CHAPTER ONE HUNDRED NINETY NINE

MODELING ESTUARIAL COHESIVE SEDIMENT TRANSPORT

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ABSTRACT

Cohesive sediment related problems in estuaries include shoaling in navigable waterways and water pollution. A two-dimensional, depth-averaged, finite element cohesive sediment transport model, CSTM-H, has been developed and may be used to assist in predicting the fate of sorbed pollutants and the frequency and quantity of dredging required to maintain navigable depths. Algorithms which describe the transport processes of redispersion, resuspension, dispersive transport, settling, deposition, bed formation and bed consolidation are incorporated in CSTM-H.

The Galerkin weighted residual method is used to solve the advection-dispersion equation with appropriate source/sink terms at each time step for the nodal suspended sediment concentrations. The model yields stable and converging solutions. Verification was carried out against a series of erosion-deposition experiments in the laboratory using kaolinite and a natural mud as sediment. A model application under prototype conditions is described.

INTRODUCTION

Fine, cohesive sediments in estuaries are comprised largely of terrigenous clay-sized particles. The remainder may include fine silts, biogenic detritus, organic matter, waste materials and sometimes small quantities of very fine sand. The electrical surface repulsive forces which act on each elementary clay particle are several orders of magnitude larger than the gravitational force. As a result, the physico-chemical properties of fine sediments are controlled mostly by the surface forces.

In water with a very low salinity (less than about one part per thousand, ppt) the elementary particles are usually found in a dispersed state. A slight increase in the salinity (up to 2-3 ppt) is sufficient to repress the repulsive surface forces between the particles, with the result that the particles coagulate to form units known as flocs. Each floc may consist of thousands of elementary particles. Coagulation depends upon inter-particle collision and cohesion resulting from collision. The three principle mechanisms of inter-particle collision in suspension are Brownian motion, internal fluid shearing and differential sedimentation. Cohesion of particles

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is caused by the presence of net attractive surface forces. The latter condition is caused by the increased concentration of dissolved ions, which serves to depress the double layer around each particle and allow the attractive forces to predominate.

Flocs have a tendency to build up or combine under favorable fluid shearing rates to form larger units known as aggregates. The transport of aggregates in estuaries is affected by the hydrodynamic conditions and by the chemical composition of the suspending fluid. Most estuaries contain abundant quantities of cohesive sediments which usually occur in the coagulated form in various orders or degrees of aggregation. The orders of aggregation classify aggregates according to their density and shear strength. Therefore, an understanding of the transport properties of these sediments requires a knowledge of the manner in which the aggregates are transported in estuarial waters.

Fine sediment related problems in estuaries include sedimentation and water pollution. Under low flow velocities, sometimes coupled with turbulent conditions which favor the formation of large aggregates, fine sediments have a tendency to deposit in dredged cuts and navigation channels, in harbors and marinas, and behind pilings placed in water (9). In addition, the mixing zone between upland fresh water and sea water in estuaries is a favorable site for bottom sediment accumulation. Inasmuch as estuaries are often used as transportation routes, it is desirable to be able to accurately estimate the amount of dredging required to maintain navigable depths in these water bodies, and also to predict the effect of new estuarial development projects such as the construction of a port facility or dredging of additional navigation channels.

A significant portion of the pollution load in water is quite often transported sorbed to cohesive sediments rather than in the non-sorbed state (16). Thus, the importance of considering the movement of cohesive sediments in predicting the fate of pollutants (e.g. pesticides, radioisotopes, and toxic elements such as lead, mercury, cadmium and nickel) cannot be over emphasized. The properties of cohesive sediments, and in particular clays, which cause the sorption of pollutants are the large surface area to volume ratio, the net negative electrical charges on their surfaces and their cation exchange capacity.

TRANSPORT MODEL

Prediction of the fate of sorbed pollutants or the annual dredging requirements of a harbor can be accomplished by modeling the movement of cohesive sediments. This requires mathematical descriptions of the various physical processes which govern cohesive sediment transport under turbulent flow. Algorithms which represent the processes of redispersion, resuspension, dispersive transport, settling, deposition, bed formation and consolidation have been developed and incorporated in a two-dimensional transport model which solves the depth-averaged advection-dispersion equation (Eq. 1) using the finite element method.

$$\frac{\partial C}{\partial t} + \frac{u\partial C}{\partial x} + \frac{v\partial C}{\partial y} = \frac{\partial}{\partial x}(D_{xx}\frac{\partial C}{\partial x} + D_{xy}\frac{\partial C}{\partial y}) + \frac{\partial}{\partial y}(D_{yx}\frac{\partial C}{\partial x} + D_{yy}\frac{\partial C}{\partial y}) + S \quad (1)$$

where C = depth-averaged suspension concentration, u,v = local depth-averaged water velocity components in the x and y directions, D_{ij} = effective sediment dispersivity tensor, and S = source/sink term which accounts for the rate of sediment addition (source) due to erosion and the rate of sediment removal (sink) due to deposition. The resulting transport model, CSTM-H, is capable of predicting the horizontal and temporal variations of the depth-averaged suspended sediment concentrations and bed surface elevations in an estuary, coastal waterway or river. Previous models are not as comprehensive as they use mathematical descriptions (or algorithms) of the considered transport processes that are based on limited studies conducted prior to the early 1970's. In this study field evidence and the considerable amount of experimental research that has been conducted on cohesive sediment transport mechanics since that time have been used to develop new algorithms. A description of the algorithms is given below.

Surficial layers of estuarial beds, typically composed of flow-deposited cohesive sediment aggregates, are stratified with respect to bed shear strength and density, and occur in three different states: stationary suspensions, partially consolidated (or consolidating) beds and settled (fully consolidated) beds. Stationary suspensions, which may be regarded as extremely under-consolidated soil, develop whenever the settling rate of concentrated mobile suspensions exceeds the rate of self-weight consolidation. They tend to have a very high water content and low shear strength and are redispersed, or mass eroded, when subjected to an excess bed shear stress, i.e. when the bed shear stress is greater than the mechanical shear strength of the bed surface. That portion of the suspension that is not redispersed undergoes: 1) consolidation, due to overburden resulting from the weight of the overlying sediment which crushes the aggregate network below, and 2) thixotropic effects, i.e. slow rearrangement of deposited aggregates attributed to internal energy and unbalanced internal stresses, both of which alter the order of aggregation of the subsurface bed layers. This results in a vertical stratification of the bed with respect to density and shear strength, with both properties typically increasing with depth (11). Differential settling caused by sorting processes is another cause of stratified bed formation.

Partially consolidated deposits have a somewhat lower water content and higher shear strength, and are eroded aggregate by aggregate when subjected to an excess shear stress. Settled beds possess a much lower water content, a much higher shear strength and as well are resuspended aggregate by aggregate when subjected to an excess shear, unless the excess shear stress is very large in which case large chunks of material may detach from the bed and be entrained. Both stationary suspensions and partially consolidated beds undergo consolidation, with the bed density and shear strength increasing with time of consolidation. In settled beds, the shear strength and density profiles exhibit relatively uniform properties over depth.

To facilitate the modeling of changes in the bed surface elevation due to erosion, deposition and consolidation, the bed is treated in the following manner: 1) it is discretized into layers and 2) bed properties, i.e. density and shear strength, are assumed to be spatially (in the x-y plane) invariant within each element, but not so from element to element, in order to account for inter-element spatial variances in shoaling and/or scouring patterns. These two factors are explained below.

The bed in each element is considered to be composed of two sections: 1) the original, settled bed that is present at the start of modeling and 2) new deposits located on top of the original bed, that result from deposition during model simulation. Each of these two sections is divided into a number of layers in order to specify the actual shear strength and bulk density profiles in the model. The new deposit section is subdivided into two sub-sections, the top referred to as unconsolidated new deposit (UND) layers and the bottom as partially consolidated new deposit (PCND) layers (Fig. 1). The number of layers indicated in Fig. 1 for each of the three bed sections are not fixed, as each section can be assigned any number of layers. Within each layer the bed shear strength and density are assumed to vary in a linear manner with depth. Previous models have used a constant bed shear strength and density for each layer, and only a single layer for the partially consolidated bed section. Therefore, the stratified nature of partially consolidated beds is not represented in these models.

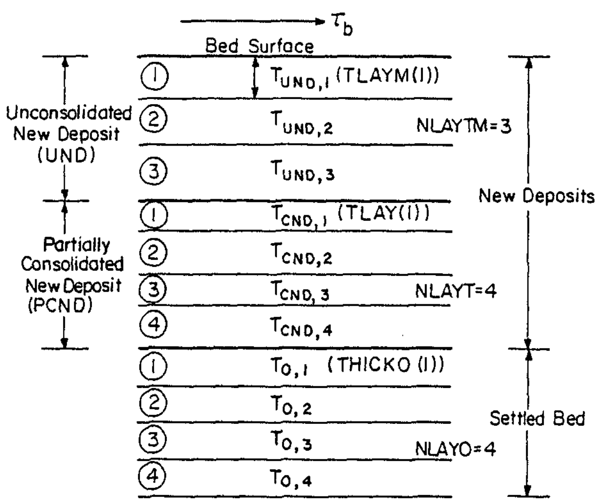

Fig. 1 Bed Schematization Used in Bed Formation Algorithm (4).

Stationary suspensions are represented as being the top section of the layered bed model, even though they do not constitute a true bed, in order to account for the subsequent redispersion and/or consolidation of these suspensions. However, the time-varying thickness of the bed in each element is equal to the sum of only the NLAYT (number of PCND layers) PCND layers and the NLAYO settled bed layers.

The bed formation algorithm uses the following procedure to form the new deposit bed layer(s). The dry sediment mass per unit bed area per element, M_D, read in as an initial condition if a new deposit is initially present on top of the settled bed in any element, or deposited during the modeling (as determined by the deposition algorithm) is used in conjunction with the assumed linear bed density profiles in the UND and PCND layers to iteratively solve for the thickness of bed formed by M_D for each element where $M_D>0$. The bed structure (i.e. bed shear strength and density profiles) of the existing bed is adjusted to account for the added sediment mass. During periods of deposition, first the UND layers are filled and then the PCND layers. The bottom PCND layer can never fill up; therefore, continuing deposition is accounted for by increasing the thickness of this layer, while the thicknesses of the overlying UND and PCND layers remain the same. This particular filling sequence was used in order to account for the consolidation of the sediment bed due to overburden during the bed formation phase by virtue of the increasing bed shear strength and density values with depth. Previous models use the assumed constant bed density value in each layer to solve explicitly for the bed thickness formed by M_D.

The erosion algorithm simulates the erosion of saturated, flow-deposited cohesive sediment beds on an element by element basis in the following manner. Redispersion of stationary suspensions (i.e. the UND layers) is represented by instantly reentraining the thickness of the bed above the level at which the bed shear stress, τ_b, is equal to the bed shear strength, τ_c. The mass of sediment that is redispersed per time-step is determined from the linearly varying τ_c and dry sediment bed density, ρ, profiles in each stationary suspension layer. The average resuspension rate, ε, of partially consolidated bed layers over one time-step, Δt, is given by the following empirical law that is analogous to the rate expression which results from a heuristic interpretation of the rate process theory of chemical reactions (11):

$$\varepsilon = \varepsilon_{oi} \exp\left\{\alpha_i \left(\frac{\tau_b - \tau_c}{\tau_c}\right)\right\} \qquad (2)$$

where ε_{oi} and α_i are empirical coefficients for the i-th PCND layer. In Eq. 2, τ_c is taken to vary linearly with z_b, the depth below the sediment-fluid interface, in the discretized manner explained previously. The rate expression given by Eq. 2 for PCND layers indicates that the resuspension rate varies exponentially with the excess bed shear stress, $\tau_b-\tau_c$. The average resuspension rate of settled bed layers is given by an empirical expression that is proportional to the first term of a Taylor series expansion of Eq. 2, and thus is linearly proportional to the excess shear stress (8). The proportionality coefficient is termed the erodibility constant, M_i, where the subscript i represents the value of M for the i-th settled bed layer below the new deposit bed sections. The dry sediment mass and bed thickness of PCND or settled bed layers eroded per time-step are determined with the appropriate rate expression as functions of the time-varying τ_c and ρ profiles using an iteration routine. New layer thicknesses and τ_c and ρ profiles are then determined.

The effect of salinity, S, on the bed shear strength and hence on the erosion rate of that bed, as determined from laboratory resuspension tests is incorporated into the erosion algorithm. The bed shear strength of a natural mud was found to nearly double in value, in a linear manner, between $S \simeq 0$ and 2 ppt, and thereafter (for $S > 2$ ppt) was found to remain practically constant (5). Consequently, the rate of erosion is predicted to decrease with increasing salinity up to 2 ppt, where it becomes essentially invariant with respect to salinity. The mud used in these tests was from Lake Francis, Nebraska, and consisted of particles 50% of which were finer than 2μm, with montmorillonite, illite, kaolinite and quartz being the predominant minerals. It had a cation exchange capacity (CEC) of 100 milliequivalents/100 grams. This high CEC value indicates a higher percentage of montmorillonite than the other two clay minerals.

In the erosion algorithm, redispersion and resuspension are simulated to occur in unsteady flows only during temporally accelerating flows, i.e. $\tau_b(t+\Delta t) > \tau_b(t)$. Thus, even though $\tau_b(t+\Delta t)$ and/or $\tau_b(t)$ may be greater than $\tau_c(z_b=0)$, no erosion will be predicted if $\tau_b(t+\Delta t) < \tau_b(t)$. This stipulation for the occurrence of erosion, and an analogous one for deposition, is based on an interpretation of typically observed Eulerian concentration-time records in estuaries. Laboratory evidence further suggests that under accelerating flows, erosion occurs without redeposition of the eroded sediment, and that during decelerating flows, sediment deposits without reentrainment of the deposits (10,11,16). During periods of steady flows, erosion or deposition may occur, but never simultaneously.

The dispersive transport terms in Eq. 1 account for the transport of sediment by processes other than advective transport. Some of these processes include the effects of transverse and vertical velocity variations in bounded shear flows and turbulent diffusion. Thus, the effective sediment dispersion coefficients in Eq. 1 must include the effect of all processes whose scale is less than the grid size of the model or what has been averaged over time and space.

In modeling dispersion of a nonconservative constituent, e.g. sediment, it is essential to determine which of the four primary dispersion mechanisms - baroclinic circulation, shear-flow dispersion, bathymetry induced dispersion and wind-induced circulations - are important in the water body being modeled. Because of well-known problems in identifying, describing and modeling the combined effects of the various dispersion mechanisms, the dispersion algorithm in CSTM-H includes only shear flow dispersion. Following the analysis of Holley (6), it is assumed that the dispersion in wide, vertically well mixed estuaries is associated primarily with the vertical shear. The limitations of this assumption, which determine the applicability of such a dispersion algorithm, are consistent with those associated with a two-dimensional, depth-averaged model.

The shear flow dispersion algorithm uses the Reynolds analogy between mass and momentum transfer, which was verified by Jobson and Sayre (7) for sediment particles less than about 100 μm in diameter, and calculates the four components of the two-dimensional sediment dispersivity tensor (Eq. 3) using the following formulation derived by Fischer (3) for bounded shear flows:

$$D_{ij} = 0.04\, u_i u_j\, d^2 I_{ij}/\bar{E} \qquad i,j = 1,2 \tag{3}$$

in which u_i = local depth-averaged velocity in the x_i-direction, $\bar{E}$ = depth-averaged diffusion coefficient in the z (vertical) direction, and I_{ij} is a dimensionless triple integral which expresses correlation between the rate of cross-stream mixing and the slope of the vertical velocity profile. Fischer (3) recommended that a value of 0.10 be used for I_{ij} since 1) in most investigations the vertical velocity profiles, u(z) and v(z), and the vertical turbulent diffusion coefficient, E_z, are not known with a high degree of accuracy, and 2) the value of I_{ij} is fairly insensitive to the shape of the vertical velocity profile. The value of $\bar{E}$ is given by 0.067 $u_* d$, in which u_* = friction velocity. This expression for $\bar{E}$ results from integrating the expression for E_z obtained by Elder (2) for shear flow down an infinitely wide inclined plane over d. Values of D_{ij} are calculated at each time step using the specified nodal values of u, v, u_* and d.

The deposition algorithm integrates the concepts proposed by various investigators (9,10) and represents a unified model of this process. The rate of deposition is given by

$$\frac{dC}{dt} = -\frac{W_s' C}{d} \tag{4}$$

where W_s' = apparent sediment settling velocity. Laboratory experiments have shown that W_s' is a function of the bed shear stress, suspension concentration, C, and salinity, S. Figure 2 shows various ranges in which W_s' is defined. Deposition is predicted to occur only in decelerating flows, i.e. $\tau_b(t + \Delta t) < \tau_b(t)$, when τ_b is less than the maximum shear stress at which deposition can occur, τ_{bmax}. In Ranges IA and IIA the sediment aggregates settle independently without much mutual interference, and therefore W_s' is independent of C. In Range IB, which corresponds to concentrations between approximately C_1 = 0.1 - 0.7 gram/liter (g/ℓ) and C_2 = 10-15 g/ℓ, W_s' increases with increasing concentration due to accompanying increase in inter-aggregate collisions, and therefore increased mutual interference. In Range IC (for $C > C_2$), W_s' decreases with increasing concentration. At such high concentrations the sediment suspension, often referred to as fluid mud or mud cake, hinders the upward flux of water expelled by consolidation of the lower suspension (9). This type of settling is referred to as hindered settling. In Range IIB, W_s' increases with increasing suspension concentration and is obtained from a log-normal relationship (10). Expressions for W_s' as a function of C, τ_b and S for the five settling domains are given by Hayter (4).

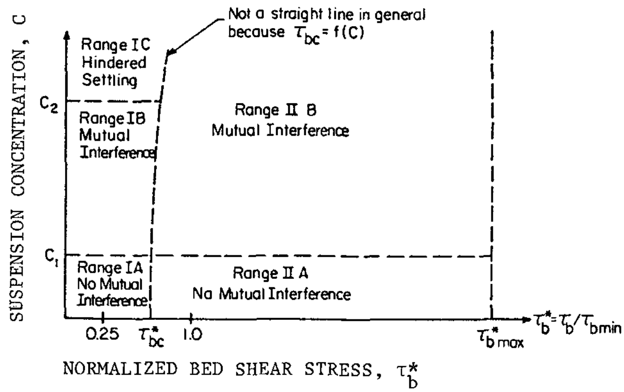

Fig. 2 Apparent Settling Velocity Description in Domains Defined by Suspended Sediment Concentration and Bed Shear Stress. τ_{bmin}, τ^*_{bmax}, τ^*_{bc} and τ_{bc} are characteristic Values of τ_{bm} (4).

The deposition rates of the Lake Francis mud were found to have a slight dependence on salinity. A power relationship between W_s' and S of the form $W_s' \alpha S^n$, with n = 0.13, was determined from analysis of deposition tests conducted at salinities ranging from 0 to 35 ppt and under bed shear stresses varying from 0.0 to 0.30 N/m^2 (5).

The amount of sediment deposited onto the bed per time-step is determined on an element-by-element basis by integrating Eq. 4 over Δt, and the thickness and structure (i.e. density and shear strength profiles) of the bed are adjusted accordingly by the previously described bed formation algorithm. When deposition is not occurring (i.e. after bed formation) the bed is simulated to undergo consolidation, which is the result of soil mass volume reduction accompanied by outflow of water from the soil pores (primary consolidation), and plastic deformation of the bed (i.e. soil aggregates) under overburden forces (secondary consolidation).

The consolidation algorithm accounts for the consolidation of a stationary suspension and partially consolidated bed by increasing the bed density and bed shear strength and decreasing the bed thickness with time. Consolidation is considered to begin after the bed formation process is complete, at which time the bed thickness will be maximum. Laboratory experiments have revealed that after a consolidation time, T_{dc}, of a certain magnitude, T_{dc1}, stationary suspensions undergo resuspension (as opposed to redispersion with $T_{dc} < T_{dc1}$) when subjected to an excess shear stress (4). Accordingly, the dry sediment mass in a stationary suspension for which $T_{dc} = T_{dc1}$ (T_{dc1} was determined to be equal to three hours in a laboratory test using kaolinite) is incorporated into the partially consolidated bed, and therefore will undergo resuspension when subjected to an excess bed shear.

The following normalized relationship was found between the depth-averaged dry sediment density $\bar{\rho}$ and T_{dc} and is used in the consolidation algorithm to determine $\bar{\rho}$ (4).

$$\frac{\bar{\rho}}{\bar{\rho}_\infty} = 1 - \alpha \exp(-\lambda T'_{dc}) \qquad (5)$$

where $T'_{dc} = T_{dc}/T_{dc\infty}$, $\bar{\rho}_\infty$ = final (i.e. fully consolidated) mean bed density at consolidation time $T_{dc\infty}$. Least squares analysis gave $\alpha = 0.845$, $\lambda = 6.58$. Owen (14) found $\bar{\rho}_\infty$ to vary linearly with the initial suspension concentration.

The dry sediment density profile, $\rho(z_b)$, found by Owen (15) and Thorn and Parsons (17) for four natural muds with $T_{dc} \geq 48$ hours can be expressed as

$$\frac{\rho(z_b)}{\bar{\rho}} = \beta \left(\frac{H-z_b}{z_b}\right)^{\delta} \qquad (6)$$

where z_b = depth below the bed surface and H = bed thickness. Both β and δ were found to be constants for $T_{dc} > 48$ hours (4). Using $\bar{\rho}$ determined by Eq. 5, the density profile $\rho(z_b)$ is determined from Eq. 6.

Due to the limited available information on bed shear strength profiles in cohesive sediment beds, the increase of the shear strength, τ_c, of a bed with T_{dc} is accounted for in the algorithm through use of a power law relationship between ρ and τ_c (14,17)

$$\tau_c = \zeta \rho^{\xi} \qquad (7)$$

with $\zeta = 6.85 \times 10^{-6}$ and $\xi = 2.44$ for Avonmouth mud (14).

The variation of $\rho(z_b)$ and $\tau_c(z_b)$ with T_{dc} is determined using the empirically determined relationships given by Eqs. 5-7. The thickness of the bed is reduced to account for the expulsion of pore water during consolidation, and to insure that sediment mass in the bed is conserved. The new deposit bed section (composed of stationary suspension and partially consolidated bed) of the layered bed is further divided into a finite number of strata in order to account for repeated periods of deposition, as typically occur in estuaries due to the oscillatory tidal flow. The top stratum may be composed of a stationary suspension and partially consolidated bed, whereas the buried strata are composed of just partially consolidated sections. The degree of consolidation of a particular stratum is accounted for by using a separate consolidation time for each stratum.

The finite element solution routine developed by Ariathurai (1) was modified to include the two cross product dispersion coefficients, D_{xy} and D_{yx}. The Galerkin weighted residual method is used to solve the advection-dispersion equation (Eq. 1) for the nodal depth-averaged suspended sediment concentrations, and a Crank-Nicholson type finite difference formulation is used to solve the temporal problem, i.e. advance the spatial solution in time. The model yields stable and converging solutions. The accuracy of the solution is affected when the Peclet number becomes too large (greater than 10^2) or too small (less than 10^{-3}).

MODEL SYNOPSIS

A synopsis of the operations performed by CSTM-H during each time-step and the data required is given below.

The average bed shear stress induced by the turbulent flow velocity of the suspending fluid is calculated for each element. Then the amount of sediment, if any, that is deposited onto or resuspended from the bed in each element during the current time-step is determined using the deposition and erosion algorithms, respectively. The dispersion algorithm then calculates the values of the four components of the two-dimensional sediment dispersivity tensor. Using these values and the prescribed velocity field and concentration boundary conditions, Eq. 1 is solved for the depth-averaged suspended sediment concentration at each node for the next time-step. The new bed elevation in each element is determined by adding or subtracting the thickness of sediment deposited onto or resuspended from, respectively, the bed profile that existed during the previous time-step. Lastly, the consolidation algorithm calculates for each element the increase in bed density and shear strength and the decrease in bed thickness due to consolidation during the previous time-step.

The following four types of data are required: 1) finite element grid of the system to be modeled, 2) two-dimensional depth-averaged velocity and salinity fields, 3) concentration initial and boundary conditions and 4) properties of the cohesive sediments which characterize their erosion, deposition, bed formation and consolidation.

VERIFICATION

Model verification was carried out against four erosion-deposition experiments, three of which were performed in an 18m long, 0.61 m wide recirculating flume and the fourth in an 0.76 m mean radius rotating annular flume. The bed shear stress history for one of the three experiments performed in the recirculating flume using kaolinite in tap water was the following: bed shear stress τ_b = 0.06 N/m^2 for two hours, then increased to 0.12 N/m^2 for the third and fourth hours, and finally decreased to 0.03 N/m^2 for the final five hours. In this nine hour experiment the bed was prepared by mixing the sediment-water suspension at a shear stress of approximately 0.5 N/m^2 for four hours, after which the flow was reduced to a shear stress of approximately 0.025 N/m^2 for eight hours. The flow in the flume was then completely stopped and the flow deposited bed was allowed to undergo consolidation for 3 hours. Figure 3 shows both the measured and predicted depth-averaged suspension concentration-time record. Satisfactory agreement between measurement and prediction is seen for this experiment, and a similar degree of agreement was obtained for the other two experiments.

The experiment in the rotating flume was conducted using the Lake Francis mud in water with 10 ppt sodium chloride concentration. The

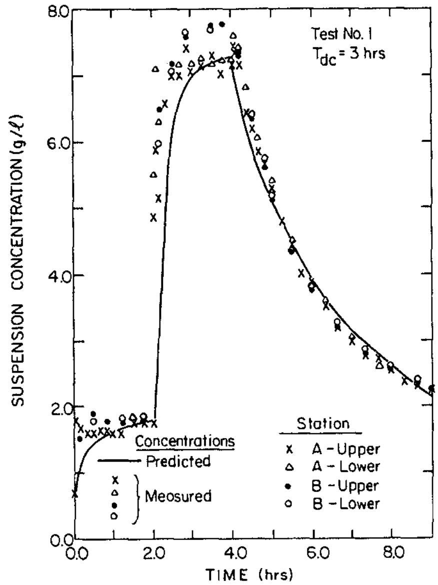

Fig. 3 Measured and Predicted Suspension Concentration for Experiment in Recirculating Flume (4).

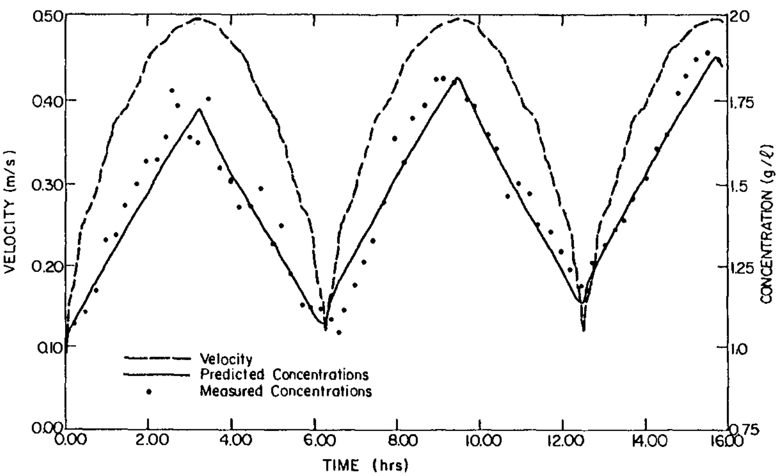

Fig. 4 Velocity - Time Record and the Measured and Predicted Suspension Concentrations for Experiment in Rotating Flume (4).

sediment-water mixture was mixed at a shear stress of 1.7 N/m^2 for 24 hours, after which the flume was stopped and the sediment allowed to deposit and undergo consolidation for 40 hours. A micro-computer driven flow control system was used to generate semi-diurnal, constant water depth (30 cm) tidal flow shown in Fig. 4. Also shown in this figure are the measured and predicted suspension concentration-time records. Except for the short time-lags between predicted and measured concentrations at the times of maximum and minimum velocities, satisfactory agreement was again achieved. The empirical parameters which characterize erosion, deposition and consolidation of the sediment used in each experiment were determined in laboratory tests. An important conclusion from the verification process is that laboratory measured, transport-related parameters can be successfully used for model simulation.

APPLICATION

The utility of the model was shown by simulation of sedimentation in Camachee Cove Yacht Harbor, located adjacent to the Intercoastal Waterway in St. Augustine, Florida. An aerial view of the basin is shown in Fig. 5. The semi-rectangular shaped basin has approximate dimensions of 300 m in length and 100 m in width, and the entrance channel is 60 m wide. The mean depth of the basin is approximately 3 m. The hydrographic and sediment data required to model both the predominantly tide-induced circulation and fine sediment transport in the basin were collected by the Coastal Engineering Laboratory of the University of Florida. The hydrodynamic modeling was performed using the two-dimensional (depth-averaged) finite element flow model RMA2 (13). Results from flow modeling as well as the required sediment data measured during the field study were used in modeling sediment transport in the basin. The results are shown in Fig. 6, which shows contours of the predicted amount (thickness) of sediment deposition in centimeters per year. The observed shoaling pattern is not unexpected, as the greatest amount of sediment deposition would occur near the entrance because of the extremely small flow velocities (maximum ~ 10^{-2} m/sec) in that vicinity and throughout the basin as well. A mean shoaling rate of 15.1 cm/year was predicted, which is reasonably close to the measured 14.6 cm/year (12). The latter value was obtained by comparing bathymetric surveys conducted in March, 1980 and September, 1982.

SUMMARY AND CONCLUSIONS

Previous fine, cohesive sediment transport models have used transport algorithms based on limited studies conducted prior to the early 1970's. Utilization of contemporary laboratory experimental and field evidence to develop algorithms which describe erosion, dispersion, settling, deposition and bed consolidation has resulted in a model with predictive capability. The following is a summary of improvements over previous models: 1) The model includes the cross product dispersion coefficients in the two-dimensional advection-dispersion equation; 2) includes a dispersion and bed consolidation algorithm; 3) calculates the erosion rate of partially consolidated beds as an exponential function of the excess bed shear stress; 4)

Fig. 5 Aerial View of Camachee Cove Yacht Basin (4).

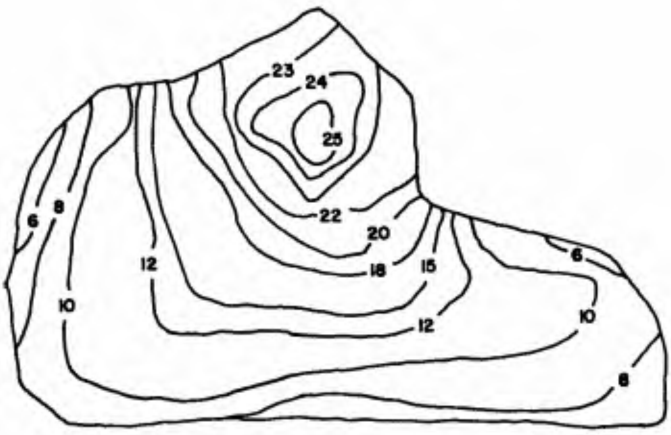

Fig. 6 Predicted Sedimentation Contours for Camachee Cove Yacht Basin, in cm/year (12).

represents the stratified nature of consolidating sediment beds by assuming a linear intra-layer bed density and shear strength variation (instead of constant values) in the layered bed model in determining the mass of sediment eroded or thickness of bed formed by deposition of a given sediment mass; 5) accounts for flow acceleration in determining occurrence of erosion or deposition under a given bed shear stress; 6) predicts that deposition occurs in decelerating flows when $\tau_b < \tau_{bmax}$, whereas previous models predict deposition only when $\tau_b < \tau_{bmin}$ in either accelerating or decelerating flows. Thus, deposition is predicted to occur in the previous models during only a small percentage (e.g. 20% for kaolinite in tap water) of the shear stress range in which deposition has been observed to occur in laboratory steady flow experiments. 7) The model accounts for the effect of salinity on the rates of erosion and deposition of fine sediments. This feature of the model is particularly important in upstream estuarial reaches as well as in downstream regions when high runoff due to storms reduces the salinity.

A two-dimensional, depth-averaged model such as CSTM-H can strictly be applied only to well-mixed estuaries, harbors and basins where the horizontal dimensions of the water body are at least one order of magnitude greater than the vertical dimension. Applications to partially mixed water bodies or especially to highly stratified water bodies should be made when only extremely rough estimates of some sedimentary process, e.g. shoaling rate, are required.

A significant conclusion from this study was that laboratory measured transport-related parameters can satisfactorily reproduce the concentration-time history in laboratory erosion-deposition experiments and a mean sedimentation rate in the prototype, given settling velocity values derived from field measurements in the latter case.

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