CHAPTER 4

SEDIMENTATION ANALYSIS OF ESTUARIES

4-1. Introduction. This chapter will provide an overview of the various concepts of sedimentation in estuaries, the processes and transport, and the analysis and modeling methods currently in use. For those readers of this manual who are concerned directly with problems of estuarine sedimentation, a more complete treatment of this subject, including notation, is presented in Appendix D.

4-2. Sediment Sources. Identification of the sources of sediment can be a key factor in problem solving.

a. Upland. The predominant source usually is erosion of lands bordering the water body, but erosion of banks by currents and waves within the estuary itself, as well as aeolian transport, introduces smaller amounts of sediment more directly. Municipal, agricultural, and industrial wastes may also be a significant source of sediments.

b. Biogenic. In biologically active areas, production within marshes and the main estuarial water body itself can significantly enhance suspended sediment load (Kranck 1979).

c. Coastal. Close to the estuarial mouth, the sediment is often of marine origin. In areas where the open seacoasts are sandy, such as along much of coastal Florida, it is common to find the bed in the mouth or entrance channel to consist predominantly of sand. Landward of the entrance the grain size decreases and the fraction of fine-grained material of marshy origin tends to increase with distance upstream (Mehta and Jones 1977). In some estuaries, e.g., the Mississippi or the Amazon, where sediment supply from upstream sources has been relatively high on a geologic time scale, the offshore ebb delta is laden with deep layers of fine-grained material (Gibbs 1977; Wells 1983). Salinity- and tide-driven flows can transport some of the ebb deltaic deposits (resuspended during flood flows coupled, oftentimes, with offshore wave activity) upstream through the channel. The material is then redeposited in reaches where the currents are too weak to transport the material further (Partheniades 1966).

4-3. Sediment Classification. For engineering purposes, sediments are customarily classified primarily according to particle size. Sediment of size greater than about 0.074 mm (No. 200 sieve size) is considered to be coarse, and less than this size, fine-grained. The boundary between cohesive and cohesionless sediment is, unfortunately, not clearly defined and generally varies with the type of material. It is, however, appropriate to state that cohesion increases with decreasing particle size. Clays (particle size < 0.005 mm) are much more cohesive than silts (0.005 to 0.074 mm), and, in fact, cohesion in natural muds is due primarily to the presence of clay-sized sediment.

a. Muds. Estuarial muds are typically composed of a wide range of materials including clay and nonclay minerals in the clay- and silt-size ranges, organic matter, and sometimes small quantities, e.g., ~5-10 percent by weight, of very fine sand.

b. Size. The particle size distribution of cohesionless materials is easily determined by sieve analysis, and reported in terms of either diameter d or in ϕ units (i.e., as $-\log_2 \times$ diameter, mm) (Vanoni 1975).

c. Settling Velocity. The key transport-related parameter of sediments is the settling velocity, which, unfortunately, does not bear a unique relationship to particle size. Laboratory settling columns can be used to measure settling velocity distribution, which may be considered as a very useful property for sediment classification (Channon 1971; Vanoni 1975).

d. Cohesive Treatment. Standard hydrometer or pipette methods are used to determine the dispersed particle size distribution (American Society for Testing and Materials (ASTM) 1964). The original sample should not be dried before determining the size distribution, inasmuch as prior drying prevents the material from dispersing adequately (Krone 1962).

e. Deflocculation. Cohesive sediment size distribution obtained without dispersion will be that of the flocculated material.

f. Settling Tests. A convenient laboratory procedure for obtaining the settling velocity of flocculated sediment consists of settling tests in a column from which suspended sediment can be withdrawn at various elevations and different times after test initiation (Owen 1976; Vanoni 1975).

4-4. Coarse Sediment Transport. Coarse-grained sediment includes material with particle sizes larger than about 0.074 mm (74 µm), the most common sediment being sand, although some estuarial beds are laden wholly with coarser material including shells and gravel (Kirby 1969).

a. Tidal Entrance. With reference to sand transport, the estuarial mouth or tidal entrance can be conveniently treated as a geomorphologic unit separate from the remainder of the estuary.

b. Formula Application. The application of sediment transport formulas developed for unidirectional flows is usually suitable to tide-dominated oscillatory flows because the tidal frequency is low, and tidal currents may be considered to be "piecewise" steady. Differences tend to arise due mainly to three causes:

(1) The complexity of flow distribution resulting from salinity effects.

(2) The condition of slack water and flow reversal following slack.

(3) The dependence of bed forms and associated bed resistance on the stage of tide and the direction of flow (Ippen 1966).

c. Rate of Transport. The total rate of sediment transport is the sum of contributions from bed load and suspended load. A dependence of bed-load rate on flow velocity cubed is consistent with the concept of relating sediment transport to unit stream power (Yang 1972; Vanoni 1975).

d. Total Load. Bed material load is that portion of the total load represented in the bed. The remainder is wash load. As is evident, this material is typically fine-grained and, unlike bed material load, it is believed to be independent (uncorrelated) of flow condition (Partheniades 1977).

e. Sediment Behavior. Whether a sediment under a given flow condition behaves as bed load or as suspended load depends on the relationship between the entrainment function and the dimensionless grain size as illustrated in Figure 4-1 (Ackers 1972).

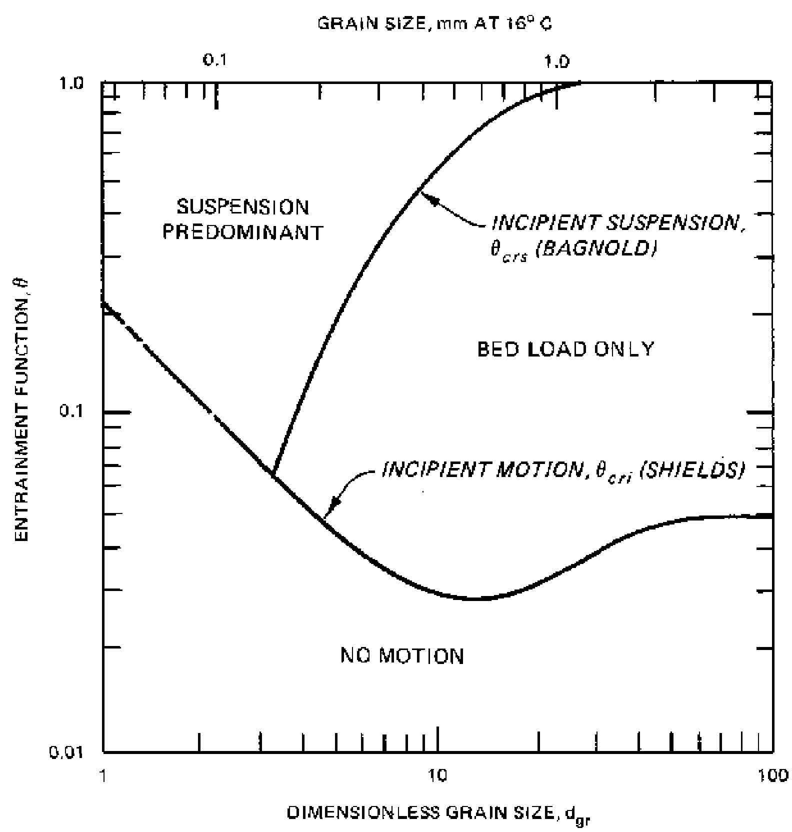

Figure 4-1. Relationship between entrainment function Θ and dimensionless grain size d_{gr} (after Ackers 1972)

f. Contribution by Load. The contribution of suspended load relative to bed load (in total load) depends on the grain size, the flow regime, and the estuarial morphology.

g. Sediment Supply. The rate of supply of "new" sediment from the river varies widely from one estuary to another, and, in a given estuary, there is usually a strong seasonal dependence as well (Krone 1979). Normally, however, the oscillatory, "to and fro," tide-controlled transport is orders of magnitude higher than the net (incoming minus outgoing) input of sediment. In the long term, such factors as changes in the upstream discharge hydrograph and sediment supply rates, morphologic changes within the estuary, sea level change, and eustatic effects will alter the sediment transport regime (Dyer 1973; McDowell and O'Connor 1977).

h. Closure. Closure or tidal choking is a potential problem at sandy entrances in which the strength of flow is insufficient to scour the bed, with the result that littoral drift is deposited in the mouth, the depths become shallow, and the entrance closes eventually (Bruun 1978). Training walls or jetties and dredging between the jetties coupled, sometimes, with a system for bypassing sand from the updrift beach to the downdrift beach can be used to keep entrances open (Bruun 1978).

4-5. Cohesive Sediment Transport. Cohesion results from interparticle electrochemical forces, which become increasingly important relative to the gravitational force with decreasing particle size below ~0.04 mm. Clays, which have sizes less than 0.005 mm, are particularly cohesive (van Olphen 1963). In addition to the negative charge on its surface, the clay particle, like all material surfaces, possesses London-van der Waals electrochemical forces of atomic origin. If sufficient salt is present, the double layer is considerably compressed and the London-van der Waals forces "stick out" beyond the double layer. In this event, the micelles will attract each other and coagulation will occur.

a. Particle Cohesion. Particle cohesion requires interparticle collision. There are three basic mechanisms for collision: Brownian motion, flow shear due to turbulence, and settling of particles at different speeds, or differential settling (Hunt 1980). Out of these, shearing in the fluid column, which is prevalent throughout the tidal cycle except at slack water, produces the strongest interparticle bonds (Krone 1972).

b. Salinity Effects. When salt concentration in water exceeds 2 to 3 ppt, coagulation of major clay types, i.e., kaolinite, illite, and montmorillonite, is complete (Hayter 1983).

c. Settling Velocity. Under continued collision, aggregates tend to build up into units of different densities, shear strengths, and sizes, and these consequently have different settling velocities. Each sediment-fluid mixture has its own characteristic settling velocity-concentration relationship (Krone 1962; Burt and Stevenson 1983).

d. Concentration Effects. At very low concentrations, e.g., ~100 mg/ℓ or less, interparticle collision frequency is restricted and the settling velocity shows no significant dependence on concentration. At higher concentrations, up to ~3,000-5,000 mg/ℓ, aggregation is enhanced with increasing concentration. At even higher concentrations the settling velocity begins to decrease with increasing concentration. This is referred to as hindered or zone settling. The term fluid mud is often used to describe a high concentration (> 10,000 mg/ℓ) suspension that characteristically exhibits the hindered settling behavior (Krone 1962).

e. Exceptions. Aggregates of sediment in the clay- and silt-size range typically behave as bed material load (however, not as bed load), while very fine material, e.g., derived from biogenic sources, often behaves as wash load, not being represented in the bed.

f. Particle Size. Inasmuch as cohesive aggregate properties (e.g., size, density, and shear strength) depend on the type of sediment-fluid mixture as well as on the flow condition itself, particle size has a different meaning here than in the case of cohesionless sediment, since aggregate size is not an easily characterized quantity. Critical shear stress for erosion depends on the mode of formation and degree of consolidation of the bed (Mehta et al. 1982). It becomes essential to conduct laboratory erosion tests to evaluate the bed shear strength for a given mud-fluid mixture (Mehta et al. 1982; Parchure 1984).

g. Deposition. The processes of cohesive sediment deposition and erosion are interlinked through bed consolidation. Rates of deposition and erosion in turn determine the rate of horizontal transport in suspension. In a tidal estuary, these processes are characteristically cyclic in nature; their interrelationship is schematized in Figure 4-2 (Mehta et al. 1982). As observed, suspension in horizontal transport interacts with the bed through tide-controlled, time-dependent, deposition-consolidation-erosion process. During consolidation (and gelling), upward escape of the pore water occurs, the bed density increases, and physicochemical changes occur within the bed as the deposited aggregates are crushed slowly under overburden. A settled, or

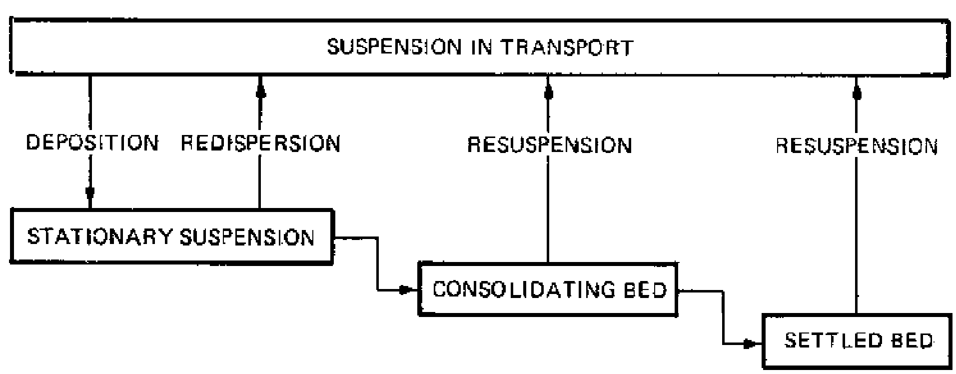

Figure 4-2. Schematic representation of the physical states of cohesive sediment in estuarial waters (from Mehta et al. 1982)

fully consolidated, bed eventually results. Relatively thin deposits, on the order of a few centimetres thickness, practically consolidate in a week or two, but thick deposits may remain underconsolidated for months or even years.

h. Erosion. Immediately following slack water, a stationary suspension begins to erode or resuspend rapidly as the flow speed picks up. This is often referred to as mass erosion or redispersion (Parker and Kirby 1982). A fully consolidated or a settled bed erodes by a slightly different process. At relatively low bed shear stresses (or velocities), aggregates from the bed surface are entrained. At high shear stresses, or under rapidly accelerating flows, erosion is much more rapid, and relatively large chunks of sediment are entrained.

i. Depth Effects. In deep estuaries, there can be a significant lag between nearbed suspension response to deposition/erosion and the corresponding response at the surface. This type of hysteresis effect is set up as a result of the time it takes for sediment to diffuse upward and the corresponding sediment settling time.

4-6. Impact of Tidal Flow and Geometry. Sedimentary boundary conditions are critically important in governing estuarial sediment transport. At the mouth, tidal forcing is determined by the open coast tide characteristics as well as the geometry of the mouth itself. At the upstream end, beyond the influence of tides, the river discharge hydrograph and sediment inflow are key factors. In addition, runoff, direct precipitation, and bank erosion by currents and waves can be significant factors that contribute to the overall sedimentary regime.

a. Deposition. Deposition-dominated environment includes flood and ebb deltas near the mouth, shoal areas within the estuary including natural and dredged navigation channels, and basins including ports and marinas.

b. Erosion. Sites where erosion is predominant tend to be localized in comparison with sites of deposition, although sometimes large previously deposited shoals disintegrate in the absence of sediment supply.

c. Mixed Environment. In a mixed deposition/erosion environment in which net scour or shoaling is small, e.g., as would occur if the regime were in a state of "live bed" equilibrium, the rates of deposition and erosion can be high individually, and these would cause significant "to and fro" transport of sediment during a tidal cycle or over a spring-neap cycle.

d. Waves. Shallow- and intermediate-depth water waves provide a critically important mechanism for incipient motion and resuspension of bottom sediment. The sediment is then advected by the tidal currents. Waves breaking at the banks can also cause a measurable increase in sediment transport rates in some cases.

e. Wind. Aeolian transport is usually ignored in typical estuarial transport calculations. However, in certain well-defined areas such as small basins, windblown material can form a significant fraction of the total deposit, particularly where sediment transport rates in the water body are not high.

f. Sea Level Rise. The rise of sea level relative to land should be considered when comparing bathymetric surveys taken at different times, for the purpose of determining long-term rates of shoaling or scour (Krone 1979).

g. Geometry. The impact of estuarial geometry on sediment transport is associated with the effect of geometry on flows that transport sediment. For example, it is quite common to find relatively well-defined flood- and ebb-dominated channels with consequent implications for the direction of sediment transport. Furthermore, deep, dredged channels often are natural sites for sedimentation as are basins constructed along estuarial banks. Natural floodplains are historic sites for deposition of alluvial material, which provides fertile soil necessary for agriculture. Diversion of tributary flows for agricultural or urban uses can have deleterious effects, on both sedimentation as well as water quality (McDowell and O'Connor 1977).

4-7. Sediment Characterization. Characterization tests for the sediment depend on the nature of sediment, i.e., coarse or fine-grained. It may be necessary to separate the coarse and fine fractions and analyze them separately.

a. Coarse Sediment. For coarse sediment it is typically useful to evaluate particle size distribution or, preferably, settling velocity distribution; material density and bed porosity; and, sometimes, the angle of repose.

b. Analysis. Size distribution is customarily obtained through sieve analysis in terms of selected sieve sizes. It is preferable to characterize sediment by its settling velocity, which is a more fundamental property than size as far as sediment transport is concerned. Details on particle size and settling velocity measurements as well as material density and bed porosity are found in Vanoni (1975). The angle of repose is a basic property associated with bank stability as well as with incipient grain movement (Lane 1955; Mehta and Christensen 1983).

c. Cohesive Sediment. For cohesive sediment, the problem of characterization is more complex than that for coarse-grained material, because sediment aggregate properties depend on the type of sediment, the fluid, and the flow condition itself.

d. Characterizing Sediment. For characterizing the sediment, it is recommended that the following be specified through various laboratory measurement procedures:

(1) Grain size distribution of dispersed sediment using, for example, the standard hydrometer test (ASTM 1964).

(2) The relationship between the median (by weight) settling velocity and the suspension concentration of the flocculated sediment, noted in Owen (1976).

(3) Clay and nonclay mineralogical composition through X-ray diffraction analysis (Grim 1968).

(4) Organic content (Jackson 1958).

(5) The cation exchange capacity, which is a measure of the degree of cohesion of the clay (Grim 1968).

e. Characterizing Fluid. For characterizing the fluid, it is recommended that the following be specified:

(1) Concentrations of important cations (e.g., sodium (Na+), calcium (Ca++), and magnesium (mg++) and anions (e.g., chlorine (Cl-) and sulfate (So_4^{--})).

(2) Total salt concentration.

(3) pH.

(4) Fluid temperature during measurements as well as in laboratory experiments for determining the rates of erosion and deposition.

Items 1, 2, and 3 can be determined through standardized chemical analysis procedures.

f. Sodium Adsorption Ratio. Recognizing that sodium, calcium, and magnesium are three comparatively more abundant and influential cations, the sodium adsorption ratio (SAR) is found to be a convenient parameter for characterizing the influence of fluid chemistry on cohesive sediment transport behavior. SAR, total salt concentration, pH, and fluid temperature have been shown to control the critical shear stress for erosion of soils with uniform bed properties (Ariathurai and Arulanandan 1978).

g. Core Samples. Inasmuch as consolidation increases bed density, it is important to obtain representative in situ bottom cores for determining the depth distribution of the density (bulk and dry) of the bed. This information enables a conversion between deposition and erosion of sediment mass per unit time and the corresponding changes in the suspension concentration (mass per unit volume).

h. Rheological Properties. In studies in which dissipation of fluid energy within the bed plays an important role, e.g., wave-mud interaction, it is essential to evaluate the rheological properties, the most important one being the viscosity, which has been found to be related to sediment concentration in an approximate manner (Krone 1963). Most commonly this includes the Bingham yield stress, for a comparatively simplified rheological description.

i. Usage of Collected Data. The characterization of sediment is necessary to aid in the identification of transport and deposition processes. Preplanning for specific project data collection programs is essential so that the proper type, quantity, and data analysis can be conducted. The preceding and following paragraphs describe various field tests and sediment analysis, which may or may not be required. The amount and type of data and required procedures and tests should be determined during the project planning stage. Too much or too little data could be costly and detrimental to the project. These chapters and appendices provide general guidance; specific guidance can be found in Appendix A or through the Hydraulics Laboratory, WES.

4-8. Transport Parameters. The movement of sediment is sensitive to flow speed and direction, and it is particularly important to characterize the flow regime including the influences of salinity, wind, and related factors for a comprehensive evaluation of the overall sediment transport regime.

a. Settling Velocity. Particle settling velocity is both an important sediment-characterizing parameter as well as a deposition-related parameter. The critical shear stress is the important erosion-related parameter. Field and laboratory procedures for evaluating these and associated parameters, where cohesionless sediment transport is concerned, are well documented in literature (Vanoni 1975). Use of sediment transport formulas without adequate calibration of the formula may lead to major errors in transport rate prediction.

b. Processes. Cohesive sediment transport processes that require parameter characterization include settling and deposition, consolidation, and erosion.

c. Procedures. Settling is principally characterized by the relationship between the settling velocity and suspension concentration. There are basically four procedures for evaluating this relationship, each under a specific set of conditions and therefore yielding results peculiar to those conditions:

(1) Tests in a laboratory settling column (ASTM 1964; Krone 1962; Hunt 1980).

(2) Tests in a laboratory flume (Krone 1962; Mehta and Partheniades 1975).

(3) Use of in situ settling tube. This tube, designed originally by Owen (1971), allows for on site measurements. By performing the settling test almost immediately following sample withdrawal from the water body, the aggregates are presumed to remain unaltered in composition.

(4) Comparison of measured suspended sediment concentration profiles (depth-concentration variation) with analytic prediction (O'Connor and Tuxford 1980; Mehta et al. 1982; Vanoni 1975).

d. Field Measurement. For prototype application, the in situ tube is preferred for measurement of settling velocity. Extensive measurements of this nature have, for instance, been obtained in the Thames Estuary in England (Burt and Stevenson 1983). Laboratory flume tests should be used for supplementary and/or confirmatory evidence. The same holds for settling columns. Different approaches will yield different results, in general.

e. Shear Stress. The rate of deposition depends on the rate at which the fraction of the settling sediment deposits, the remainder consisting of aggregates that break up near the bed under the action of bed shear stress and are reentrained. The critical shear stress for erosion τ_s can be evaluated from laboratory flume experiments (Krone 1962). For a uniform sediment (narrow primary particle size distribution), single values of settling velocity W_s and critical shear stress for deposition τ_{cd} will suffice. For a graded sediment (e.g., a typical mud with a relatively wide range of sizes from coarse silt to fine clay), W_s and τ_{cd} will have corresponding wide ranges.

f. Gelling. Freshly deposited mud undergoes increases in both density and physicochemical changes associated with interparticle bonds, known as gelling. Following bed formation, gelling is complete in about a day (Krone 1983).

g. Bed Thickness. From the perspective of estuarial sediment transport, density increase and physicochemical changes are important because these in turn control corresponding changes in the bed shear strength with respect to erosion (Mehta et al. 1982). For relatively thin beds, e.g., on the order of a few centimetres in thickness, consolidation is practically complete in a period on the order of 1 or 2 weeks, and the rate of bed deformation becomes small in comparison with its value immediately following bed formation. Density and erosional shear strength become nearly invariant with further passage of time.

h. Bed Shear Strength. Investigators have found an approximate power-law relationship between the bed shear strength and density, specific to the type of sediment and fluid used (Migniot 1968; Owen 1970; Thorn and Parsons 1980).

4-9. Causes of Sediment Deposition. The rate of sediment mass deposition increases with increasing settling velocity W_s and with suspension concentration C and decreases with increasing bed shear stress τ_b, given τ_{cd}. It follows that the mass of sediment deposited depends on the availability of entrained sediment, its settling velocity, and flow condition as reflected primarily in the bed shear stress. This type of reasoning is generally applicable to cohesive as well as cohesionless sediment.

a. Definition. A deposition-dominated environment is characterized by a region of relatively low bed shear stress in which the rate of supply of sediment to the bed well exceeds the rate of depletion by erosion (Ippen 1966; Mehta et al. 1982).

b. Long-Term Monitoring. Estuaries tend to be in a state of quasi-equilibrium as far as the hydrodynamic and sedimentary processes are concerned. Superimposed on these processes of annual cycle of variation of tides, freshwater flows, salinity intrusion, and sediment transport, longer period variations in the physical regime also occur. Slow filling up of the existing deep channel or thalweg, coupled with scouring of a new channel elsewhere, may occur over a 10-20 year period (Calcutta Port Commissioners 1973; McDowell and O'Connor 1977). It is therefore critically important to understand the long-term estuarial behavior through an adequate monitoring program, particularly one involving extensive bathymetric surveys.

4-10. Consolidation. Consolidation is the volume change in deposited material with time. Fine or cohesive sediment deposits consolidate. Hindered settling can result in the formation of fluid mud. As sediments consolidate toward fully settled states, a self-weight component may be important to further consolidation.

a. Fluid Mud. The formation of fluid muds can alter the transport mode of fine-grained sediments and is therefore important to sediment dispersal analyses. Fine-grained material with high moisture or low bulk density has relatively low shear strength and can flow under the effects of gravity or the overlying flow. Fluid mud layers often collect in navigation channels.

b. Consolidation Tests. The amount of consolidation that disposed dredged material will undergo can be predicted by settling tube or accelerated consolidation tests and models (Montgomery 1978; Cargill 1983 and 1985). Similar zone or column settling tests can be performed on fine-grained sediments to determine settling characteristics over a range of high suspension concentrations. If self-weight consolidation modeling is to be carried out, special controlled-strain consolidation testing is required. Controlled-strain consolidation testing is performed at the WES Geotechnical Laboratory.

4-11. Physical Models. Physical hydraulic models are scaled representations of prototype estuaries. Physical hydraulic models can be important tools in sedimentation analysis of estuaries, and should be considered as one component of a program to study sedimentation if three-dimensional flow effects are known or suspected to be important. Most physical modeling of estuaries is performed at the WES Hydraulics Laboratory.

a. Scale. Sediments and sediment transport rates must be scaled in the models. Scale ratios for coarse sediments transported by quasi-steady hydraulic shear stresses are an acceptable compromise permitting useful predictions. Shoaling indices are employed. Scale ratios for fine sediments are more difficult to establish, and qualitative methods are used for hydraulic model prediction.

b. Processes. Physical hydraulic models have been successfully used to predict tidal currents, circulation, riverflows, salinity distributions, and dispersion processes. Many or all of these processes influence sedimentation. Physical hydraulic models have been successfully incorporated into hybrid model studies as will be discussed in a later section. Because they are real, physical representations, physical hydraulic models display system dynamics in a manner that can be readily assimilated by both modeler and lay persons. Physical hydraulic models can simulate long periods of time, spring-to-neap cycles, or hydrographs.

c. Test Procedures. During model verification hydraulic and salinity adjustments are made first. Sedimentation is verified to shoaling volumes computed from a series of prototype hydrographic surveys. Methods are developed during model verification to introduce, distribute, and collect model sediments.

4-12. Analytical Models. Analytical models are considerable simplifications of estuarine sedimentation processes but are useful for such tasks as screening, checking the reasonableness of other methods, and identifying important processes. The following are some examples of analytical models.

a. Prototype Data Treatment. Analytical models are a method of treating prototype data. Time series velocities and concentrations can be integrated using assumed critical shear stresses to estimate depositional flux or net deposition. Several equations can be used for this purpose and form the basis for a closed-form mathematical solution.

b. Flux Analysis. An alternate or supplemental analysis to that of the last section is horizontal suspended flux analysis using prototype data. Horizontal flux analysis makes no assumption about deposition characteristics of sediments. Deposition or erosion is inferred from longitudinal gradients of sediment flux in this method. Measurements of currents, salinities, and suspended sediment concentration over depth and over a tidal cycle can be used to calculate the total fluxes at a station.

c. Depositional Models. Zero-dimensional (in the spatial domain) models can be applied to basins or to channels with relatively steady and uniform flows. A slightly more complex model incorporating tidal prism input could be applied to an estuary as a whole or to tidal basins (Appendix D).

4-13. Numerical Models. A number of estuaries have been numerically modeled at the WES Hydraulics Laboratory. A two-dimensional (in the horizontal plane) numerical sedimentation model is included in the Corps’ TABS modeling system. TABS is available to qualified users Corps-wide. Training on the TABS system is available at WES.

a. Model Processes. Numerical sediment models are transport models with nonconservative bed interaction terms. Sediments are numerically transported by advective currents and by diffusion; therefore, sediment models require that currents be supplied by a hydrodynamic (usually numerical) model. Interactions between suspended sediments and the bed are governed by process equations in sediment transport models. Coarse sediment-bed interaction terms usually depend on the gradient of the transport potential of the material.

Fine sediment-bed interaction terms consist of process description for erosion and deposition. Bed structure or layering is usually modeled in some way to account for changes in density and shear strength with depth in fine sediments. Numerical sediment models are classified by their dimensions, sediment type, and the equations that are solved.

b. Model Applications. Numerical models are the most advanced modeling method available for simulating sedimentation. Numerical modeling, like other modeling methods, remains an art-science, and successful application to real problems depends heavily on the skill and intuition of the model user.

4-14. Hybrid Models. Combining two or more models in a solution method is a hybrid model. Hybrid models attempt to use the best modeling methods available for each "part" of sedimentation problems: current structure and sediment transport. The following are the most frequently used hybrid techniques, starting with the most rigorous.

a. Physical-Numerical. The physical-numerical hybrid modeling approach uses a physical model to predict currents and a numerical model to predict sediment transport. This approach has been successfully applied to a number of estuarine sediment problems at the WES Hydraulics Laboratory (McAnally et al. 1983). The physical model can be used to generate boundary conditions for the detailed numerical mesh or grid of the sediment model.

b. Physical-Analytical. The physical-analytical hybrid modeling approach uses a physical model for currents and an analytical model to predict sedimentation. Velocities and bed shear stress histories can be collected at various points in the physical model. Physical model results can then be extended using some appropriate analytical expression(s).

c. Numerical-Analytical. A numerical-analytical hybrid model uses a numerical model to predict sedimentation. The numerical-analytical hybrid technique avoids the costs associated with numerical sediment modeling, but at the expense of considerable rigorousness. The results from a hydrodynamic model can be used to address limited questions on sedimentation with analytical models. The shear stress at various points can be evaluated to predict an indication of deposition or erosion (Hauck 1989).

4-15. Field Data Requirements. All analyses depend on field data. Field data acquisition may be the most costly part of a sedimentation study. Required data can be grouped into system definition and behavior and boundary data. The following discussion is limited to sediment data requirements.

a. A good way to determine system behavior is to conduct a boat survey in which currents, salinities, and suspended sediment concentrations are collected at short time intervals (half hour) with depth at several stations across several cross sections over a tidal cycle. Tides at several locations and supporting measurements or observations of winds and other conditions are also required.

b. Bed sediment properties are required for system definition. Methods for sediment characterization were described in earlier sections. Fine-grained sediments require settling velocity evaluation, since settling is not related directly to individual particle size. Vertical profiles of suspended sediment concentration can be used to deduce settling velocities. Settling velocities can be estimated in the field using settling tube samplers. Settling experiments in the field are preferred to laboratory tests, although conditions may require the latter. It is usually not practical to carry out enough settling tests in the field to obtain sufficient spatial and temporal coverage. Therefore it is necessary to supplement field settling data with analysis of many vertical suspended sediment profiles or high-resolution particle size analysis (such as Coulter Counter analysis). Water column measurements of sediment concentration should be supplemented by some measurements near or at the sediment bed-water interface. Specifically, the presence of fluid mud should be checked using acoustic soundings, densimetric profiling, or low-disturbance coring devices. Shallow coring is also a good method of determining bed structures such as armoring, density differences, or layering.

c. Classification by the methods described in earlier sections may be useful in estimating sediment properties from existing data. Settling velocities, critical shear stresses for erosion and deposition, and the densities of fine-grained deposited material are properties that might require supplemental laboratory study.