions of γ_0 in the equilibrium range ($u_{*ws} < u_{*bf}$), in the break-off range ($u_{*bf} \leq u_{*ws} < u_{*up}$) and under the sheet-flow condition ($u_{*ws} \geq u_{*up}$):

$$\gamma_0 = 0.0355\tau_*^{1.94} \quad \text{for } u_{*ws} < u_{*bf} \qquad (58a)$$

$$\gamma_0 = 0.0206\tau_*^{-1.931} \quad \text{for } u_{*bf} \leq u_{*ws} < u_{*up} \qquad (58b)$$

$$\gamma_0 = 0.00013 \quad \text{for } u_{*ws} \geq u_{*up} \qquad (58c)$$

For the current-only case, both velocity and ssc profiles will be predicted. The velocity profile is given as:

$$u_z = (u_{*c}/\kappa)\ln(z/z_0) \qquad (59)$$

and the ssc profile is predicted from:

$$C_z = C_0\ (z/z_0)^{-\alpha} \qquad (60)$$

Now $\alpha = 0.74W_s/\kappa u_{*c}$ and u_{*c} is the total current shear velocity. C_0 will be predicted from equations 57 and 58 with τ_{ws} and u_{*ws} being replaced by τ_{cs} and u_{*cs} respectively.

For the combined wave-current case, the velocity profile will be predicted by equation 26 which is re-stated here:

$$u_z = (u_{*c}/\kappa)(u_{*c}/u_{*cw})\ln(z/z_0) \quad \text{for } z \leq \delta_{cw} \qquad (26a)$$

$$u_z = (u_{*c}/\kappa)\ln(z/z_{0c}) \quad \text{for } z \geq \delta_{cw} \qquad (26b)$$

The ssc profiles are predicted using a modified Rouse equation proposed by Glenn and Grant (1987) and has been tested by Li et al. (1996a) using field data:

$$C_z = C_0\ (z/z_0)^{-\alpha 1} \quad \text{for } z < \delta_{cw} \qquad (61a)$$

$$C_z = C_{\delta cw}\ (z/\delta_{cw})^{-\alpha 2} \quad \text{for } z > \delta_{cw} \qquad (61b)$$

where the Rouse suspension parameter within the wave-current boundary layer $\alpha 1$ is equal to $0.74W_s/\kappa u_{*cw}$ and the Rouse suspension parameter above the wave-current boundary layer $\alpha 2$ is equal to $0.74W_s/\kappa u_{*c}$. The reference concentration C_0 is again predicted using equations 57 and 58 with τ_{ws} and u_{*ws} now being replaced by τ_{cws} and u_{*cwb} respectively. $C_{\delta cw}$ is the suspended sediment concentration at the top of the wave-current boundary layer δ_{cw} and is given by equation 61a by equating z to δ_{cw}.

After the computation of the velocity and ssc profiles, their product of u_zC_z is numerically integrated over the water depth to obtain the suspended-load transport rate Q_s:

$$Q_s = u_z C_z \Delta z$$

where Δz represents a small increment of height from the seabed. The direction of the suspended-load transport is assumed to be that of the steady current.

3.7 Subroutine BEDFORM

Various bed shear stresses and near-bed velocities (u_{100} for currents, u_b for waves) are used in this subroutine to estimate different types of bedforms. For sediments finer than 0.063 mm (silts and clay), there will be no bedform development (although formation of small ripples in silt was observed in a few flume experiments, e.g. Jopling and Forbes, 1979). For gravels ($D > 2$ mm) and coarse to very-coarse sands (0.5 mm $< D \leq 2$ mm), there is no method available yet for predicting the bedform dimensions and only bedform types will be predicted. For sediments ranging from very-fine sand to medium sand (0.063 mm $\leq D \leq 0.5$ mm), both bedform type and dimension are predicted.

For sediments coarser than 2 mm, gravel ripples are predicted. For coarse and very coarse sands, current ripples will be predicted if $u_b = 0$ and wave ripples will be defined if $u_{100} = 0$. If neither u_{100} nor u_b is zero, combined-flow ripples are present and the ratio of the wave Shields parameter relative to that of the steady current, θ_{ws}/θ_{cs}, is then used to further define if the ripples are wave dominant ($\theta_{ws}/\theta_{cs} > 1$) or current dominant ($\theta_{ws}/\theta_{cs} \leq 1$). For wave or wave-dominant ripples in this grain size range, u_b is used to predict bedform types according to Amos (1990) as shown in Table 1. For current or current-dominant ripples, u_{100} will be used to predict the bedform types (see Table 1).

For grain sizes ranging from very-fine sand to medium sand, the values of u_b and u_{100} are used to first decide if wave, current or combined-flow ripples are present. For wave ripples or current ripples, u_{*cs} and u_{*ws} are respectively compared against various critical shear velocities to determine the following bedform types:

For $u_b = 0$, current ripples

if $u_{*cs} < u_{*cr}$, no transport; input ripple height and length will be used

if $u_{*cs} \geq u_{*up}$, current-induced upper-plane bed

if $u_{*cr} \leq u_{*cs} \leq u_{*up}$, active current ripples present

Table 1 Near-bed velocities and possible bedform types (modified from Amos, 1990).

Bedform	Bounds	Sand			
		Fine	Medium	Coarse	V. Coarse
(1) Current-ripples based on u_{100}					
Flat Bed (Lower)	Upper Lower	< 13 cm/s	< 20 cm/s	< 25 cm/s	< 40 cm/s
Current Ripples	Upper Lower	60 cm/s 13 cm/s	50 cm/s 20 cm/s	35 cm/s 25 cm/s	no ripples
2-D Mega-Ripples	Upper Lower	no 2-D mega-ripples	60 cm/s 50 cm/s	60 cm/s 40 cm/s	60 cm/s 40 cm/s
Sand Waves	Upper Lower	no sand waves	100 cm/s 60 cm/s	100 cm/s 50 cm/s	100 cm/s 40 cm/s
3-D Mega-Ripples	Upper Lower	no 3-D mega-ripples	150 cm/s 60 cm/s	150 cm/s 60 cm/s	no 3-D mega-ripples
Upper-Plane Bed and Sand Ribbons	Upper Lower	85 cm/s 60 cm/s	170 cm/s 150 cm/s	240 cm/s 150 cm/s	295 cm/s 100 cm/s
(2) Wave-ripples based on u_b					
Wave Ripples	Upper Lower	70 cm/s 10 cm/s	100 cm/s 13 cm/s	125 cm/s 20 cm/s	200 cm/s 30 cm/s
Wave Induced Upper-Plane Bed	Upper Lower	- 70 cm/s	- 80 cm/s	- 90 cm/s	- 100 cm/s

For $u_{100} = 0$, wave ripples

if $u_{*ws} < u_{*cr}$, no transport; input ripple height and length will be used

if $u_{*ws} \geq u_{*up}$, wave-induced upper-plane bed

if $u_{*cr} \leq u_{*ws} \leq u_{*up}$, active wave ripples present

If neither u_{100} and u_b is equal to 0, combined-flow ripples are predicted

For active current ripples, the mean velocity u_{100} is used to further predict sub-types of current ripples according to Amos (1990; see Table 1). The dimensions of active current ripples are predicted based on Yalin (1964) and Allen (1970) as given by equations 17 and 19 in section 3.3. The dimensions of active wave ripples are based on Allen (1970) and Boyd et al. (1988) as described by equations 18 and 19 in section 3.3.

For combined-flow ripples, ripple-enhanced shear velocity u_{*cwe}, the skin-friction combined shear velocity u_{*cws} and the bedload combined shear velocity u_{*cwb} are compared with various critical shear velocities to determine the following types of bedforms (Li and Amos, in press):

if $u_{*cwe} < u_{*cr}$, no transport; input ripple height and length will be used

if $u_{*cws} < u_{*cr}$ and $u_{*cwe} \geq u_{*cr}$, weak-transport ripples

if $u_{*cws} \geq u_{*cr}$ and $u_{*cwb} < u_{*bf}$, equilibrium ripples which can be further divided into:

$u_{*ws}/u_{*cs} < 0.75$, current-dominant ripples

$u_{*ws}/u_{*cs} \geq 1.25$, wave-dominant ripples

$0.75 \leq u_{*ws}/u_{*cs} < 1.25$, combined wave/current ripples

if $u_{*bf} \leq u_{*cwb} < u_{*up}$, break-off ripples (wave-dominant)

if $u_{*cwb} \geq u_{*up}$, upper-plane bed under combined flow

The heights and lengths of combined-flow ripples are predicted according to the combined-flow ripple predictor of Li and Amos (in press) which are already given in equations 34 to 37 in section 3.3.

4. MODEL CALIBRATION

Many sediment transport models have been proposed for combined flow conditions, but there is a lack of good-quality field measurements of the hydrodynamics and seabed responses for the calibration of these models. In recent years, researchers have begun to realize that the establishment of the critical shear stresses for various transport phases and more accurate predictions of bedforms are the basis and key for further improving our understanding and prediction of sediment transport under combined waves and currents (e.g. Grant and Madsen, 1986; Glenn and Grant, 1987; Amos et al., 1988; Vincent et al., 1991; Wiberg and Nelson, 1992; Li, 1994; Wiberg and Harris, 1994; Green et al., 1995; Li et al., 1996a; Li and Amos, in press; Li et al., in press). Under the funding of PERD and sponsoring by industrial partners (Pan Canadian and Mobil), a research project has been undertaken at the Geological Survey of Canada - Atlantic (GSCA) to study seabed stability and storm sediment transport on Sable Island Bank (SIB), the Scotian Shelf (Fig. 5). The GSCA instrumented tripod RALPH and other instrument packages have been deployed at 9 different sites in the SIB region and several good-quality data sets have been collected (Amos et al., 1994a; Zevenhuizen and Li, 1994; Li et al., 1994 and 1996b). Analyses of these data sets have advanced our understanding on the initiation of various transport modes and the bedform development under combined waves and currents (Li et al., 1996a; Li and Amos, in press; Li et al., in press; Li and Amos, in review[a,b]). Some of these data will be used in this section to support and calibrate the revisions made in SEDTRANS96.

The first data set that we will use was collected by RALPH at site 1 of the SIB region (see Fig. 5) in 39 m water depth over medium sand sediment (D = 0.34 mm) in early winter of 1993 (January 17 to February 14; see Li et al., 1994). The second data set chosen was collected at site 2 of the region by a S4 wave-current meter and an instrumented tripod similar to RALPH in 56 m water depth over fine sand (D = 0.20 mm) in late winter of 1993 (February 27 to March 25, see Li et al., 1996b). RALPH is an instrumented tripod developed at GSCA for long-term in situ measurements of waves, currents, and seabed responses (Heffler, 1984; Amos et al., 1994b). RALPH used in the early-winter deployment included a flux-gate compass, a pressure transducer for wave measurements, two acoustic current meters for velocity measurements and two optical transmissometers to record suspended sediment concentration. RALPH has been upgraded more recently to include more sophisticated sensors (Heffler, 1996). The InterOcean S4 wave-current meter is a self-contained, spherical, electromagnetic gauge that measured depth, waves, current magnitude and direction. While a super-8 movie camera with flash and attached graded shadow bar was used on RALPH for monitoring the seabed responses, an underwater video camera was used in the second deployment for this purpose. The burst-sampled wave and current data from both deployments were first analyzed to obtain burst-averaged water depth, mean velocity at 50 cm or 100 cm above the seabed, mean-current direction, significant wave height, peak spectral wave period, and wave propagation direction. These parameters were used in the Grant and Madsen (1986) combined-flow bottom boundary layer model the basis and key for further improving our understanding and prediction of sediment transport under combined waves and currents (e.g. Grant and Madsen, 1986; Glenn and Grant, 1987; Amos et al., 1988; Vincent et al., 1991; Wiberg and Nelson, 1992; Li, 1994; Wiberg and Harris, 1994; Green et al., 1995; Li et al., 1996a; Li and Amos, in press; Li et al., in press). Under the funding of PERD and sponsoring by industrial partners (Pan Canadian and Mobil), a research project has been undertaken at the Geological Survey of Canada - Atlantic (GSCA) to study seabed stability and storm sediment transport on Sable Island Bank (SIB), the Scotian Shelf (Fig. 5). The GSCA instrumented tripod RALPH and other instrument packages have been deployed at 9 different sites in the SIB region and several good-quality data sets have been collected (Amos et al., 1994a; Zevenhuizen and Li, 1994; Li et al., 1994 and 1996b). Analyses of these data sets have advanced our understanding on the initiation of various transport modes and the bedform development under combined waves and currents (Li et al., 1996a; Li and Amos, in press; Li et al., in press; Li and Amos, in review[a,b]). Some of these data will be used in this section to support and calibrate the revisions made in SEDTRANS96.

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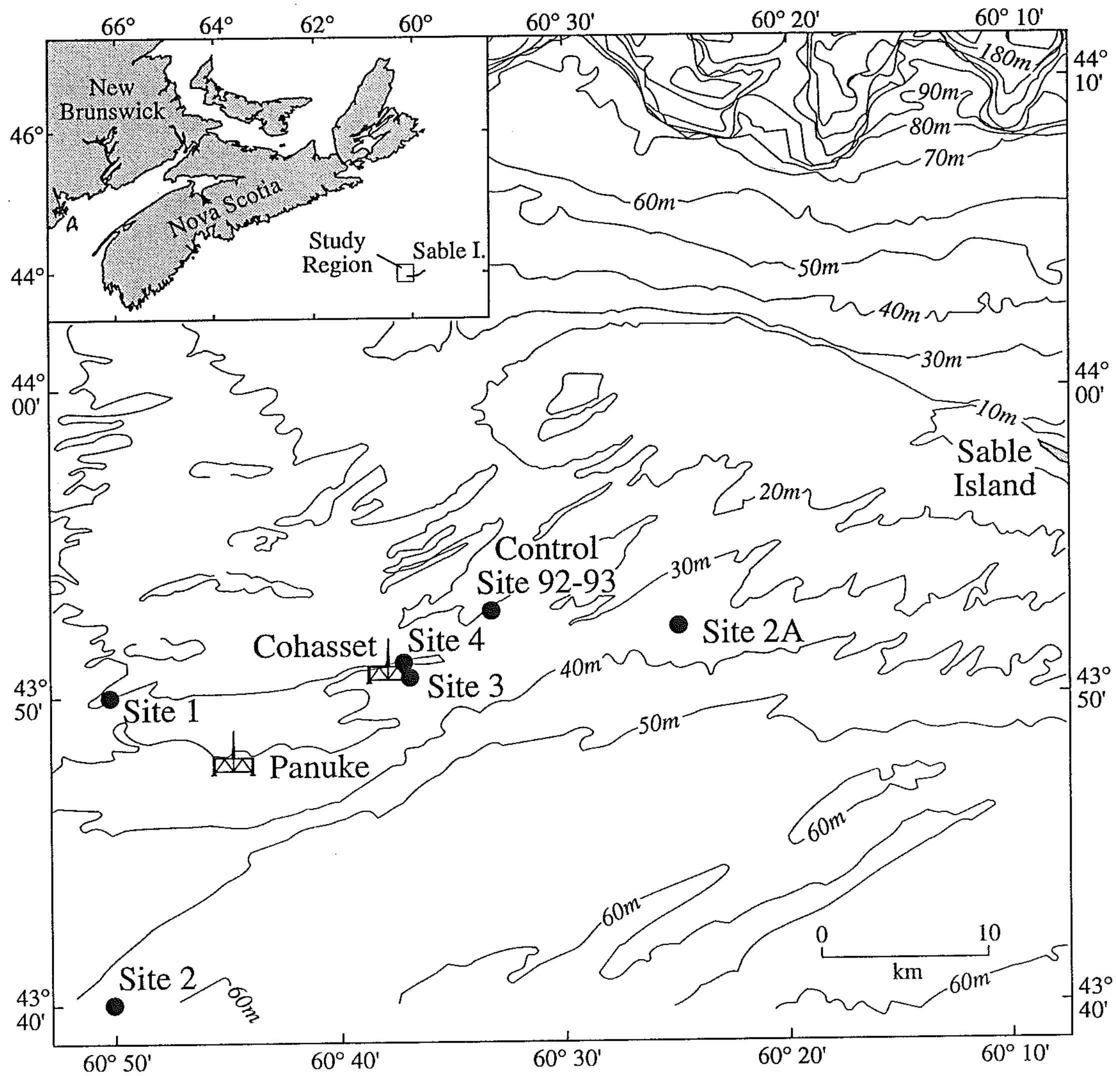

Figure 5 The location map showing the study region on Sable Island Bank, Scotian shelf, and the sites of instrument deployment of the GSCA seabed stability and storm sediment transport project.

(via SEDTRANS96) to compute various bed shear stresses. The seabed images were then analyzed to determine the sediment transport modes and the types and geometry of various bedforms. These results were compared against the model-predicted bed shear stresses to evaluate the critical shear stresses for different sediment transport modes and the prediction of ripple types and dimension under the combined-flow conditions.

4.1 Thresholds of Sediment Transport

The computation of critical shear stresses (or shear velocities) for various sediment transport modes have been described in section 3.2. It is conventional to compare the average skin-friction shear stresses against these critical values to determine the initiation of bedload transport, suspension and sheet-flow transport. Recent studies, however, have shown that this tends to under-estimate the onset of these transport modes and that the enhanced shear stresses by ripples and due to bedload transport need to be used for proper predictions of these transport modes.

Fig. 6a shows the time series plot of the average skin-friction combined shear velocity u_{*cws} of the site 1 data in comparison with the critical shear velocities for bedload (u_{*cr} = 1.5 cm/s, lower dashed line) and suspended-load (u_{*crs} = 3.5 cm/s, upper dashed line). Various observed transport modes are represented by different symbols: open circles for no transport, triangles for bedload transport, squares for sand suspension and diamonds for sheet-flow transport. The critical shear velocity for sheet-flow u_{*up} = 5.8 cm/s is not plotted in Fig. 6a due to the small scale of the vertical axis. Fig. 6a demonstrates that the observed initiation of bedload transport, as defined by the boundary between the open circles and triangles, is significantly below the bedload threshold u_{*cr}. Similarly, the observed transition from bedload to suspension transport (defined by the boundary between triangles and squares) and that from suspension to sheet-flow (the boundary between squares and diamonds) also occurred at u_{*cws} values much lower than the corresponding critical shear velocities u_{*crs} and u_{*up}. These discrepancies suggest that the direct comparison of the average skin-friction shear velocity with the various critical shear velocities will under-estimate the onset of different transport modes. In contrast to Fig. 6a, the ripple-enhanced combined shear velocity u_{*cwe} and the bedload combined shear velocity u_{*cwb}, computed following the procedures given in section 3.3, are plotted in Fig. 6b for the same data set. Now we find that the observed onset of bedload, suspension, and sheet-flow transport are in reasonable agreement with the critical shear velocities for these transport modes. This indicates

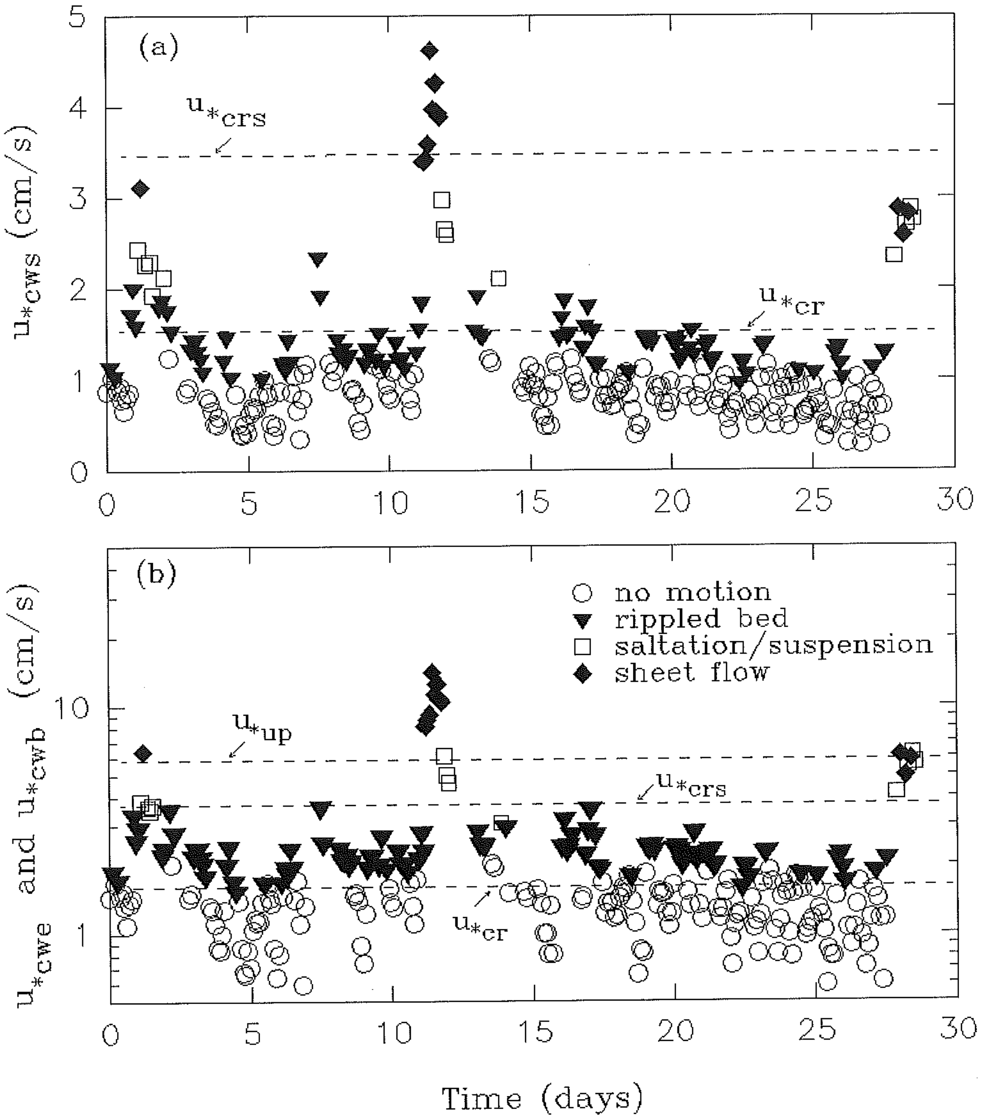

Figure 6 Time-series plots of combined shear velocities for selected bursts from the 1993 site 1 deployment over medium sand: (a) true skin-friction combined shear velocity u_{*cws} and (b) ripple-enhanced (u_{*cwe}) or bedload (u_{*cwb}) combined shear velocity. Observed transport modes are indicated by different symbols (see text for definition) and the dashed lines, from bottom to top, respectively represent the critical shear velocities for bedload, suspension and sheet-flow transport.

that the enhanced combined shear velocity at the ripple crest and the combined shear velocity due to bedload transport should be used to determine the initiation of bedload, sand suspension, and sheet-flow transport respectively.

Similar comparisons are also made in Fig. 7 for the site 2 data in order to see if the findings obtained from Fig. 6 over medium sand are also valid over fine sand. Here the skin-friction combined shear velocity (u_{*cws}, in open symbols) and the ripple- or bedload-enhanced shear velocities (u_{*cwe} or u_{*cwb}, in solid symbols) during a storm build-up are plotted against time. Various observed transport modes are again represented by different symbols: circles for no transport, triangles for bedload, squares for suspension, and diamonds for sheet-flow. The three dashed lines (from bottom to top) indicate the critical shear velocities for bedload, suspension and sheet-flow transport respectively. Fig. 7 shows that the use of the skin-friction combined shear velocity again causes under-prediction of the onset of various transport modes under combined flow condition. At the observed initiation of bedload transport (hour 40), for instance, u_{*cws} is only about 0.5 cm/s which is significantly lower than the critical shear velocity of u_{*cr} = 1.3 cm/s. Also u_{*cws} is only equal to 2.5 cm/s when sheet-flow was observed and this is much below the established sheet-flow threshold of u_{*up} = 4.9 cm/s. When the ripple-enhanced shear velocity u_{*cwe} (for bursts where $u_{*cws} < u_{*cr}$) and bedload shear velocity u_{*cwb} (for bursts where $u_{*cws} \geq u_{*cr}$) are used, however, much improved agreement is achieved between these critical shear velocities and the observed onset of various transport modes (solid symbols in Fig. 7). This further supports the findings in Fig. 6 for medium sand. Therefore SEDTRANS96 has adopted the use of u_{*cwe} and u_{*cwb} in defining the onset of various sediment transport modes and predicting ripple geometry under combined waves and currents.

4.2 Ripple Prediction

Many wave-ripple predictors have been derived based on field and laboratory data (e.g., Nielsen, 1981 and Grant and Madsen, 1982). Limited field measurements of combined-flow ripples, however, have shown that these wave-ripple predictors are not applicable to combined waves and currents (Osborne and Vincent, 1993; Li et al., 1996a).

The measured ripple height and ripple roughness height k_{br}, calculated from equation 20 based on the measured ripple height and length, are plotted in Fig. 8 as time series for the site 1 data. The

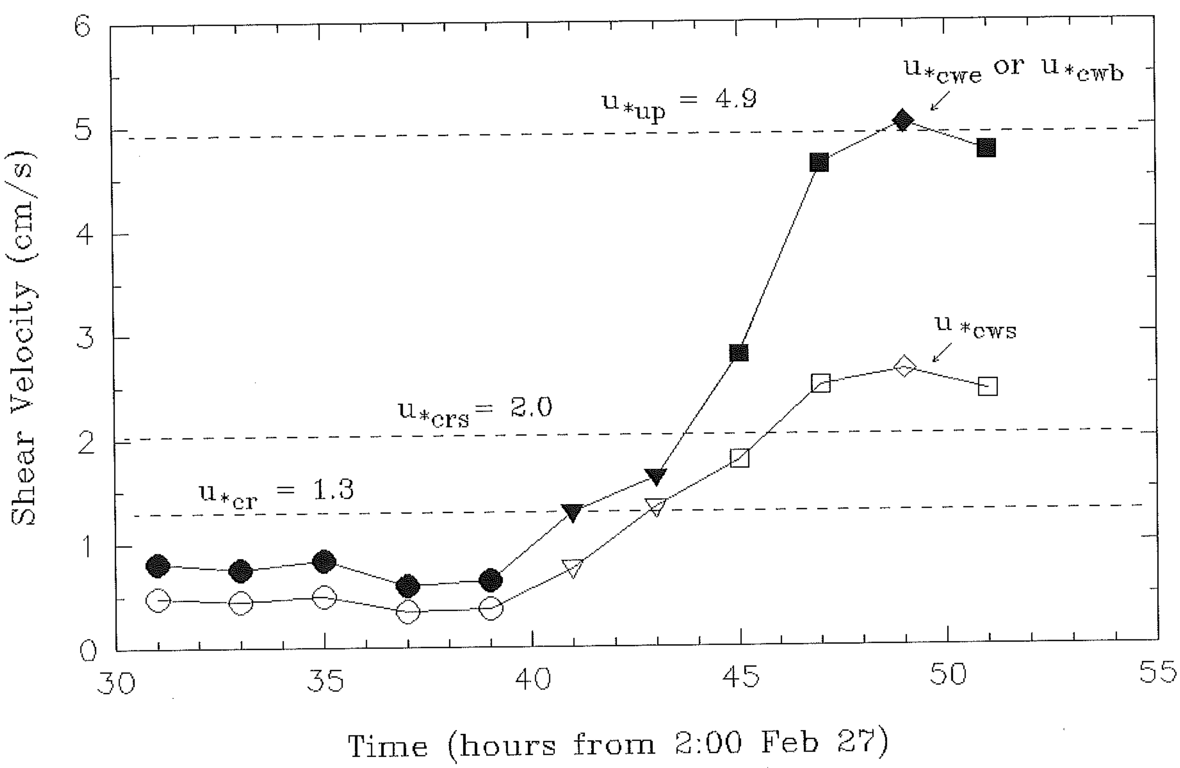

Figure 7 Time-series plots of the skin-friction (u_{*cws}, in open symbols) and the ripple-enhanced or bedload (u_{*cwe} and u_{*cwb}, in solid symbols) combined shear velocities during a storm build-up observed during the 1993 site 2 deployment over fine-sand sediment. Observed transport modes are again shown by different symbols (see text for definition) and the dashed-lines represent the various threshold shear velocities.

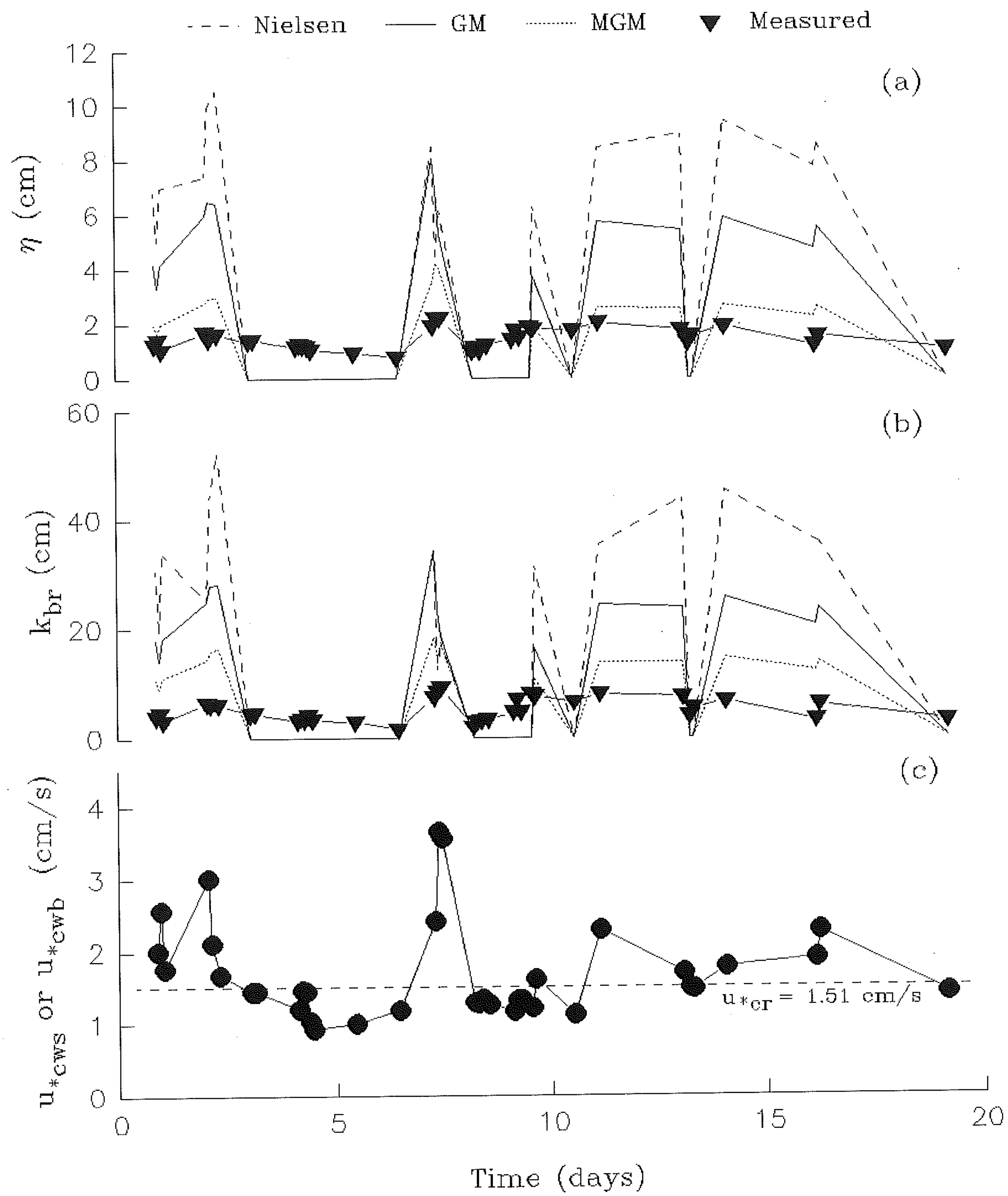

Figure 8 Time-series plots of (a) the measured ripple height η, (b) ripple roughness height k_{br} and (c) the skin-friction or bedload combined shear velocity (u_{*cws} or u_{*cwb}) of selected bursts from the 1993 site 1 deployment. The ripple heights and ripple roughness heights predicted by the Grant and Madsen (1982; GM, solid line), Nielsen (1981; Nielsen, dashed line) and the modified Grant and Madsen predictor of Li et al. (1996a; MGM, dotted line) are included for evaluation. The dashed line in (c) is the threshold shear velocity for bedload transport.

solid line represents the predictions by the Nielsen (1981) method, the long-dashed line by the Grant and Madsen (1982, GM) method, and the short-dashed line by a modified Grant-Madsen method (MGM) proposed by Li et al. (1996a). The bottom plot of Fig. 8 shows the time series of the skin-friction (for $u_{*cws} < u_{*cr}$) or bedload (for $u_{*cws} \geq u_{*cr}$) combined shear velocities corresponding to the measured ripples. The dashed line in Fig. 8 indicates the critical shear velocity for sediment transport (u_{*cr} = 1.5 cm/s). Fig. 8 clearly shows that though the modified Grant-Madsen method gave the best prediction, the wave-ripple predictors in general significantly over-estimated ripple height and ripple roughness height. Also shown is that when the average skin-friction combined shear velocity was below the critical shear velocity for sediment movement (around day 5 and day 10 in Fig. 8c), all predictors predicted no ripple formation though active ripples were observed. This is because these methods have neglected the shear stress enhancement by pre-existing ripples. Thus our data from the Scotian Shelf further supports the findings of Osborne and Vincent (1993) and Li et al. (1996a), i.e. widely-cited wave-ripple predictors do not work well under combined-flow conditions.

Because of this discrepancy and the complex non-linear interaction between waves and steady currents under the combined flow, Li and Amos (in press) have proposed a combined-flow ripple predictor (equations 34 to 37 in section 3.3) based on the ripple measurements collected at site 1 on Sable Island Bank. There are four key improvements in this new ripple predictor: (1) Since it is the combined shear stress that determines the overall bedform development under combined flows, the skin-friction (u_{*cws}) and bedload (u_{*cwb}) combined shear velocities are used in the new predictor; (2) The enhanced shear velocity u_{*cwe} at the ripple crest is used in order to properly predict ripples under the weak-transport condition; (3) The bedload-enhanced combined shear velocity u_{*cwb} is used to correctly predict the ripple break-off and wash-out at high transport stages; (4) Different ripple types with significantly different ripple steepness (η/λ) values can develop for different relative strength of wave versus current (Li and Amos, in press). Thus the ratio of u_{*ws}/u_{*cs} is used to determine the ripple types and hence ripple steepness. Fig. 9 compares the measured ripple heights and ripple roughness heights with the predicted values for the same data set as shown in Fig. 8. The solid line with triangles represents the measurements and the dashed line represents the model prediction. Since the new predictor was derived from this same data set, Fig. 9 does not offer an independent test of the method. However, it does show that the new predictor fits the source data reasonably well.

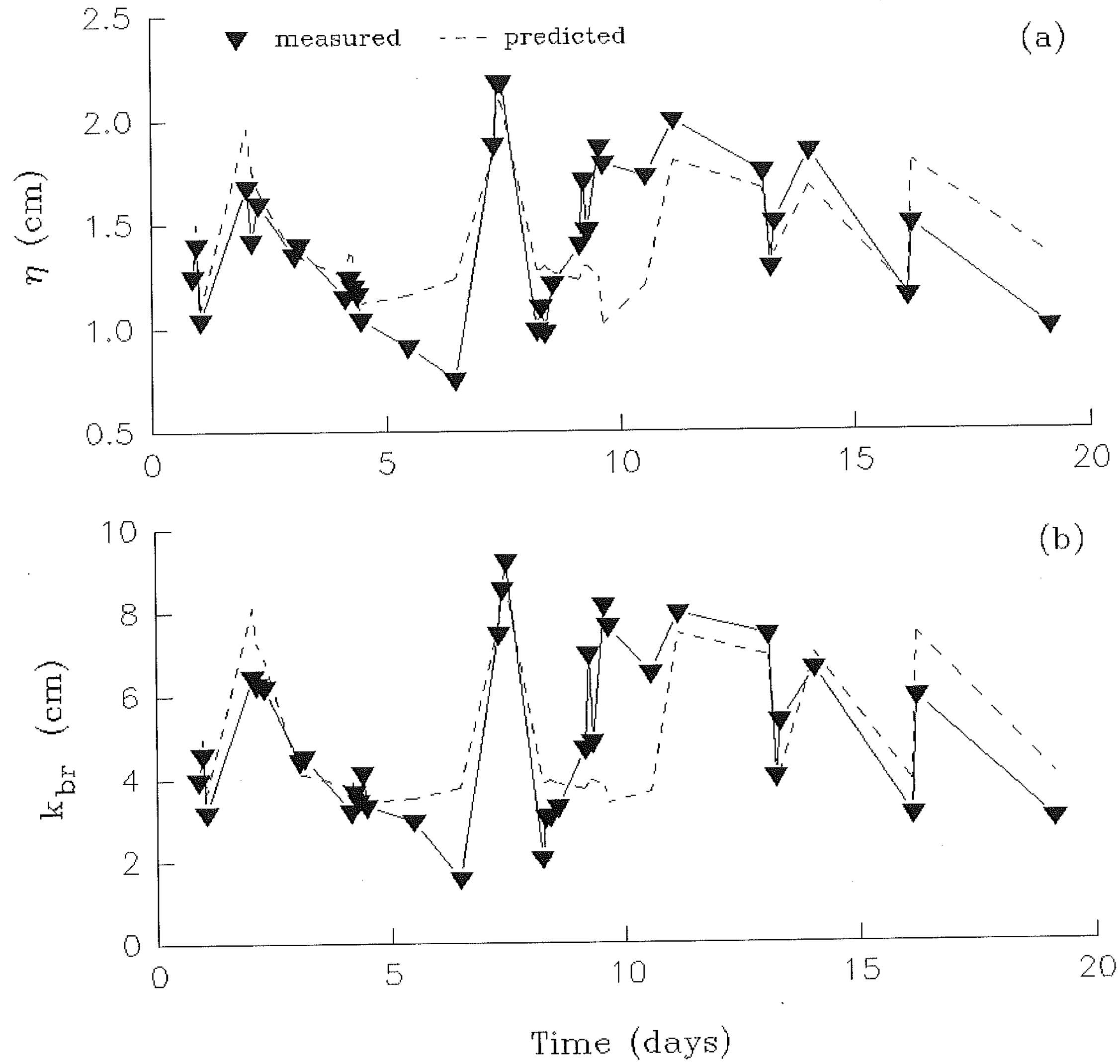

Figure 9 Time-series plots of (a) the measured ripple height η and (b) ripple roughness height k_{br} of selected bursts from the 1993 site 1 deployment. The dashed lines represent the predicted ripple height and ripple roughness height by the proposed empirical ripple predictor for combined flows.

4.3 Prediction of Bedload Transport

The four sediment transport formulae for sand described in section 3.5 were derived using mostly unidirectional flume data. There have been limited attempts to test the use of these formulae under combined waves and currents by radioactive and fluorescent tracer experiments (e.g. Gadd et al., 1978; Heathershaw, 1981; Lees, 1983; Pattiaratchi and Collins, 1985). In general, these experiments showed that the sediment transport rates predicted using these formulae differed from the measured transport rates by more than one order of magnitude. Based on very limited measurements of ripple lengths and ripple migration rates in a 1982 field experiment on Sable Island Bank, Li and Amos (1993, 1995) have calibrated the prediction of bedload transport rates by SEDTRANS92. Though reasonable agreement was found, the data quality was limited and the testing was for fine sand only. In describing the FRICFAC and TIMING subroutines, we have argued that shear stresses enhanced due to the presence of ripples and the bedload transport need to be used to properly predict ripple development and sediment transport time. Conventionally, the average skin-friction shear stress needs to be used in equations 42 to 46 in the computation of sediment transport rates. If bed shear stress increases from ripple trough to crest and the enhanced stress at the ripple crest needs be used in predicting the onset of bedload transport, one then may ask should this ripple-enhanced shear stress also be used for the prediction of sediment transport rates? We are aware that at least one study has suggested the use of this ripple-enhanced shear stress (Wiberg et al. 1994). In this section, we will use the site 1 data collected in 1993 over medium sand and the data collected in 1982 over fine sand to test the new theories adopted in subroutines FRICFAC and TIMING and to calibrate the predictions of sediment transport rates by SEDTRANS96.

The bedload sediment transport rate can be obtained by considering the volume of sediment involved in the migration of ripples. For a ripple of height η and migration rate R_m, the mean mass transport rate per unit width per unit time will be:

$$Q_m = 0.5\rho_b\eta R_m \qquad (62)$$

where ρ_b is the bulk sediment density (= 1.8 g/cm^3). Kachel and Sternberg (1971) suggested that the maximum transport rate at the ripple crest should be twice that given by (62). We are, however, more concerned with the mean transport rate. The measured ripple heights and migration rates of the 1993 site 1 data and 1982 data have been used in equation 62 to obtain the measured bedload sediment transport rates Q_m. For the 1982 data, only ripple lengths were measured and the ripple heights were calculated based on Allen (1970) as given by equation 19. In the first step, we will use the flow dynamics and ripple migration data collected at site 1 to determine whether the average or the ripple-enhanced shear stress better predicts sediment transport rates and duration. The Einstein-Brown bedload formula is chosen to do this because this is a bedload method (our measured transport rates based on ripple migration data are mostly in bedload mode) and it has been tested by limited wave flume data (Madsen and Grant, 1976). The time series of the measured and predicted sediment transport rates, using the average skin-friction shear stress τ_{cws}, are compared in Fig. 10a and 10b. These plots show that the use of the skin-friction shear stresses severely under-predicts the frequency and duration of sediment transport under the site 1 field experiment conditions. This under-prediction is most likely due to the neglect of the shear stress enhancement by ripples (see Fig. 6). The ripple-enhanced shear stresses, obtained from equation 33, was thus used in the Einstein-Brown formula to predict sediment transport rates for the same set of data and the time series of these predicted transport rates is plotted in Fig. 10c. Comparing Fig. 10a and 10c indicates that the duration and frequency of sediment transport are reasonably predicted when the ripple-enhanced shear stresses were used in the TIMING and TRANSPO subroutines of SEDTRANS96, though the magnitude seemed to be over-predicted.

To further evaluate the suitability of the average skin-friction shear stress and the maximum enhanced shear stresses at the ripple crest in predicting the sediment transport rate, the ripple-enhanced shear stresses were used in TIMING to determine sediment transport duration and τ_{cws} and τ_{cwe} were then used respectively in the Einstein-Brown bedload method to predict sediment transport rates for the site 1 data. The measured and predicted sediment transport rates are compared in scatter plots in Fig. 11a and 11b respectively. Circles represent the 1993 site 1 data over medium sand and triangles the 1982 data over fine sand. Dashed lines in both figures indicate the perfect agreement. Fig. 11 clearly shows that sediment transport rates can be under-predicted by a factor of 5 when the average skin-friction shear stresses are used. In contrast, the use of the ripple-enhanced shear stresses resulted in an over-prediction roughly by a factor of 5, particularly at higher transport rates (Fig. 11b).

When ripples are present, bed shear stress increases from the ripple trough to the crest. It thus can be expected that the maximum value of the shear stress at the crest will give the highest transport rate across the ripple length and thus will not be representative of the mean transport rate averaged across the ripple wavelength. Since sediment transport rate is proportional to the third or higher power

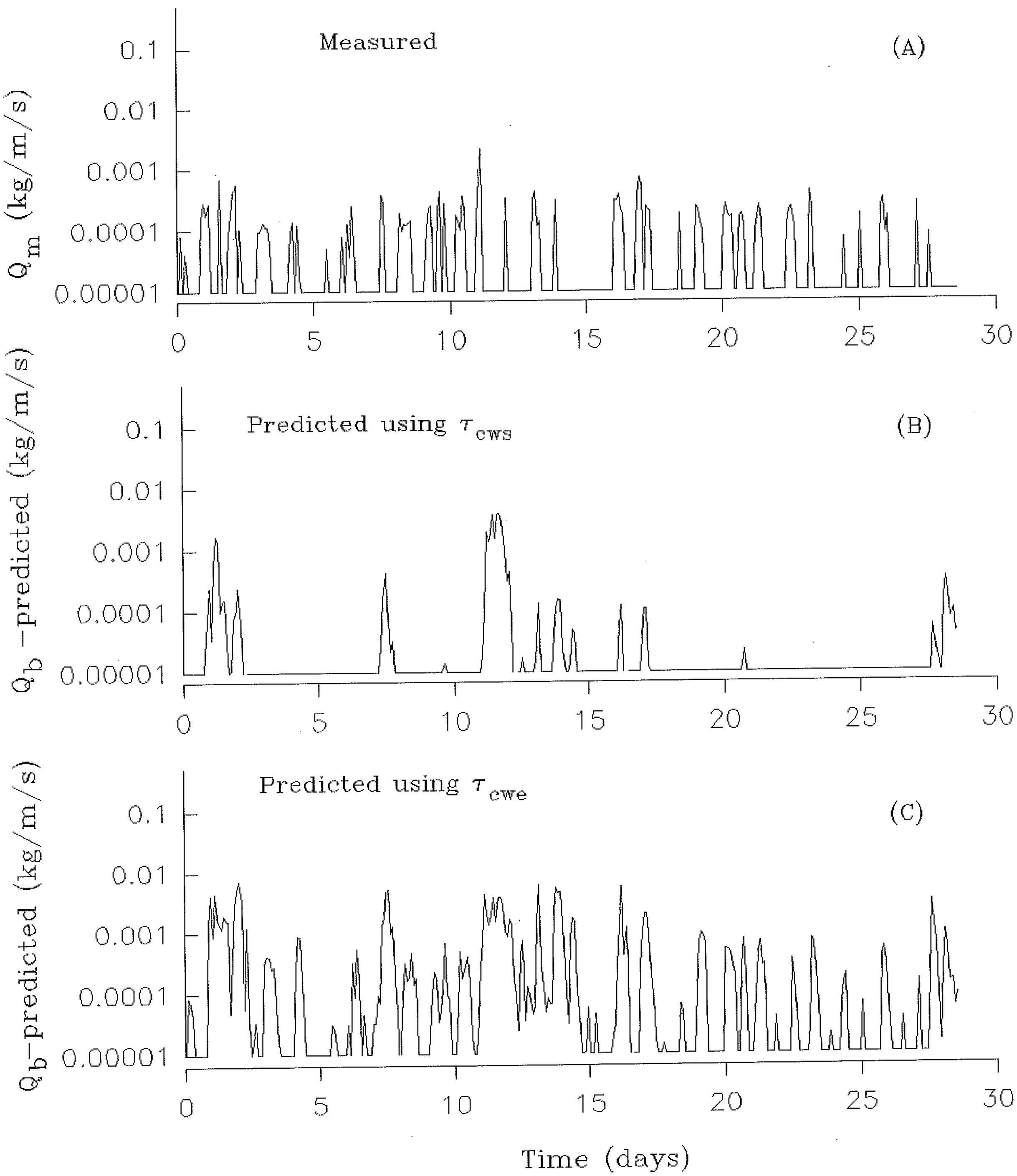

Figure 10 Time-series plot of (a) the measured sediment transport rate Q_m in comparison with the predicted sediment transport rates, Q_b-predicted, by the Einstein-Brown formula using (b) the average skin-friction shear stress τ_{cws}, and (c) the ripple-enhanced shear stress, τ_{cwe}.

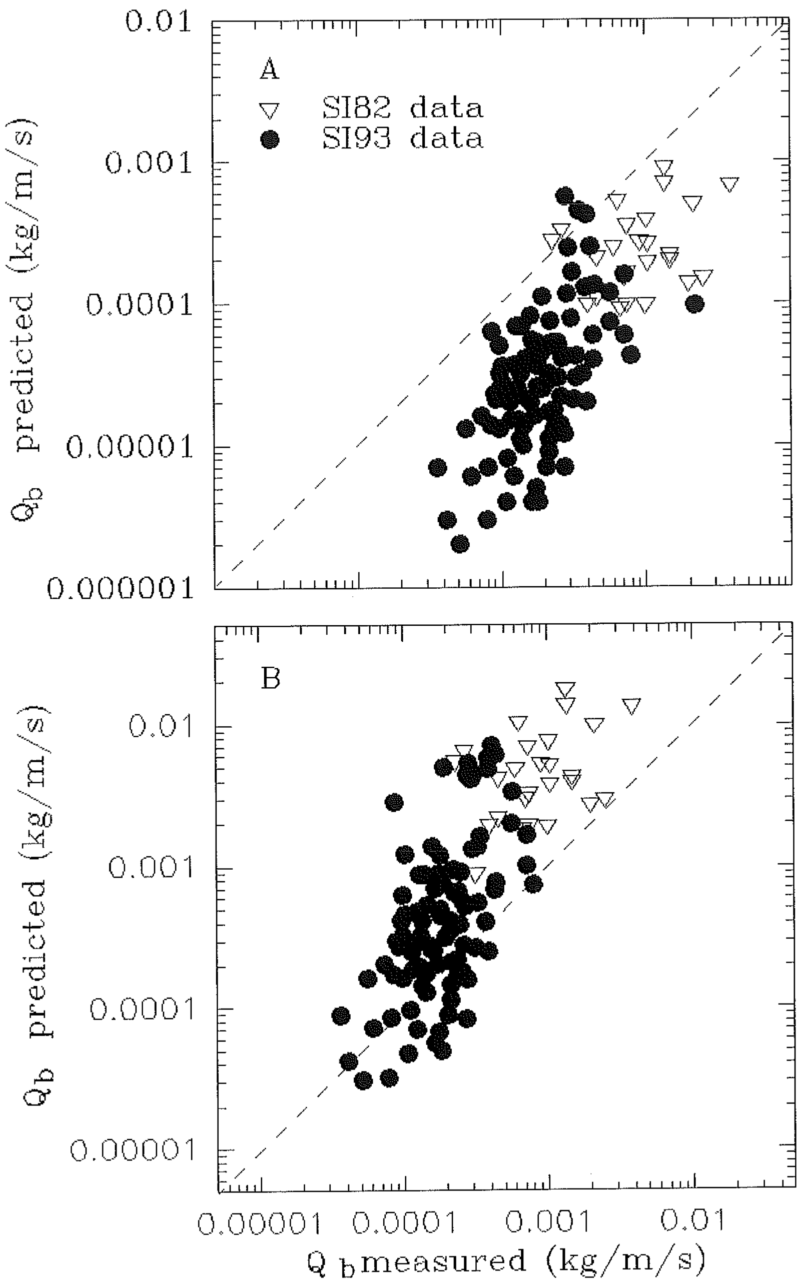

Figure 11 Scatter plots of the measured and predicted sediment transport rates from the Einstein Brown formula using (a) the average skin-friction shear stress and (b) the ripple-enhanced shear stress. Circles are data from the 1993 site 1 deployment over medium sand and triangles are data from the 1982 deployment over fine sand. The dashed lines represent the perfect agreement.

of shear velocity, the mean transport rate averaged over the ripple length will be skewed toward the higher values and this may explain the under-prediction by using the average skin-friction shear stress. Therefore effective shear stresses between these two values need to be found for better prediction of the sediment transport rate. Based on the facts that the ripple-enhancement of shear stress is most effective in weak-transport range and equilibrium range and that the effective shear stress should asymptotically approach the average skin-friction shear stress at higher transport stages when the ripple steepness approaches zero, we propose to use the following effective shear stresses, τ'_{cws}, in the TRANSPO subroutine to predict sediment transport rates at various stages of bedform development:

$$\tau'_{cws} = (\tau_{cr} + \tau_{cwe})/2 \quad \text{for } u_{*cwe} \geq u_{*cr} \text{ and } u_{*cwb} < u_{*bf} \tag{63a}$$

$$\tau'_{cws} = [1/(2+\alpha)](\alpha\tau_{cr} + \tau_{cws} + \tau_{cwe}) \quad \text{for } u_{*bf} \leq u_{*cwb} < u_{*up} \tag{63b}$$

$$\tau'_{cws} = \tau_{cws} \quad \text{for } u_{*cwb} \geq u_{*up} \tag{63c}$$

where $\alpha = (u_{*up} - u_{*cwb})/(u_{*up} - u_{*bf})$ can be taken as a ripple break-off parameter which indicates how far ripples are into the break-off range and how close they approach the upper-plane bed condition. The physical meaning of equation 63 is that in the weak-transport and equilibrium ranges, sediment transport occurs only on a portion of the ripple stoss slope over which the bed shear stress ranges from τ_{cr} to τ_{cwe}. The average of these two values is taken to be the effective bed shear stress at these stages (63a). In the ripple break-off range (63b), all three shear stresses (the critical, the average and the ripple-enhanced) are important when the bedload shear stress just reaches the break-off threshold ($u_{*cwb} = u_{*bf}$ and hence $\alpha = 1$). As u_{*cwb} increases towards u_{*up}, the bed becomes planer and the bed shear stress is higher than τ_{cr} on almost the entire ripple stoss side. Thus the effect of τ_{cr} on τ_{cws}' gradually drops out and the value of the effective shear stress now mainly depends on the values of the average and ripple-enhanced shear stresses (though the value of u_{*cwe} also decreases). Finally when upper-plane bed is reached (63c, $u_{*cwb} \geq u_{*up}$), there will be no ripple enhancement of the bed shear stress and the effective shear stress is now equal to the average bed shear stress. The new effective shear stresses given by equation 63 have again been used in subroutine TRANSPO for the calculation of sediment transport, and the predicted and measured sediment transport rates are compared in Fig. 12 for the four chosen sediment transport formulae: 12A for the Engelund-Hansen total load formula, 12B for the Einstein-Brown bedload formula, 12C for the Bagnold total load formula and 12D for the Yalin bedload formula. Compared to Fig. 11, Fig. 12 shows that using the effective shear stresses given by equation 63 for different bedform development stages reasonably predicts sediment transport rates for both fine and medium sand and that the error is generally less than a factor of 5 (A large portion of this error probably lies in the field measurements of ripple height and ripple migration rate). Fig. 12

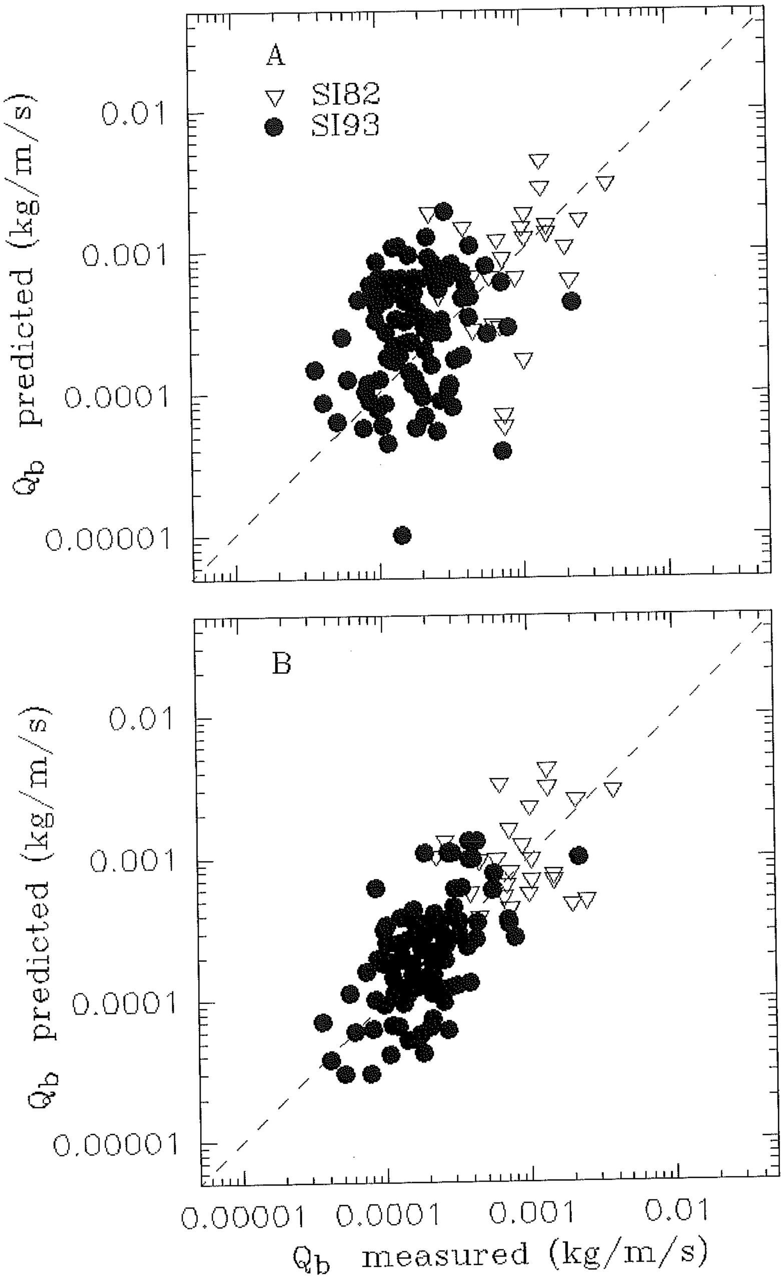

Figure 12 Scatter plots of the measured and predicted sediment transport rates from (a) the Engelund Hansen total-load formula, (b) the Einstein-Brown bedload formula, (c) the Bagnold total-load and (d) the Yalin bedload formula. The proposed effective shear stress was used in the predictions. Circles are data from the 1993 site 1 deployment over medium sand and triangles are data from the 1982 deployment over fine sand. The dashed lines again represent the perfect

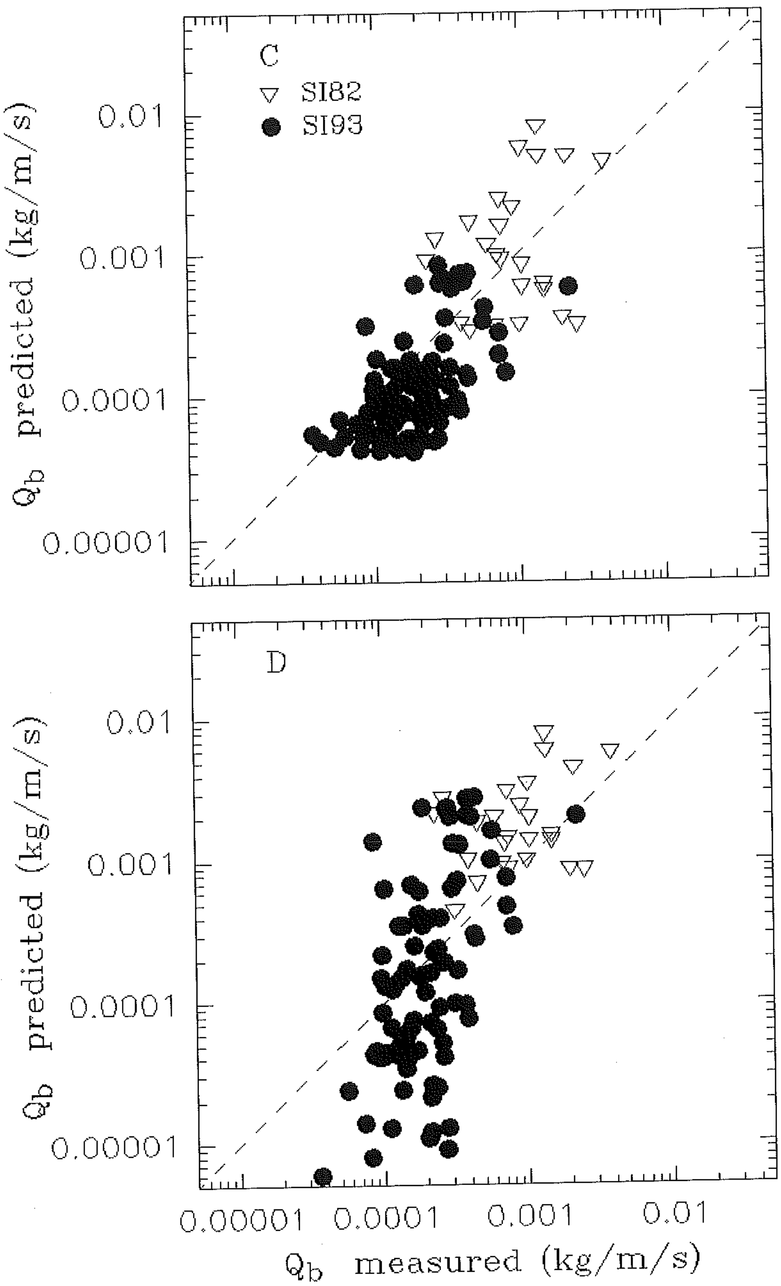
C
SI82
SI93
D
0.01
0.001
0.0001
0.00001
Qb predicted (kg/m/s)
0.00001
0.0001
0.001
0.01
Qb measured (kg/m/s)

Figure 12(c,d)

also shows that the Einstein-Brown bedload method and the Bagnold total load method give the best prediction of sediment transport rates under the combined-flow conditions. Larger scatter exists in the prediction by the Engelund-Hansen total load method, while the Yalin bedload method tends to under-predict sediment transport rates at the low transport stages and slightly over-predicts at higher transport stages.

5. CONCLUSIONS AND RECOMMENDATIONS

The Geological Survey of Canada sediment transport model has been upgraded based on new advances in our understanding of the boundary layer dynamics and sediment transport processes for both cohesive and non-cohesive sediment (e.g. Wiberg and Nelson, 1992; Madsen et al., 1993; Mehta, 1993; van Rijn et al., 1993; Li, 1994; Vincent and Downing, 1994; Wright et al., 1994; Amos et al., 1996a and in press; Li et al., 1996a; Li and Amos, in press; Li et al., in press). The following key improvements are made in SEDTRANS96:

(1) A suite of batch files are used so that the running of SEDTRANS96 in different modes and the graphical output of the results are now menu-driven. SEDTRANS96 also generates a series of text and data output files to provide more complete information on boundary layer parameters, bedform types and dimension, profiles of velocity and suspended sediment concentration as well as bedload and suspended load transport rates and directions.

(2) Critical shear stresses for bedload, suspension and sheet-flow transport tested for the combined-flow conditions are adopted in SEDTRANS96. It is found that though the conventional thresholds for unidirectional flows are applicable under combined waves and currents, the enhanced shear stresses due to the presence of ripples and bedload transport layer have to be compared against these criteria to ensure the proper prediction of the initiation of these transport modes.

(3) A combined-flow ripple and bed roughness predictor proposed by Li and Amos (in press) is included in the subroutine FRICFAC so that SEDTRANS96 now can reasonably predict time-dependent bed roughness for combined flows and the effects of bedload transport on bed shear stresses and the profiles of velocity and sediment suspension are accounted for.

(4) The wave and current shear stresses, instead of shear velocities, are used in the vectorial addition in TIMING and TRANSPO to obtain the combined wave-current shear stress so that the physics of these two subroutines are now more sound.

(5) For fine-grained sediments or under storm conditions, suspended-load transport forms an important (if not the dominant) part of the total sediment transport rate. Thus the modified Rouse (1937) equation is used in this version of the model to predict the vertical profile of sediment suspension and its product with the velocity profile is integrated through depth to obtain the suspended-load sediment flux.

(6) The seabed is often covered by ripples at low to moderate transport stages and bed shear stress increases from the ripple trough to the crest under these conditions. Our field data show that using the average skin-friction shear stress under-predicts the sediment transport rates, while using the maximum ripple-enhanced shear stress causes over-prediction. A scheme of effective shear stresses is proposed as a function of sediment transport and bedform development stages. This new shear-stress scheme, as well as the upgraded critical shear stress and transport time algorithms, have been calibrated against measured bedform transport rates over fine sand and medium sand. This calibration suggests that under combined flows, the Einstein-Brown (Brown, 1950) and Bagnold (1963) methods seem to give better predictions of sediment transport rates than the methods of Engelund-Hansen (1967) and Yalin (1963) and that the difference between the measured and predicted transport rates has been reduced from more than one order of magnitude to generally less than a factor of 5.

(7) Based on new advances in cohesive sediment transport study (Amos et al., 1996a and in press), a totally new cohesive sediment transport algorithm is proposed in SEDTRANS96. Cohesive sediment transport is separated into depositional, stable and erosional states according to the relative values of the applied shear stress τ_b, the critical shear stress for deposition τ_d and the critical shear stress for erosion τ_e. A steady-state condition is assumed in the stable state ($\tau_d < \tau_b < \tau_e$). In the depositional state, τ_b is smaller than τ_d and deposition only occurs. For given initial sediment concentration and deposition duration, a finite-difference scheme is used to predict the final deposition rate and sediment concentration c. In the erosional state, $\tau_b \geq \tau_e$ and erosion only occurs. In situ measurements have been used to define a vertical profile of the critical erosion stress $\tau_e(z)$ as a function of down-core erosion depth. The profile of $\tau_e(z)$, the applied shear stress and the erosion time

are brought into an empirical erosion rate equation and the finite-difference scheme is again used to predict the final erosion rate and sediment concentration. For all three states, sediment concentration is multiplied by the mean velocity u and water depth h to obtain the final sediment transport rate.

(8) For visual presentation of the model results, SEDTRANS96 now calls MATLAB, a numeric computation and visualization software package, to generate plots of the velocity profile, the suspended sediment concentration profile, and the time series of the predicted skin-friction combined shear velocity, bedload and suspended-load transport rates, and the direction of the bedload sediment transport.

Due to the complexity of the sediment transport processes and the limited available technologies, our understanding of the boundary layer dynamics and sediment transport processes is limited and our sediment transport models are far from being complete and accurate. As new technologies and research method become available, our understanding of these processes will improve and this determines that sediment transport models must also be continuously re-evaluated and upgraded. Although SEDTRANS96 is a significant improvement from previous versions, shortcomings certainly still exist. The critical shear stresses adopted in SEDTRANS96 have only been tested by limited field observations over fine and medium sand. Its applicability to coarse sand and gravel is uncertain. Similarly, the combined-flow ripple predictor used in SEDTRANS96 is based on field ripple data over medium sand sediment. It needs to be tested by independent data and its applicability to other grain sizes (fine sand and coarse sand) also has to be tested against field measurements. Large wave ripples and hummocky megaripples can form due to the fall out of sand from suspension during the decaying of storms and the formation of these large bedforms has significant effects on the bed shear stress and sediment suspension (e.g. Hay and Wilson, 1994; Amos et al., 1996b; Li and Amos, in review[a]). Presently we do not have a good understanding of their formation mechanism and the ripple predictor in SEDTRANS96 is not capable of predicting these large wave ripples. The modified Rouse suspension equation (Glenn and Grant, 1987) has been included in SEDTRANS96 for the prediction of suspended-load transport rates. Though this method has been tested with limited field data (Li et al., 1996a), suspended-load sediment transport is a completely separate and complicated issue and we need to have complete simultaneous information about the boundary layer dynamics and seabed conditions to reasonably predict this. The required information includes the heterogeneity of the bottom sediment and its effects on sand suspension, bedform development and effect on sand resuspension, the upward diffusion/advection of the suspended sediment and the prediction of the vertical distribution of the grain size as well as concentration of the suspended sediment (e.g. Nielsen, 1984; Hanes et al., 1988; Vincent et al., 1991; Hay and Sheng, 1992; Vincent and Downing, 1994; Wiberg et al., 1994; Li et al., 1996a). Our improved understanding of sediment transport thresholds and bedform formation under combined waves and currents forms a solid foundation for us to move on to the issues of sand resuspension and the prediction of sediment suspension profiles in the future. As for cohesive sediment transport, we have proposed a new frame-work in SEDTRANS96 based on our current knowledge of cohesive sediment dynamics. These algorithms need to be tested by high-quality in situ measurements in order to calibrate their applicability to various types of muds formed in different environments.

Just as SEDTRANS92 is being upgraded to SEDTRANS96, our sediment transport research method and technologies at GSCA are also dramatically improving. The recent upgrade of the GSCA instrumented platform RALPH (Heffler, 1996), the upgrading of the Sea Carousel (Amos et al., 1994b) and the development of a mini-carousel, and the development of the multibeam bathymetric survey technology (Courtney and Fader, 1994) will all have significant impacts on our understanding of sediment transport processes and their predictions.

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APPENDIX 1

PROGRAM LISTINGS FOR SEDTRANS96

```
      PROGRAM SEDTRANS96
C**********************************************************************************************
C**********************************************************************************************
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      CHARACTER*15 NAME

C  THIS IS THE INTERACTIVE VERSION

C              SED96:  A SEDIMENT TRANSPORT MODEL
C                    FOR CONTINENTAL SHELVES
C
C              GEOLOGICAL SURVEY OF CANADA (ATLANTIC)
C                 CREATED IN:  SEPTEMBER, 1992
C                LAST MODIFIED: DECEMBER 18, 1996

C  THIS PROGRAM PREDICTS SEDIMENT TRANSPORT FOR EITHER STEADY CURRENTS OR COMBINED
C  WAVES AND CURRENTS. THE COMBINED-FLOW BOTTOM BOUNDARY LAYER MODEL OF GRANT AND
C  MADSEN (1986) IS USED AND A CHOICE OF TRANSPORT FORMULAE IS AVAILABLE TO THE USER.
C
C  THE AVAILABLE OPTIONS ARE:
C  IOPT1  =   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
C             2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
C             3 - BAGNOLD (1963) TOTAL LOAD EQUATION
C             4 - YALIN (1963) BEDLOAD EQUATION
C             5 - COHESIVE SEDIMENTS

C**************************************************************************
C  THE FOLLOWING MODIFICATIONS HAVE BEEN MADE FROM SEDTRANS92:
C     1.  THE ENHANCED SKIN-FRICTION SHEAR VELOCITY AT THE RIPPLE CREST IS USED TO
C         DETERMINE THE INITIATION OF BEDLOAD TRANSPORT AND TIMES OF VARIOUS TRANSPORT
C         PHASES.
C     2.  THE SUM OF GRAIN SIZE AND BEDLOAD ROUGHNESSES IS USED IN FRICFAC.FOR TO COMPUTE
C         TRANSPORT-RELATED WAVE-CURRENT UST'S WHICH ARE USED TO DETERMINE THE
C         THRESHOLD CONDITIONS OF SUSPENSION AND SHEET FLOW TRANSPORT.
C     3.  TIME-DEPENDENT RIPPLE TYPE AND GEOMETRY ARE PREDICTED FOR COMBINED FLOWS BASED
C         ON THE SABLE ISLAND BANK FIELD DATA.
C     4.  WAVE AND CURRENT SHEAR STRESSES, INSTEAD OF SHEAR VELOCITIES, ARE VECTORIALLY
C         ADDED TO OBTAIN THE COMBINED SHEAR STRESS IN TIMING AND TRANSPO SUBROUTINES.
C     5.  A SCHEME OF EFFECTIVE SHEAR STRESS IS ADOPTED IN THE CALCULATION OF SEDIMENT
C         TRANSPORT RATES.
C     6.  VELOCITY PROFILE AND SUSPENDED SEDIMENT CONCENTRATION PROFILE ARE PREDICTED
C         BASED ON THE GM86 MODEL AND GLENN AND GRANT (1987) METHOD. THESE ARE THEN
C         INTEGRATED NUMERICALLY TO OBTAIN THE SUSPENDED SEDIMENT TRANSPORT RATE IN
C         SUBROUTINE PROFL.FOR.
C     7.  NUMEROUS OUTPUT DATA FILES WILL BE GENERATED TO PROVIDE COMPLETE INFORMATION
C         ON BOUNDARY LAYER DYNAMICS AND SEABED RESPONSES
C     8.  NEW ALGORITHMS ARE USED FOR COHESIVE SEDIMENT TRANSPORT BASED ON RECENT
C         ADVANCES IN THIS FIELD.
C
C  THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED AND THEIR LIMITATIONS.
C
C  ALL DIMENSIONAL VARIABLES ARE IN SI UNITS.
C
C  THE DETAILED TEXT OUTPUT WILL BE SENT TO THE TERMINAL AS WELL AS THE FILE NAMED BY THE
C  USER (LOGICAL UNIT #7). THE KEY PARAMETERS ARE TABULATED IN "SEDOUTI1" AND "SEDOUTI2"
C  (UNITS #6 AND #8). THE PREDICTED VELOCITY AND SUSPENSION PROFILE DATA ARE STORED IN THE
```

```
C  FILE 'PROFILE.DAT' (LOGICAL UNIT #9)
C
C  ALL WARNINGS, MESSAGES, ETC. ARE DIRECTED TO THE TERMINAL
C
C***************************************************************************
C SET UP INPUT AND OUTPUT FILES
C
      WRITE (*,10)
 10   FORMAT(/,' ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED: ')
      READ (*,20) NAME
 20   FORMAT(A15)
      OPEN (7, FILE=NAME, STATUS='UNKNOWN', FORM='FORMATTED')
      OPEN (6, FILE='SEDOUTI1', STATUS = 'UNKNOWN', FORM='FORMATTED')
      OPEN (8, FILE='SEDOUTI2', STATUS = 'UNKNOWN', FORM='FORMATTED')
      OPEN (9, FILE='PROFILE.DAT', STATUS='UNKNOWN', FORM='FORMATTED')
C WRITE THE HEADERS TO THE TABULAR OUTPUT FILE SEDOUTI1
      WRITE (6,30)
 30   FORMAT('BT#   UB   AB   FCWS  DCW   Z0   Z0C   HR    LR')

C***************************************************************************
C READ IN THE INPUT PARAMETERS
C   IRUN = RUN OR CYCLE NUMBER
C   D = WATER DEPTH (M)
C   UZ = AMBIENT CURRENT AT HEIGHT Z ABOVE THE SEAFLOOR (M/S)
C   Z  = HEIGHT OF UZ ABOVE SEAFLOOR
C   CDIR = DIRECTION OF AMBIENT CURRENT (DEGREES)
C   HT = WAVE HEIGHT (M)
C   PER = WAVE PERIOD (S)
C   WDIR = WAVE PROPAGATION DIRECTION (DEGREES)
C   GD = SEDIMENT GRAIN DIAMETER (M)
C   RHINP = INPUT RIPPLE HEIGHT (M)
C   RLINP = INPUT RIPPLE LENGTH (M)
C   BETA = BED SLOPE (DEGREE)
C   RHOS = DENSITY OF SEDIMENT  (KG/M**3)
C   RHOW = DENSITY OF FLUID (WATER)  (KG/M**3)
C   QI = THE INPUT DATA QUIT INDEX
C   IOPT1 = SEDIMENT TRANSPORT FORMULA OPTION NUMBER
C   FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C
C VARIABLES FOR COHESIVE SEDIMENT METHOD:
C   CONC0 = INITIAL ESTIMATE OF SEDIMENT CONCENTRATION (mg/l)
C   TAOCE = CRITICAL STRESS FOR EROSION (Pa)
C   TAOCD = CRITICAL STRESS FOR DEPOSITION (Pa)
C   TIMEDR = DEPOSITION OR EROSION DURATION (minutes)
C   WS = SETTLING VELOCITY FOR COHESIVE SEDIMENT (m/s)
C   PRS = PROBABILITY OF RESUSPENSION (NORMALLY ASSUMED = 0)
C   RKERO = PROPORTIONALITY COEFFICIENT FOR EROSION RATE (DEFAULT = 1.62)

 50   CALL READIN (IRUN,D,UZ,Z,CDIR,HT,PER,WDIR,GD,RHINP,RLINP,BETA,RHOS,RHOW,QI,IOPT1,FRACT,
     @CONC0,TAOCE,TAOCD,TIMEDR,WS,PRS,RKERO)

C WRITE THE HEADERS TO THE TABULAR OUTPUT FILE SEDOUTI2
      IF (IOPT1 .EQ. 5) THEN
          WRITE (8,60)
      ELSE
          WRITE (8,70)
```

```
      ENDIF
60    FORMAT('BT#  USTCS   USTCWS RD0      RE0       CONC QS0'
     @'     QS        QSDIR')
70    FORMAT('BT# USTCS  USTWS  USTCWS USTC   USTW   USTCW    QB'
     @'        QS     QBDIR')

C QI = THE INPUT DATA QUIT INDEX (RE-ENTER INPUT OR NO MORE RUNS REQUIRED)
      IF (QI .EQ. 1.0) GO TO 100

C*************************************************************************
C WRITE OUT THE INPUT PARAMETERS TO FILE AND THE TERMINAL
C
      CALL INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,RHINP,RLINP,RHOS,RHOW,FRACT,CONC0,TAOCE,
     @TAOCD,WS,TIMEDR,PRS,RKERO,IOPT1)

C*************************************************************************
C CALCULATE WAVE INDUCED BOTTOM VELOCITY AND ORBITAL DIAMETER
C
C OUTPUT VARIABLES:
C   UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C   AB = EXCURSION AMPLITUDE OF BOTTOM WAVE ORBIT (M) (1/2 OF THE ORBITAL DIAMETER)
C   WL = WAVE LENGTH (M)
C   IBRK = WAVE-BREAKING CRITERION
C
      CALL OSCIL(HT,PER,D,UB,AB,WL,IBRK)

C*************************************************************************
C CALCULATE THRESHOLD CRITERIA FOR SEDIMENT TRANSPORT
C
C OUTPUT VARIABLES:
C   USTCRB = CRITICAL SHEAR VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/SEC)
C   USTCRS = CRITICAL SHEAR VELOCITY FOR INITIATION OF SUSPENDED LOAD TRANSPORT (M/SEC)
C   USTUP  = CRITICAL SHEAR VELOCITY FOR INITIATION OF SHEET FLOW TRANSPORT (M/SEC)
C   FALL   = SETTLING VELOCITY FOR NON-COHESIVE SEDIMENT (M/SEC)

C THRESH SUBROUTINE NOT APPLICABLE FOR COHESIVE SEDIMENTS, GOTO FRICFAC
      IF (IOPT1.EQ.5) GOTO 80

      CALL THRESH(UB,GD,RHOS,RHOW,IOPT1,USTCRB,USTCRS,USTUP,FALL)

C*************************************************************************
C CALCULATE FRICTION FACTOR, AMBIENT CURRENT AND BOTTOM STRESSES
C
C OUTPUT VARIABLES:
C   Z0 = BED ROUGHNESS LENGTH (M)
C   Z0C = APPARENT BED ROUGHNESS LENGTH (M)
C   FCW = BOTTOM (SKIN) FRICTION FACTOR
C   UA = CURRENT SPEED AT THE TOP OF THE WAVE-CURRENT BOUNDARY LAYER (M/S)
C   PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE WAVE
C          BOUNDARY LAYER (RADIANS)
C   U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/SEC)
C   PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M ABOVE SEABED (RADIANS)
C          NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED OUTSIDE THE WAVE BOUNDARY LAYER.
C   USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY (M/S)
C   USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY (M/S)
C   USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY (M/S)
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C   USTCWSE = RIPPLE-ENHANCED COMBINED SHEAR VELOCITY (M/S)
C   USTCWSB = BEDLOAD-RELATED COMBINED SHEAR VELOCITY (M/S)
C   USTC = TOTAL CURRENT SHEAR VELOCITY (M/S)
C   USTW = TOTAL WAVE SHEAR VELOCITY (M/S)
C   USTCW = TOTAL COMBINED SHEAR VELOCITY (M/S)
C   DELTACW = HEIGHT OF THE WAVE-CURRENT BOUNDARY LAYER (M)
C   RHEIGHT = PREDICTED RIPPLE HEIGHT (M)
C   RLENGTH = PREDICTED RIPPLE LENGTH (M)
C   RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION

 80    CONTINUE
       CALL FRICFAC(IRUN,UZ,Z,CDIR,UB,AB,PER,WDIR,GD,RHINP,RLINP,RHOW,RHOS,USTCRB,USTUP,Z0,Z0C,
       @FCW,UA,PHIB,U100,PHI100,USTCS,USTWS,USTCWS,USTCWSE,USTCWSB,USTC,USTW,USTCW,
       @DELTACW,RHEIGHT,RLENGTH,RPLCOEF)

C***************************************************************************
C CALCULATE THE DURATION OF DIFFERENT SEDIMENT TRANSPORT PHASES
C
C OUTPUT VARIABLES:
C   TB1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT CEASES (S)
C   TB2 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT RECOMMENCES (S)
C   TS1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH SUSPENDED LOAD TRANSPORT CEASES (S)
C   TS2 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH SUSPENDED LOAD TRANSPORT
C         RECOMMENCES (S)
C   PERBED = PERCENTAGE OF TIME SPENT IN ONLY BEDLOAD TRANSPORT PHASE
C   PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT PHASE
C   USTCWSM = MAXIMIZED SKIN-FRICTION COMBINED SHEAR VELOCITY

C TIMING.FOR AND PROFL.FOR ARE NOT NEEDED FOR COHESIVE SEDIMENT METHOD
       IF (IOPT1.EQ.5) GOTO 90

       CALL TIMING(RPLCOEF,RHOW,UA,PHIB,UB,PER,U100,USTCRB,USTCRS,USTCS,USTWS,USTCWS,
       @USTCWSB,TB1,TB2,TS1,TS2,PERBED,PERSUSP,USTCWSM)

C***************************************************************************
C CALCULATE VELOCITY PROFILE, SUSPENDED SEDIMENT CONCENTRATION PROFILE AND THE
C SUSPENDED SEDIMENT TRANSPORT RATE AND DIRECTION
C
C OUTPUT VARIABLES:
C   C0 = REFERENCE CONCENTRATION AT Z0 (KG/M^3)
C   GAMMA0 = SAND RESUSPENSION COEFFICIENT
C   QS = SUSPENDED SEDIMENT TRANSPORT RATE (KG/M/S)
C   QSDIR = DIRECTION OF SUSPENDED SEDIMENT TRANSPORT (DEGREE)
C
       CALL PROFL(IRUN,RHOW,FALL,UB,CDIR,USTCS,USTWS,USTCWS,USTCWSB,USTCWSE,USTC,USTW,
       @USTCW,USTCRB,USTCRS,USTUP,Z0,Z0C,DELTACW,C0,GAMMA0,QS,QSDIR)

C***************************************************************************
C CALCULATE SEDIMENT TRANSPORT RATE AND DIRECTION
C
C OUTPUT VARIABLES:
C   SED = TIME-AVERAGED VOLUME SEDIMENT TRANSPORT RATE (VOLUME OF SEDIMENT
C             SOLIDS TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME, M^3/S/M)
C   SEDM = TIME-AVERAGED MASS SEDIMENT TRANSPORT RATE (MASS OF SEDIMENT
C             SOLIDS TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME, KG/S/M)
C   SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH, DEGREES)
```

```
C OUTPUT VARIABLES FOR COHESIVE SEDIMENT METHOD:
C   RD0 = INITIAL DEPOSITION RATE (kg/m^2/s)
C   RD = FINAL DEPOSITION RATE (kg/m^2/s)
C   RE0 = INITIAL EROSION RATE (kg/m^2/s)
C   RE = FINAL EROSION RATE (kg/m^2/s)
C   TIME0 = CALCULATED TIME (minutes) WHEN CONC. HAS DECREASED TO BE LESS THAN 1 MG/L
C           DUE TO DEPOSITION OR WHEN DOWN-CORE CRITICAL EROSION SHEAR STRESS HAS BECOME
C           EQUAL TO THE APPLIED BED SHEAR STRESS SO THAT EROSION HAS STOPPED
C   QS0 = INITIAL MASS SEDIMENT TRANSPORT RATE (kg/m/s)
C   CONC = FINAL CALCULATED SEDIMENT CONCENTRATION (mg/l)
C   SED = VOLUME SEDIMENT TRANSPORT RATE (M^3/M/S)
C   SEDM = MASS SEDIMENT TRANSPORT RATE (KG/M/S)
C   SEDDIR = DIRECTION OF SEDIMENT TRANSPORT (DEGREE)
C
 90   CONTINUE
      CALL TRANSPO(D,UA,UB,U100,PHIB,PHI100,FCW,PER,GD,FRACT,BETA,RHOS,RHOW,USTCRB,USTCS,
     @USTWS,USTCWS,USTCWSB,RPLCOEF,CDIR,WDIR,TB1,TB2,TS1,PERBED,PERSUSP,IOPT1,CONC0,
     @TAOCD,TAOCE,TIMEDR,WS,RD0,RD,RE0,RE,TIME0,QS0,CONC,SED,SEDM,SEDDIR)

C*****************************************************************************
C FINAL OUTPUTS OF THE MODEL
C
      CALL OUTOUT(IRUN,RHOW,UB,AB,WL,FCW,DELTACW,UA,U100,PHIB,USTCS,USTWS,USTCWS,USTCWSB,
     @USTC,USTW,USTCW,Z0,Z0C,RHEIGHT,RLENGTH,USTCRB,USTCRS,TS1,TB1,TS2,TB2,PERBED,PERSUSP,
     @IOPT1,RK,QS,QSDIR,SEDM,SED,SEDDIR,CONC,TAOCE,TAOCD,RD0,RD,RE0,RE,TIME0,CONC0,QS0)

C*****************************************************************************
C PREDICT POTENTIAL BEDFORM TYPES
C
C OUTPUT VARIABLES:
C   RHEIGHT = PREDICTED RIPPLE HEIGHT
C   RLENGTH = PREDICTED RIPPLE LENGTH
C   RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION
C
      CALL BEDFORM(U100,UA,UB,GD,FCW,PHIB,RHOW,RHOS,AB,IOPT1,RHEIGHT,RLENGTH,USTCS,USTWS,
     @USTCWS,USTCWSE,USTCWSB,USTCRB,USTUP)

C*****************************************************************************
C GIVE USER THE OPTION OF DOING ANOTHER RUN
C
 100  CONTINUE
C
      WRITE (*,110)
 110  FORMAT(///,' ENTER 1 TO DO ANOTHER RUN, 0 TO STOP: ')
C READ IN IND, A TEMPORARY INDICATOR OF CHOICE
      READ (*,*) IND
      IF (IND .EQ. 0) GOTO 999
      GO TO 50

C**********************************************************************************************
C**********************************************************************************************
C
 999  STOP
C END OF THE MAIN PROGRAM
      END
```

```
      PROGRAM SEDTRANS96
C*************************************************************************
C*************************************************************************
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      CHARACTER*1 IYN

      CHARACTER*80 CHR

C  THIS IS THE BATCH VERSION

C                 SED96: A SEDIMENT TRANSPORT MODEL
C                      FOR CONTINENTAL SHELVES
C
C                GEOLOGICAL SURVEY OF CANADA (ATLANTIC)
C                   CREATED IN:  SEPTEMBER, 1992
C                  LAST MODIFIED: DECEMBER 18, 1996

C  THIS PROGRAM PREDICTS SEDIMENT TRANSPORT FOR EITHER STEADY CURRENTS OR COMBINED
C  WAVES AND CURRENTS. THE COMBINED-FLOW BOTTOM BOUNDARY LAYER MODEL OF GRANT AND
C  MADSEN (1986) IS USED AND A CHOICE OF TRANSPORT FORMULAE IS AVAILABLE TO THE USER.

C  THE AVAILABLE OPTIONS ARE:
C  IOPT1 =  1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
C           2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
C           3 - BAGNOLD (1963) TOTAL LOAD EQUATION
C           4 - YALIN (1963) BEDLOAD EQUATION
C           5 - COHESIVE SEDIMENTS
C
C*************************************************************************
C  THE FOLLOWING MODIFICATIONS HAVE BEEN MADE FROM SEDTRANS92:
C    1.  THE ENHANCED SKIN-FRICTION SHEAR VELOCITY AT THE RIPPLE CREST IS USED TO
C        DETERMINE THE INITIATION OF BEDLOAD TRANSPORT AND TIMES OF VARIOUS TRANSPORT
C        PHASES.
C    2.  THE SUM OF GRAIN SIZE AND BEDLOAD ROUGHNESSES IS USED IN FRICFAC.FOR TO COMPUTE
C        TRANSPORT-RELATED WAVE-CURRENT UST'S WHICH ARE USED TO DETERMINE THE
C        THRESHOLDS OF SUSPENSION AND SHEET FLOW TRANSPORT.
C    3.  TIME-DEPENDENT RIPPLE TYPE AND GEOMETRY ARE PREDICTED FOR COMBINED FLOWS
C        BASED ON THE SABLE ISLAND BANK FIELD DATA.
C    4.  WAVE AND CURRENT SHEAR STRESSES, INSTEAD OF SHEAR VELOCITIES, ARE VECTORIALLY
C        ADDED TO OBTAIN THE COMBINED SHEAR STRESS IN TIMING AND TRANSPO SUBROUTINES.
C    5.  A SCHEME OF EFFECTIVE SHEAR STRESS IS ADOPTED IN THE CALCULATION OF SEDIMENT
C        TRANSPORT RATES.
C    6.  VELOCITY PROFILE AND SUSPENDED SEDIMENT CONCENTRATION PROFILE ARE PREDICTED
C        BASED ON THE GM86 MODEL AND GLENN AND GRANT (1987) METHOD. THESE ARE THEN
C        INTEGRATED NUMERICALLY TO OBTAIN THE SUSPENDED SEDIMENT TRANSPORT RATE IN
C        SUBROUTINE PROFL.FOR.
C    7.  SEVERAL OUTPUT DATA FILES WILL BE GENERATED TO PROVIDE COMPLETE INFORMATION
C        ON BOUNDARY LAYER DYNAMICS AND SEABED RESPONSES
C    8.  NEW ALGORITHMS ARE USED FOR COHESIVE SEDIMENT TRANSPORT BASED ON RECENT
C        ADVANCES IN THIS FIELD.
C
C  THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED AND THEIR LIMITATIONS.
C
C  ALL DIMENSIONAL VARIABLES ARE IN SI UNITS
C
C  INPUT DATA SHOULD BE STORED IN FILE 'INDATA' (LOGICAL UNIT #3). DETAILED TEXT OUTPUT WILL
```

```
C  BE SENT TO FILE "OUTDATA" (UNIT #7) AND THE TABULATED OUTPUT SENT TO FILES "SEDOUT1.DAT"
C  AND "SEDOUT2.DAT" (UNITS #6 AND #8). PREDICTED VELOCITY AND SUSPENSION PROFILES ARE
C  STORED IN FILE "PROFILE" (UNIT #9)
C
C  ALL WARNINGS, MESSAGES, ETC. ARE DIRECTED TO THE TERMINAL

C  ASSIGN 0 TO THE END-OF-FILE QUIT INDEX IND
      IND = 0

C**************************************************************************
C SET UP INPUT AND OUTPUT FILES
C
      OPEN (3, FILE='INDATA',STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN (7, FILE='OUTDATA',STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN (6, FILE='SEDOUT1.DAT',STATUS ='UNKNOWN',FORM='FORMATTED')
      OPEN (8, FILE='SEDOUT2.DAT',STATUS ='UNKNOWN',FORM='FORMATTED')
      OPEN (9, FILE='PROFILE', STATUS='UNKNOWN', FORM='FORMATTED')
C
C WRITE THE HEADERS TO THE TABULAR OUTPUT FILE SEDOUT1.DAT
      WRITE (6,10)
 10   FORMAT('BT#  UB   AB   FCWS  DCW   Z0   Z0C   HR   LR')
C WRITE THE HEADERS TO THE TABULAR OUTPUT FILE SEDOUT2.DAT
      WRITE (*,15)
 15   FORMAT(/,' IS THE MODEL RUNNING FOR COHESIVE SEDIMENT? (Y/N): ')
      READ (*,'(A1)') IYN
      IF (IYN.EQ.'Y'.or.iyn .eq. 'y') THEN
         WRITE (8,20)
      ELSE
         WRITE (8,30)
      ENDIF
 20   FORMAT('BT#  USTCS   USTCWS RD0     RE0      CONC QS0'
     @'      QS        QSDIR')
 30   FORMAT('BT# USTCS  USTWS  USTCWS USTC   USTW   USTCW    QB'
     @'       QS     QBDIR')

C SKIP THE HEADER LINE OF THE INPUT FILE INDATA
      READ (3,'(A80)')

C**************************************************************************
C READ IN THE INPUT PARAMETERS
C
C   IRUN = RUN OR CYCLE NUMBER
C   D = WATER DEPTH (M)
C   UZ = AMBIENT CURRENT AT HEIGHT Z ABOVE THE SEAFLOOR (M/S)
C   Z = HEIGHT OF UZ ABOVE SEAFLOOR
C   CDIR = DIRECTION OF AMBIENT CURRENT (DEGREES TRUE)
C   HT = WAVE HEIGHT (M)
C   PER = WAVE PERIOD (S)
C   WDIR = WAVE PROPAGATION DIRECTION (DEGREES TRUE)
C   GD = SEDIMENT GRAIN DIAMETER (M)
C   RHINP = INPUT RIPPLE HEIGHT (M)
C   RLINP = INPUT RIPPLE LENGTH (M)
C   BETA = BED SLOPE (DEGREE)
C   FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C   RHOS = DENSITY OF SEDIMENT   (KG/M**3)
C   RHOW = DENSITY OF FLUID  (KG/M**3)
```

```
C   IOPT1 = SEDIMENT TRANSPORT FORMULA OPTION NUMBER
C
C VARIABLES USED FOR COHESIVE SEDIMENT TRANSPORT CALCULATIONS
C
C   CONC0 = INITIAL ESTIMATE OF SEDIMENT CONCENTRATION (ppm) (ie mg/l)
C   TAOCE = CRITICAL STRESS FOR EROSION (Pa)
C   TAOCD = CRITICAL STRESS FOR DEPOSITION (Pa)
C   TIMEDR = DEPOSITION OR EROSION DURATION (minutes)
C   WS = SETTLING VELOCITY (m/s)
C   PRS = PROBABILITY OF RESUSPENSION (NORMALLY ASSUMED = 0)
C   RKERO = PROPORTIONALITY COEFFICIENT FOR EROSION RATE (DEFAULT = 2.0)
C
 1    CALL READBCH(IRUN,D,UZ,Z,CDIR,HT,PER,WDIR,GD,RHINP,RLINP,BETA,FRACT,RHOS,RHOW,IOPT1,
     @CONC0,TAOCE,TAOCD,TIMEDR,WS,PRS,RKERO)

C***********************************************************************
C WRITE OUT THE INPUT PARAMETERS TO FILE AND TERMINAL
C
      CALL INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,RHINP,RLINP,RHOS,RHOW,FRACT,CONC0,TAOCE,
     @TAOCD,WS,TIMEDR,PRS,RKERO,IOPT1)

C***********************************************************************
C CALCULATE WAVE INDUCED BOTTOM VELOCITY AND ORBIT SIZE
C
C OUTPUT VARIABLES:
C   UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C   AB = EXCURSION AMPLITUDE OF BOTTOM WAVE ORBIT (M) (1/2 OF THE ORBIT SIZE)
C   WL = WAVE LENGTH (M)
C   IBRK = WAVE-BREAKING CRITERION
C
      CALL OSCIL(HT,PER,D,UB,AB,WL,IBRK)

C***********************************************************************
C CALCULATE THRESHOLD CRITERIA FOR SEDIMENT TRANSPORT
C
C OUTPUT VARIABLES:
C   USTCRB = CRITICAL SHEAR VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/SEC)
C   USTCRS = CRITICAL SHEAR VELOCITY FOR INITIATION OF SUSPENDED LOAD TRANSPORT (M/SEC)
C   USTUP = CRITICAL SHEAR VELOCITY FOR INITIATION OF SHEET FLOW TRANSPORT (M/SEC)
C   FALL = SETTLING VELOCITY FOR NON-COHESIVE SEDIMENT (M/SEC)

C THRESH SUBROUTINE NOT APPLICABLE FOR COHESIVE SEDIMENTS, GOTO FRICFAC
      IF (IOPT1.EQ.5) GOTO 40

      CALL THRESH(UB,GD,RHOS,RHOW,IOPT1,USTCRB,USTCRS,USTUP,FALL)

C***********************************************************************
C CALCULATE FRICTION FACTOR, AMBIENT CURRENT AND BOTTOM STRESSES
C
C OUTPUT VARIABLES:
C   Z0 = BED ROUGHNESS LENGTH (M)
C   Z0C = APPARENT BED ROUGHNESS LENGTH (M)
C   FCW = BOTTOM (SKIN) FRICTION FACTOR
C   UA = CURRENT SPEED AT THE TOP OF THE WAVE-CURRENT BOUNDARY LAYER (M/S)
C   PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE WAVE BOUNDARY
C         LAYER (RADIANS)
```

```
C   U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/SEC)
C   PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M ABOVE SEABED (RADIANS)
C           NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED OUTSIDE THE WAVE BOUNDARY LAYER.
C   USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY (M/S)
C   USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY (M/S)
C   USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY (M/S)
C   USTCWSE = RIPPLE-ENHANCED COMBINED SHEAR VELOCITY (M/S)
C   USTCWSB = BEDLOAD-RELATED COMBINED SHEAR VELOCITY (M/S)
C   USTC = TOTAL CURRENT SHEAR VELOCITY (M/S)
C   USTW = TOTAL WAVE SHEAR VELOCITY (M/S)
C   USTCW = TOTAL COMBINED SHEAR VELOCITY (M/S)
C   DELTACW = HEIGHT OF THE WAVE-CURRENT BOUNDARY LAYER (M)
C   RHEIGHT = PREDICTED RIPPLE HEIGHT (M)
C   RLENGTH = PREDICTED RIPPLE LENGTH (M)
C   RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION
C
 40   CONTINUE
      CALL FRICFAC(IRUN,UZ,Z,CDIR,UB,AB,PER,WDIR,GD,RHINP,RLINP,RHOW,RHOS,USTCRB,USTUP,Z0,Z0C,
      @FCW,UA,PHIB,U100,PHI100,USTCS,USTWS,USTCWS,USTCWSE,USTCWSB,USTC,USTW,USTCW,DELTACW,
      @RHEIGHT,RLENGTH,RPLCOEF)

C*************************************************************************
C CALCULATE THE DURATION OF DIFFERENT SEDIMENT TRANSPORT PHASES
C
C OUTPUT VARIABLES:
C   TB1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD TRANSPORT CEASES (SEC)
C   TB2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH BEDLOAD TRANSPORT RECOMMENCES (SEC)
C   TS1 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED LOAD TRANSPORT CEASES (SEC)
C   TS2 = TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH SUSPENDED LOAD TRANSPORT
C             RECOMMENCES (SEC)
C   PERBED = PERCENTAGE OF TIME SPENT IN ONLY BEDLOAD TRANSPORT PHASE
C   PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT PHASE
C   USTCWSM = MAXIMIZED SKIN-FRICTION COMBINED SHEAR VELOCITY

C TIMING.FOR AND PROFL.FOR ARE NOT NEEDED FOR COHESIVE SEDIMENT METHOD
      IF (IOPT1.EQ.5) GOTO 50

      CALL TIMING(RPLCOEF,RHOW,UA,PHIB,UB,PER,U100,USTCRB,USTCRS,USTCS,USTWS,USTCWS,
      @USTCWSB,TB1,TB2,TS1,TS2,PERBED,PERSUSP,USTCWSM)

C*************************************************************************
C CALCULATE VELOCITY PROFILE, SUSPENDED SEDIMENT CONCENTRATION PROFILE AND
C THE SUSPENDED SEDIMENT TRANSPORT RATE AND DIRECTION
C
C OUTPUT VARIABLES:
C   C0 = REFERENCE CONCENTRATION AT Z0 (KG/M^3)
C   GAMMA0 = SAND RESUSPENSION COEFFICIENT
C   QS = SUSPENDED SEDIMENT TRANSPORT RATE (KG/M/S)
C   QSDIR = DIRECTION OF SUSPENDED SEDIMENT TRANSPORT (DEGREE)
C
      CALL PROFL(IRUN,RHOW,FALL,UB,CDIR,USTCS,USTWS,USTCWS,USTCWSB,USTCWSE,USTC,USTW,
      @USTCW,USTCRB,USTCRS,USTUP,Z0,Z0C,DELTACW,C0,GAMMA0,QS,QSDIR)

C*************************************************************************
C CALCULATE SEDIMENT TRANSPORT RATE AND DIRECTION
C
```

```
C OUTPUT VARIABLES:
C   SED = TIME-AVERAGED VOLUME SEDIMENT TRANSPORT RATE (VOLUME OF SEDIMENT SOLIDS
C           TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME, M^3/S/M)
C   SEDM = TIME-AVERAGED MASS SEDIMENT TRANSPORT RATE (MASS OF SEDIMENT SOLIDS
C           TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME, KG/S/M)
C   SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH, DEGREES)
C
C OUTPUT VARIABLES FOR COHESIVE SEDIMENT METHOD:
C   RD0 = INITIAL DEPOSITION RATE (kg/m^2/s)
C   RD = FINAL DEPOSITION RATE (kg/m^2/s)
C   RE0 = INITIAL EROSION RATE (kg/m^2/s)
C   RE = FINAL EROSION RATE (kg/m^2/s)
C   TIME0 = CALCULATED TIME (minutes) WHEN CONC. HAS DECREASED TO BE LESS THAN 1 MG/L
C           DUE TO DEPOSITION OR WHEN DOWN-CORE CRITICAL EROSION SHEAR STRESS HAS BECOME
C           EQUAL TO THE APPLIED BED SHEAR STRESS SO THAT EROSION HAS STOPPED
C   QS0 = INITIAL MASS SEDIMENT TRANSPORT RATE (kg/m/s)
C   CONC = FINAL CALCULATED SEDIMENT CONCENTRATION (mg/l)
C   SED = VOLUME SEDIMENT TRANSPORT RATE (M^3/M/S)
C   SEDM = MASS SEDIMENT TRANSPORT RATE (KG/M/S)
C   SEDDIR = DIRECTION OF SEDIMENT TRANSPORT (DEGREE)
C
 50   CONTINUE
      CALL TRANSPO(D,UA,UB,U100,PHIB,PHI100,FCW,PER,GD,FRACT,BETA,RHOS,RHOW,USTCRB,USTCS,
     @USTWS,USTCWS,USTCWSB,RPLCOEF,CDIR,WDIR,TB1,TB2,TS1,PERBED,PERSUSP,IOPT1,CONC0,TAOCD,
     @TAOCE,TIMEDR,WS,RD0,RD,RE0,RE,TIME0,QS0,CONC,SED,SEDM,SEDDIR)

C***********************************************************************
C FINAL OUTPUTS OF THE MODEL
C
      CALL OUTOUT(IRUN,RHOW,UB,AB,WL,FCW,DELTACW,UA,U100,PHIB,USTCS,USTWS,USTCWS,USTCWSB,
     @USTC,USTW,USTCW,Z0,Z0C,RHEIGHT,RLENGTH,USTCRB,USTCRS,TS1,TB1,TS2,TB2,PERBED,
     @PERSUSP,IOPT1,RK,QS,QSDIR,SEDM,SED,SEDDIR,CONC,TAOCE,TAOCD,RD0,RD,RE0,RE,TIME0,
     @CONC0,QS0)

C***********************************************************************
C PREDICT POTENTIAL BEDFORM TYPES
C
      CALL BEDFORM(U100,UA,UB,GD,FCW,PHIB,RHOW,RHOS,AB,IOPT1,RHEIGHT,RLENGTH,USTCS,USTWS,
     @USTCWS,USTCWSE,USTCWSB,USTCRB,USTUP)

C***********************************************************************
C IF END OF THE INPUT FILE, TERMINATE THE PROGRAM
      IF (IND .EQ. 1) THEN
         GOTO 999
      ELSE
         GO TO 1
      ENDIF

C*************************************************************************
C*************************************************************************
C
 999  CONTINUE
      STOP
C END OF THE MAIN PROGRAM
      END
```

```
      SUBROUTINE READIN(IRUN,D,UZ,Z,CDIR,HT,PER,WDIR,GD,RHINP,RLINP,BETA,RHOS,RHOW,QI,IOPT1,
     @FRACT,CONC0,TAOCE,TAOCD,TIMEDR,WS,PRS,RKERO)

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*1 IYN
      COMMON /CHECK/ICHK
C
C THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING SEDTRANS92.
C
      PI = ACOS(-1.)
C
C------------------------------------------------------------------
C VARIABLES:
C     IRUN = RUN OR CYCLE NUMBER
C     D = WATER DEPTH (M)
C     UZ = AMBIENT CURRENT AT HEIGHT Z ABOVE THE SEAFLOOR (M/S)
C     Z = HEIGHT OF UZ ABOVE SEAFLOOR
C     CDIR = DIRECTION OF AMBIENT CURRENT (DEGREES)
C     HT = WAVE HEIGHT (M)
C     PER = WAVE PERIOD (S)
C     WDIR = WAVE PROPAGATION DIRECTION (DEGREES)
C     GD = SEDIMENT GRAIN DIAMETER (M)
C     RHINP = INPUT RIPPLE HEIGHT (M)
C     RLINP = INPUT RIPPLE LENGTH (M)
C     RHOS = DENSITY OF SEDIMENT  (KG/M**3)
C     RHOW = DENSITY OF FLUID (WATER)  (KG/M**3)
C     RHINP = INPUT RIPPLE HEIGHT (M)
C     RLINP = INPUT RIPPLE LENGTH (M)
C     BETA = BED SLOPE (DEGREE)
C     QI = QUIT INDEX
C     FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C
C     IOPT1 = SEDIMENT TRANSPORT PREDICTOR OPTION NUMBER
C             1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
C             2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
C             3 - BAGNOLD (1963) TOTAL LOAD EQUATION
C             4 - YALIN (1963) BEDLOAD EQUATION
C             5 - COHESIVE SEDIMENT
C
C VARIABLES FOR COHESIVE SEDIMENT METHOD:
C     CONC0 = INITIAL ESTIMATE OF SEDIMENT CONCENTRATION (ppm) (ie mg/l)
C     TAOCE = CRITICAL STRESS FOR EROSION (Pa)
C     TAOCD = CRITICAL STRESS FOR DEPOSITION (Pa)
C     TIMEDR = DEPOSITION OR EROSION DURATION (minutes)
C     WS = SETTLING VELOCITY (m/s)
C     PRS = PROBABILITY OF RESUSPENSION (NORMALLY ASSUMED = 0)
C     RKERO = PROPORTIONALITY COEFFICIENT FOR EROSION RATE (DEFAULT = 1.62)
C
C------------------------------------------------------------------
C INTERACTIVE DATA ENTRY
C
   10 WRITE (*,20)
   20 FORMAT('IF YOU WISH TO ABORT A RUN, ENTER -99 AS RESPONSE',/,
     @T11,'TO ANY OF THE FOLLOWING QUESTIONS')

C INITIALIZE QUIT INDEX TO 0
```

```
      QI=0.0

C ENTER DATA
      WRITE (*,30)
 30   FORMAT(//,' ENTER RUN NUMBER (1 - 9999): ')
      READ (*,*) IRUN
      IF (IRUN .EQ. -99.) GO TO 666
C
      WRITE (*,40)
 40   FORMAT(//,' ENTER WATER DEPTH (m): ')
      READ (*,*) D
      IF ( D .EQ. -99.) GO TO 666
C
      WRITE (*,50)
 50   FORMAT(//,' ENTER CURRENT SPEED,DIRECTION AND HEIGHT ABOVE',
      @/,' SEABED (m/s, degrees, m): ')
      READ (*,*)  UZ,CDIR,Z
      IF (UZ .EQ. -99. .OR. CDIR .EQ. -99. .OR. Z .EQ. -99.) GO TO 666
C
      WRITE (*,60)
 60   FORMAT(//,' ENTER WAVE HEIGHT, PERIOD AND DIRECTION',/,
      @' (m, seconds, degrees): ')
      READ (*,*) HT,PER,WDIR
      IF (HT .EQ. -99. .OR. PER .EQ. -99. .OR. WDIR .EQ. -99.) GO TO 666
C
      WRITE (*,70)
 70   FORMAT(//,' ENTER GRAIN SIZE, RIPPLE HEIGHT AND LENGTH (m)')
      READ (*,*) GD,RHINP,RLINP
      IF (GD .EQ. -99. .OR. RHOS .EQ. -99.) GO TO 666

      WRITE (*,80)
 80   FORMAT(//,' ENTER BED SLOPE (DEGREE): ')
      READ (*,*) BETA
C
 90   WRITE (*,100)
 100  FORMAT (//,' CHOOSE BETWEEN:',/,
      @ '   1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION',/,
      @ '   2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION',/,
      @ '   3 - BAGNOLD (1963) TOTAL LOAD EQUATION',/,
      @ '   4 - YALIN (1963) BEDLOAD EQUATION',/,
      & '   5 - COHESIVE SEDIMENT TRANSPORT METHOD',/,
      @ ' ENTER 1,2,3,4 OR 5: ')
      READ (*,*) IOPT1
      IF (IOPT1 .EQ. -99) GO TO 666
      IF (IOPT1 .LT. 1 .OR. IOPT1 .GT. 5) GO TO 90
C ASSIGN VALUES TO DENSITIES AND GRAIN SIZE CLASS FRACTION
      IF (IOPT1 .EQ. 5) THEN
         RHOS=1800.
      ELSE
         RHOS=2650.
      ENDIF
      RHOW=1025.
      FRACT=1.0

      GO TO 777
```

```
 666  QI=1.0

C--------------------------------------------
C CHECK THE GRAIN SIZE LIMITS FOR EACH THEORY
C--------------------------------------------
 777  CONTINUE
      IFLAG = 0
      GOTO (210,230,250,270,310) IOPT1
 210  IF (GD.LT.0.00015) THEN
         WRITE (*,220)
 220     FORMAT (//' ***WARNING*** - ENGELUND-HANSEN FORMULA NOT',
      @   ' RECOMMENDED'/T18,'FOR USE WITH SEDIMENTS FINER',
      @   ' THAN 0.15 MM')
         IFLAG=1
      ENDIF
      GOTO 500
 230  IF (GD .LT. 0.0003 .OR. GD .GT. .0286) THEN
        WRITE (*,240)
           PRINT*,' CHECK INPUT DATA FOR RUN # ',IRUN
 240    FORMAT (//' ***WARNING*** - EINSTEIN-BROWN FORMULA IS BASED',
      @ ' ON LABORATORY'/T18,'EXPERIMENTS USING SEDIMENTS WITH',
      @ ' GRAIN SIZES'/T18,'OF 0.3 TO 28.6 MM')
        IFLAG=1
      ENDIF
      GOTO 500
 250  IF (GD.LT.0.00018 .OR. GD.GT.0.00045)THEN
        WRITE (*,260)
        PRINT*,' CHECK INPUT DATA FOR RUN # ',IRUN
 260  FORMAT (//' ***WARNING*** - BAGNOLD FORMULA IS BASED',
      @ ' ON LABORATORY TESTS'/T18,'WITH GRAIN SIZES BETWEEN',
      @ ' 0.18 AND 0.45 MM')
        IFLAG=1
      ENDIF
      GOTO 500
 270  IF (GD.LT.0.0002)THEN
        WRITE (*,280)
        PRINT*,' CHECK INPUT DATA FOR RUN # ',IRUN
 280    FORMAT (//' ***WARNING*** - YALIN FORMULA IS NOT RECOMMENDED',
      @ ' FOR USE'/T18,'WITH SEDIMENTS SMALLER THAN 0.2MM, BASED',
      @ ' ON'/T18,'THE RESULTS OF SENSITIVITY ANALYSES')
        IFLAG=1
      ENDIF
      GOTO 500
 310  IF (GD.GT.0.000016)THEN
        WRITE (*,320)
        WRITE (7,320)
        PRINT*,' CHECK INPUT DATA FOR RUN # ',IRUN
 320    FORMAT (//' ***WARNING*** - THE COHESIVE SEDIMENT METHOD IS',/,
      @ T17,'INTENDED FOR FINE SILT AND FINER SEDIMENTS')
        IFLAG=1
      ENDIF

 500  CONTINUE

C IF THE GRAIN SIZE IS NOT WITHIN THE LIMITS FOR THE SEDIMENT TRANSPORT FORMULA, THEN GIVE
C THE USER THE OPTION OF ENTERING A DIFFERENT GRAIN SIZE FOR THE RUN.
```

```
      IF (IFLAG.EQ.1) THEN
         WRITE (*,510)
 510     FORMAT (//' SELECT NEW VALUE FOR SEDIMENT GRAIN SIZE?'/
     @ ' (ENTER Y/N): ')
         READ (*,'(A1)') IYN
         IF (IYN.EQ.'Y'.or.iyn .eq. 'y') THEN
               WRITE (*,520)
 520        FORMAT (//' ENTER SEDIMENT GRAIN SIZE (M): ')
               READ (*,*) GD
               GO TO 777
         ENDIF
      ENDIF
C
C-----------------------------------------------------------------
C IF COHESIVE SEDIMENT METHOD IS USED, INPUT THE REQUIRED PARAMETERS
C-----------------------------------------------------------------
      IF(IOPT1 .EQ. 5)THEN
         PRINT*,'INPUT THE INITIAL SEDIMENT CONCENTRATION (mg/l): '
         READ (*,*)CONC0
         PRINT*,'INPUT THE CRITICAL STRESS FOR EROSION (Pa): '
         READ (*,*)TAOCE
         PRINT*,'INPUT THE CRITICAL STRESS FOR DEPOSITION (Pa): '
         READ (*,*)TAOCD
         PRINT*,'INPUT THE DEPOSITION/EROSION DURATION (minutes): '
         READ (*,*)TIMEDR
         PRINT*,'INPUT THE SETTLING VELOCITY (m/s): '
         READ (*,*)Ws
         PRINT*,'INPUT THE PROBABILITY OF RESUSPENSION'
         PRINT*,'(NORMALLY ASSUMED = 0): '
         READ (*,*)PRS
         PRINT*,'INPUT THE PROPORTIONALITY COEFFICIENT FOR EROSION RATE'
         PRINT*,'(THE DEFAULT VALUE IS 1.62): '
         READ (*,*)RKERO
      ENDIF

 999  RETURN
      END
```

```
      SUBROUTINE READBCH(IRUN,D,UZ,Z,CDIR,HT,PER,WDIR,GD,RHINP,RLINP,
      @BETA,FRACT,RHOS,RHOW,IOPT1,CONC0,TAOCE,TAOCD,TIMEDR,WS,
      @PRS,RKERO)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      COMMON /CHECK/ICHK
C
C THIS SUBROUTINE CONTROLS USER INPUT OF THE DATA REQUIRED FOR RUNNING BATCH-MODE SED96.
C
C ASSIGN 0 TO THE END-OF-FILE QUIT INDEX IND
      IND = 0
C ASSIGN THE VALUE PI=3.14 TO PI
      PI = ACOS(-1.)
C-------------------------------------------------------------------
C INPUT VARIABLES:
C
C   IRUN = RUN OR CYCLE NUMBER
C   D = WATER DEPTH (M)
C   UZ = AMBIENT CURRENT AT HEIGHT Z ABOVE THE SEAFLOOR (M/S)
C   Z = HEIGHT OF UZ ABOVE SEAFLOOR
C   CDIR = DIRECTION OF AMBIENT CURRENT (DEGREES)
C   HT = WAVE HEIGHT (M)
C   PER = WAVE PERIOD (S)
C   WDIR = WAVE PROPAGATION DIRECTION (DEGREES)
C   GD = SEDIMENT GRAIN DIAMETER (M)
C   RHINP = INPUT RIPPLE HEIGHT (M)
C   RLINP = INPUT RIPPLE LENGTH (M)
C   FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C   RHOS = DENSITY OF SEDIMENT  (KG/M**3)
C   RHOW = DENSITY OF FLUID (WATER)  (KG/M**3)
C   IOPT1 = SEDIMENT TRANSPORT PREDICTOR OPTION NUMBER
C   IND = AN INDICATOR OF THE END OF THE FILE
C
C   IOPT1 = SEDIMENT TRANSPORT PREDICTOR OPTION NUMBER
C         1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION
C         2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION
C         3 - BAGNOLD (1963) TOTAL LOAD EQUATION
C         4 - YALIN (1963) BEDLOAD EQUATION
C         5 - COHESIVE SEDIMENT METHOD
C
C VARIABLES FOR COHESIVE SEDIMENT METHOD:
C
C   CONC0 = INITIAL ESTIMATE OF SEDIMENT CONCENTRATION (mg/l)
C   TAOCE = CRITICAL STRESS FOR EROSION (Pa)
C   TAOCD = CRITICAL STRESS FOR DEPOSITION (Pa)
C   WS = SETTLING VELOCITY (m/s)
C   PRS = PROBABILITY OF RESUSPENSION (NORMALLY ASSUMED = 0)
C   RKERO = PROPORTIONALITY COEFFICIENT FOR EROSION RATE (DEFAULT = 1.62)
C
C------------------------------------------
C BATCH DATA ENTRY
C------------------------------------------
 200  CONTINUE
      READ (3,*,ERR=200,END=1001)IRUN,D,UZ,Z,CDIR,HT,PER,WDIR,GD,RHINP,RLINP,BETA,FRACT,
      @RHOS,RHOW,IOPT1,CONC0,TAOCE,TAOCD,TIMEDR,WS
C ASSIGN DEFAULT VALUES TO PRS AND RKERO
```

```
      PRS=0
      RKERO=1.62

C--------------------------------------------
C CHECK THE GRAIN SIZE LIMITS FOR EACH THEORY
C--------------------------------------------
 999  CONTINUE
      GOTO(204,214,224,234,254)IOPT1
 204  IF (GD.LT.0.00015) THEN
         WRITE (7,205)
 205     FORMAT (//' ***WARNING*** - ENGELUND-HANSEN FORMULA NOT',
     @  ' RECOMMENDED'/T18,'FOR USE WITH SEDIMENTS SMALLER',
     @   ' THAN 0.15 MM')
      ENDIF
      GOTO 1000
 214  IF (GD.LT.0.0003 .OR. GD.GT..0286) THEN
         WRITE (7,215)
 215     FORMAT (//' ***WARNING*** - EINSTEIN-BROWN FORMULA IS BASED',
     @       ' ON LABORATORY'/T18,'EXPERIMENTS USING SEDIMENTS WITH',
     @       ' GRAIN SIZES'/T18,'OF 0.3 TO 28.6 MM')
      ENDIF
      GOTO 1000
 224  IF (GD.LT.0.00018 .OR. GD.GT.0.00045) THEN
         WRITE (7,225)
 225     FORMAT (//' ***WARNING*** - BAGNOLD FORMULA IS BASED',
     @  ' ON LABORATORY TESTS'/T18,'WITH GRAIN SIZES BETWEEN',
     @   ' 0.18 AND 0.45 MM')
      ENDIF
      GOTO 1000
 234  IF (GD.LT.0.0002) THEN
         WRITE (7,235)
 235     FORMAT (//' ***WARNING*** - YALIN FORMULA IS NOT RECOMMENDED',
     @  ' FOR USE'/T18,'WITH SEDIMENTS SMALLER THAN 0.2MM, BASED',
     @   ' ON'/T18,'THE RESULTS OF SENSITIVITY ANALYSES')
      ENDIF
      GOTO 1000
 254  IF (GD.GT.0.000016) THEN
         WRITE (7,255)
 255     FORMAT (//' ***WARNING*** - THE COHESIVE SEDIMENT METHOD IS',/,
     @  T17,'INTENDED FOR FINE SILT OR FINER SEDIMENTS')
      ENDIF
C
 1000 RETURN

 1001 CONTINUE
C END OF INPUT FILE, ASSIGN 1 TO IND
      IND = 1
C IND IS A TEMPORARY INDICATOR OF END OF FILE
      PRINT*,'ALL DONE, THANK YOU FOR USING SEDTRANS96.'
      STOP
      END
```

```
      SUBROUTINE INOUT(IRUN,D,UZ,CDIR,Z,HT,PER,WDIR,GD,RHINP,RLINP,RHOS,RHOW,FRACT,CONC0,
     @TAOCE,TAOCD,WS,TIMEDR,PRS,RKERO,IOPT1)
C
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C INOUT FOR IAFSED
C
C THIS SUBROUTINE PRINTS THE VALUES OF THE INPUT PARAMETERS FROM SUBROUTINE READIN TO
C BOTH THE MONITOR AND THE OUTPUT FILE
C
      IF (IRUN.EQ.1) THEN
            WRITE (*,5)
            WRITE (7,5)
  5   FORMAT(/,T11,'SED96:  A SEDIMENT TRANSPORT MODEL ',/,
     @      T11,'        FOR CONTINENTAL SHELF CONDITIONS',//,
     @      T11,'GEOLOGICAL SURVEY OF CANADA (ATLANTIC)',/,
     @      T11,'CREATED: SEPTEMBER, 1992',/
     @      T11,'LAST UPDATED: DECEMBER, 1996',//,
     @      T11,'THE USER SHOULD BE FAMILIAR WITH THE EQUATIONS USED',/,
     @      T11,'AND THEIR LIMITATIONS',//,
     @      T11,'ALL DIMENSIONAL VARIABLES ARE IN SI UNITS',/)
      ENDIF
C
C  IRUN = RUN OR CYCLE NUMBER
C  D = WATER DEPTH (M)
C  UZ = AMBIENT CURRENT AT HEIGHT Z ABOVE THE SEAFLOOR (M/S)
C  Z = HEIGHT OF UZ ABOVE SEAFLOOR
C  CDIR = DIRECTION OF AMBIENT CURRENT (DEGREES TRUE)
C  HT = WAVE HEIGHT (M)
C  PER = WAVE PERIOD (S)
C  WDIR = WAVE PROPAGATION DIRECTION (DEGREES TRUE)
C  GD = SEDIMENT GRAIN DIAMETER (M)
C  RHINP = INPUT RIPPLE HEIGHT (M)
C  RLINP = INPUT RIPPLE LENGTH (M)
C  RHOS = DENSITY OF SEDIMENT  (KG/M**3)
C  RHOW = DENSITY OF FLUID (WATER)  (KG/M**3)
C  FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C  IOPT1 = SEDIMENT TRANSPORT PREDICTOR OPTION NUMBER
C
C ******************************************************************
C VARIABLES USED FOR COHESIVE SEDIMENT TRANSPORT CALCULATIONS
C
C  CONC0 = INITIAL ESTIMATE OF SEDIMENT CONCENTRATION (mg/l)
C  CONC = CALCULATED SEDIMENT CONCENTRATION (mg/l)
C  TAOCE = CRITICAL STRESS FOR EROSION (Pa)
C  TAOCD = CRITICAL STRESS FOR DEPOSITION (Pa)
C  WS = SETTLING VELOCITY (m/s)
C  PRS = PROBABILITY OF RESUSPENSION (NORMALLY ASSUMED = 1.0)
C  RKERO = PROPORTIONALITY COEFFICIENT FOR EROSION RATE (DEFAULT = 1.62)
C ******************************************************************
C
      WRITE (*,15) IRUN
      WRITE (7,15) IRUN
 15   FORMAT(/,T21,'RUN NUMBER ',I9,/,T4,'INPUT DATA:',/)
C
      WRITE (*,25) D,UZ,CDIR,Z
```

```
      WRITE (7,25) D,UZ,CDIR,Z
 25   FORMAT(T11,'WATER DEPTH =',F7.2,' M',/,T11,'CURRENT SPEED =',F7.2,
     @' M/SEC',/,T11,'CURRENT DIRECTION =',F7.2,' DEGREES NORTH',/,
     @T11,'HEIGHT ABOVE BED =',F7.2,' M')
C
      WRITE (*,35) HT,PER,WDIR
      WRITE (7,35) HT,PER,WDIR
 35   FORMAT(T11,'WAVE HEIGHT =',F7.2,' M',/,T11,'WAVE PERIOD =',F6.2,
     @' SEC',/,T11,'WAVE DIRECTION =',F7.2,' DEGREES NORTH',/)
C
      WRITE (*,45) RHOW,RHOS,GD
      WRITE (7,45) RHOW,RHOS,GD
 45   FORMAT(T11,'FLUID DENSITY =',F7.1,' KG/M^3',/T11,
     @'SEDIMENT DENSITY =',F7.1,' KG/M^3',/T11,
     @'SEDIMENT GRAIN SIZE =',F9.6,' M')
C
      WRITE (*,55) FRACT,RHINP,RLINP
      WRITE (7,55) FRACT,RHINP,RLINP
 55   FORMAT(T11,'FRACTION OF SEABED MATERIAL = ',F4.2,/T11,
     @'RIPPLE HEIGHT =',F7.4,' M',/,T11,
     @'RIPPLE LENGTH =',F7.4,' M')
C
C ***************************************************************
C IF COHESIVE SEDIMENT METHOD IS USED, INPUT THE REQUIRED PARAMETERS
C ***************************************************************
      IF (IOPT1 .EQ. 5) THEN
         WRITE (*,65) CONC0,TAOCE,TAOCD,WS,TIMEDR,PRS,RKERO
         WRITE (7,65) CONC0,TAOCE,TAOCD,WS,TIMEDR,PRS,RKERO
 65      FORMAT(T11,'THE INITIAL ESTIMATE OF SEDIMENT CONCENTR. ='
     &  ,F7.2,' (mg/l)',/,T11,
     &  'THE CRITICAL STRESS FOR EROSION = ',F7.3,' (Pa)',/,T11,
     &  'THE CRITICAL STRESS FOR DEPOSITION  = ',F7.3,' (Pa)',/,T11,
     &  'THE SETTLING VELOCITY  = ',F7.5,' (m/s)',/,T11,
     &  'THE EROSION/DEPOSITION DURATION = ',F7.1,' (minutes)',/,T11,
     &  'THE PROBABILITY OF RESUSPENSION = ',F7.1,/,T11,
     &  'THE PROPORTIONALITY COEFFICIENT FOR EROSION RATE = ',F7.2)
      ENDIF
C *******************************************************************

      RETURN
      END
```

```
      SUBROUTINE OSCIL(HT,PER,D,UB,AB,WL,IBRK)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C
C THIS SUBROUTINE CALCULATES WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND DISPLACEMENT
C USING LINEAR WAVE THEORY.  A CHECK IS ALSO MADE FOR WAVE BREAKING.
C

C INPUT VARIABLES:
C        D = WATER DEPTH (M)
C        HT = WAVE HEIGHT (M)
C        PER = WAVE PERIOD (SEC)
C
C OUTPUT VARIABLES:
C        UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C        AB = EXCURSION AMPLITUDE OF BOTTOM WAVE ORBIT (M) (1/2 OF THE ORBITAL DIAMETER)
C        WL = WAVELENGTH FROM LWT DISPERSION EQUATION (M)
C
C INTERMEDIATE VARIABLES:
C        C = CONVERSION FACTOR TO CGS UNITS
C        G = ACCELERATION DUE TO GRAVITY (M/SEC**2)
C        HB = BREAKING WAVE HT. FOR GIVEN WAVE PERIOD, WATER DEPTH (M)
C        IBRK = WAVE BREAKING CRITERION
C        K = WAVE NUMBER (RAD/M)
C        KD = K*D
C        W = WAVE ANGULAR FREQUENCY (RAD/SEC)
C        WL0 = DEEP WATER WAVE LENGTH (M)

      G=9.81
      PI=2.*ASIN(1.)
      UB=0.0
      AB=0.0
      WL=0.0
C
C-------------------------------------------------------------------
C CHECK FOR CURRENT ONLY CASE INCLUDING 'DEEP WATER' WAVE CONDITIONS. FOR DEEP WATER
C WAVE CONDITIONS THE NORMAL CRITERION IS D/WL GREATER THAN 0.5. TO ENSURE NO APPRECIABLE
C WAVE INDUCED BOTTOM STRESS, THIS CODE USES THE CRITERION OF D/WL GREATER THAN 2.0
C
C IF THERE IS NO WAVE, GOTO 30 AND EXIT
      IF (PER .EQ. 0) GOTO 30
C OBTAIN DEEP-WATER WAVE LENGTH
      WL0 = G*PER*PER/(2*PI)
      IF ((D/WL0) .GT. 2.) THEN
        UB=0.0
        AB=0.0
        WL=0.0
        WRITE(*,10)
 10     FORMAT(/,T5,'DEEP WATER, NO WAVE EFFECT',/)
        RETURN
      ENDIF
C
C-------------------------------------------------------------------
C CALCULATE WAVELENGTH BY NEWTON-RAPHSON SOLUTION OF LWT DISPERSION EQUATION.
C
```

```
      W=2.*PI/PER
      RKD0=W**2*D/G
      RKD=RKD0
   20 CONTINUE
      DKD=(1./TANH(RKD)-RKD/RKD0)/(1./RKD0+1./SINH(RKD)**2)
      RKD=RKD+DKD
      IF (ABS(DKD) .GE. 1.0E-4) GO TO 20
      WL=WL0*TANH(RKD)
C
C-------------------------------------------------------------------
C NEXT CHECK FOR BREAKING WAVES USING THE MICHE (1944) CRITERION
C
      IBRK=0
      HB=0.142*WL*TANH(RKD)
      IF (HT .GE. HB) THEN
        WRITE (*,25)
        WRITE (7,25)
        IBRK=1
      ENDIF
   25 FORMAT(///,' ***WARNING***',/,' THIS CASE CORRESPONDS TO BREAKING',
     @' WAVE CONDITIONS WHERE',/,' LINEAR WAVE THEORY IS NOT VALID')
C-------------------------------------------------------------------
C CALCULATE WAVE-INDUCED BOTTOM PARTICLE VELOCITY AND ORBIT SIZE
      UB=PI*HT/(PER*SINH(RKD))
      AB=UB/W
C-------------------------------------------------------------------
C
   30 RETURN
      END
```

```
      SUBROUTINE THRESH(UB,GD,RHOS,RHOW,IOPT1,USTCRB,USTCRS,USTUP,FALL)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE CALCULATES THE THRESHOLD SHEAR VELOCITIES FOR BEDLOAD,
C SUSPENDED-LOAD, AND SHEET-FLOW SEDIMENT TRANSPORT MODES. THE CRITICAL STRESS FOR
C BEDLOAD TRANSPORT IS BASED ON THE YALIN METHOD MODIFIED FROM MILLER ET AL. (1977). THE
C CRITICAL STRESS FOR SUSPENDED LOAD IS BASED ON THE WORK OF BAGNOLD (1966), WHERE THE
C PARTICLE FALL VELOCITY IS AS GIVEN BY GIBBS ET AL. (1971). THE SHEET FLOW CRITICAL SHEAR
C STRESS IS ACCORDING TO KOMAR AND MILLER (1975) AND LI AND AMOS (IN REVIEW).
C

C INPUT VARIABLES:
C       UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C       GD = SEDIMENT GRAIN SIZE (M)
C       RHOS = SEDIMENT DENSITY (KG/M**3)
C       RHOW = FLUID DENSITY (KG/M**3)
C       IOPT1 = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA
C
C OUTPUT VARIABLES:
C       USTCRB = CRITICAL SHEAR VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/S)
C       USTCRS = CRITICAL SHEAR VELOCITY FOR INITIATION OF SUSPENDED LOAD TRANSPORT (M/S)
C       USTUP  = CRITICAL SHEAR VELOCITY FOR INITIATION OF UPPER PLANE BED SHEET FLOW (M/S)
C       FALL   = FALL VELOCITY OF SEDIMENT GRAINS AS GIVEN BY GIBBS ET AL. (1971) (M/SEC)
C
C INTERMEDIATE VARIABLES:
C       DRHO = SEDIMENT DENSITY - FLUID DENSITY (KG/M**3)
C       G = ACCELERATION DUE TO GRAVITY (M/SEC**2)
C       GYALIN = LOG OF THE YALIN PARAMETER
C       TCB = CRITICAL SHEAR STRESS FOR BEDLOAD TRANSPORT (NEWTONS/M**2)
C       TCS = CRITICAL SHEAR STRESS FOR SUSPENDED LOAD TRANSPORT (NEWTONS/M**2)
C       THETAUP = SHEET-FLOW SHIELDS PARAMETER
C       VISC = DYNAMIC VISCOSITY OF THE FLUID (KG/M*SEC (OR N.S/M**2))
C       VISK = KINEMATIC VISCOSITY OF FLUID (M**2/SEC)
C       YALIN = YALIN PARAMETER
C
C INITIALIZE CONSTANTS
      G= 9.81
      VISC=1.3D-3
      VISK=VISC/RHOW
      DRHO=RHOS-RHOW
      YALIN=0
      GYALIN=0
C
C          Dynamic Viscosity of Sea Water (SI units)
C  Temp.   S=Salinity
C  (C)       S=5      S=10      S=20      S=30      S=40
C   0     .00180   0.00182   0.00184   0.00189   0.00190
C   5    0.00153   0.00154   0.00157   0.00159   0.00162
C  10    0.00132   0.00133   0.00140   0.00138   0.00140
C  15    0.00115   0.00116   0.00118   0.00121   0.00123
C  20    0.00102   0.00103   0.00105   0.00107   0.00109
C  25    0.00090   0.00091   0.00093   0.00095   0.00097
C  30    0.00081   0.00082   0.00084   0.00086   0.00088
C           ** From Handbook of Marine Science
C
```

```
C-----------------------------------------------------------------
C CALCULATE THRESHOLD SHEAR VELOCITY FOR BEDLOAD TRANSPORT, USTCRB
C-----------------------------------------------------------------
C YALIN METHOD MODIFIED FROM MILLER ET AL. (1977).
C
      YALIN=SQRT((DRHO*G*GD**3)/(RHOW*VISK**2))
      GYALIN=ALOG10(YALIN)
      IF (YALIN .GE. 3000) THEN
         TCB=0.045*DRHO*G*GD
      ELSE IF (YALIN .LE. 100) THEN
         TCB=DRHO*G*GD*10.**((0.041*GYALIN**2)-0.356*GYALIN-0.977)
      ELSE
         TCB=DRHO*G*GD*10.**(0.132*GYALIN-1.804)
      ENDIF
C CONVERT SHEAR STRESS TCB TO SHEAR VELOCITY USTCRB
      USTCRB=SQRT(TCB/RHOW)

C-------------------------------------------------------------------------
C CALCULATE THRESHOLD SHEAR VELOCITY FOR SUSPENDED LOAD TRANSPORT, USTCRS
C-------------------------------------------------------------------------
C CALCULATE FALL VELOCITY FROM GIBBS ET AL. (1971)
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*
     &      (.00015476+0.099205*GD)))/(RHOW*(.00011607+0.074405*GD))
C CALCULATE USTCRS BASED ON BAGNOLD (1966)
      TCS=0.64*RHOW*FALL**2
      USTCRS=SQRT(TCS/RHOW)
C FOR USTCRB>USTCRS OF VERY FINE SAND, EQUAL USTCRB TO USTCRS
      IF (USTCRB .GT. USTCRS) USTCRB=USTCRS

C-------------------------------------------------------------------------
C CALCULATE THRESHOLD SHEAR VELOCITY FOR SHEET-FLOW TRANSPORT, USTUP
C-------------------------------------------------------------------------
C CALCULATE SHEET-FLOW SHIELDS PARAMETER ACCORDING TO LI AND AMOS (IN REVIEW)
      THETAUP=0.172*(100*GD)**(-0.376)
C CONVERT SHIELDS PARAMETER TO SHEAR VELOCITY
      USTUP=SQRT(THETAUP*((RHOS-RHOW)*G*GD)/RHOW)

      RETURN
      END
```

```
      SUBROUTINE FRICFAC(IRUN,UZ,Z,CDIR,UB,AB,PER,WDIR,GD,RHINP,RLINP,RHOW,RHOS,USTCRB,USTUP,
     &Z0,Z0C,FCW,UA,PHIB,U100,PHI100,USTCS,USTWS,USTCWS,USTCWSE,USTCWSB,USTC,USTW,USTCW,
     &DELTACW,RHEIGHT,RLENGTH,RPLCOEF)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES THE FRICTION FACTOR, SHEAR VELOCITIES AND RIPPLE DIMENSIONS
C FOR VARIOUS WAVE AND CURRENT CONDITIONS.

C FOR COMBINED FLOW, GRAIN-SIZE ROUGHNESS IS FIRST USED TO OBTAIN THE SKIN-FRICTION SHEAR
C VELOCITY WHICH IS USED TO CALCULATE THE BEDLOAD ROUGHNESS. THE COMBINED GRAIN AND
C BEDLOAD ROUGHNESS IS USED TO OBTAIN A TRANSPORT-RELATED SHEAR VELOCITY WHICH IS USED
C TO COMPUTE RIPPLE GEOMETRY AND DETERMINE IF TRANSPORT IS IN SHEET-FLOW MODE.

C INPUT VARIABLES:
C      UZ = CURRENT SPEED AT HEIGHT Z (M) ABOVE SEABED (M/SEC)
C      Z = HEIGHT ABOVE SEABED AT WHICH CURRENT IS MEASURED (M)
C      CDIR = CURRENT DIRECTION AT 1 M. ABOVE SEABED (AZIMUTH)
C      UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C      AB = EXCURSION AMPLITUDE OF BOTTOM WAVE ORBIT (M) (1/2 OF THE ORBITAL DIAMETER)
C      PER = WAVE PERIOD (SEC)
C      WDIR = WAVE PROPAGATION DIRECTION (AZIMUTH)
C      GD = SEDIMENT GRAIN SIZE (M)
C      RHINP = INPUT RIPPLE HEIGHT (M)
C      RLINP = INPUT RIPPLE LENGTH (M)
C      RHOW = DENSITY OF FLUID (WATER)  (KG/M**3)
C      RHOS = DENSITY OF SEDIMENT GRAIN  (KG/M**3)
C      USTCRB = CRITICAL SHEAR VELOCITY FOR BEDLOAD TRANSPORT (M/SEC)
C      USTUP = CRITICAL SHEAR VELOCITY FOR INITIATION OF UPPER PLANE BED SHEET FLOW (M/SEC)

C OUTPUT VARIABLES:
C      Z0 = BED ROUGHNESS LENGTH (M)
C      Z0C = APPARENT BED ROUGHNESS LENGTH (M)
C      FCW = BOTTOM FRICTION FACTOR
C      UA = CURRENT SPEED AT THE TOP OF THE WAVE-CURRENT BOUNDARY LAYER
C      PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE WAVE
C             BOUNDARY LAYER (RADIANS)
C      U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/SEC)
C      PHI100 = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS AT 1 M ABOVE SEABED (RADIANS)
C               NOTE:  PHI100 = PHIZ AS LONG AS PHIZ IS MEASURED
C               OUTSIDE THE WAVE BOUNDARY LAYER.
C      USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY (M/S)
C      USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY (M/S)
C      USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY (M/S)
C      USTCWSE = RIPPLE-ENHANCED COMBINED SHEAR VELOCITY (M/S)
C      USTCWSB = BEDLOAD-RELATED COMBINED SHEAR VELOCITY (M/S)
C      USTC = TOTAL CURRENT SHEAR VELOCITY (M/S)
C      USTW = TOTAL WAVE SHEAR VELOCITY (M/S)
C      USTCW = TOTAL COMBINED SHEAR VELOCITY (M/S)
C      DELTACW = HEIGHT OF THE WAVE-CURRENT BOUNDARY LAYER (M)
C      RHEIGHT = PREDICTED RIPPLE HEIGHT (M)
C      RLENGTH = PREDICTED RIPPLE LENGTH (M)
C      RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION

C INTERMEDIATE VARIABLES:
C      BKB = BEDLOAD ROUGHNESS HEIGHT
```

```
C       FBAD = TOTAL FRICTION FACTOR INCLUDING FORM DRAG
C       FCWB = TRANSPORT-RELATED FRICTION FACTOR
C       GKB = GRAIN ROUGHNESS HEIGHT
C       PHIBAD = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS, WITHIN
C               WAVE B.L. AND NEGLECTING FORM DRAG (RADIANS)
C       RATIO = UA/UB TO DETERMINE THE VALIDITY OF EQUATION OF MOTION USED BY GRANT AND
C                 MADSEN (1979)
C       RKB =  BED ROUGHNESS HEIGHT
C       RKBC = APPARENT BOTTOM ROUGHNESS (M)
C       SKB = SUM OF GRAIN AND BEDLOAD ROUGHNESS HEIGHT (M)
C       STEEP = RIPPLE STEEPNESS
C       TKB = TOTAL BOTTOM ROUGHNESS HEIGHT
C       UBAD = CURRENT SPEED NEGLECTING FORM DRAG (M/SEC)
C       USTCSB = BEDLOAD CURRENT SHEAR VELOCITY (M/S)
C       USTCWSBE = RIPPLE-ENHANCED BEDLOAD COMBINED SHEAR VELOCITY (M/S)
C       USTWSB = BEDLOAD WAVE SHEAR VELOCITY (M/S)

C INITIALIZE PARAMETERS
      VISC=1.3D-3
      VISK=VISC/RHOW
      PI=2.*ASIN(1.)
      FCW=0
      U100=0
      PHI100=0
      PHIB=0
      USTCS=0
      USTWS=0
      USTCWS=0
      USTC=0.0
      USTW=0.0
      USTCW=0.0
      USTCWSE=0
      USTCWSB=0
      Z0=0
      Z0C=0
      DELTACW=0
      RHEIGHT=0
      RLENGTH=0
      RPLCOEF=1

C********************
C PURE CURRENT CASE
C********************
      IF (UB .EQ. 0.0) THEN

C GET PRELIMINARY BED ROUGHNESS HEIGHT RKB ACCORDING TO GRANT AND MADSEN (1982). IF THERE
C IS NO MEASUREMENT OF RIPPLE HEIGHTS, RKB=2.5*GD, OTHERWISE USE THE MEASURED INPUT RIPPLE
C HEIGHT AND LENGTH TO OBTAIN RKB=27.7*RHINP*RHINP/RLINP:
        IF (RHINP .EQ. 0) THEN
          RKB=2.5*GD
        ELSE
          RKB=27.7*RHINP*RHINP/RLINP
        ENDIF

C CALL FRIC1 TO OBTAIN FCW AND THE PRELIMINARY ESTIMATES OF U100 AND USTC
        CALL FRIC1(UZ,Z,GD,RKB,FCW,UA,U100,USTC)
```

```
      PHIB=0.0
      PHI100=0.0
C COMPUTE PRELIMINARY SKIN-FRICTION CURRENT SHEAR VELOCITY
      USTCS=SQRT(0.5*FCW*U100**2)

C ASSIGN AN ARBITRARY VALUE TO THE USTCS CONVERGENCE CRITERION DELTA
      DELTA=1.0
 100  IF (DELTA .LT. 0.0001) GOTO 200

C PREDICT CURRENT RIPPLE DIMENSIONS:
C FOR NO-TRANSPORT CASE OR COARSE AND VERY-COARSE SANDS, BEDFORM DIMENSION WILL NOT BE
C PREDICTED AND INPUT VALUES WILL BE USED. FOR SHEET-FLOW, RIPPLE HEIGHT AND LENGTH WILL
C BE 0. OTHERWISE, RIPPLE HEIGHT AND LENGTH WILL BE PREDICTED ACCORDING TO YALIN (1964) AND
C ALLEN (1970), RESPECTIVELY.
      IF (USTCS .LT. USTCRB .OR. GD .GE. 0.0005) THEN
       RHEIGHT=RHINP
       RLENGTH=RLINP
      ELSE
       IF (USTCS .GE. USTUP) THEN
         RHEIGHT=0
         RLENGTH=0
       ELSE
         RLENGTH=1000*GD
         RHEIGHT=0.00074*(100*RLENGTH)**1.19
       ENDIF
      ENDIF
      IF (RHEIGHT .EQ. 0) THEN
       USTC=USTCS
       RKB=30*EXP(LOG(Z)-0.4*UZ/USTC)
      ELSE
       RKB=27.7*RHEIGHT*RHEIGHT/RLENGTH
      ENDIF
C CALL FRIC1 WITH NEW RKB TO OBTAIN NEW U100 AND USTC
      CALL FRIC1(UZ,Z,GD,RKB,FCW,UA,U100,USTC)
C ASSIGN THE INITIAL USTCS TO A TEMPORARY VARIABLE
      USTCSP=USTCS
C COMPUTE THE NEW SKIN-FRICTION CURRENT SHEAR VELOCITY
      USTCS=SQRT(0.5*FCW*U100**2)
C OBTAIN THE USTCS CONVERGENCE CRITERION DELTA
      DELTA=DABS(USTCSP/USTCS-1)
C GOTO 100 TO COMPARE THE DELTA VALUE WITH THE SET CRITERION VALUE
      GOTO 100

 200  CONTINUE
C GET FINAL BED ROUGHNESS Z0
      Z0=RKB/30
      RETURN
    ENDIF

C*************************
C WAVES AND CURRENT CASE
C*************************
    IF (UZ .NE. 0.0) THEN
C ASSIGN PHI100 TO PHIB
      PHI100=DMIN1(ABS(CDIR-WDIR),ABS(180.-ABS(CDIR-WDIR)),
   @ 360.-ABS(CDIR-WDIR))*ASIN(1.)/90.
```

```
      PHIB=PHI100
C COMPUTE SKIN-FRICTION FCW AND UST'S BASED ON GRAIN ROUGHNESS HEIGHT GKB
      GKB = 2.5*GD
      CALL FRIC2(IRUN,UZ,Z,PHI100,UB,PER,GKB,RKBC,FCW,UA,PHIB,U100,USTCS,USTWS,USTCWS,
     @DELTACW)
C COMPUTE INITIAL BED ROUGHNESS HEIGHTS BASED ON SKIN-FRICTION UST'S
      CALL ROUGH1(RHINP,RLINP,AB,UB,USTCS,USTWS,USTCWS,USTCRB,USTUP,GD,RHOW,RHOS,RHEIGHT,
     @RLENGTH,STEEP,BKB,SKB,TKB,USTCWSE,RPLCOEF)

C COMPUTE TRANSPORT-RELATED FCWB AND UST'S USING THE SUM OF GRAIN AND BEDLOAD
C ROUGHNESS HEIGHTS, SKB.
      CALL FRIC2(IRUN,UZ,Z,PHI100,UB,PER,SKB,RKBC,FCWB,UA,PHIB,U100,USTCSB,USTWSB,USTCWSB,
     @DELTACW)
C COMPUTE FINAL BED ROUGHNESS HEIGHTS BASED ON TRANSPORT-RELATED UST'S. USE PREDICTED
C RIPPLE GEOMETRY FROM ROUGH1 AS INPUTS IF THE RIPPLE-ENHANCED SHEAR VELOCITY U*CWSE IS
C LARGER THAN BEDLOAD THRESHOLD SHEAR VELOCITY U*CRB
      IF (USTCWSE .GE. USTCRB) THEN
        RHINP=RHEIGHT
        RLINP=RLENGTH
      ENDIF
      CALL ROUGH2(RHINP,RLINP,SKB,UB,USTCSB,USTWSB,USTCWSB,USTCRB,USTUP,GD,RHOW,RHOS,
     @RHEIGHT,RLENGTH,STEEP,TKB,USTCWSBE,RPLCOEF)
C COMPUTE TOTAL FCW (FBAD) AND UST'S BASED ON TOTAL ROUGHNESS HEIGHT TKB.
      CALL FRIC2(IRUN,UZ,Z,PHI100,UB,PER,TKB,RKBC,FBAD,UA,PHIB,U100,USTC,USTW,USTCW,DELTACW)
C OBTAIN BED ROUGHNESS Z0, APPARENT BED ROUGHNESS Z0C AND FINAL USTCWSE
      Z0=TKB/30
      Z0C=RKBC
      USTCWSE=RPLCOEF*USTCWS
C CHECK RATIO OF UA/UB
      RATIO=UA/UB
      IF (RATIO.GT.1.) WRITE (*,15) IRUN
      IF (RATIO.GT.1.) WRITE (7,15) IRUN
 15   FORMAT(//,' ***WARNING*** ',/,' FOR BT#',I3,' UA/UB>1.0',2X,
     @ ' GRANT AND MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
C
      RETURN
    ENDIF

C******************
C PURE WAVES CASE
C******************
C CALL FRIC3 AND USE GRAIN SIZE TO COMPUTE SKIN-FRICTION FWS AND U*WS
    CALL FRIC3(AB,GD,FCWS)
    UA=0.0
    U100=0.0
    PHIB=0.0
    PHI100=0.0
    W=2.*PI/PER
    USTWS=SQRT(0.5*FCWS*UB**2)
C PREDICT WAVE RIPPLE DIMENSIONS
C FOR NO-TRANSPORT CASE OR COARSE AND VERY-COARSE SANDS, BEDFORM DIMENSION WILL NOT BE
C PREDICTED AND INPUT VALUES WILL BE USED
    IF (USTWS .LT. USTCRB .OR. GD .GE. 0.0005) THEN
      RHEIGHT=RHINP
      RLENGTH=RLINP
    ELSE
```

```
C FOR FINE OR MEDIUM SAND IN ACTIVE TRANSPORT, RIPPLES ARE PREDICTED ACCORDING TO BOYD ET
C AL. (1988) AND ALLEN (1970)
        IF (USTWS .GE. USTUP) THEN
          RHEIGHT=0
          RLENGTH=0
        ELSE
          RLENGTH=AB*557*(UB*AB/VISK)**(-0.68)
          RHEIGHT=0.00074*(100*RLENGTH)**1.19
        ENDIF
      ENDIF
C OBTAIN NEW BED ROUGHNESS HEIGHT RKB
      IF (RLENGTH .EQ. 0) THEN
        RKB=2.5*GD
      ELSE
        RKB=27.7*RHEIGHT*RHEIGHT/RLENGTH
      ENDIF
C CALL FRIC3 USING NEW ROUGHNESS HEIGHT TO COMPUTE THE TOTAL FW AND U*W
      CALL FRIC3(AB,RKB,FCW)
      USTW=SQRT(0.5*FCW*UB**2)
      DELTACW=2.*0.4*USTW/W
      Z0=RKB/30
C END OF THE FRICFAC SUBROUTINE
      RETURN
      END

C***************************************************************************
      SUBROUTINE FRIC1(UZ,Z,GD,RKB,FCW,UA,U100,USTC)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE. A
C CONSTANT FRICTION FACTOR IS ASSUMED, BASED ON THE WORK OF STERNBERG (1971) AND
C SOULSBY (1983).
C
C INPUT VARIABLES:
C        UZ = CURRENT SPEED AT HEIGHT Z (M) ABOVE SEABED (M/SEC)
C        GD = SEDIMENT GRAIN SIZE (M)
C        RKB = BOTTOM ROUGHNESS (M)
C
C OUTPUT VARIABLES:
C        U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/SEC)
C        FCW = BOTTOM FRICTION FACTOR FOR THE PURE CURRENT CASE
C        UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (M/SEC)
C
      FCW=6.0E-3
      IF(RKB .EQ. 0.0) RKB=2.5*GD
      USTC=0.4*UZ/LOG(30*Z/RKB)
      U100=(USTC/0.4)*LOG(1*30/RKB)
      UA=U100
      RETURN
      END

C***************************************************************************
      SUBROUTINE FRIC2(IRUN,UZ,Z,PHI100,UB,PER,RKB,RKBC,FCW,UA,PHIB,U100,USTC,USTW,USTCW,
     @DELTACW)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
```

```
C THIS SUBROUTINE CALCULATES THE FRICTION FACTOR FOR COMBINED WAVE AND CURRENT
C CONDITIONS USING THE METHOD OF GRANT AND MADSEN (1986). THIS METHOD IS NOT VALID FOR
C CURRENT-DOMINANT CONDITIONS, APPROXIMATELY UA/UB > 1.0.
C

C INPUT VARIABLES:
C       UZ = CURRENT SPEED AT HEIGHT Z (M) ABOVE SEABED (M/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 (M/SEC)
C       PER = WAVE PERIOD (SEC)
C       RKB = BOTTOM ROUGHNESS HEIGHT (M)
C
C OUTPUT VARIABLES:
C       FCW = BOTTOM FRICTION FACTOR FOR THE COMBINED CASE
C       UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (M/SEC)
C       U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/SEC)
C       PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C              WAVE BOUNDARY LAYER (RADIANS)
C       RKBC = APPARENT BOTTOM ROUGHNESS (M)
C       USTC = CURRENT SHEAR VELOCITY OF GM (M/SEC)
C       USTW = WAVE SHEAR VELOCITY OF GM (M/SEC)
C       USTCW = COMBINED SHEAR VELOCITY OF GM (M/SEC)
C       DELTACW = HEIGHT OF THE WAVE-CURRENT BOUNDARY LAYER (M)
C
C INTERMEDIATE VARIABLES:
C       Z0 = DYNAMIC BOTTOM ROUGHNESS LENGTH
C       CR = FACTOR DESCRIBING RELATIVE RATIO OF USTC/USTW
C       DELTA = ITERATION CRITERION FOR UST CALCULATION
C
C INITIALIZE ITERATION PARAMETERS
C
    PI=2.*ASIN(1.)
    W=2.*PI/PER
    PHIB=PHI100
    DELTA=1.0
    CR=1.0
    FCW=0.01

C CALCULATE UST'S BY ITERATION (GM,1986)
 10 IF (DELTA .LT. 0.00001) GO TO 200
    Z0=RKB/30.
    TEMP=CR*UB/(Z0*W)
C INITIALIZE THE ITERATION CRITERION EPSILON
    EPSILON=1.0
 50 IF (EPSILON .LT. 0.00001) GO TO 100
C CALCULATE FCW ACCORDING TO GM (1986). NEWTON-RAPHSON SOLUTION IS USED IN ITERATION.
    X=4*SQRT(FCW)
    A=0.24*X-1.65+DLOG10(TEMP*X)-1/X
    B=0.24+1/X**2+1/(X*DLOG(10.))
    DX=A/B
    XNEW=X-DX
    FCWNEW=(XNEW/4)**2
    EPSILON=DABS(FCWNEW/FCW-1)
    FCW=FCWNEW
    GO TO 50
```

```
 100 CONTINUE
C CALCULATE USTW, USTCW AND DELTACW (BOUNDARY LAYER THICKNESS)
      USTW=SQRT(0.5*CR*FCW*UB**2)
      USTCW=SQRT(CR)*USTW
      DELTACW=2.*0.4*USTCW/W
C CALCULATE CURRENT SHEAR VELOCITY USTC
C     FOR DELTACW<=Z0, NO WAVE EFFECT AND PURE CURRENT ASSUMED
      IF (DELTACW .LE. Z0) THEN
        FCW=6.0E-3
        U100=UZ*LOG(30.0/RKB)/LOG(30.*Z/RKB)
        UA=U100
        PHIB=0.0
        USTC=SQRT(0.5*FCW*U100**2)
        USTCW=USTC
        USTW=0
C GET FINAL BED ROUGHNESS AND BED ROUGHNESS HEIGHT USING LOG LAW
        Z0=EXP(LOG(Z)-UZ*0.4/USTC)
        RKB=30*Z0
        RKBC=RKB
        RETURN
      ENDIF
      AA=DLOG(DELTACW/Z0)/USTCW
      BB=DLOG(Z/DELTACW)
      CC=-0.4*UZ
      DD=SQRT(BB**2-4*AA*CC)
      USTC=0.5*(-BB+DD)/AA
      RKBC=DELTACW*EXP(-AA*USTC)
      CRNEW=SQRT(1.0+2*(USTC/USTW)**2*COS(PHIB)
     @          +(USTC/USTW)**4)
      DELTA=DABS(CRNEW/CR-1)
      CR=CRNEW
      GO TO 10

 200 CONTINUE
C CALCULATE VELOCITY AT THE TOP OF THE WAVE-CURRENT BOUNDARY LAYER
      UA=(USTC/0.4)*DLOG(DELTACW/RKBC)
      IF (DELTACW .GT. Z) THEN
        WRITE (*,55) IRUN
        WRITE (7,55) IRUN
 55     FORMAT(///,' ***WARNING***',/,' FOR BT#',I3,' DELTACW>Z',2X,
     @ ' GRANT AND MADSEN (1979) METHOD MAY NOT BE APPROPRIATE')
      ENDIF
C CALCULATE VELOCITY AT 1M ABOVE THE BOTTOM
      IF (DELTACW .GT. 1.) THEN
        U100=(USTC/USTCW)*(USTC/0.4)*DLOG(1./Z0)
      ELSE
        U100=(USTC/0.4)*DLOG(1./RKBC)
      ENDIF
      RETURN
      END

C***********************************************************************
      SUBROUTINE FRIC3(AB,RKB,FCW)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE CALCULATES THE BOTTOM FRICTION FACTOR FOR THE PURE WAVE CONDITION
```

```
C USING THE METHOD OF JONSSON (1966) AS MODIFIED BY NIELSEN (1979).  THE BOTTOM ROUGHNESS IS
C TAKEN AS THE GRAIN DIAMETER AS IN GRANT AND MADSEN (1976).
C
C INPUT VARIABLES:
C        AB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE DISPLACEMENT (M)
C        RKB = BED ROUGHNESS HEIGHT (M)
C
C OUTPUT VARIABLES:
C        FCW = BOTTOM FRICTION FACTOR FOR THE PURE WAVE CASE
C
      FCW=DMIN1(EXP(5.213*(RKB/AB)**0.194-5.977),0.28D0)
      RETURN
      END

C************************************************************************
      SUBROUTINE ROUGH1(RHINP,RLINP,AB,UB,USTCS,USTWS,USTCWS,USTCRB,USTUP,GD,RHOW,RHOS,
     @RHEIGHT,RLENGTH,STEEP,BKB,SKB,TKB,USTCWSE,RPLCOEF)
      IMPLICIT DOUBLE PRECISION(A-H,K,O-Z)
C
C THIS SUBROUTINE USES SKIN-FRICTION SHEAR VELOCITIES TO CALCULATE THE INITIAL RIPPLE
C GEOMETRY AND VARIOUS ROUGHNESS HEIGHTS BASED ON THE GM86 COMBINED-FLOW BBL MODEL
C AND THE LATEST SIB DATA
C
C INPUT VARIABLES
C     RHINP = INITIAL RIPPLE HEIGHT (M)
C     RLINP = INITIAL RIPPLE LENGTH (M)
C     AB = EXCURSION LENGTH OF BOTTOM WAVE ORBIT (M) (1/2 OF THE ORBITAL DIAMETER)
C     UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C     USTCS = GM CURRENT SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTWS = GM WAVE SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCWS = GM COMBINED SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCRB = CRITICAL SHEAR VELOCITY FOR THE INITIATION OF BEDLOAD TRANSPORT
C     USTUP = CRITICAL SHEAR VELOCITY FOR UPPER PLANE BED
C     GD = SEDIMENT GRAIN SIZE
C     RHOW = FLUID DENSITY; RHOS=SEDIMENT GRAIN DENSITY
C     RHOS = SEDIMENT DENSITY;
C
C OUTPUT VARIABLES
C     RHEIGHT = PREDICTED RIPPLE HEIGHT
C     RLENGTH = PREDICTED RIPPLE LENGTH
C     STEEP = PREDICTED RIPPLE STEEPNESS
C     BKB = PREDICTED BEDLOAD ROUGHNESS HEIGHT
C     SKB = PREDICTED GRAIN + BEDLOAD ROUGHNESS HEIGHT
C     TKB = PREDICTED TOTAL BOTTOM ROUGHNESS HEIGHT
C     USTCWSE = EFFECTIVE SHEAR VELOCITY AT THE RIPPLE CREST
C     RPLCOEF = UST CONVERSION COEFFICIENT
C
C INTERMEDIATE VARIABLES
C     G = GRAVITY ACCELERATION
C     SST = DIMENSIONLESS SEDIMENT GRAIN SIZE PARAMETER
C     PSICR = CRITICAL SHIELDS PARAMETER FOR BEDLOAD TRANSPORT
C     PSIBF = GM82 CRITICAL SHIELDS PARAMETER FOR RIPPLE BREAK-OFF
C     USTBF = CRITICAL SHEAR VELOCITY FOR RIPPLE BREAK-OFF
C     PSIUP = CRITICAL SHIELDS PARAMETER FOR UPPER PLANE BED
C     MOBIL = WAVE MOBILITY NUMBER OF NIELSEN
C     PSIWS = WAVE SHIELDS PARAMETER
```

```
C    HTM = BEDLOAD LAYER HEIGHT
C    GKB = GRAIN ROUGHNESS HEIGHT (=2.5*GD)
C

C INITIALIZING PARAMETERS
      G=9.81
      VISC=1.3D-3
      VISK=VISC/RHOW
      S=RHOS/RHOW
      SST=GD*((S-1)*G*GD)**0.5/(4*VISK)
      PSICR=(USTCRB**2)/((S-1)*G*GD)
      PSIBF=1.8*(SST**0.6)*PSICR
      USTBF=(PSIBF*(S-1)*G*GD)**0.5

C COMPUTE THE INITIAL RIPPLE CONVERSION COEFFICIENT RPLCOEF. IT IS EQUAL TO 1 FOR FLAT BED,
C OTHERWISE IS CALCULATED ACCORDING TO NIELSEN (1992)
      IF (RHINP .EQ. 0 .OR. USTCWS .GE. USTUP) THEN
         RPLCOEF=1
      ELSE
         RPLCOEF=1/(1-3.14*RHINP/RLINP)
      ENDIF
C COMPUTE EFFECTIVE SHEAR VELOCITY AT THE RIPPLE CREST
      USTCWSE=USTCWS*RPLCOEF

C-----------------------------------------------------------------
C FOR COARSE AND VERY-COARSE SANDS, BEDFORM GEOMETRY CANNOT BE PREDICTED YET AND THE
C INITIAL RIPPLE HEIGHT AND LENGTH WILL BE USED
      IF (GD .GE. 0.0005) THEN
         RHEIGHT=RHINP
         RLENGTH=RLINP
         IF (RLENGTH .EQ. 0) STEEP = 0
         IF (RLENGTH .GT. 0) STEEP=RHEIGHT/RLENGTH
         GO TO 33
      ENDIF

C---------------------------------------------------------------------
C FOR NO TRANSPORT CASE, USE THE INITIAL RIPPLE HEIGHT AND LENGTH
      IF (USTCWSE .LT. USTCRB) THEN
         RHEIGHT=RHINP
         RLENGTH=RLINP
         IF (RLENGTH .EQ. 0) STEEP = 0
         IF (RLENGTH .GT. 0) STEEP=RHEIGHT/RLENGTH
         GO TO 33
      ENDIF

C-----------------------------------------------------------------
C COMPUTE RIPPLES FOR ACTIVE TRANSPORT CASE

C RIPPLES IN THE WEAK-TRANSPORT RANGE
      IF (USTCWSE .GE. USTCRB .AND. USTCWS .LT. USTCRB) THEN
         STEEP=0.11
         RHEIGHT=GD*(19.59*(USTCWS/USTCRB)+20.92)
         RLENGTH=RHEIGHT/STEEP
      ENDIF

C RIPPLES IN THE EQUILIBRIUM RANGE
```

```
      IF(USTCWS .GE. USTCRB .AND. USTCWS .LT. USTBF) THEN
C COMPUTE WAVE-DOMINANT RIPPLES FOR U*WS/U*CS>=1.25
         IF (USTWS/USTCS .GE. 1.25) THEN
            STEEP=0.15
            RHEIGHT=GD*(9.86*(USTCWS/USTCRB)+37.91)
            RLENGTH=RHEIGHT/STEEP
         ELSE
C COMPUTE COMBINED WAVE-CURRENT OR CURRENT-DOMINANT RIPPLES
            STEEP=0.12
            RHEIGHT=GD*(22.15*(USTCWS/USTCRB)+6.38)
            RLENGTH=RHEIGHT/STEEP
         ENDIF
      ENDIF

C RIPPLES IN THE BREAK-OFF RANGE
C COMPUTE BREAK-OFF RIPPLES USING SIB METHOD
      IF (USTCWS .GE. USTBF .AND. USTCWS .LT. USTUP) THEN
         RLENGTH = 530*GD
         STEEP=(0.15/(1-USTBF/USTUP))*(1-USTCWS/USTUP)
         RHEIGHT = RLENGTH*STEEP
      ENDIF

C NO RIPPLES UNDER SHEET FLOW CONDITIONS
      IF (USTCWS .GE. USTUP) THEN
         RHEIGHT=0
         RLENGTH=0
         STEEP=0
      ENDIF

 33   CONTINUE
C COMPUTE THE TRUE RIPPLE CONVERSION COEFFICIENT RPLCOEF
      IF (RHEIGHT .EQ. 0 .OR. RLENGTH .EQ. 0) THEN
         RPLCOEF=1
      ELSE
         RPLCOEF=1/(1-3.14*RHEIGHT/RLENGTH)
      ENDIF

C CALCULATE BEDLOAD LAYER HEIGHT HTM USING THE NIELSEN (1992) METHOD MODIFIED BASED ON
C THE SIB DATA OF LI ET AL. (IN REVIEW)
      IF (USTCWS .GE. USTCRB) THEN
         HTM=2.9*GD*((USTCWS**2)/((S-1)*G*GD)-PSICR)**0.75
      ELSE
         HTM=0
      ENDIF

C COMPUTE VARIOUS ROUGHNESS HEIGHTS: RKB, RIPPLE ROUGHNESS HEIGHT; BKB, BEDLOAD
C ROUGHNESS HEIGHT; GKB, GRAIN ROUGHNESS HEIGHT; SKB, THE SUM OF GKB AND BKB; AND TKB,
C TOTAL BED ROUGHNESS HEIGHT.
      RKB=27.7*RHEIGHT*STEEP
      BKB=180*HTM
      SKB=2.5*GD+BKB
      TKB=RKB+SKB
C
      RETURN
      END
```

```
C**********************************************************************
      SUBROUTINE ROUGH2(RHINP,RLINP,SKB,UB,USTCS,USTWS,USTCWS,USTCRB,USTUP,GD,RHOW,RHOS,
     @RHEIGHT,RLENGTH,STEEP,TKB,USTCWSE,RPLCOEF)
      IMPLICIT DOUBLE PRECISION(A-H,K,O-Z)
C
C THIS SUBROUTINE CALCULATES THE FINAL RIPPLE GEOMETRY AND VARIOUS ROUGHNESS HEIGHTS
C BASED ON THE LATEST SIB RESULTS AND COMBINED FLOW BBL MODELS
C
C INPUT VARIABLES
C     RHINP =INITIAL RIPPLE HEIGHT (M)
C     RLINP =INITIAL RIPPLE LENGTH (M)
C     SKB = THE SUM OF GRAIN AND BEDLOAD ROUGHNESS HEIGHTS (M)
C     UB = MAXIMUM WAVE INDUCED ORBITAL VELOCITY AT THE BOTTOM (M/S)
C     USTCS = GM CURRENT SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTWS = GM WAVE SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCWS = GM COMBINED SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCRB = CRITICAL SHEAR VELOCITY FOR THE INITIATION OF BEDLOAD TRANSPORT
C     USTUP = CRITICAL SHEAR VELOCITY FOR UPPER PLANE BED
C     GD = SEDIMENT GRAIN SIZE
C     RHOW = FLUID DENSITY
C     RHOS = SEDIMENT DENSITY
C
C OUTPUT VARIABLES
C     RHEIGHT = PREDICTED RIPPLE HEIGHT
C     RLENGTH = PREDICTED RIPPLE LENGTH
C     STEEP = PREDICTED RIPPLE STEEPNESS
C     TKB = PREDICTED TOTAL BOTTOM ROUGHNESS HEIGHT
C     USTCWSE = EFFECTIVE SHEAR VELOCITY AT THE RIPPLE CREST
C     RPLCOEF = UST CONVERSION COEFFICIENT
C
C INTERMEDIATE VARIABLES
C     G = GRAVITY ACCELERATION
C     SST = DIMENSIONLESS SEDIMENT GRAIN SIZE PARAMETER
C     PSICR = CRITICAL SHIELDS PARAMETER FOR BEDLOAD TRANSPORT
C     PSIBF = GM82 CRITICAL SHIELDS PARAMETER FOR RIPPLE BREAK-OFF
C     USTBF = CRITICAL SHEAR VELOCITY FOR RIPPLE BREAK-OFF
C     PSIUP = CRITICAL SHIELDS PARAMETER FOR UPPER PLANE BED
C     MOBIL = WAVE MOBILITY NUMBER OF NIELSEN
C     PSIWS = WAVE SHIELDS PARAMETER
C     GKB = GRAIN ROUGHNESS HEIGHT (=2.5*GD)
C

C INITIALIZING PARAMETERS
      G=9.81
      VISC=1.3D-3
      VISK=VISC/RHOW
      S=RHOS/RHOW
      SST=GD*((S-1)*G*GD)**0.5/(4*VISK)
      PSICR=(USTCRB**2)/((S-1)*G*GD)
      PSIBF=1.8*(SST**0.6)*PSICR
      USTBF=(PSIBF*(S-1)*G*GD)**0.5

C----------------------------------------------------------------
C FOR COARSE AND VERY-COARSE SANDS, BEDFORM GEOMETRY CANNOT BE PREDICTED YET AND THE
C INITIAL RIPPLE HEIGHT AND LENGTH WILL BE USED
      IF (GD .GE. 0.005) THEN
```

```
      RHEIGHT=RHINP
      RLENGTH=RLINP
      IF (RLENGTH .EQ. 0) STEEP = 0
      IF (RLENGTH .GT. 0) STEEP=RHEIGHT/RLENGTH
      GO TO 33
   ENDIF

C------------------------------------------------------------------
C COMPUTE THE INITIAL RIPPLE CONVERSION COEFFICIENT RPLCOEF. IT IS EQUAL TO 1 FOR FLAT BED,
C OTHERWISE IS CALCULATED ACCORDING TO NIELSEN (1992)
   IF (RHINP .EQ. 0 .OR. USTCWS .GE. USTUP) THEN
      RPLCOEF=1
   ELSE
      RPLCOEF=1/(1-3.14*RHINP/RLINP)
   ENDIF

C COMPUTE EFFECTIVE SHEAR VELOCITY AT THE RIPPLE CREST
   USTCWSE=USTCWS*RPLCOEF

C------------------------------------------------------------------------
C FOR NO TRANSPORT CASE, USE THE INITIAL RIPPLE HEIGHT AND LENGTH
   IF(USTCWSE .LT. USTCRB) THEN
      RHEIGHT=RHINP
      RLENGTH=RLINP
      IF (RLENGTH .EQ. 0) STEEP = 0
      IF (RLENGTH .GT. 0) STEEP=RHEIGHT/RLENGTH
      GO TO 33
   ENDIF

C------------------------------------------------------------------
C COMPUTE RIPPLES FOR ACTIVE TRANSPORT CASE

C COMPUTE RIPPLES IN THE WEAK TRANSPORT RANGE BASED ON THE SIB METHOD
   IF (USTCWSE .GE. USTCRB .AND. USTCWS .LT. USTCRB) THEN
      STEEP=0.11
      RHEIGHT=GD*(19.59*(USTCWS/USTCRB)+20.92)
      RLENGTH=RHEIGHT/STEEP
   ENDIF

C COMPUTE RIPPLES IN THE EQUILIBRIUM RANGE BASED ON THE SIB METHOD
   IF (USTCWS .GE. USTCRB .AND. USTCWS .LT. USTBF) THEN
C COMPUTE WAVE-DOMINANT RIPPLES FOR U*WS/U*CS>=1.25
      IF (USTWS/USTCS .GE. 1.25) THEN
         STEEP=0.15
         RHEIGHT=GD*(9.86*(USTCWS/USTCRB)+37.91)
         RLENGTH=RHEIGHT/STEEP
      ELSE
C COMPUTE WAVE-CURRENT OR CURRENT-DOMINANT RIPPLES
         STEEP=0.12
         RHEIGHT=GD*(22.15*(USTCWS/USTCRB)+6.38)
         RLENGTH=RHEIGHT/STEEP
      ENDIF
   ENDIF

C COMPUTE RIPPLES IN THE BREAK-OFF RANGE BASED ON THE SIB METHOD
   IF (USTCWS .GE. USTBF .AND. USTCWS .LT. USTUP) THEN
```

```
        RLENGTH = 530*GD
        STEEP=(0.15/(1-USTBF/USTUP))*(1-USTCWS/USTUP)
        RHEIGHT = RLENGTH*STEEP
      ENDIF

C NO RIPPLES UNDER SHEET FLOW CONDITIONS
      IF (USTCWS .GE. USTUP) THEN
         RHEIGHT=0
         RLENGTH=0
         STEEP=0
      ENDIF

 33   CONTINUE
C COMPUTE THE FINAL RIPPLE CONVERSION COEFFICIENT RPLCOEF
      IF (RHEIGHT .EQ. 0 ) THEN
         RPLCOEF=1
      ELSE
         RPLCOEF=1/(1-3.14*RHEIGHT/RLENGTH)
      ENDIF

C COMPUTE THE FINAL RIPPLE AND TOTAL ROUGHNESS HEIGHTS; GRAIN-BEDLOAD ROUGHNESS HEIGHT
C SKB IS FROM ROUGH1 BASED ON THE SKIN-FRICTION UST'S
      RKB=27.7*RHEIGHT*STEEP
      TKB=RKB+SKB
C
      RETURN
      END
```

```
      SUBROUTINE TIMING(RPLCOEF,RHOW,UA,PHIB,UB,PER,U100,USTCRB,USTCRS,USTCS,USTWS,USTCWS,
     @USTCWSB,TB1,TB2,TS1,TS2,PERBED,PERSUSP,USTCWSM)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE USES EFFECTIVE SHEAR STRESSES AT RIPPLE CREST TO CALCULATE THE DURATION
C OF SEDIMENT TRANSPORT PHASES (NO TRANSPORT, BEDLOAD TRANSPORT, SUSPENDED LOAD
C TRANSPORT) BY CALCULATING WHEN THE RESPECTIVE CRITICAL SHEAR STRESSES ARE EXCEEDED.
C

C INPUT VARIABLES:
C     PER = WAVE PERIOD (SEC)
C     PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C            WAVE BOUNDARY LAYER (RADIANS)
C     RHOW = DENSITY OF FLUID  (KG/M**3)
C     RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION
C     U100 = CURRENT VELOCITY AT 1 M ABOVE THE BED (M/S)
C     UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC. (M/SEC)
C     UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (M/SEC)
C     USTCRB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/SEC)
C     USTCRS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED LOAD TRANSPORT (M/SEC)
C     USTCS = CURRENT SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTWS = WAVE SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCWS = COMBINED SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCWSB = BEDLOAD COMBINED SHEAR VELOCITY (M/S)
C
C  OUTPUT VARIABLES:
C     PERBED = PERCENTAGE OF TIME SPENT IN ONLY BEDLOAD TRANSPORT PHASE.
C     PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT PHASE.
C     TS1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH SUSPENDED LOAD TRANSPORT CEASES (S)
C     TB1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT CEASES (SEC)
C     TS2 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH SUSPENDED LOAD TRANSPORT
              RECOMMENCES (S)
C     TB2 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT RECOMMENCES (S)
C     USTCWSM = MAXIMIZED COMBINED SHEAR VELOCITY (M/S)
C
C  INTERMEDIATE VARIABLES:
C     USTCSE = RIPPLE-ENHANCED CURRENT SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTCWSE = RIPPLE-ENHANCED COMBINED SKIN-FRICTION SHEAR VELOCITY (M/S)
C     USTWSE = RIPPLE-ENHANCED WAVE SKIN-FRICTION SHEAR VELOCITY (M/S)
C     XS1 = B+SQRT(B24ACS) USED IN SUSPENDED TIME CALCULATION UNDER CREST
C     XB1 = B+SQRT(B24ACB) USED IN BEDLOAD TIME CALCULATION UNDER CREST
C     XS2 = B-SQRT(B24ACS) USED IN SUSPENDED TIME CALCULATION UNDER TROUGH
C     XB2 = B-SQRT(B24ACB) USED IN BEDLOAD TIME CALCULATION UNDER TROUGH
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
C
      PI=2.*ASIN(1.)
      USTCWSM=0
      TS1=0.0
      TB1=0.0
      TS2=0.0
      TB2=0.0
      PERSUSP=0.0
```

```
      PERBED=0.0

C*****************************
C PURE CURRENT CASE
C*****************************
      IF (UB .EQ. 0.0) THEN
        IF (USTCS .GE. USTCRS) PERSUSP=100
        IF (USTCS .GE. USTCRB .AND. USTCS .LT. USTCRS) PERBED=100
        RETURN
      ENDIF

C*****************************
C WAVE PRESENT CASE
C*****************************
C COMPUTE RIPPLE-ENHANCED SKIN-FRICTION CURRENT SHEAR VELOCITY
      USTCSE=USTCS*RPLCOEF
C COMPUTE RIPPLE-ENHANCED SKIN-FRICTION WAVE SHEAR VELOCITY
      IF (UB .NE. 0.0) USTWSE=USTWS*RPLCOEF
C COMPUTE THE RIPPLE-ENHANCED SKIN-FRICTION COMBINED SHEAR VELOCITY
      USTCWSE=USTCWS*RPLCOEF
C ASSIGN RIPPLE-ENHANCED COMBINED SHEAR VELOCITY TO THE MAXIMUM SHEAR VELOCITY
      USTCWSM=USTCWSE
C COVERT RIPPLE-ENHANCED SHEAR VELOCITIES TO SHEAR STRESSES
      TAOCS=RHOW*USTCSE**2
      TAOWS=RHOW*USTWSE**2
      TAOCRB=RHOW*USTCRB**2
      TAOCRS=RHOW*USTCRS**2

C--------------------------------
C FOR WAVE-ONLY CONDITION
C--------------------------------
      IF (UA .EQ. 0.0) THEN
C CHECK IF SAND SUSPENSION OCCURS
        IF (USTCRS .LT. USTWSE) THEN
          TS1=PER/(2.*PI)*ACOS(TAOCRS/TAOWS)
          TS2=PER/2.-TS1
          PERSUSP=400.*TS1/PER
        ENDIF
C CHECK IF ONLY BEDLOAD TRANSPORT OCCURS AT TIMES
        IF (USTCRB .LT. USTCRS .AND. USTCRB .LT. USTWSE) THEN
          TB1=PER/(2.*PI)*ACOS(TAOCRB/TAOWS)
          TB2=PER/2.-TB1
          PERBED=400.*(TB1-TS1)/PER
        ENDIF
        RETURN
      ENDIF

C--------------------------------
C COMBINED WAVE-CURRENT CONDITION
C--------------------------------
C*** FIRST CALCULATE TIMES FOR SUSPENDED LOAD ***
      IF (USTCWSE .LT. USTCRS) THEN
        PERSUSP=0
        GO TO 50
      ENDIF
      B24ACS=(TAOCRS**2.0-(TAOCS*SIN(PHIB))**2.0)/(TAOWS**2.0)
```

```
      IF (B24ACS .LE. 0.0) THEN
C CRITICAL STRESS FOR SUSPENSION OF SEDIMENT ALWAYS EXCEEDED
        TS1=PER/2.
        PERSUSP=100.0
        PERBED=0.0
        RETURN
      ENDIF
      B=-TAOCS*COS(PHIB)/TAOWS
      XS1=B+SQRT(B24ACS)
      IF (XS1 .GE. 1.0) THEN
C CRITICAL STRESS FOR SUSPENSION OF SEDIMENT NEVER EXCEEDED
        PERSUSP=0.0
        GO TO 50
      ENDIF
      IF (XS1 .LE. -1.0) THEN
C SECOND CASE WHERE CRITICAL STRESS FOR SUSPENSION OF SEDIMENT IS ALWAYS EXCEEDED
        TS1=PER/2.
        PERSUSP=100.0
        PERBED=0.0
        RETURN
      ELSE
C CRITICAL STRESS FOR SUSPENSION OF SEDIMENT SOMETIMES EXCEEDED
        TS1=PER/(2.*PI)*ACOS(XS1)
      ENDIF
      XS2=B-SQRT(B24ACS)
      IF (XS2 .LE. -1.0) THEN
C CRITICAL STRESS FOR SUSPENSION OF SEDIMENT NOT EXCEEDED DURING TROUGH
        PERSUSP=200.*TS1/PER
      ELSE
C CRITICAL STRESS FOR SUSPENSION OF SEDIMENT EXCEEDED DURING TROUGH
        TS2=PER/(2.*PI)*ACOS(XS2)
        PERSUSP=(2.*(TS1-TS2)+PER)/PER*100.
      ENDIF

C*** CALCULATE TIMES FOR BEDLOAD ***
C CALCULATE TIMES FOR BEDLOAD ONLY IF USTCRB < USTCRS
 50   IF (USTCRB .GE. USTCRS ) RETURN
C FOR EFFECTIVE SHEAR VELOCITY < USTCRB, NO BEDLOAD TRANSPORT
      IF (USTCWSE .LT. USTCRB) THEN
        PERBED=0
        RETURN
      ENDIF
      B24ACB=(TAOCRB**2-(TAOCS*SIN(PHIB))**2)/(TAOWS**2)
      IF (B24ACB .LE. 0.0) THEN
C CRITICAL STRESS FOR BEDLOAD TRANSPORT ALWAYS EXCEEDED
        TB1=PER/2.
        PERBED=100.-PERSUSP
        RETURN
      ENDIF
      B=-TAOCS*COS(PHIB)/TAOWS
      XB1=B+SQRT(B24ACB)
      IF (XB1 .GE. 1.0) THEN
C CRITICAL STRESS FOR BEDLOAD TRANSPORT NEVER EXCEEDED
        PERBED=0.0
        RETURN
      ENDIF
```

```
      IF (XB1 .LE. -1.0) THEN
C SECOND CASE WHERE CRITICAL STRESS FOR BEDLOAD TRANSPORT IS ALWAYS EXCEEDED.
        TB1=PER/2.
        PERBED=100.-PERSUSP
        RETURN
      ENDIF
C CRITICAL STRESS FOR BEDLOAD TRANSPORT EXCEEDED DURING CREST
      TB1=PER/(2.*PI)*ACOS(XB1)
      XB2=B-SQRT(B24ACB)
      IF (XB2 .LE. -1.0) THEN
C CRITICAL STRESS FOR BEDLOAD TRANSPORT NOT EXCEEDED DURING TROUGH
        PERBED=200.*TB1/PER-PERSUSP
      ELSE
C CRITICAL STRESS FOR BEDLOAD TRANSPORT EXCEEDED DURING TROUGH
        TB2=PER/(2.*PI)*ACOS(XB2)
        PERBED=(2.*(TB1-TB2)+PER)/PER*100.-PERSUSP
      ENDIF

C END OF THE TIMING SUBROUTINE
      RETURN
      END
```

```
      SUBROUTINE TRANSPO(D,UA,UB,U100,PHIB,PHI100,FCW,PER,GD,FRACT,BETA,RHOS,RHOW,USTCRB,
     @USTCS,USTWS,USTCWS,USTCWSB,RPLCOEF,CDIR,WDIR,TB1,TB2,TS1,PERBED,PERSUSP,IOPT1,CONC0,
     @TAOCD,TAOCE,TIMEDR,WS,RD0,RD,RE0,RE,TIME0,QS0,CONC,SED,SEDM,SEDDIR)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE USES THE EFFECTIVE COMBINED SHEAR STRESS TAOCWS TO CALCULATE THE
C TIME-AVERAGED NET SEDIMENT TRANSPORT RATE BY A CHOICE OF METHODS.  FOR THE PURE WAVE
C CASE, THERE IS NO NET TRANSPORT SINCE TRANSPORT DURING THE WAVE CREST IS EQUAL AND
C OPPOSITE TO THAT DURING THE WAVE TROUGH (DUE TO THE USE OF LINEAR WAVE THEORY). FOR
C THE PURE CURRENT AND MIXED CONDITIONS, THE USER MAKES A CHOICE BETWEEN TRANSPORT
C FORMULAE, HOWEVER IF SUSPENDED LOAD TRANSPORT IS SIGNIFICANT IT IS RECOMMENDED THAT A
C TOTAL LOAD FORMULA BE USED.
C
C THE OPTIONS AVAILABLE ARE:
C          1 - ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION,
C          2 - EINSTEIN-BROWN (1950) BEDLOAD EQUATION,
C          3 - BAGNOLD (1963) TOTAL LOAD EQUATION,
C          4 - YALIN (1963) BEDLOAD EQUATION,
C          5 - COHESIVE SEDIMENT METHOD.
C THE CHOICE IS CONTROLLED BE THE VALUE OF "IOPT1" (1 TO 5) WHICH IS READ IN SUBROUTINE
C READIN (READBCH FOR THE BATCH PROGRAM)

C INPUT VARIABLES:
C
C     D = WATER DEPTH (M)
C     UA = CURRENT SPEED TO BE USED IN BOTTOM STRESS CALC (M/SEC)
C     UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (M/SEC)
C     U100 = CURRENT SPEED AT 1 M. ABOVE SEABED (M/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 ABOVE SEABED (RADIANS)
C     FCW = BOTTOM FRICTION FACTOR
C     PER = WAVE PERIOD (SEC)
C     GD = SEDIMENT GRAIN SIZE (M)
C     FRACT = FRACTION OF THE TOTAL SEDIMENT WITH GRAIN SIZE GD
C     BETA = BED SLOPE (DEGREE)
C     RHOS = SEDIMENT DENSITY (KG/M**3)
C     RHOW = FLUID DENSITY (KG/M**3)
C     USTCRB = CRITICAL SHEAR VELOCITY FOR BEDLOAD TRANSPORT
C     USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY
C     USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY
C     USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY
C     USTCWSB = BEDLOAD COMBINED SHEAR VELOCITY
C     RPLCOEF = RIPPLE COEFFICIENT FOR SHEAR VELOCITY CONVERSION
C     CDIR = CURRENT DIRECTION (AZIMUTH,DEGREES)
C     WDIR = WAVE DIRECTION (AZIMUTH,DEGREES)
C     TB1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT CEASES (S)
C     TB2 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH BEDLOAD TRANSPORT RECOMMENCES (S)
C     TS1 = TIME AFTER PASSAGE OF WAVE CREST AT WHICH SUSPENDED LOAD TRANSPORT CEASES (S)
C     PERBED = PERCENTAGE OF TIME SPENT IN BEDLOAD TRANSPORT PHASE
C     PERSUSP = PERCENTAGE OF TIME SPENT IN SUSPENDED LOAD TRANSPORT PHASE
C     IOPT1 = OPTION SELECTED FOR SEDIMENT TRANSPORT FORMULA

C OUTPUT VARIABLES:
C
```

```
C     SED = TIME-AVERAGED NET SEDIMENT TRANSPORT AS VOLUME TRANSPORTED PER
C             UNIT BED WIDTH PER UNIT TIME (M**3/M/S)
C     SEDM = TIME-AVERAGED NET SEDIMENT TRANSPORT AS MASS OF SEDIMENT
C              SOLIDS TRANSPORTED PER UNIT BED WIDTH PER UNIT TIME (KG/M/S)
C     SEDDIR = DIRECTION OF NET SEDIMENT TRANSPORT (AZIMUTH,DEGREES)

C INPUT/OUTPUT VARIABLES OF COHESIVE SEDIMENT METHOD
C
C     CONC0 = INITIAL SEDIMENT CONCENTRATION (mg/l)
C     TAOCD = CRITICAL SHEAR STRESS FOR DEPOSITION (Pa)
C     TAOCE = CRITICAL SHEAR STRESS FOR EROSION (Pa)
C     TIMEDR = EROSION OR DEPOSITION TIME DURATION (minutes)
C     WS = SETTLING VELOCITY (m/s)
C     RD0 = INITIAL DEPOSITION RATE (kg/m^2/s)
C     RD = FINAL DEPOSITION RATE (kg/m^2/s)
C     RE0 = INITIAL EROSION RATE (kg/m^2/s)
C     RE = FINAL EROSION RATE (kg/m^2/s)
C     TIME0 = CALCULATED TIME (minutes) WHEN CONC. HAS DECREASED TO BE LESS THAN 1 MG/L DUE
C               TO DEPOSITION OR WHEN DOWN-CORE CRITICAL EROSION SHEAR STRESS HAS BECOME
C               EQUAL TO THE APPLIED BED SHEAR STRESS SO THAT EROSION HAS STOPPED
C     QS0 = INITIAL MASS SEDIMENT TRANSPORT RATE (kg/m/s)
C     CONC = FINAL CALCULATED SEDIMENT CONCENTRATION (mg/l)
C
C INTERMEDIATE VARIABLES:
C
C     PHI = ANGLE OF REPOSE (TAKEN TO BE 30 DEGREES)
C     S = SPECIFIC GRAVITY OF WATER
C     TAOCS=SKIN-FRICTION CURRENT SHEAR STRESS
C     TAOWS=SKIN-FRICTION WAVE SHEAR STRESS
C     VCB = CRITICAL FLOW VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/S)

C INITIALIZE AND DEFINE CONSTANTS AND VARIABLES
      G=9.81
      VISC=1.3D-3
      VISK=VISC/RHOW
      PI=2.*ASIN(1.)
      DRHO=RHOS-RHOW
      DGAMMA=G*DRHO
      PHI=30
      IF (PER .NE. 0.0) W=2.*PI/PER
      SED=0.0
      SEDM=0.0
      SEDDIR=0.0
      RE0=0
      RE=0
      RD0=0
      RD=0
      QS0=0

C COMPUTE RIPPLE BREAKOFF AND SHEETFLOW THRESHOLD CRITERION
C INTERMEDIATE VARIABLES ARE:
C   PSICR = CRITICAL SHIELDS PARAMETER FOR BEDLOAD TRANSPORT
C   PSIBF = CRITICAL SHIELDS PARAMETER FOR RIPPLE BREAK-OFF
C   USTBF = CRITICAL SHEAR VELOCITY FOR RIPPLE BREAK-OFF
C   PSIUP = CRITICAL SHIELDS PARAMETER FOR SHEET-FLOW TRANSPORT
C   USTBF = CRITICAL SHEAR VELOCITY FOR SHEET-FLOW TRANSPORT
```

```
      S=RHOS/RHOW
      SST=GD*((S-1)*G*GD)**0.5/(4*VISK)
      PSICR=(USTCRB**2)/((S-1)*G*GD)
      PSIBF=1.8*(SST**0.6)*PSICR
      USTBF=(PSIBF*(S-1)*G*GD)**0.5
      PSIUP=0.413*(1000*GD)**(-0.4)
      USTUP=(PSIUP*(S-1)*G*GD)**0.5

C CALCULATE THE CRITICAL SHEAR STRESS AND FLOW VELOCITY FOR BEDLOAD TRANSPORT
      TAOCRB=RHOW*USTCRB**2
      VCB=SQRT(2.*TAOCRB/(RHOW*FCW))
C CALCULATE FALL VELOCITY FROM GIBBS ET AL. (1971)
      FALL=(-3.*VISC+SQRT(9.*VISC**2+G*(GD/2.)**2*RHOW*DRHO*
     &        (.00015476+0.099205*GD)))/(RHOW*(.00011607+0.074405*GD))

C*******************************
C WAVES ONLY (NO CURRENT)
C*******************************
C FOR THE PURE WAVE CASE, NO NET TRANSPORT OCCURS. EXIT PROGRAM.
      IF (UA .EQ. 0.0) RETURN

C*******************************
C CURRENT ONLY (NO WAVES)
C*******************************
C NO INTEGRATION IS REQUIRED FOR THE PURE CURRENT CASE. WHEN TRANSPORT IS ALL IN
C SUSPENDED LOAD, THEN A WARNING MESSAGE IS PRINTED CONCERNING THE USE OF "BEDLOAD"
C TRANSPORT METHOD

C SKIP THIS SECTION IF THERE ARE BOTH WAVES AND CURRENTS
      IF (UB .NE. 0.0) GOTO 888

C CHECK IF THERE IS ANY TRANSPORT FOR NON-COHESIVE SEDIMENTS, IF NOT THEN EXIT.
      IF (IOPT1 .NE. 5) THEN
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) RETURN
      ENDIF

C PRINT WARNING MESSAGE IF PREDICTOR CHOICE MAY BE INAPPROPRIATE BECAUSE THERE IS NO
C BEDLOAD TRANSPORT (NON-COHESIVE ONLY!).
      IF (IOPT1 .NE. 5) THEN
        IF (PERBED .EQ. 0.0 .AND. IOPT1 .EQ. 2) THEN
          WRITE (7,10)
 10       FORMAT(/,' NO "PURE" BEDLOAD TRANSPORT PHASE THEREFORE THE',/,
     @    ' EINSTEIN-BROWN EQUATION MAY BE INAPPROPRIATE')
        ENDIF
        IF (PERBED .EQ. 0.0 .AND. IOPT1 .EQ. 4) THEN
          WRITE (7,20)
 20       FORMAT(/,' NO "PURE" BEDLOAD TRANSPORT PHASE THEREFORE THE',/,
     @    ' YALIN EQUATION MAY BE INAPPROPRIATE')
        ENDIF
      ENDIF

C OBTAIN CURRENT SHEAR STRESS TAO0, UA=U100 FOR STEADY CURRENT
      TAO0=RHOW*USTCS**2
C CALL RESPECTIVE FORMULA BASED ON THE CHOICE OF THE USER
      GOTO (1,2,3,4,5) IOPT1
  1   CALL ENGHAN(U100,TAO0,RHOW,GD,DGAMMA,SED)
```

```
      SEDDIR=CDIR
      GOTO 999
    2 CALL EINBWN(FALL,GD,TAO0,DGAMMA,SED)
      SEDDIR=CDIR
      GOTO 999
    3 CALL BAGNLD(GD,RHOS,U100,VCB,SED)
      SEDDIR=CDIR
      GOTO 999
    4 CALL YALIN(FCW,UA,VCB,RHOW,RHOS,TAOCRB,G,DRHO,GD,SED)
      SEDDIR=CDIR
      GOTO 999
    5 CALL AMOSGB(RHOW,RHOS,CONC0,TAOCE,TAOCD,USTCS,WS,
     &TIMEDR,UA,D,RD0,RD,RE0,RE,TIME0,QS0,SED,CONC)
      SEDDIR=CDIR
      GOTO 999

888 CONTINUE
C***************************
C COMBINED WAVE AND CURRENT
C***************************
C THE COMBINED WAVE AND CURRENT CASE REQUIRES INTEGRATION OF THE INSTANTANEOUS
C TRANSPORT OVER THE WAVE PERIOD. THE USE OF LWT ALLOWS INTEGRATION TO BE DONE OVER
C ONLY HALF A WAVE CYCLE. BAGNOLD'S METHOD DOES NOT REQUIRE INTEGRATION. THE X- AND Y-
C COMPONENTS OF TRANSPORT ARE CONSIDERED SEPARATELY, WHERE THE X-COMPONENT IS PARALLEL
C TO THE WAVE DIRECTION AND THE Y-COMPONENT IS NORMAL TO THE WAVE DIRECTION.
C
C INTERMEDIATE VARIABLES:
C     NC = NUMBER OF INTEGRATION UNDER WAVE CREST
C     NT = NUMBER OF INTEGRATION UNDER WAVE TROUGH
C     RLWRT = LOWER LIMIT OF TRANSPORT INTEGRATION UNDER TROUGH
C     SEDXC = TOTAL VOLUME TRANSPORT IN WAVE DIRECTION UNDER CREST
C     SEDXT = TOTAL VOLUME TRANSPORT IN WAVE DIRECTION UNDER TROUGH
C     SEDYC = TOTAL VOLUME TRANSPORT IN Y DIRECTION UNDER CREST
C     SEDYT = TOTAL VOLUME TRANSPORT IN Y DIRECTION UNDER TROUGH
C     STEPC = INTEGRATION TIME STEP OF SEDIMENT TRANSPORT UNDER CREST
C     STEPT = INTEGRATION TIME STEP OF SEDIMENT TRANSPORT UNDER TROUGH
C     TIMEC = SEDIMENT TRANSPORT TIME UNDER CREST
C     TIMET = SEDIMENT TRANSPORT TIME UNDER TROUGH

C FOR IOPT1=1 TO 4, CHECK IF CRITICAL STRESS IS EVER EXCEEDED, IF NOT THEN EXIT.
      IF (IOPT1 .NE. 5) THEN
        IF (TB1 .EQ. 0.0 .AND. TS1 .EQ. 0.0) RETURN
        IF (PERBED .EQ. 0.0 .AND. PERSUSP .EQ. 0.0) RETURN
      ENDIF

C INITIALIZE CONSTANTS AND VARIABLES
      SEDXC=0.0
      SEDXT=0.0
      SEDYC=0.0
      SEDYT=0.0
      RLWRT=0.0

C COMPUTE THE TRANSPORT TIMES FOR WAVE CREST AND TROUGH RESPECTIVELY
      IF (TB1 .EQ. PER/2 .OR. TS1 .EQ. PER/2) THEN
        TIMEC = PER/4
        TIMET = PER/4
```

```
        RLWRT = PER/4
      ELSE IF (TB1 .GT. 0 .AND. TB2 .GT. 0) THEN
        TIMEC = TB1
        TIMET = PER/2 - TB2
        RLWRT = TB2
      ELSE
        TIMEC=TB1
        TIMET=0.
      ENDIF

C COMPUTE THE INTEGRATION TIME STEPS
      IF (TIMEC .GE. 10.) THEN
        NC = 20
      ELSE
        NC =10
      ENDIF
      IF (TIMET .GE. 10.) THEN
        NT = 20
      ELSE
        NT = 10
      ENDIF
      STEPC = TIMEC/NC
      STEPT = TIMET/NT

C DECIDE THE TRANSPORT FORMULA ACCORDING TO IOPT1
      GOTO (11,12,13,14,15) IOPT1

 11   CALL ENGHANB(RHOW,DGAMMA,GD,U100,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,USTBF,
     @USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
      GOTO 998

 12   CALL EINBWNB(RHOW,DGAMMA,GD,FALL,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,USTBF,
     @USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
      GOTO 998

 13   CALL BAGNLDB(RHOW,DGAMMA,U100,CDIR,USTCWS,USTCWSB,USTCRB,USTBF,USTUP,RPLCOEF,
     @SED,SEDDIR)
      GOTO 998

 14   CALL YALINB(RHOW,RHOS,DGAMMA,GD,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,USTBF,
     @USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
      GOTO 998

 15   CALL AMOSGBB(RHOW,RHOS,CONC0,TAOCE,TAOCD,USTCWS,WS,TIMEDR,U100,D,RD0,RD,RE0,RE,
     @TIME0,QS0,SED,CONC)
      SEDDIR=CDIR

998   CONTINUE

C COMPUTE THE VOLUME TRANSPORT RATE SED AND ITS DIRECTION. BAGNOLD AND COHESIVE
C SEDIMENT METHODS OUTPUT SED AND SEDDIR DIRECTLY.
      IF (IOPT1 .NE. 3 .AND. IOPT1 .NE. 5) THEN
        SEDX=(SEDXC+SEDXT)/PER
        SEDY=(SEDYC+SEDYT)/PER
        SED=SQRT(SEDX**2+SEDY**2)
        IF (SEDY .EQ. 0. .AND. SEDX .EQ. 0.) THEN
```

```
        SEDDIR = 0.
      ELSE
        PHIS=ATAN2(SEDY,SEDX)
        DIF=SIGN((PHI100-PHIS)*180./PI,CDIR-WDIR)
        CWDIF=ABS(CDIR-WDIR)
        IF(CWDIF .LE. 90.0) SEDDIR=CDIR-DIF
        IF (CWDIF .LE. 180.0 .AND. CWDIF .GT. 90.0) SEDDIR=CDIR+DIF
        IF (CWDIF .LE. 270.0 .AND. CWDIF .GT. 180.0) SEDDIR=CDIR-DIF
        IF (CWDIF .LE. 360.0 .AND. CWDIF .GT. 270.0) SEDDIR=CDIR+DIF
        IF (SEDDIR .LT. 0.0) SEDDIR=SEDDIR+360.0
        IF (SEDDIR .GE. 360.0) SEDDIR=SEDDIR-360.0
      ENDIF
    ENDIF

C INCLUDE BED-SLOPE EFFECT AND THEN CONVERT VOLUME FLUX SED IN M^2/M/S TO MASS FLUX
C SEDM IN KG/SEC/M
999 SED=SED*(1-TAN(BETA/57.3)/TAN(PHI/57.3))
    SEDM = RHOS*SED

C END OF SUBROUTINE TRANSPO
    RETURN
    END

C*********************************************************************
    SUBROUTINE ENGHAN(U100,TAO0,RHOW,GD,DGAMMA,SED)
    IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE ENGELUND AND
C HANSEN (1967) TOTAL LOAD EQUATION FOR CURRENTS ONLY.

     V=U100
     SED=0.05*V**2*SQRT(TAO0**3*RHOW)/(GD*DGAMMA**2)
     RETURN
     END

C*********************************************************************
    SUBROUTINE EINBWN(FALL,GD,TAO0,DGAMMA,SED)
    IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE EINSTEIN AND
C BROWN (1950) BEDLOAD EQUATION FOR CURRENTS ONLY.

    SED = 40.0*FALL*GD*(TAO0/(DGAMMA*GD))**3
    RETURN
    END

C*********************************************************************
    SUBROUTINE BAGNLD(GD,RHOS,U100,VCB,SED)
    IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE BAGNOLD (1963)
C TOTAL LOAD EQUATION FOR CURRENTS ONLY.

    BETA=1.73D0
    IF (GD .LE. 0.00031) BETA=7.22D0
    SED=BETA/RHOS*(U100-VCB)**3
```

```
      RETURN
      END

C*********************************************************************
      SUBROUTINE YALIN(FCW,UA,VCB,RHOW,RHOS,TAOCRB,G,DRHO,GD,SED)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE YALIN (1963)
C BEDLOAD EQUATION FOR CURRENTS ONLY.

      USTAR=SQRT(FCW/2.)*UA
      S=(UA/VCB)**2-1.0
      A=2.45*(RHOW/RHOS)**0.4*SQRT(TAOCRB/(G*DRHO*GD))
      SED=0.635*GD*USTAR*S*(1.0-DLOG(1.0+A*S)/(A*S))
      RETURN
      END

C*************************************************************************
      SUBROUTINE ENGHANB(RHOW,DGAMMA,GD,U100,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,
     @USTBF,USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO ENGELUND AND
C HANSEN (1967) TOTAL LOAD EQUATION FOR COMBINED WAVE AND CURRENT FLOWS.

C INTERMEDIATE VARIABLES:
C     GSXC = WAVE-PARALLEL VOLUME TRANSPORT IN TIME STEPC
C     GSXT = WAVE-PARALLEL VOLUME TRANSPORT IN TIME STEPT
C     GSYC = WAVE-NORMAL VOLUME TRANSPORT IN TIME STEPC
C     GSYT = WAVE-NORMAL VOLUME TRANSPORT IN TIME STEPT

C INITIALIZE PARAMETERS
      GSXC = 0
      GSXT = 0
      GSYC = 0
      GSYT = 0
      SEDXC= 0
      SEDYC= 0
      SEDXT= 0
      SEDYT= 0

C PRESERVE THE BURST-AVERAGED SHEAR VELOCITIES
      USTCSGM=USTCS
      USTWSGM=USTWS
      USTCWSGM=USTCWS

C OBTAIN THE CONSTANT IN THE E-H EQUATION
      CONST=0.05*(RHOW*U100/DGAMMA)**2/GD
C OBTAIN THE SHEAR VELOCITY RATIO ALPHA FOR BREAK-OFF RIPPLES
      ALPHA=(USTUP-USTCWSB)/(USTUP-USTBF)
C CONVERT SHEAR VELOCITIES TO SHEAR STRESSES
      TAOCRB=RHOW*USTCRB**2
      TAOCS=RHOW*USTCS**2
      TAOWS=RHOW*USTWS**2
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE X DIRECTION
      TAOCSX=TAOCS*COS(PHIB)
```

```
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE Y DIRECTION
    TAOCSY=TAOCS*SIN(PHIB)

C ------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE WAVE CREST
    DO 111 I = 0, (NC-1)
      TAOCWSX=TAOCSX+0.5*TAOWS*(COS(W*I*STEPC)+COS(W*(I+1)*STEPC))
      TAOCWS=SQRT(TAOCSY**2+TAOCWSX**2)
      TAOCWSE=(RPLCOEF**2)*TAOCWS
C FOR WEAK-TRANSPORT RIPPLES
      IF (USTCWSGM .LT. USTCRB) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR EQUILIBRIUM RIPPLES
      IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR BREAK-OFF RIPPLES
      IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
        TAOCWS=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR UPPER-PLANE BED
      IF (USTCWSB .GE. USTUP) USTCWS=SQRT(TAOCWS/RHOW)

      SED=CONST*STEPC*USTCWS**3
      PHIS=ATAN2(TAOCSY,TAOCWSX)
      GSXC=SED*COS(PHIS)
      GSYC=SED*SIN(PHIS)
      SEDXC=SEDXC+GSXC
      SEDYC=SEDYC+GSYC
111  CONTINUE
    SEDXC=2*SEDXC
    SEDYC=2*SEDYC

C ------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE WAVE TROUGH
    IF (TIMET .EQ. 0.) GO TO 333
    DO 222 I = 0, (NT-1)
      TAOCWSX=TAOCSX+0.5*TAOWS*(COS(W*(RLWRT+I*STEPT))
   @          +COS(W*(RLWRT+(I+1)*STEPT)))
      TAOCWS=SQRT(TAOCSY**2+TAOCWSX**2)
      TAOCWSE=(RPLCOEF**2)*TAOCWS
C FOR WEAK-TRANSPORT RIPPLES
      IF (USTCWSGM .LT. USTCRB) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR EQUILIBRIUM RIPPLES
      IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR BREAK-OFF RIPPLES
```

```
      IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
        TAOCWS=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR UPPER-PLANE BED
      IF (USTCWSB .GE. USTUP) USTCWS=SQRT(TAOCWS/RHOW)

      SED=CONST*STEPT*USTCWS**3
      PHIS=ATAN2(TAOCSY,TAOCWSX)
      IF (PHIS .LT. 0) THEN
        GSXT=-SED*COS(PHIS)
        GSYT=-SED*SIN(PHIS)
      ELSE
        GSXT=SED*COS(PHIS)
        GSYT=SED*SIN(PHIS)
      ENDIF
      SEDXT=SEDXT+GSXT
      SEDYT=SEDYT+GSYT
222  CONTINUE
     SEDXT=2*SEDXT
     SEDYT=2*SEDYT

C ---------------------------------------------------
333  CONTINUE
C RETURN THE BURST-AVERAGED SHEAR VELOCITIES
     USTCS=USTCSGM
     USTWS=USTWSGM
     USTCWS=USTCWSGM

     RETURN
     END

C*****************************************************************
     SUBROUTINE EINBWNB(RHOW,DGAMMA,GD,FALL,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,
    @USTBF,USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
     IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE EINSTEIN AND
C BROWN (BROWN, 1950) BEDLOAD EQUATION FOR COMBINED WAVE AND CURRENT FLOWS.

C INITIALIZE PARAMETERS
     GSXC = 0
     GSXT = 0
     GSYC = 0
     GSYT = 0
     SEDXC= 0
     SEDYC= 0
     SEDXT= 0
     SEDYT= 0

C PRESERVE THE BURST-AVERAGED SHEAR VELOCITIES
     USTCSGM=USTCS
     USTWSGM=USTWS
     USTCWSGM=USTCWS

C OBTAIN THE CONSTANT IN THE E-B EQUATION
```

```
      CONST=40*FALL*GD*(RHOW/(GD*DGAMMA))**3
C OBTAIN THE SHEAR VELOCITY RATIO ALPHA FOR BREAK-OFF RIPPLES
      ALPHA=(USTUP-USTCWSB)/(USTUP-USTBF)
C CONVERT SHEAR VELOCITIES TO SHEAR STRESSES
      TAOCRB=RHOW*USTCRB**2
      TAOCS=RHOW*USTCS**2
      TAOWS=RHOW*USTWS**2
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE X DIRECTION
      TAOCSX=TAOCS*COS(PHIB)
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE Y DIRECTION
      TAOCSY=TAOCS*SIN(PHIB)

C ----------------------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE WAVE CREST THROUGH INTEGRATION
      DO 111 I = 0, (NC-1)
        TAOCWSX=TAOCSX+0.5*TAOWS*(COS(W*I*STEPC)+COS(W*(I+1)*STEPC))
        TAOCWS=SQRT(TAOCSY**2+TAOCWSX**2)
        TAOCWSE=(RPLCOEF**2)*TAOCWS
C FOR WEAK-TRANSPORT RIPPLES
        IF (USTCWSGM .LT. USTCRB) THEN
          TAOCWS=0.5*(TAOCRB+TAOCWSE)
          USTCWS=SQRT(TAOCWS/RHOW)
        ENDIF
C FOR EQUILIBRIUM RIPPLES
        IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
          TAOCWS=0.5*(TAOCRB+TAOCWSE)
          USTCWS=SQRT(TAOCWS/RHOW)
        ENDIF
C FOR BREAK-OFF RIPPLES
        IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
          TAOCWS=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS+TAOCWSE)
          USTCWS=SQRT(TAOCWS/RHOW)
        ENDIF
C FOR UPPER-PLANE BED
        IF (USTCWSB .GE. USTUP) USTCWS=SQRT(TAOCWS/RHOW)

        SED=CONST*STEPC*USTCWS**6
        PHIS=ATAN2(TAOCSY,TAOCWSX)
        GSXC=SED*COS(PHIS)
        GSYC=SED*SIN(PHIS)
        SEDXC=SEDXC+GSXC
        SEDYC=SEDYC+GSYC
111   CONTINUE
      SEDXC=2*SEDXC
      SEDYC=2*SEDYC

C ----------------------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE WAVE TROUGH THROUGH INTEGRATION
      IF (TIMET .EQ. 0.) GO TO 333
      DO 222 I = 0, (NT-1)
        TAOCWSX=TAOCSX+0.5*TAOWS*(COS(W*(RLWRT+I*STEPT))
     @          +COS(W*(RLWRT+(I+1)*STEPT)))
        TAOCWS=SQRT(TAOCSY**2+TAOCWSX**2)
        TAOCWSE=(RPLCOEF**2)*TAOCWS
C FOR WEAK-TRANSPORT RIPPLES
        IF (USTCWSGM .LT. USTCRB) THEN
```

```
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR EQUILIBRIUM RIPPLES
      IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR BREAK-OFF RIPPLES
      IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
        TAOCWS=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS+TAOCWSE)
        USTCWS=SQRT(TAOCWS/RHOW)
      ENDIF
C FOR UPPER-PLANE BED
      IF (USTCWSB .GE. USTUP) USTCWS=SQRT(TAOCWS/RHOW)

      SED=CONST*STEPT*USTCWS**6
      PHIS=ATAN2(TAOCSY,TAOCWSX)
      IF (PHIS .LT. 0) THEN
          GSXT=-SED*COS(PHIS)
          GSYT=-SED*SIN(PHIS)
      ELSE
          GSXT=SED*COS(PHIS)
          GSYT=SED*SIN(PHIS)
      ENDIF
      SEDXT=SEDXT+GSXT
      SEDYT=SEDYT+GSYT
222  CONTINUE
    SEDXT=2*SEDXT
    SEDYT=2*SEDYT

C -----------------------------------------------------------------
333  CONTINUE
C RETURN THE BURST-AVERAGED SHEAR VELOCITIES
    USTCS=USTCSGM
    USTWS=USTWSGM
    USTCWS=USTCWSGM

    RETURN
    END

C*********************************************************************
    SUBROUTINE BAGNLDB(RHOW,DGAMMA,U100,CDIR,USTCWS,USTCWSB,USTCRB,USTBF,USTUP,RPLCOEF,
   @SED,SEDDIR)
    IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES ACCORDING TO THE MODIFIED
C BAGNOLD (1963) TOTAL LOAD EQUATION FOR COMBINED CURRENTS AND WAVES.

C OBTAIN THE SHEAR VELOCITY RATIO ALPHA FOR BREAK-OFF RIPPLES
    ALPHA=(USTUP-USTCWSB)/(USTUP-USTBF)
C COMPUTE EFFECTIVE SHEAR VELOCITY AT THE RIPPLE CREST
    USTCWSE=USTCWS*RPLCOEF
C CONVERT SHEAR VELOCITIES TO SHEAR STRESSES
    TAOCRB = RHOW*USTCRB**2
    TAOCWS = RHOW*USTCWS**2
```

```
      TAOCWSE = RHOW*USTCWSE**2

C ----------------------------------------------------------------
C COMPUTE THE EFFECTIVE SHEAR STRESS CAUSING SEDIMENT TRANSPORT FOR
C WEAK-TRANSPORT RIPPLES
      IF (USTCWSGM .LT. USTCRB) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
      ENDIF
C FOR EQUILIBRIUM RIPPLES
      IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
        TAOCWS=0.5*(TAOCRB+TAOCWSE)
      ENDIF
C FOR BREAK-OFF RIPPLES
      IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
        TAOCWS=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS+TAOCWSE)
      ENDIF
C FOR UPPER-PLANE BED
      IF (USTCWSB .GE. USTUP) TAOCWS=TAOCWS
C ----------------------------------------------------------------

C COMPUTE NORMALIZED EXCESS SHEAR STRESS EST
      EST = (TAOCWS - TAOCRB)/TAOCRB
C CALCULATE TOTAL TRANSPORT RATE; RK IS BASED ON STERNBERG (1972)
      IF (EST .LT. 0) THEN
        SED = 0
      ELSE
        RK = 0.005*EXP(0.7*EST)
        SED=RK*TAOCWS*U100/DGAMMA
      ENDIF
      SEDDIR=CDIR

      RETURN
      END

C*******************************************************************
      SUBROUTINE YALINB(RHOW,RHOS,DGAMMA,GD,USTCS,USTWS,USTCWS,USTCWSB,PHIB,USTCRB,USTBF,
     @USTUP,RPLCOEF,W,NC,NT,TIMET,STEPC,STEPT,RLWRT,SEDXC,SEDXT,SEDYC,SEDYT)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES SEDIMENT TRANSPORT RATES FOR COMBINED WAVES AND CURRENTS
C ACCORDING TO THE MODIFIED YALIN (1963) BEDLOAD EQUATION.

      GSXC = 0
      GSXT = 0
      GSYC = 0
      GSYT = 0
      SEDXC= 0
      SEDYC= 0
      SEDXT= 0
      SEDYT= 0

C PRESERVE THE BURST-AVERAGED SHEAR VELOCITIES
      USTCSGM=USTCS
      USTWSGM=USTWS
      USTCWSGM=USTCWS
```

```
C OBTAIN THE TRANSPORT PARAMETER A OF YALIN METHOD
      A=2.45*SQRT((RHOW*USTCRB**2)/(DGAMMA*GD))*(RHOW/RHOS)**0.4
C OBTAIN THE CONSTANT IN THE YALIN EQUATION
      CONST=0.635*GD
C OBTAIN THE SHEAR VELOCITY RATIO ALPHA FOR BREAK-OFF RIPPLES
      ALPHA=(USTUP-USTCWSB)/(USTUP-USTBF)
C CONVERT SHEAR VELOCITIES TO SHEAR STRESSES
      TAOCS=RHOW*USTCS**2
      TAOWS=RHOW*USTWS**2
      TAOCRB=RHOW*USTCRB**2
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE X DIRECTION
      TAOCSX=TAOCS*COS(PHIB)
C COMPUTE STEADY CURRENT SHEAR STRESS IN THE Y DIRECTION
      TAOCSY=TAOCS*SIN(PHIB)

C ------------------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE WAVE CREST
      DO 111 I = 0, (NC-1)
        TAOCWSX1=TAOCSX+TAOWS*COS(W*I*STEPC)
        TAOCWSX2=TAOCSX+TAOWS*COS(W*(I+1)*STEPC)
        TAOCWS1=SQRT(TAOCSY**2+TAOCWSX1**2)
        TAOCWS2=SQRT(TAOCSY**2+TAOCWSX2**2)
        TAOCWSE1=(RPLCOEF**2)*TAOCWS1
        TAOCWSE2=(RPLCOEF**2)*TAOCWS2
C FOR WEAK-TRANSPORT RIPPLES
        IF (USTCWSGM .LT. USTCRB) THEN
          TAOCWS1=0.5*(TAOCRB+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=0.5*(TAOCRB+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR EQUILIBRIUM RIPPLES
        IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
          TAOCWS1=0.5*(TAOCRB+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=0.5*(TAOCRB+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR BREAK-OFF RIPPLES
        IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
          TAOCWS1=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS1+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS2+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR UPPER-PLANE BED
        IF (USTCWSB .GE. USTUP) THEN
          USTCWS1=SQRT(TAOCWS1/RHOW)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF

C NO TRANSPORT WHEN S1 OR S2 IS < 0 (USTCWS < USTCRB)
        S1=USTCWS1**2/USTCRB**2-1
        IF (S1 .LT. 0) S1 = 0.0
        S2=USTCWS2**2/USTCRB**2-1
        IF (S2 .LT. 0) S2 = 0.0
```

```
        FACTOR1=DABS(S1-LOG(1+A*S1)/A)
        FACTOR2=DABS(S2-LOG(1+A*S2)/A)
        SED=CONST*0.5*(USTCWS1+USTCWS2)*STEPC*0.5*(FACTOR1+FACTOR2)
        PHIS=ATAN2(TAOCSY,0.5*(TAOCWSX1+TAOCWSX2))
        GSXC=SED*COS(PHIS)
        GSYC=SED*SIN(PHIS)
        SEDXC=SEDXC+GSXC
        SEDYC=SEDYC+GSYC
111   CONTINUE
      SEDXC=2*SEDXC
      SEDYC=2*SEDYC

C ---------------------------------------------------------
C COMPUTE TRANSPORT VOLUME UNDER THE TROUGH
      IF (TIMET .EQ. 0.) GO TO 333
      DO 222 I = 0, (NT-1)
        TAOCWSX1=TAOCSX+TAOWS*COS(W*(RLWRT+I*STEPT))
        TAOCWSX2=TAOCSX+TAOWS*COS(W*(RLWRT+(I+1)*STEPT))
        TAOCWS1=SQRT(TAOCSY**2+TAOCWSX1**2)
        TAOCWS2=SQRT(TAOCSY**2+TAOCWSX2**2)
        TAOCWSE1=(RPLCOEF**2)*TAOCWS1
        TAOCWSE2=(RPLCOEF**2)*TAOCWS2
C FOR WEAK-TRANSPORT RIPPLES
        IF (USTCWSGM .LT. USTCRB) THEN
          TAOCWS1=0.5*(TAOCRB+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=0.5*(TAOCRB+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR EQULIBRIUM RIPPLES
        IF (USTCWSB .GE. USTCRB .AND. USTCWSB .LT. USTBF) THEN
          TAOCWS1=0.5*(TAOCRB+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=0.5*(TAOCRB+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR BREAK-OFF RIPPLES
        IF (USTCWSB .GE. USTBF .AND. USTCWSB .LT. USTUP) THEN
          TAOCWS1=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS1+TAOCWSE1)
          USTCWS1=SQRT(TAOCWS1/RHOW)
          TAOCWS2=(1/(2+ALPHA))*(ALPHA*TAOCRB+TAOCWS2+TAOCWSE2)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF
C FOR UPPER-PLANE BED
        IF (USTCWSB .GE. USTUP) THEN
          USTCWS1=SQRT(TAOCWS1/RHOW)
          USTCWS2=SQRT(TAOCWS2/RHOW)
        ENDIF

C NO TRANSPORT WHEN S1 OR S2 IS < 0 (USTCWS < USTCRB)
        S1=USTCWS1**2/USTCRB**2-1
        IF (S1 .LT. 0) S1 = 0.0
        S2=USTCWS2**2/USTCRB**2-1
        IF (S2 .LT. 0) S2 = 0.0
        FACTOR1=DABS(S1-LOG(1+A*S1)/A)
        FACTOR2=DABS(S2-LOG(1+A*S2)/A)
```

```
        SED=CONST*0.5*(USTCWS1+USTCWS2)*STEPT*0.5*(FACTOR1+FACTOR2)
        PHIS=ATAN2(TAOCSY,0.5*(TAOCWSX1+TAOCWSX2))
        IF (PHIS .LT. 0) THEN
            GSXT=-SED*COS(PHIS)
            GSYT=-SED*SIN(PHIS)
        ELSE
            GSXT=SED*COS(PHIS)
            GSYT=SED*SIN(PHIS)
        ENDIF
        SEDXT=SEDXT+GSXT
        SEDYT=SEDYT+GSYT
222   CONTINUE
      SEDXT=2*SEDXT
      SEDYT=2*SEDYT

C --------------------------------------------------------
333   CONTINUE
C RETURN THE BURST-AVERAGED SHEAR VELOCITIES
      USTCS=USTCSGM
      USTWS=USTWSGM
      USTCWS=USTCWSGM

      RETURN
      END

C*******************************************************************
      SUBROUTINE AMOSGB(RHOW,RHOS,CONC0,TAOCE,TAOCD,USTCS,WS,TIMEDR,UA,D,RD0,RD,RE0,RE,
     @TIME0,QS0,SED,CONC)
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES COHESIVE SEDIMENT TRANSPORT RATES FOR PURE CURRENTS
C ACCORDING TO THE NEW COHESIVE SEDIMENT ALGORITHMS BASED ON AMOS AND GREENBERG (1980)
C AND AMOS ET AL. (1992; IN REVIEW)

C INITIALIZE PARAMETERS
      G=9.8
      PI=3.14
      RD0=0
      RD=0
      RE0=0
      RE=0
      QS0=0
      TIME0=0
      SED=0
      SEDM=0

C ASSIGN TIME INCREMENT (IN SECONDS)
      DELTAT=300
C ASSIGN INTERNAL FRICTION ANGLE PHI (DEGREES)
      PHI=30
C CONVERT INITIAL CONCENTRATION CONC0 FROM MG/L TO KG/M^3
      CONC0=CONC0/1000
C COMPUTE THE INITIAL MASS TRANSPORT RATE (KG/M/S)
      QS0=CONC0*UA*D
C CALCULATE CURRENT TAO0 SHEAR STRESS
      TAO0=RHOW*USTCS**2
```

```
C --------------------------------
C DEPOSITIONAL CASE (TAO0<TAOCD)
C --------------------------------
C FOR TAO0<TAOCD, DEPOSITION OCCURS AND NO EROSION
    IF (TAO0 .LT. TAOCD) THEN
C ASSIGN VALUE TO THE RESUSPENSION PROBABILITY PRS
      PRS=0
C COMPUTE THE INITIAL DEPOSITION RATE RD0 (KG/M^2/S)
      RD0=CONC0*WS*(1-PRS)*(1-TAO0/TAOCD)
C INITIALIZE CONCENTRATION CHANGE
      CONCCHNG=0
C DETERMINE NUMERICAL INTEGRATION STEPS J IN 5 MINUTE INTERVALS
      J=TIMEDR/5
C INTEGRATING THE DECREASE OF CONCENTRATION DUE TO DEPOSITION
      DO 10 IT=1,J
        IF ((CONC0-CONCCHNG) .LE. 0.001) THEN
C COMPUTE THE TIME (MINUTES) WHEN CONCENTRATION REACHED ZERO
          TIME0=IT*5
          GOTO 20
        ENDIF
C CALCULATE STEP-WISE DEPOSITION RATE RD, DEPOSITED MASS DMASS, AND
C CONC CHANGE CONCCHNG
        RD=(CONC0-CONCCHNG)*WS*(1-PRS)*(1-TAO0/TAOCD)
        DMASS=RD*DELTAT
        CONCCHNG=CONCCHNG+DMASS/D
 10   CONTINUE
C COMPUTE THE FINAL CONCENTRATION
 20   CONC=CONC0-CONCCHNG
      GOTO 100
    ENDIF

C --------------------------------
C STABLE CASE (TAOCD<TAO0<TAOCE)
C --------------------------------
C FOR TAOCD<TAO0<TAOCE, THERE IS NO EROSION OR DEPOSITION
    IF (TAO0 .GE. TAOCD .AND. TAO0 .LT. TAOCE) THEN
C ASSIGN THE INITIAL CONCENTRATION AS THE CURRENT CONCENTRATION
      CONC=CONC0
      GOTO 100
    ENDIF

C --------------------------------
C EROSIONAL CASE (TAO0>TAOCE)
C --------------------------------
C FOR TAO0>TAOCE, EROSION OCCURS AND NO DEPOSITION
    IF (TAO0 .GE. TAOCE) THEN
C DETERMINE NUMERICAL INTEGRATION STEPS J IN 5 MINUTE INTERVALS
      J=TIMEDR/5
C ASSIGN VALUE TO THE MINIMUM EROSION RATE E0
      E0=0.000051
C ASSIGN VALUE TO THE EROSION PROPORTIONALITY COEFFICIENT RKERO
      RKERO=1.62
C COMPUTE THE INITIAL EROSION RATE
      RE0=E0*EXP(RKERO*(TAO0-TAOCE)**0.5)
C INITIALIZE THE TOTAL EROSION DEPTH ZS AND TOTAL EROSION MASS EMASST (KG/M^2)
      ZS=0
```

```
      EMASST=0
C BEGIN NUMERICAL INTEGRATION FOR TOTAL EROSION MASS EMASST
      DO 30 IT=1,J
C COMPUTE THE INCREASED CRITICAL EROSION SHEAR STRESS TAOCEZ AT ZS
        TAOCEZ=TAOCE+0.01*ZS*(RHOS-RHOW)*G*DTAN(PI*PHI/180.)
C COMPUTE THE TIME WHEN TAOCEZ BECOMES EQUAL TO TAO0
        IF (TAO0 .LE. TAOCEZ) THEN
          TIME0=60*IT
          GOTO 40
        ENDIF
C CALCULATE STEP-WISE EROSION RATE RE, ERODED MASS EMASS, AND EROSION DEPTH EDEPTH
        RE=E0*EXP(RKERO*(TAO0-TAOCEZ)**0.5)
        EMASS=RE*DELTAT
        EDEPTH=EMASS/RHOS
C OBTAIN TOTAL ERODED MASS AND EROSION DEPTH
        EMASST=EMASST+EMASS
        ZS=ZS+EDEPTH
        CONC=CONC0+EMASST/D
 30   CONTINUE
C COMPUTE THE FINAL CONCENTRATION
 40   CONC=CONC0+EMASST/D
    ENDIF

100 CONTINUE
C OBTAIN FINAL MASS SEDIMENT TRANSPORT RATE (KG/M/S)
    SEDM=CONC*D*UA
C CONVERT TO VOLUME TRANSPORT RATE (M^3/M/S)
    SED=SEDM/RHOS
C CONVERT CONCENTRATIONS BACK TO MG/LITRE
    CONC0=1000*CONC0
    CONC=1000*CONC

    RETURN
    END

C*********************************************************************
    SUBROUTINE AMOSGBB(RHOW,RHOS,CONC0,TAOCE,TAOCD,USTCWS,WS,TIMEDR,U100,D,RD0,RD,RE0,RE,
   @TIME0,QS0,SED,CONC)
    IMPLICIT DOUBLE PRECISION(A-H,O-Z)

C THIS SUBROUTINE CALCULATES COHESIVE SEDIMENT TRANSPORT RATES FOR PURE CURRENTS
C ACCORDING TO THE IMPROVED AMOS and GREENBERG METHOD (AMOS AND GREENBURG, 1980; AMOS
C ET AL., 1992; AMOS ET AL, IN REVIEW)

C INITIALIZE PARAMETERS
    G=9.8
    PI=3.14
    RD0=0
    RD=0
    RE0=0
    RE=0
    QS0=0
    TIME0=0
    SED=0
    SEDM=0
```

```
C ASSIGN TIME INCREMENT (IN SECONDS)
    DELTAT=300
C ASSIGN INTERNAL FRICTION ANGLE PHI (DEGREES)
    PHI=30
C CONVERT CONC0 FROM MG/L TO KG/M^3
    CONC0=CONC0/1000
C COMPUTE THE INITIAL MASS TRANSPORT RATE (KG/M/S)
    QS0=CONC0*U100*D
C CALCULATE COMBINED SHEAR STRESS
    TAOCWS=RHOW*USTCWS**2

C --------------------------------
C DEPOSITIONAL CASE (TAOCWS<TAOCD)
C --------------------------------
C FOR TAOCWS<TAOCD, DEPOSITION OCCURS AND NO EROSION
    IF (TAOCWS .LT. TAOCD) THEN
C ASSIGN VALUE TO THE RESUSPENSION PROBABILITY PRS
      PRS=0
C COMPUTE THE INITIAL DEPOSITION RATE RD0 (KG/M^2/S)
      RD0=CONC0*WS*(1-PRS)*(1-TAOCWS/TAOCD)
C INITIALIZE CONCENTRATION CHANGE
      CONCCHNG=0
C DETERMINE NUMERICAL INTEGRATION STEPS J IN 5 MINUTE INTERVALS
      J=TIMEDR/5
C INTEGRATING THE DECREASE OF CONCENTRATION DUE TO DEPOSITION
      DO 10 IT=1,J
        IF ((CONC0-CONCCHNG) .LE. 0.001) THEN
C COMPUTE THE TIME (MINUTES) WHEN CONCENTRATION DECREASED TO <1 MG/L
          TIME0=IT*5
          GOTO 20
        ENDIF
C CALCULATE STEP-WISE DEPOSITION RATE RD, DEPOSITED MASS DMASS,
C AND CONC CHANGE CONCCHNG
        RD=(CONC0-CONCCHNG)*WS*(1-PRS)*(1-TAOCWS/TAOCD)
        DMASS=RD*DELTAT
        CONCCHNG=CONCCHNG+DMASS/D
 10   CONTINUE
 20   CONC=CONC0-CONCCHNG
      GOTO 100
    ENDIF

C --------------------------------
C STABLE CASE (TAOCD<TAOCWS<TAOCE)
C --------------------------------
C FOR TAOCD<TAOCWS<TAOCE, THERE IS NO EROSION OR DEPOSITION
    IF (TAOCWS .GE. TAOCD .AND. TAOCWS .LT. TAOCE) THEN
C ASSIGN THE INITIAL CONCENTRATION AS THE CURRENT CONCENTRATION
      CONC=CONC0
      GOTO 100
    ENDIF

C --------------------------------
C EROSIONAL CASE (TAOCWS>TAOCE)
C --------------------------------
C FOR TAOCWS>TAOCE, EROSION OCCURS AND NO DEPOSITION
    IF (TAOCWS .GE. TAOCE) THEN
```

```
C DETERMINE NUMERICAL INTEGRATION STEPS J IN 5 MINUTE INTERVALS
      J=TIMEDR/5
C ASSIGN THE DEFAULT VALUE TO THE MINIMUM EROSION RATE E0 (KG/M^2/S)
      E0=0.000051
C ASSIGN VALUE TO THE EROSION PROPORTIONALITY COEFFICIENT RKERO
      RKERO=1.62
C COMPUTE THE INITIAL EROSION RATE RE0
      RE0=E0*EXP(RKERO*(TAOCWS-TAOCE)**0.5)
C INITIALIZE THE TOTAL EROSION DEPTH ZS AND TOTAL EROSION MASS EMASST (KG/M^2)
      ZS=0
      EMASST=0
C BEGIN NUMERICAL INTEGRATION FOR TOTAL EROSION MASS EMASST
      DO 30 IT=1,J
C COMPUTE THE INCREASED CRITICAL EROSION SHEAR STRESS TAOCEZ AT ZS
        TAOCEZ=TAOCE+0.01*ZS*(RHOS-RHOW)*G*DTAN(PI*PHI/180.)
C COMPUTE THE TIME WHEN TAOCEZ BECOMES EQUAL TO TAOCWS (EROSION STOPS)
        IF (TAOCWS .LT. TAOCEZ) THEN
          TIME0=5*IT
          GOTO 40
        ENDIF
C CALCULATE STEP-WISE EROSION RATE RE, ERODED MASS EMASS, AND EROSION DEPTH EDEPTH
        RE=E0*EXP(RKERO*(TAOCWS-TAOCEZ)**0.5)
        EMASS=RE*DELTAT
        EDEPTH=EMASS/RHOS
C OBTAIN TOTAL ERODED MASS AND EROSION DEPTH
        EMASST=EMASST+EMASS
        ZS=ZS+EDEPTH
 30   CONTINUE
C COMPUTE THE FINAL CONCENTRATION
 40   CONC=CONC0+EMASST/D
    ENDIF

100 CONTINUE
C OBTAIN FINAL MASS SEDIMENT TRANSPORT RATE (KG/M/S)
    SEDM=CONC*D*U100
C CONVERT TO VOLUME TRANSPORT RATE (M^3/M/S)
    SED=SEDM/RHOS
C CONVERT CONCENTRATIONS BACK TO MG/LITRE
    CONC0=1000*CONC0
    CONC=1000*CONC

    RETURN
    END
```

```
      SUBROUTINE PROFL(IRUN,RHOW,FALL,UB,CDIR,USTCS,USTWS,USTCWS,USTCWSB,USTCWSE,USTC,
     @USTW,USTCW,USTCRB,USTCRS,USTUP,Z0,Z0C,DELTACW,C0,GAMMA0,QS,QSDIR)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE PREDICTS THE VELOCITY AND SUSPENDED SEDIMENT CONCENTRATION (SSC)
C PROFILES BASED ON THE GM86 COMBINED-FLOW BBL MODEL AND THE MODIFIED ROUSE EQUATION
C ACCORDING TO GLENN AND GRANT (1987). THE CALCULATED SSC AND VELOCITY PROFILES ARE THEN
C NUMERICALLY INTEGRATED TO OBTAIN THE SUSPENDED LOAD SEDIMENT TRANSPORT RATE.
C

C INPUT VARIABLES:
C
C     CDIR = CURRENT DIRECTION
C     DELTACW = HEIGHT OF THE WAVE-CURRENT BOUNDARY LAYER
C     FALL = SAND SETTLING VELOCITY
C     RHOW = FLUID DENSITY
C     UB = WAVE ORBITAL VELOCITY
C     USTC = TOTAL CURRENT SHEAR VELOCITY
C     USTCRB = CRITICAL FLUID VELOCITY FOR INITIATION OF BEDLOAD TRANSPORT (M/S)
C     USTCRS = CRITICAL FLUID VELOCITY FOR INITIATION OF SUSPENDED LOAD TRANSPORT (M/S)
C     USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY
C     USTCW = TOTAL COMBINED WAVE AND CURRENT SHEAR VELOCITY
C     USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY
C     USTCWSB = BEDLOAD COMBINED SHEAR VELOCITY
C     USTCWSE = RIPPLE-ENHANCED SKIN-FRICTION COMBINED SHEAR VELOCITY
C     USTUP = CRITICAL FLUID VELOCITY FOR SHEET FLOW TRANSPORT (M/SEC)
C     USTW = TOTAL WAVE SHEAR VELOCITY
C     USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY
C     Z0 = BED ROUGHNESS LENGTH (M)
C     Z0C = APPARENT BED ROUGHNESS LENGTH (M)
C
C OUTPUT VARIABLES:
C     C0 = REFERENCE CONCENTRATION AT Z0 (KG/M^3)
C     GAMMA0 = SAND RESUSPENSION COEFFICIENT
C     QS = SUSPENDED SEDIMENT TRANSPORT RATE (KG/M/S)
C     QSDIR = DIRECTION OF SUSPENDED SEDIMENT TRANSPORT (DEGREE)
C
C INTERMEDIATE VARIABLES:
C
C     CB = BULK BOTTOM SEDIMENT CONCENTRATION (KG/M^3)
C     CZ = PREDICTED SUSPENDED SEDIMENT CONCENTRATION AT HEIGHT Z (KG/M^3)
C     CZD = PREDICTED SUSPENDED SEDIMENT CONCENTRATION AT DELTACW (KG/M^3)
C     TAOST = NORMALIZED EXCESS SHEAR STRESS
C     UZ = PREDICTED MEAN VELOCITY AT HEIGHT Z (M/S)
C     Z = HEIGHT ABOVE THE SEABED (M)
C     ZKAPPA = VON KARMAN CONSTANT (=0.4)

C DEFINE ARRAY VARIABLES
      DIMENSION Z(12),CZ(12),UZ(12)
C ASSIGN HEIGHTS FOR THE PREDICTIONS OF VELOCITY AND CONCENTRATION
      DATA Z /0.01,0.02,0.03,0.05,0.07,0.1,0.2,0.3,0.5,0.7,1.0,2.0/

C SET DEFAULT VALUES TO ZERO
      C0=0
      CZD=0
```

```
      GAMMA0=0
      QS=0

C ASSIGN VALUES TO CONSTANTS
      ZKAPPA=0.4
      CB=1722.5

C FOR USTCRB>USTCRS OF VERY FINE SAND, EQUAL USTCRB TO USTCRS
      IF (USTCRB .GT. USTCRS) USTCRB=USTCRS
C CONVERT SHEAR VELOCITIES TO SHEAR STRESSES
      TAOCS=RHOW*USTCS**2
      TAOWS=RHOW*USTWS**2
      TAOCWS=RHOW*USTCWS**2
      TAOCRB=RHOW*USTCRB**2

C******************************
C  COMPUTE THE VELOCITY PROFILE
C******************************
C  PURE WAVE CASE
      IF (USTCS .EQ. 0) THEN
        WRITE(*,5) IRUN
        WRITE(9,5) IRUN
 5      FORMAT(T4,'BT#',I3,' WAVE ONLY, NO VELOCITY PROFILE')
        GOTO 25
      ENDIF
C  PURE CURRENT CASE:
      IF (UB .EQ. 0) THEN
        DO 10 I=1,12,1
        UZ(I)=(USTC/ZKAPPA)*ALOG(Z(I)/Z0)
 10     CONTINUE
      ELSE
C  COMBINED WAVES ADN CURRENT:
        DO 20 I=1,12,1
        IF(Z(I) .LE. DELTACW)THEN
          UZ(I)=(USTC/ZKAPPA)*(USTC/USTCW)*ALOG(Z(I)/Z0)
        ELSE
          UZ(I)=(USTC/ZKAPPA)*ALOG(Z(I)/Z0C)
        ENDIF
 20     CONTINUE
      ENDIF

C*****************************************************
C  COMPUTE THE SUSPENDED SEDIMENT CONCENTRATION PROFILE
C*****************************************************
 25   CONTINUE
C PURE CURRENT CASE
      IF (UB .EQ. 0) THEN
        IF (USTCS .LT. USTCRS) THEN
          QS=0
          WRITE (*,30) IRUN
          WRITE (9,30) IRUN
 30       FORMAT(T4,'BT#',I3,' CURRENT ONLY, U*CS<U*CRS, '
     @    'NO SUSPENDED LOAD TRANSPORT',/)
          GOTO 300
        ELSE
          TAOST=(TAOCS-TAOCRB)/TAOCRB
```

```
C PREDICT GAMMA0 BASED ON LI ET AL. (1996)
        IF (USTCS .GT. USTCRS .AND. USTCS .LT. USTUP) THEN
          GAMMA0=0.0206*(TAOST)**(-1.931)
        ELSE
          GAMMA0=0.00013
        ENDIF
        C0=CB*GAMMA0*TAOST
        DO 40 I=1,12
          CZ(I)=C0*(Z(I)/Z0)**(-0.74*FALL/(0.4*USTC))
 40     CONTINUE
      ENDIF
    ELSE
      IF (USTCS .EQ. 0) THEN
C PURE WAVE CASE
        IF (USTWS .LT. USTCRS) THEN
          QS=0
          WRITE (*,50) IRUN
          WRITE (9,50) IRUN
 50       FORMAT(T4,'BT#',I3,' WAVE ONLY, U*WS<U*CRS, '
    @     'NO SUSPENDED LOAD TRANSPORT',/)
          GOTO 300
        ELSE
          TAOST=(TAOWS-TAOCRB)/TAOCRB
C PREDICT GAMMA0 BASED ON LI ET AL. (1996)
          IF (USTWS .GT. USTCRS .AND. USTWS .LT. USTUP) THEN
            GAMMA0=0.0206*(TAOST)**(-1.931)
          ELSE
            GAMMA0=0.00013
          ENDIF
          C0=CB*GAMMA0*TAOST
          DO 60 I=1,12
            CZ(I)=C0*(Z(I)/Z0)**(-0.74*FALL/(0.4*USTW))
 60       CONTINUE
        ENDIF
      ELSE
C COMBINED WAVE-CURRENT CASE:
C FOR USTCWSB<USTCRS, NO SUSPENSION PROFILE WILL BE PREDICTED
        IF (USTCWSB .LT. USTCRS) THEN
          QS=0
C ASSIGN ZERO VALUES TO ALL CZ(I)
          DO 70 I=1,12
            CZ(I)=0
 70       CONTINUE
          WRITE(*,80) IRUN
          WRITE(9,80) IRUN
 80       FORMAT(T4,'BT#',I3,'  U*CWSB<U*CRS, NO SUSPENSION'
    @     'LOAD TRANSPORT',/)
          GO TO 300
        ELSE
C PREDICT GAMMA0 BASED ON LI ET AL. (IN 1996)
          TAOST=(TAOCWS-TAOCRB)/TAOCRB
          IF (USTCWSB .GT. USTCRS .AND. USTCWSB .LT. USTUP) THEN
            GAMMA0=0.0206*(TAOST)**(-1.931)
          ELSE
            GAMMA0=0.00013
          ENDIF
```

```
C CALCULATE REFERENCE CONCENTRATIONS C0 AT Z0 AND CZD AT DELTACW
          C0=CB*GAMMA0*TAOST
          CZD=C0*(DELTACW/Z0)**(-0.74*FALL/(0.4*USTCW))
C PREDICT SUSPENSION PROFILE BASED ON THE MODIFIED ROUSE EQUATION
          DO 90 I=1,12
            IF (Z(I) .LE. DELTACW) THEN
              CZ(I)=C0*(Z(I)/Z0)**(-0.74*FALL/(0.4*USTCW))
            ELSE
              CZ(I)=CZD*(Z(I)/DELTACW)**(-0.74*FALL/(0.4*USTC))
            ENDIF
 90       CONTINUE
        ENDIF
      ENDIF
    ENDIF

C**********************************************************************
C  INTEGRATE VELOCITY AND SSC PROFILE FOR SUSPENDED LOAD TRANSPORT RATE
C**********************************************************************
    Z(0)=0
    DO 95 I=1,12
      QS=QS+(Z(I)-Z(I-1))*UZ(I)*CZ(I)
 95 CONTINUE
C  ASSIGN THE CURRENT DIRECTION AS THE DIRECTION OF QS
    QSDIR=CDIR

C**********************************************************************
C  OUTPUT THE PROFILES TO THE SCREEN AND THE OUTPUT DATA FILE "PROFILE.DAT"
C**********************************************************************
    WRITE(*,'(/,''********************'')')
    WRITE(*,100) IRUN
    WRITE(9,100) IRUN
100  FORMAT(T4,'BT# 'I3,/,
   @T4,'HEIGHT,M  VEL.M/S  CONC. KG/M^3')
    DO 200 I=1,12
      WRITE(*,'(3(F10.6))')Z(I),UZ(I),CZ(I)
      WRITE(9,'(3(F10.6))')Z(I),UZ(I),CZ(I)
200  CONTINUE

300  CONTINUE
    RETURN
    END
```

```
      SUBROUTINE BEDFORM(U100,UA,UB,GD,FCW,PHIB,RHOW,RHOS,AB,IOPT1,RHEIGHT,RLENGTH,USTCS,
     @USTWS,USTCWS,USTCWSE,USTCWSB,USTCRB,USTUP)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE PREDICTS THE EXPECTED TYPES OF BEDFORM FOR THE GIVEN FLOW CONDITIONS.
C THE BEDFORM TYPE IS ONLY APPROXIMATE FOR COARSE AND VERY COARSE SANDS SINCE IT IS BASED
C ON VELOCITY MEASUREMENTS ONLY. THE LIMITS ARE FROM AMOS (1990) AND LI AND AMOS (IN
C PRESS). RIPPLE DIMENSION FOR FINE AND MEDIUM SANDS IS PREDICTED IN FRICFAC SUBROUTINE.
C

C  INPUT VARIABLES:
C
C       U100 = CURRENT SPEED AT 1 M. ABOVE SEABED ( M/SEC)
C       UA = MEAN VELOCITY AT TOP OF THE WAVE BOUNDARY LAYER (M/SEC)
C       UB = MAXIMUM WAVE-INDUCED BOTTOM PARTICLE VELOCITY (M/SEC)
C       GD = SEDIMENT GRAIN SIZE (M)
C       FCW = BOTTOM (SKIN) FRICTION FACTOR
C       PHIB = ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS WITHIN THE
C               WAVE BOUNDARY LAYER (RADIANS)
C       RHOS = DENSITY OF SEDIMENT   (KG/M**3)
C       RHOW = DENSITY OF FLUID  (KG/M**3)
C       AB = EXCURSION LENGTH OF BOTTOM WAVE ORBIT (M)
C       IOPT1 = SEDIMENT TRANSPORT FORMULA OPTION NUMBER
C       RHEIGHT = PREDICTED RIPPLE HEIGHT (M)
C       RLENGTH = PREDICTED RIPPLE LENGTH (M)
C       USTCS = SKIN-FRICTION CURRENT SHEAR VELOCITY (M/S)
C       USTWS = SKIN-FRICTION WAVE SHEAR VELOCITY (M/S)
C       USTCWS = SKIN-FRICTION COMBINED SHEAR VELOCITY (M/)
C       USTCWSE = RIPPLE-ENHANCED COMBINED SHEAR VELOCITY (M/S)
C       USTCWSB = BEDLOAD-RELATED COMBINED SHEAR VELOCITY (M/S)
C       USTCRB = CRITICAL SHEAR VELOCITY FOR BEDLOAD TRANSPORT (M/SEC)
C       USTCRS = CRITICAL SHEAR VELOCITY FOR SUSPENDED LOAD TRANSPORT (M/SEC)
C       USTUP  = CRITICAL SHEAR VELOCITY FOR SHEET FLOW (M/SEC)
C
C INTERMEDIATE VARIABLES
C
C       VISC = DYNAMIC VISCOSITY OF THE FLUID (KG/M*SEC (OR N.S/M**2))
C       VISK = KINEMATIC VISCOSITY OF FLUID (M**2/SEC)
C       SST = DIMENSIONLESS SEDIMENT GRAIN SIZE PARAMETER
C       PSICR = CRITICAL SHIELDS PARAMETER FOR BEDLOAD TRANSPORT
C       PSIBF = CRITICAL SHIELDS PARAMETER FOR RIPPLE BREAK-OFF
C       USTBF = CRITICAL SHEAR VELOCITY FOR RIPPLE BREAK-OFF
C       PSIWS = SKIN-FRICTION WAVE SHIELDS PARAMETER
C       PSICS = SKIN-FRICTION CURRENT SHIELDS PARAMETER
C
      G = 9.81
      VISC = 1.3D-3
      VISK = VISC/RHOW
      S = RHOS/RHOW
      SST = GD*((S-1)*G*GD)**0.5/(4*VISK)
      PSICR = (USTCRB**2)/((S-1)*G*GD)
      PSIBF = 1.8*(SST**0.6)*PSICR
      USTBF = (PSIBF*(S-1)*G*GD)**0.5
      PSIWS=RHOW*FCW*UB*UB/(2.*(RHOS-RHOW)*G*GD)
      PSICS=RHOW*USTCS**2
```

```
      PI = 2.*ASIN(1.)
      IF (USTCS .EQ. 0) THEN
        RATIO=1
      ELSE
        RATIO=USTWS/USTCS
      ENDIF

C ----------------------------------------------------
C SKIP THE BEDFORM SECTION IF SEDIMENTS ARE COHESIVE
C ----------------------------------------------------
      IF (IOPT1.EQ.5) THEN
        WRITE (*,1005)
        WRITE (7,1005)
        GOTO 1010
      ENDIF

C ----------------------------------------------------
C SET UP FORMAT STATEMENTS
C ----------------------------------------------------
      WRITE (*,15)
      WRITE (7,15)
 15   FORMAT(/,T11,'EXPECTED BEDFORMS ARE ',
     @'(AMOS, 1990; LI AND AMOS, IN PREP.):',/)

C WAVES ONLY
 20   FORMAT(T21,'WAVE INDUCED BEDFORMS:')
 25   FORMAT(T21,'WAVE RIPPLES')
 30   FORMAT(T21,'WAVE RIPPLES OR WAVE-INDUCED (UPPER) FLAT BED')
 35   FORMAT(T21,'WAVE-INDUCED (UPPER) FLAT BED')

C CURRENTS ONLY
 40   FORMAT(T21,'CURRENT INDUCED BEDFORMS:')
 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,'UPPER FLAT BED AND SEDIMENT IN SUSPENSION')

C COMBINED WAVES AND CURRENTS
155   FORMAT(T21,'NO TRANSPORT')
156   FORMAT(T21,'NO TRANSPORT  FLAT BED')
165   FORMAT(T21,'BEDFORMS UNKNOWN FOR CO-DIRECTIONAL MIXED FLOW',/,
     &T21,'CONDITIONS BUT:')
166   FORMAT(T21,'WORK BY AMOS ET AL (1987) SHOWS THAT INDEPENDENT',/,
     &T21,'WAVE AND CURRENT BEDFORMS MAY EXIST WHICH WOULD BE:',/)
167   FORMAT(T21,'COMBINED-FLOW BEDFORMS PREDICTED BASED ON ',/,
     &T21,'SIB DATA OF LI AND AMOS (IN PRESS)',/)
168   FORMAT(T21,'WEAK-TRANSPORT RIPPLES')
169   FORMAT(T21,'BREAK-OFF RIPPLES')
170   FORMAT(T21,'EQUILIBRIUM RIPPLES')
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171  FORMAT(T21,'CURRENT-DOMINATED RIPPLES')
172  FORMAT(T21,'WAVE-CURRENT RIPPLES')
173  FORMAT(T21,'WAVE-DOMINATED RIPPLES')
175  FORMAT(T21,'POSSIBLE GRAVEL RIPPLES (E.G. .2 M HIGH & 2 M LONG)'
    &,/,T21,'(SEE FORBES AND BOYD (1987) FOR FURTHER DETAIL)')
185  FORMAT(T21,'BEDFORM DIMENSIONS NOT YET AVAILABLE')
265  FORMAT(T21,'BEDFORMS UNKNOWN FOR ORTHOGONAL MIXED FLOW CONDITIONS
    &',/,T21,'FOR OTHER THAN VERY FINE-MEDIUM SAND BUT:')
266  FORMAT(T21,'WORK BY AMOS ET AL (1987) SHOWS THAT INDEPENDENT',/,
    &T21,'WAVE AND CURRENT BEDFORMS EXIST WHICH ARE:',/)
405  FORMAT(T21,'VERY COARSE SAND (WENTWORTH SCALE)')
415  FORMAT(T21,'COARSE SAND (WENTWORTH SCALE)')
425  FORMAT(T21,'MEDIUM SAND (WENTWORTH SCALE)')
435  FORMAT(T21,'FINE OR VERY FINE SAND (WENTWORTH SCALE)')
445  FORMAT(T21,'SILT OR CLAY (WENTWORTH SCALE)'
    &,/,T21,'NO BEDFORM DATA AVAILABLE')
505  FORMAT(T21,'CURRENT-DOMINATED BEDFORMS')
512  FORMAT(T21,'WAVE-DOMINATED BEDFORMS')
513  FORMAT(T21,'POORLY DEVELOPED RIPPLES MAY EXIST DEPENDING ON',/,T21
    &,'LOCAL BIOTURBATION RATES AND BROADNESS OF WAVE SPECTRUM')
605  FORMAT(T21,'WAVE RIPPLE LENGTH FROM BOYD ET AL (1988) =',F6.3,
    &' M',/,T21,'WAVE RIPPLE HEIGHT FROM ALLEN (1970)      =',F6.3,
    &' M')
610  FORMAT(T21,'CURRENT RIPPLE LENGTH FROM YALIN (1964) =',F6.3,
    &' M',/,T21,'RIPPLE HEIGHT FROM ALLEN (1970)         =',F6.3,' M')
620  FORMAT (T21,'RIPPLE HEIGHT= ',F7.3,' M',/,
    &T21,'RIPPLE LENGTH= ',F7.3,' M')
1005  FORMAT(//,T11,'NO BEDFORM ESTIMATES FOR COHESIVE SEDIMENTS ')

C -------------------------------------------------------------------
C GRANULE AND GRAVEL SIZES (WENTWORTH SCALE) UNDER ALL FLOW CONDITIONS
C -------------------------------------------------------------------
    IF (GD .GT. 0.002) THEN
      WRITE(7,175)
      WRITE(*,175)
      RETURN
    ENDIF

C -------------------------------------------------------------------
C  FOR CLAY OR SILT (WENTWORTH SCALE), BEDFORM WILL NOT BE PREDICTED
C -------------------------------------------------------------------
    IF (GD .LE. 0.000063) THEN
      WRITE(7,445)
      WRITE(*,445)
      RETURN
    ENDIF

C ----------------------
C FOR SAND SEDIMENT
C ----------------------
C SINCE THE GRAIN SIZE CLASSIFICATION IS BASED ON THE WENTWORTH SCALE WHICH IS BASED ON
C PHI SIZES, THE PHI UNITS CAN BE USED TO DIRECT THIS PROGRAM.
C PHI IS THE NEXT HIGHEST PHI UNIT (  IE VERY FINE SAND     =4
C                                        FINE SAND          =3
C                                        MEDIUM SAND        =2
C                                        COARSE SAND        =1
```

```
C                                      VERY COARSE SAND       =0)
C OBTAIN THE CONVERSION COEFFICIENT FROM METER TO PHI
      CONV=4.D0/DLOG(0.0625D0)
C CALCULATE PHI VALUE
      PHI=CONV*DLOG(1000.D0*GD/2.D0)
C GET THE INTEGER OF PHI AND GOTO RESPECTIVE SECTIONS FOR BEDFORM TYPE PREDICTION
      GOTO (1,2,3,4,5) INT(PHI+1)

C
C VERY COARSE SAND (WENTWORTH SCALE)
C
  1   CONTINUE
      WRITE(7,405)
      WRITE(*,405)
      WRITE(7,185)
      WRITE(*,185)
C --- FIRST, CHECK FOR COMBINED FLOW CONDITIONS
      IF (UB .NE. 0. .AND. UA .NE. 0.) THEN
        IF (PHIB*180/PI .LE. 45.) THEN
C CO-DIRECTIONAL WAVES AND CURRENTS
          WRITE (*,165)
          WRITE (7,165)
          WRITE (*,166)
          WRITE (7,166)
        ELSE
C ORTHOGONAL WAVES AND CURRENTS
          WRITE (*,265)
          WRITE (7,265)
          WRITE (*,166)
          WRITE (7,166)
        ENDIF
C PREDICT BEDFORM TYPES BASED ON THE RATIO OF PSIWS/PSICS
        IF (RATIO .GE. 1) THEN
C WAVE-DOMINANT BEDFORMS
          WRITE (*,512)
          WRITE (7,512)
          IF (UB .LT. 0.3) WRITE (*,155)
          IF (UB .LT. 0.3) WRITE (7,155)
          IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (*,25)
          IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (7,25)
          IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (*,30)
          IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (7,30)
          IF (UB .GE. 2.0) WRITE (*,35)
          IF (UB .GE. 2.0) WRITE (7,35)
        ELSE
C CURRENT-DOMINANT BEDFORMS
          WRITE (*,505)
          WRITE (7,505)
          IF (U100 .LT. 0.4) WRITE (*,155)
          IF (U100 .LT. 0.4) WRITE (7,155)
          IF (U100 .GE. 0.4 .AND. U100 .LE. 0.45) WRITE (*,95)
          IF (U100 .GE. 0.4 .AND. U100 .LE. 0.45) WRITE (7,95)
          IF (U100 .GE. 0.45 .AND. U100 .LE. 0.5) WRITE (*,75)
          IF (U100 .GE. 0.45 .AND. U100 .LE. 0.5) WRITE (7,75)
          IF (U100 .GE. 0.5 .AND. U100 .LE. 0.6) WRITE (*,95)
```

```
        IF (U100 .GE. 0.5 .AND. U100 .LE. 0.6) WRITE (7,95)
        IF (U100 .GE. 0.6 .AND. U100 .LE. 1.0) WRITE (*,105)
        IF (U100 .GE. 0.6 .AND. U100 .LE. 1.0) WRITE (7,105)
        IF (U100 .GE. 1.0 .AND. U100 .LE. 2.95) WRITE (*,135)
        IF (U100 .GE. 1.0 .AND. U100 .LE. 2.95) WRITE (7,135)
        IF (U100 .GE. 2.95) WRITE (*,145)
        IF (U100 .GE. 2.95) WRITE (7,145)
      ENDIF
    ENDIF
C --- PURE WAVE CASE
    IF (UB .NE. 0.0 .AND. UA .EQ. 0) THEN
      WRITE (*,20)
      WRITE (7,20)
      IF (UB .LT. 0.3) WRITE (*,155)
      IF (UB .LT. 0.3) WRITE (7,155)
      IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (*,25)
      IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (7,25)
      IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (*,30)
      IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (7,30)
      IF (UB .GE. 2.0) WRITE (*,35)
      IF (UB .GE. 2.0) WRITE (7,35)
    ENDIF
C --- PURE CURRENT CASE
    IF (UA .NE. 0.0 .AND. UB .EQ. 0) THEN
      WRITE (*,40)
      WRITE (7,40)
      IF (U100 .LT. 0.4) WRITE (*,155)
      IF (U100 .LT. 0.4) WRITE (7,155)
      IF (U100 .GE. 0.4 .AND. U100 .LE. 0.45) WRITE (*,95)
      IF (U100 .GE. 0.4 .AND. U100 .LE. 0.45) WRITE (7,95)
      IF (U100 .GE. 0.45 .AND. U100 .LE. 0.5) WRITE (*,75)
      IF (U100 .GE. 0.45 .AND. U100 .LE. 0.5) WRITE (7,75)
      IF (U100 .GE. 0.5 .AND. U100 .LE. 0.6) WRITE (*,95)
      IF (U100 .GE. 0.5 .AND. U100 .LE. 0.6) WRITE (7,95)
      IF (U100 .GE. 0.6 .AND. U100 .LE. 1.0) WRITE (*,105)
      IF (U100 .GE. 0.6 .AND. U100 .LE. 1.0) WRITE (7,105)
      IF (U100 .GE. 1.0 .AND. U100 .LE. 2.95) WRITE (*,135)
      IF (U100 .GE. 1.0 .AND. U100 .LE. 2.95) WRITE (7,135)
      IF (U100 .GE. 2.95) WRITE (*,145)
      IF (U100 .GE. 2.95) WRITE (7,145)
    ENDIF
    RETURN
C
C COARSE SAND (WENTWORTH SCALE)
C
  2 CONTINUE
    WRITE(7,415)
    WRITE(*,415)
    WRITE(7,185)
    WRITE(*,185)
C --- FIRST, CHECK FOR COMBINED FLOW CONDITIONS
    IF(UB.NE.0. .AND. UA.NE.0.)THEN
      IF(PHIB*180/PI .LE. 45.)THEN
C CO-DIRECTIONAL WAVES AND CURRENTS
        WRITE (*,165)
        WRITE (7,165)
```

```
          WRITE (*,166)
          WRITE (7,166)
        ELSE
C ORTHOGONAL WAVES AND CURRENTS
          WRITE (*,265)
          WRITE (7,265)
          WRITE (*,166)
          WRITE (7,166)
        ENDIF
C PREDICT BEDFORM TYPES BASED ON THE RATIO OF PSIWS/PSICS
        IF (RATIO .GE. 1) THEN
C WAVE-DOMINANT BEDFORMS
          WRITE (*,512)
          WRITE (7,512)
          IF (UB .LT. 0.3) WRITE (*,155)
          IF (UB .LT. 0.3) WRITE (7,155)
          IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (*,25)
          IF (UB .GE. 0.3 .AND. UB .LT. 1.0) WRITE (7,25)
          IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (*,30)
          IF (UB .GE. 1.0 .AND. UB .LT. 2.0) WRITE (7,30)
          IF (UB .GE. 2.0) WRITE (*,35)
          IF (UB .GE. 2.0) WRITE (7,35)
        ELSE
C CURRENT-DOMINANT BEDFORMS
          WRITE (*,505)
          WRITE (7,505)
          IF (U100 .LT. 0.25) WRITE (*,155)
          IF (U100 .LT. 0.25) WRITE (7,155)
          IF (U100 .GE. 0.25 .AND. U100 .LT. 0.35) WRITE (*,45)
          IF (U100 .GE. 0.25 .AND. U100 .LT. 0.35) WRITE (7,45)
          IF (U100 .GE. 0.35 .AND. U100 .LT. 0.4) WRITE (*,55)
          IF (U100 .GE. 0.35 .AND. U100 .LT. 0.4) WRITE (7,55)
          IF (U100 .GE. 0.4 .AND. U100 .LT. 0.45) WRITE (*,65)
          IF (U100 .GE. 0.4 .AND. U100 .LT. 0.45) WRITE (7,65)
          IF (U100 .GE. 0.45 .AND. U100 .LT. 0.5) WRITE (*,85)
          IF (U100 .GE. 0.45 .AND. U100 .LT. 0.5) WRITE (7,85)
          IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (*,95)
          IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (7,95)
          IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (*,115)
          IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (7,115)
          IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (*,125)
          IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (7,125)
          IF (U100 .GE. 1.5 .AND. U100 .LT. 2.4) WRITE (*,135)
          IF (U100 .GE. 1.5 .AND. U100 .LT. 2.4) WRITE (7,135)
          IF (U100 .GE. 2.4) WRITE (*,145)
          IF (U100 .GE. 2.4) WRITE (7,145)
        ENDIF
      ENDIF
C --- PURE WAVE CASE
      IF (UB .NE. 0.0 .AND. UA .EQ. 0) THEN
        WRITE (*,20)
        WRITE (7,20)
        IF (UB .LT. 0.2) WRITE (*,155)
        IF (UB .LT. 0.2) WRITE (7,155)
        IF (UB .GE. 0.2 .AND. UB .LT. 0.9) WRITE (*,25)
        IF (UB .GE. 0.2 .AND. UB .LT. 0.9) WRITE (7,25)
```

```
        IF (UB .GE. 0.9 .AND. UB .LT. 1.25) WRITE (*,30)
        IF (UB .GE. 0.9 .AND. UB .LT. 1.25) WRITE (7,30)
        IF (UB .GE. 1.25) WRITE (*,35)
        IF (UB .GE. 1.25) WRITE (7,35)
      ENDIF
C --- PURE CURRENT CASE
      IF (UA .NE. 0.0 .AND. UB .EQ. 0) THEN
        WRITE (*,40)
        WRITE (7,40)
        IF (U100 .LT. 0.25) WRITE (*,155)
        IF (U100 .LT. 0.25) WRITE (7,155)
        IF (U100 .GE. 0.25 .AND. U100 .LT. 0.35) WRITE (*,45)
        IF (U100 .GE. 0.25 .AND. U100 .LT. 0.35) WRITE (7,45)
        IF (U100 .GE. 0.35 .AND. U100 .LT. 0.4) WRITE (*,55)
        IF (U100 .GE. 0.35 .AND. U100 .LT. 0.4) WRITE (7,55)
        IF (U100 .GE. 0.4 .AND. U100 .LT. 0.45) WRITE (*,65)
        IF (U100 .GE. 0.4 .AND. U100 .LT. 0.45) WRITE (7,65)
        IF (U100 .GE. 0.45 .AND. U100 .LT. 0.5) WRITE (*,85)
        IF (U100 .GE. 0.45 .AND. U100 .LT. 0.5) WRITE (7,85)
        IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (*,95)
        IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (7,95)
        IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (*,115)
        IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (7,115)
        IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (*,125)
        IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (7,125)
        IF (U100 .GE. 1.5 .AND. U100 .LT. 2.4) WRITE (*,135)
        IF (U100 .GE. 1.5 .AND. U100 .LT. 2.4) WRITE (7,135)
        IF (U100 .GE. 2.4) WRITE (*,145)
        IF (U100 .GE. 2.4) WRITE (7,145)
      ENDIF
      RETURN
C
C  MEDIUM SAND (WENTWORTH SCALE)
C
  3   CONTINUE
      WRITE(7,425)
      WRITE(*,425)
C  FIRST, CHECK FOR COMBINED FLOW CONDITIONS. IF NOT, GO TO 31
      IF(UB.EQ.0. .OR. UA.EQ.0.) GOTO 31
C GO TO 10 FOR BEDFORM TYPES AND DIMENSION UNDER COMBINED FLOWS
      GOTO 10
C
C FINE SAND (WENTWORTH SCALE)
C
  4   CONTINUE
      WRITE(7,435)
      WRITE(*,435)
C --- FIRST, CHECK FOR COMBINED FLOW CONDITIONS. IF NOT, GO TO 41.
      IF(UB.EQ.0. .OR. UA.EQ.0.) GOTO 41
C GO TO 10 FOR BEDFORM TYPES AND DIMENSION UNDER COMBINED FLOWS
      GOTO 10
C
C VERY FINE SAND (WENTWORTH SCALE)
C
  5   CONTINUE
      WRITE(7,435)
```

```
      WRITE(*,435)
C --- FIRST, CHECK FOR COMBINED FLOW CONDITIONS. IF NOT, GO TO 41.
      IF(UB.EQ.0. .OR. UA.EQ.0.) GOTO 41

 10   CONTINUE
C PREDICT BEDFORM TYPES AND DIMENSIONS UNDER COMBINED FLOWS BASED ON LI AND
C AMOS (IN PRESS)
      WRITE(7,167)
      WRITE(*,167)
C NO TRANSPORT IF RIPPLE-ENHANCED SHEAR VELOCITY < CRITICAL SHEAR VELOCITY
      IF (USTCWSE .LT. USTCRB) THEN
        WRITE(7,155)
        WRITE(*,155)
        GOTO 1007
      ENDIF
C UPPER FLAT BED PREDICTED IF BEDLOAD-ENHANCED UST > SHEET-FLOW THRESHOLD
      IF (USTCWSB .GE. USTUP) THEN
        WRITE(7,145)
        WRITE(*,145)
        GOTO 1007
      ENDIF
C WEAK-TRANSPORT RIPPLES
      IF (USTCWSE .GE. USTCRB .AND. USTCWS .LT. USTCRB) THEN
        WRITE(7,168)
        WRITE(*,168)
        GOTO 1007
      ENDIF
C BREAK-OFF RIPPLES
      IF (USTCWSB .GE. USTBF) THEN
        WRITE(7,169)
        WRITE(*,169)
C EQUILIBRIUM RIPPLES
      ELSE
        WRITE(7,170)
        WRITE(*,170)
      ENDIF
C PREDICT SUB-TYPES FOR EQUILIBRIUM AND BREAK-OFF RIPPLES
      IF (RATIO .LT. 0.75) THEN
        WRITE(7,171)
        WRITE(*,171)
      ENDIF
      IF (RATIO .GE. 0.75 .AND. RATIO .LE. 1.25) THEN
        WRITE(7,172)
        WRITE(*,172)
      ENDIF
      IF (RATIO .GT. 1.25) THEN
        WRITE(7,173)
        WRITE(*,173)
      ENDIF
C MOVE TO 1007 FOR PRINTING OUT COMBINED-FLOW RIPPLE HEIGHT AND LENGTH OBTAINED
C FROM FRICFAC.FOR SUBROUTINE
      GOTO 1007

C MEDIUM SAND, NON COMBINED-FLOW CASES
 31   CONTINUE
C PURE WAVE CASE, MEDIUM SAND
```

```
      IF (UB .NE. 0.0) THEN
        WRITE (*,20)
        WRITE (7,20)
        IF (USTWS .LT. USTCRB) WRITE (7,155)
        IF (USTWS .LT. USTCRB) WRITE (*,155)
        IF (USTWS .GE. USTCRB .AND. USTWS .LT. USTUP) WRITE (7,25)
        IF (USTWS .GE. USTCRB .AND. USTWS .LT. USTUP) WRITE (*,25)
        IF (USTWS .GE. USTUP) WRITE (7,35)
        IF (USTWS .GE. USTUP) WRITE (*,35)
        IF (UB .GE. 1.0) WRITE (7,35)
        IF (UB .GE. 1.0) WRITE (*,35)
C FOR WAVE RIPPLE HEIGHT AND LENGTH PREDICTION, MOVE TO 43
        GOTO 43
      ENDIF
C  PURE CURRENT CASE, MEDIUM SAND
      IF (UA .NE. 0.0) THEN
        WRITE (*,40)
        WRITE (7,40)
        IF (USTCS .LT. USTCRB) WRITE (7,155)
        IF (USTCS .LT. USTCRB) WRITE (*,155)
        IF (USTCS .GE. USTCRB .AND. USTCS .LT. USTUP) THEN
          IF (U100 .LT. 0.5) WRITE (7,45)
          IF (U100 .LT. 0.5) WRITE (*,45)
          IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (7,85)
          IF (U100 .GE. 0.5 .AND. U100 .LT. 0.6) WRITE (*,85)
          IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (7,115)
          IF (U100 .GE. 0.6 .AND. U100 .LT. 1.0) WRITE (*,115)
          IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (7,125)
          IF (U100 .GE. 1.0 .AND. U100 .LT. 1.5) WRITE (*,125)
          IF (U100 .GE. 1.5) WRITE (7,135)
          IF (U100 .GE. 1.5) WRITE (*,135)
        ENDIF
        IF (USTCS .GE. USTUP) WRITE (7,145)
        IF (USTCS .GE. USTUP) WRITE (*,145)
C FOR CURRENT RIPPLE HEIGHT AND LENGTH PREDICTION, MOVE TO 44
        GOTO 44
      ENDIF
      RETURN

C FINE AND VERY FINE SANDS, NON-COMBINED FLOW CASES
 41   CONTINUE
C PURE WAVE CASE, FINE AND VERY-FINE SANDS
      IF (UB .NE. 0.0) THEN
        WRITE (7,20)
        WRITE (*,20)
        IF (USTWS .LT. USTCRB) WRITE (7,155)
        IF (USTWS .LT. USTCRB) WRITE (*,155)
        IF (USTWS .GE. USTCRB .AND. USTWS .LT. USTUP) WRITE (7,25)
        IF (USTWS .GE. USTCRB .AND. USTWS .LT. USTUP) WRITE (*,25)
        IF (USTWS .GE. USTUP) WRITE (7,35)
        IF (USTWS .GE. USTUP) WRITE (*,35)
C FOR WAVE RIPPLE HEIGHT AND LENGTH PREDICTION, GO TO 43
        GOTO 43
      ENDIF
C PURE CURRENT CASE, FINE AND VERY-FINE SAND
      IF (UB .EQ. 0.0) THEN
```

```
        WRITE (7,40)
        WRITE (*,40)
        IF (USTCS .LT. USTCRB) WRITE (7,155)
        IF (USTCS .LT. USTCRB) WRITE (*,155)
        IF (USTCS .GE. USTCRB .AND. USTCS .LT. USTUP) WRITE (7,45)
        IF (USTCS .GE. USTCRB .AND. USTCS .LT. USTUP) WRITE (*,45)
        IF (USTCS .GE. USTUP) WRITE (7,145)
        IF (USTCS .GE. USTUP) WRITE (*,145)
C FOR CURRENT RIPPLE HEIGHT AND LENGTH PREDICTION, GO TO 44
        GOTO 44
      ENDIF

 43   CONTINUE
C --- PREDICTING RIPPLE DIMENSION FOR WAVE-INDUCED RIPPLES
C FIRST CHECK FOR POORLY-DEVELOPED RIPPLES
      IF(PSICS.LT.0.04 .AND. (PSIWS+PSICS).GE.0.04 .AND.
     &(PSIWS+PSICS).LT.0.18 )THEN
        WRITE(*,513)
        WRITE(7,513)
      ENDIF
C PRINT OUT DIMENSIONS OF WAVE-INDUCED RIPPLES OF BOYD ET AL. (1988) AND ALLEN (1970) AS
C PREDICTED IN FRICFAC SUBROUTINE
      RL=RLENGTH
      RH=RHEIGHT
      WRITE(*,605)RL,RH
      WRITE(7,605)RL,RH
      GOTO 1010

 44   CONTINUE
C --- PREDICTING RIPPLE DIMENSION FOR CURRENT-INDUCED RIPPLES. DIMENSIONS OF CURRENT RIPPLES
C AFTER YALIN (1964) AND ALLEN (1970) ARE DONE IN FRICFAC AND ARE MERELY PRINTED OUT HERE
      RL=RLENGTH
      RH=RHEIGHT
      WRITE(*,610)RL,RH
      WRITE(7,610)RL,RH
      GOTO 1010

1007  CONTINUE
C --- PREDICTING RIPPLE DIMENSION FOR COMBINED-FLOW RIPPLES. COMBINED-FLOW RIPPLE HEIGHT
C AND LENGTH ARE PREDICTED IN FRICFAC SUBROUTINE AND ARE MERELY PRINTED OUT HERE
      WRITE(7,620) RHEIGHT,RLENGTH
      WRITE(*,620) RHEIGHT,RLENGTH

1010  RETURN
      END
```

```
      SUBROUTINE OUTOUT(IRUN,RHOW,UB,AB,WL,FCW,DELTACW,UA,U100,PHIB,USTCS,USTWS,USTCWS,
     @USTCWSB,USTC,USTW,USTCW,Z0,Z0C,RHEIGHT,RLENGTH,USTCRB,USTCRS,TS1,TB1,TS2,TB2,
     @PERBED,PERSUSP,IOPT1,RK,QS,QSDIR,SEDM,SED,SEDDIR,CONC,TAOCE,TAOCD,RD0,RD,RE0,RE,
     @TIME0,CONC0,QS0)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C THIS SUBROUTINE WRITES THE VALUES OF THE OUTPUT PARAMETERS FROM ALL SUBROUTINES
C

C OBTAIN BOTTOM SHEAR STRESS TAO0
      IF (UB .EQ. 0) THEN
        TAO0=RHOW*USTCS**2
      ELSE
        IF (USTCS .EQ. 0) THEN
          TAO0=RHOW*USTWS**2
        ELSE
          TAO0=RHOW*USTCWS**2
        ENDIF
      ENDIF

C ------------------------------------
C OUTPUT WAVE AND CURRENT PARAMETERS
C ------------------------------------
      WRITE (*,15)
      WRITE (7,15)
 15   FORMAT(/,T4,'RESULTS:',/)
      WRITE (*,25) UB,AB,WL
      WRITE (7,25) UB,AB,WL
 25   FORMAT(T11,'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'VELOCITY, FROM LINEAR WAVE THEORY',T56,'=',F8.3,' M/SEC',/,T11,
     @'MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE',/,T11,
     @'DISPLACEMENT, FROM LINEAR WAVE THEORY',T56,'=',F8.3,' M',/,T11,
     @'WAVELENGTH, FROM LWT DISPERSION EQUATION =',F7.2,' M',/)
      WRITE (*,35) FCW
      WRITE (7,35) FCW
 35   FORMAT(T11,'BOTTOM FRICTION FACTOR =',F7.4)
      IF (UB .EQ. 0.0) THEN
        WRITE (*,45)
        WRITE (7,45)
 45     FORMAT(T11,'(STERNBERG, 1971)')
      ELSE IF (UA .EQ. 0.0) THEN
        WRITE (*,55)
        WRITE (7,55)
 55     FORMAT(T11,'(JONSSON, 1966)')
      ELSE
        WRITE (*,65)
        WRITE (7,65)
 65     FORMAT(T11,'(GRANT AND MADSEN, 1986)')
      ENDIF
      WRITE (*,75) U100,UA,PHIB*90./ASIN(1.)
      WRITE (7,75) U100,UA,PHIB*90./ASIN(1.)
 75   FORMAT(T11,'CURRENT SPEED 1 M. ABOVE SEABED',T53,'=',F7.2,
     @' M/SEC',/,T11,'CURRENT SPEED TO BE USED IN BOTTOM STRESS',/,T11,
     @'CALCULATIONS',T53,'=',F7.2,' M/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',/T11)

C -----------------------------------------------------------
C OUTPUT CRITICAL SHEAR STRESSES AND TIMES OF TRANSPORT MODES
C -----------------------------------------------------------
C FOR COHESIVE SEDIMENTS, SKIP OUTPUTTING
      IF (IOPT1.EQ.5) GOTO 110

      WRITE (*,85) USTCRB,USTCRS
      WRITE (7,85) USTCRB,USTCRS
 85   FORMAT(T11,'CRITICAL SHEAR VELOCITY FOR INITIATION OF',/,T11,
     @'BEDLOAD TRANSPORT',T53,'=',F7.4,' M/SEC',/,T11,
     @'CRITICAL SHEAR VELOCITY FOR INITIATION OF',/,T11,
     @'SUSPENDED LOAD TRANSPORT',T53,'=',F7.4,' M/SEC',/)
      WRITE (*,95) TS1,TB1,TS2,TB2
      WRITE (7,95) TS1,TB1,TS2,TB2
 95   FORMAT(T11,'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT CEASES',T54,'=',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'SUSPENDED LOAD TRANSPORT RECOMMENCES       =',F6.2,' SEC',/,T11,
     @'TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH',/,T11,
     @'BEDLOAD TRANSPORT RECOMMENCES              =',F6.2,' SEC',/)
      WRITE (*,105) PERBED,PERSUSP
      WRITE (7,105) PERBED,PERSUSP
105   FORMAT(T11,'PERCENT OF TIME IN ONLY BEDLOAD TRANSPORT PHASE   ='
     &,F7.2,/,
     @T11,'PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE =',F7.2,/)

C -----------------------------------
C OUTPUTS OF COHESIVE SEDIMENT METHOD
C -----------------------------------
110   CONTINUE
      IF (IOPT1.EQ.5) THEN
        IF (TAO0 .LT. TAOCD) THEN
          WRITE (*,120) RD0,RD
          WRITE (7,120) RD0,RD
120       FORMAT(T11,'TAO0<TAOCD, DEPOSITION ONLY.',/,T11,
     @    'THE INITIAL DEPOSITION RATE = ',F8.6,' (KG/M^2/S)',/,T11,
     @    'THE FINAL DEPOSITION RATE = ',F8.6,' (KG/M^2/S)')
          IF (TIME0 .NE. 0) THEN
            WRITE (*,130) TIME0
            WRITE (7,130) TIME0
130         FORMAT(T11,'CONC DEPLETED IN ',F4.0,' MINUTES')
          ENDIF
        ENDIF
        IF (TAO0 .GE. TAOCD .AND. TAO0 .LT. TAOCE) THEN
          WRITE (*,140)
          WRITE (7,140)
140       FORMAT(/,T11,'TAOCD<TAO0<TAOCE, NO DEPOSITION OR EROSION')
        ENDIF
        IF (TAO0 .GE. TAOCE) THEN
          WRITE (*,150)RE0,RE
          WRITE (7,150)RE0,RE
```

```
150        FORMAT(/,T11,'TAO0>=TAOCE, EROSION OCCURRED.',/,T11,
    @      'THE INITIAL EROSION RATE = ',F8.6,' (KG/M^2/S)',/,T11,
    @      'THE FINAL EROSION RATE = ',F8.6,' (KG/M^2/S)')
          IF (TIMEO .NE. 0) THEN
            WRITE (*,160) TIMEO
            WRITE (7,160) TIMEO
160         FORMAT(/,T11,'TAOCE EQUALLED TAO0 IN',F4.0,' MINUTES')
          ENDIF
        ENDIF
      ENDIF

C -------------------------------------------
C OUTPUT SEDIMENT TRANSPORT RATE AND DIRECTION
C -------------------------------------------
      WRITE (*,170) SEDDIR,SED,SEDM
      WRITE (7,170) SEDDIR,SED,SEDM
170  FORMAT(T11,'DIRECTION OF NET SEDIMENT TRANSPORT =',F7.2,
    @' DEGREES TRUE',/,T11,'TIME-AVERAGED NET SEDIMENT TRANSPORT =',
    @G12.4,' M^3/SEC/M '/T49,F10.6,' KG/SEC/M',/,T6)

C ------------------------------------------------------
C OUTPUT KEY PARAMETERS TO THE TABULAR OUTPUT DATA FILES
C ------------------------------------------------------
      WRITE (6,180) IRUN,UB,AB,FCW,DELTACW,Z0,Z0C,RHEIGHT,RLENGTH
180  FORMAT(I3,8F7.4)
      IF (IOPT1 .EQ. 5) THEN
        WRITE(8,190) IRUN,USTCS,USTCWS,RD0,RE0,CONC,
    @                   QS0,SEDM,SEDDIR
      ELSE
        WRITE(8,200) IRUN,USTCS,USTWS,USTCWS,USTC,
    @                   USTW,USTCW,SEDM,QS,SEDDIR
      ENDIF
190  FORMAT(I3,2F8.4,2F9.6,F6.1,2F9.6,F6.1)
200  FORMAT(I3,6F7.4,2F9.6,F6.1)

C ------------------------------------------
C OUTPUT TRANSPORT FORMULA USED IN THE MODEL
C ------------------------------------------
      IF (UA .NE. 0.0) THEN
        GOTO(210,230,250,270,330)IOPT1
C IOPT1 = 1
210     WRITE (*,220)
        WRITE (7,220)
220     FORMAT(T11,'(ENGELUND-HANSEN (1967) TOTAL LOAD EQUATION)')
        GOTO 360
C IOPT1 = 2
230     WRITE (*,240)
        WRITE (7,240)
240     FORMAT(T11,'(EINSTEIN-BROWN (1950) BEDLOAD EQUATION)')
        GOTO 360
C IOPT1 = 3
250     IF (UB .EQ. 0.0) THEN
          WRITE (*,260) RK
          WRITE (7,260) RK
260       FORMAT(T11,'(MODIFIED BAGNOLD (GADD, 1978) BEDLOAD EQUATION'/
    @            T11,' EFFICIENCY FACTOR, K = ',F4.2)
```

```
        ELSE
          WRITE (*,265) RK
          WRITE (7,265) RK
265       FORMAT(T11,'(BAGNOLD (1963) TOTAL LOAD EQUATION)'/
     @            T11,' EFFICIENCY FACTOR, K = ',F4.2)
        ENDIF
        GOTO 360
C IOPT1 = 4
270     WRITE (*,280)
        WRITE (7,280)
280     FORMAT(T11,'(YALIN (1963) BEDLOAD EQUATION)')
        GOTO 360
C IOPT1 = 5
330     WRITE (*,340)
        WRITE (7,340)
340     FORMAT (T11,'COHESIVE SEDIMENT METHOD '
     &  'SUSPENDED LOAD',/)
        WRITE (*,350)CONC
        WRITE (7,350)CONC
350     FORMAT (T11,'CALCULATED SEDIMENT CONCENTRATION (ppm) (ie mg/l) = ',1P,E8.2)

360     CONTINUE
        WRITE (*,370)
        WRITE (7,370)
370     FORMAT (T11,' FRICTION FACTOR FROM GRANT & MADSEN (1986) ',
     @       ' '/T11,' (FOR WAVE-DOMINATED FLOWS)')
      ENDIF

C END OF SUBROUTINE OUTOUT
      RETURN
      END
```

APPENDIX 2

A SAMPLE RUN AND OUTPUTS OF IAFSED
SEE "LIST OF SYMBOLS" FOR PARAMETER DEFINITIONS

I. Running menu96:

```
C:\SED96>menu96

    **** SEDTRANS96 Menu ****
1. Run model in interactive mode
2. Run model in batch mode
3. Plot results in Matlab
4. Return to Dos

Type the number of your choice and press Enter: 1

Run SEDTRANS96 in interactive mode

ENTER FILE NAME IN WHICH OUTPUT WILL BE STORED: TEST1
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): 23

ENTER CURRENT SPEED, DIRECTION AND HEIGHT ABOVE
SEABED (m/s, degrees, m): 0.3 10 0.5

ENTER WAVE HEIGHT, PERIOD AND DIRECTION
(m, seconds, degrees): 1 10 20

ENTER GRAIN SIZE, RIPPLE HEIGHT AND LENGTH (m): 0.00023 0.01 0.1

ENTER BED SLOPE (degrees): 5

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

***WARNING***
EINSTEIN-BROWN FORMULA IS BASED ON LABORATORY
EXPERIMENTS USING SEDIMENTS WITH GRAIN SIZES
OF 0.3 TO 28.6 MM

CHECK INPUT DATA FOR RUN #1
SELECT NEW VALUE FOR SEDIMENT GRAIN SIZE?
(ENTER Y/N): N
```

II. File TEST1:

SED96: A SEDIMENT TRANSPORT MODEL
FOR CONTINENTAL SHELF CONDITIONS

GEOLOGICAL SURVEY OF CANADA (ATLANTIC)
CREATED: SEPTEMBER, 1992
LAST UPDATED: DECEMBER, 1996

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

ALL DIMENSIONAL VARIABLES ARE IN SI UNITS

RUN NUMBER 1

INPUT DATA:

WATER DEPTH = 23.00 M
CURRENT SPEED = 0.30 M/SEC
CURRENT DIRECTION = 10.00 DEGREES NORTH
HEIGHT ABOVE BED = 0.50 M
WAVE HEIGHT = 1.00 M
WAVE PERIOD = 10.00 SEC
WAVE DIRECTION = 20.00 DEGREES NORTH

FLUID DENSITY = 1025.0 KG/M^3
SEDIMENT DENSITY = 2650.0 KG/M^3
SEDIMENT GRAIN SIZE = 0.000230 M
FRACTION OF SEABED MATERIAL = 1.00
RIPPLE HEIGHT = 0.0100 M
RIPPLE LENGTH = 0.1000 M

RESULTS:

MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
VELOCITY, FROM LINEAR WAVE THEORY = 0.224 M/SEC
MAX. WAVE-INDUCED BOTTOM HORIZONTAL PARTICLE
DISPLACEMENT, FROM LINEAR WAVE THEORY = 0.357 M
WAVELENGTH, FROM LWT DISPERSION EQUATION = 127.03 M

BOTTOM FRICTION FACTOR = 0.0098
(GRANT AND MADSEN, 1986)
CURRENT SPEED 1 M. ABOVE SEABED = 0.35 M/SEC
CURRENT SPEED TO BE USED IN BOTTOM STRESS
CALCULATIONS = 0.16 M/SEC
ANGLE BETWEEN WAVE AND CURRENT DIRECTIONS
WITHIN WAVE BOUNDARY LAYER = 10.00 DEGREES

NOTE: THIS APPLIES TO MIXED FLOW CONDITIONS ONLY

CRITICAL SHEAR VELOCITY FOR INITIATION OF
BEDLOAD TRANSPORT = 0.0134 M/SEC
CRITICAL SHEAR VELOCITY FOR INITIATION OF
SUSPENDED LOAD TRANSPORT = 0.0200 M/SEC

TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT CEASES = 2.16 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT CEASES = 2.94 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
SUSPENDED LOAD TRANSPORT RECOMMENCES = 0.00 SEC
TIME, AFTER PASSAGE OF WAVE CREST, AT WHICH
BEDLOAD TRANSPORT RECOMMENCES = 0.00 SEC

PERCENT OF TIME IN ONLY BEDLOAD TRANSPORT PHASE = 15.68
PERCENT OF TIME IN SUSPENDED LOAD TRANSPORT PHASE = 43.14

DIRECTION OF NET SEDIMENT TRANSPORT = 15.31 DEGREES TRUE
TIME-AVERAGED NET SEDIMENT TRANSPORT = 0.3752E-06 M^3/SEC/M
0.000994 KG/SEC/M

EINSTEIN-BROWN (1950) BEDLOAD EQUATION
FRICTION FACTOR FROM GRANT & MADSEN (1986)
(FOR WAVE-DOMINATED FLOWS)

EXPECTED BEDFORMS ARE (AMOS, 1990; LI AND AMOS, IN PRESS):

FINE OR VERY FINE SAND (WENTWORTH SCALE)
COMBINED-FLOW BEDFORMS PREDICTED BASED ON
SIB DATA OF LI AND AMOS (IN PRESS)

BREAK-OFF RIPPLES
WAVE-CURRENT RIPPLES
RIPPLE HEIGHT = 0.003 M
RIPPLE LENGTH = 0.122 M

ENTER 1 TO DO ANOTHER RUN, 0 TO STOP: 0

III. File SEDOUTI1

bt#	u_b	A_b	f_{cws}	δ_{cw}	z_0	z_{0c}	η	λ
1	0.2245	0.3573	0.0098	0.0613	0.0010	0.0059	0.0027	0.1219

IV. File SEDOUTI2

bt#	u_{*cs}	u_{*ws}	u_{*cws}	u_{*c}	u_{*w}	u_{*cw}	Q_b	Q_s	$Q_{b\text{-}dir}$
1	0.0162	0.0201	0.0258	0.0271	0.0399	0.0481	0.000994	0.007549	15.3

V. File PROFILE.DAT

bt# 1

HEIGHT,M	VEL. M/S	CONC. KG/M^3
0.010000	0.088861	1.476115
0.020000	0.115257	0.757329
0.030000	0.130698	0.512556
0.050000	0.150151	0.313432
0.070000	0.166899	0.205233
0.100000	0.191045	0.111460
0.200000	0.237969	0.034031
0.300000	0.265418	0.017001
0.500000	0.300000	0.007092
0.700000	0.322778	0.003987
1.000000	0.346924	0.002165
2.000000	0.393849	0.000661

APPENDIX 3

A SAMPLE RUN AND OUTPUTS OF BCHSED
SEE "LIST OF SYMBOLS" FOR PARAMETER DEFINITIONS

I. File INDATA:

bt#	h	u_z	z_r	C_{dir}	H_s	T	W_{dir}	D	η	λ	β	F	ρ_s	ρ	E	c_0	τ_e	τ_d	t	W_{cs}
1	23	0.14	1.0	10	0.85	8.0	20	0.00023	0.01	0.1	0	1	2650	1025	2	0	0	0	0	0
2	23	0.15	1.0	20	0.85	8.0	20	0.00023	0.01	0.1	0	1	2650	1025	2	0	0	0	0	0
3	23	0.20	1.0	30	0.90	8.5	20	0.00023	0.01	0.1	0	1	2650	1025	2	0	0	0	0	0
4	23	0.22	1.0	40	1.00	8.5	20	0.00023	0.01	0.1	0	1	2650	1025	2	0	0	0	0	0
5	23	0.25	1.0	50	1.20	9.0	20	0.00023	0.01	0.1	0	1	2650	1025	2	0	0	0	0	0

II. File SEDOUT1.DAT

bt#	u_b	A_b	f_{cws}	δ_{cw}	z_0	z_{0c}	η	λ
1	0.1443	0.1837	0.0127	0.0373	0.0019	0.0131	0.0124	0.0828
2	0.1443	0.1837	0.0126	0.0380	0.0020	0.0127	0.0126	0.0838
3	0.1679	0.2272	0.0116	0.0461	0.0020	0.0121	0.0144	0.1219
4	0.1866	0.2524	0.0113	0.0469	0.0016	0.0103	0.0117	0.1219
5	0.2413	0.3457	0.0104	0.0528	0.0010	0.0086	0.0052	0.1219

III. File SEDOUT2.DAT

bt#	u_{*cs}	u_{*ws}	u_{*cws}	u_{*c}	u_{*w}	u_{*cw}	Q_b	Q_s	$Q_{b\text{-}dir}$
1	0.0075	0.0132	0.0152	0.0129	0.0343	0.0366	0.000382	0.006537	15.3
2	0.0079	0.0133	0.0155	0.0137	0.0347	0.0373	0.000447	0.006776	20.0
3	0.0103	0.0154	0.0185	0.0181	0.0386	0.0426	0.000384	0.007760	24.6
4	0.0113	0.0168	0.0201	0.0192	0.0391	0.0434	0.000448	0.005882	29.2
5	0.0132	0.0204	0.0239	0.0210	0.0415	0.0460	0.000713	0.003828	33.4

IV. File PROFILE

BT# 1

HEIGHT,M	VEL.M/S	CONC. KG/M^3
0.010000	0.018865	13.815163
0.020000	0.026753	5.747019
0.030000	0.031367	3.440508
0.050000	0.043299	0.912789
0.070000	0.054160	0.272793
0.100000	0.065673	0.075823
0.200000	0.088048	0.006298
0.300000	0.101136	0.001469
0.500000	0.117625	0.000235
0.700000	0.128487	0.000070
1.000000	0.140000	0.000020
2.000000	0.162375	0.000002

BT# 2

HEIGHT,M	VEL.M/S	CONC. KG/M^3
0.010000	0.020702	12.444311
0.020000	0.029483	5.257009
0.030000	0.034620	3.175609
0.050000	0.047059	0.936918
0.070000	0.058621	0.301271

0.100000	0.070878	0.090496
0.200000	0.094696	0.008741
0.300000	0.108629	0.002227
0.500000	0.126182	0.000398
0.700000	0.137744	0.000128
1.000000	0.150000	0.000038
2.000000	0.173818	0.000004

BT# 3

HEIGHT,M	VEL.M/S	CONC. KG/M^3
0.010000	0.031198	6.669628
0.020000	0.044553	3.136289
0.030000	0.052365	2.017123
0.050000	0.064332	1.025931
0.070000	0.079570	0.433750
0.100000	0.095723	0.174145
0.200000	0.127113	0.029560
0.300000	0.145476	0.010475
0.500000	0.168609	0.002835
0.700000	0.183847	0.001199
1.000000	0.200000	0.000481
2.000000	0.231391	0.000082

BT# 4

HEIGHT,M	VEL.M/S	CONC. KG/M^3
0.010000	0.039794	3.903410
0.020000	0.054598	1.860415
0.030000	0.063257	1.206005
0.050000	0.075870	0.641451
0.070000	0.092058	0.285257
0.100000	0.109218	0.120831
0.200000	0.142567	0.022761
0.300000	0.162075	0.008572
0.500000	0.186651	0.002505
0.700000	0.202840	0.001114
1.000000	0.220000	0.000472
2.000000	0.253349	0.000089

BT# 5

HEIGHT,M	VEL.M/S	CONC. KG/M^3
0.010000	0.055530	1.649636
0.020000	0.072155	0.821021
0.030000	0.081880	0.545871
0.050000	0.094132	0.326411
0.070000	0.110276	0.165760
0.100000	0.129017	0.075488
0.200000	0.165436	0.016369
0.300000	0.186740	0.006694

0.500000	0.213580	0.002170
0.700000	0.231259	0.001033
1.000000	0.250000	0.000471
2.000000	0.286420	0.000102