Chapter 6

Model Studies

6-1. General. Physical and mathematical models are useful tools in the solution of sedimentation problems. A physical model study is in order when existing design criteria are inadequate to meet the required level of confidence for a specific project. The large number of variables that effect sediment transport, together with the infinite variety of boundary conditions with hydraulic structures and natural channels, often makes it impossible to develop comprehensive optimal relationships to use as the basis for design. Consequently, many hydraulic phenomena are studied by means of physical models, using the basic principles of similitude to correlate model and prototype behavior. Physical model tests are generally desirable where local scour or sediment deposition could endanger the functionality of a hydraulic structure or river modification. Physical models provide a means for checking project performance and devising modifications to obtain the best possible design at minimum cost. Mathematical models are applicable when the sediment behavior can be predicted analytically. Mathematical models generally require more data to calibrate and verify than physical models, but once this is accomplished, it becomes relatively simple to test various modifications and design proposals. The design engineer must be familiar with the theoretical background of the mathematical model, including its limitations and applications; he must avoid the tempting "black box syndrome" which may yield computer output impressive in volume but meaningless in substance. Physical and mathematical models should be used to supplement, but not replace, theoretical knowledge, good judgment, and experience.

6-2. Undistorted Physical Model. Undistorted physical models are generally used to determine local scour patterns downstream from hydraulic structures. Usually the bed material cannot be scaled down as required by laws of similitude, so results are generally qualitative rather than quantitative. These qualitative results can be used to compare the local scour effects at various designs of outlet works, bridge piers, abutments, spur dikes, protective aprons, training walls, and sediment diversion and exclusion structures. The theory of physical model design is discussed in detail in several publications [9], [15], [3], and [70]. For sediment models, where the gravity force dominates the flow, similitude will require equality of Froude number in the model and prototype. The following Froudian scale relations (prototype/model) apply to undistorted models.

Manning's n	Length	Area	Volume	Time	Velocity	Discharge
Lr1/6	Lr	Lr2	Lr3	Lr1/2	Lr1/2	Lr5/2

6-3. Model Scales. The length ratio Lr is the prototype-to-model ratio Lp/Lm. The transfer relations above are based on equal force of gravity and density of fluid in model and prototype. Physical models must be designed such that turbulent flow will prevail with the model velocities and depths in order that essential flow patterns are preserved. Model Reynolds Numbers greater than 1800 are generally required to ensure turbulent flow. Since the model Reynolds number will always be smaller than the prototype Reynolds number, there will be some scale distortion of certain phenomena such as zones of separation, wave dissipation, flow instability, and turbulence in the model. Particular care should be taken in interpreting those effects that are known to be strongly dependent on viscous forces. It is frequently impossible to preserve similitude with respect to size and weight of bed material in physical models. However, several investigators have concluded that the effect of bed material size on scour depths is insignificant. Amad [1] found that bed material size effected rate of scour around a spur dike but had no effect on ultimate scour depth. Liu et al [38] concluded that bed material size had an insignificant effect on the depth of local scour at bridges. Laursen [36] agreed as long as there was sediment transport into the scoured region. Vanoni [2] reached the same conclusion based on a thorough review of available references. These investigations increase confidence in results obtained from physical models where bed material similitude is not maintained. However, there remains insufficient prototype-to-model comparisons to prove conclusively that bed material size is insignificant in local scour problems and model results should be considered qualitative.

6-4. Distorted Physical Models. Movable bed physical models of river channels, flood ways, harbor, and estuaries often require a distortion of the vertical scale in order to ensure movement of the model bed material. Vertical scale distortion also allows for measurable depths and slopes as well as ensuring turbulent flow in the model. The scale relations for distorted models are given in reference [3]. If the bed slope is made equal to the energy slope ratio, the slope ratio will also be equal to the amount of model distortion.

$$Sr = Yr / Xr \qquad (6\text{-}1)$$

where:

Yr = the vertical scale ratio
Xr = the horizontal scale ratio, prototype to model.

The Manning equation can then be used to obtain a roughness criteria for model design [15].

$$nr = Rr(2/3) / Xr(1/2) \qquad (6\text{-}2)$$

For a wide channel the equation above reduces to

$$nr = Yr(2/3) / Xr(1/2) \qquad (6\text{-}3)$$

The required roughness in the model can be computed by equation (6-2) and used as a guide in designing the model. To ensure sediment movement at low model velocities, it is often necessary to use a model bed material lighter than sand. Coal dust (Specific Gravity = 1.3 approximately) and plastics (Specific Gravity = 1.2) are common model bed materials. Scale distortion in movable bed models presents several problems. Vertical distortion may increase the bank slopes beyond the angle of repose so that they will no longer stand. One remedy is to make the banks rigid, but this can only be done if the banks are known to be stable. Scale distortion also increases the longitudinal slope of the river making it necessary to increase model roughness. However, roughness is primarily a function of bed forms and cannot be arbitrarily adjusted. Vertical distortion also distorts the lateral distribution of the velocity. This creates simulation problems at confluences, bifurcations, and sharp bends. The problems related to vertical distortion generally limit movable bed models to mild sloped streams where the distortion ratio should be limited to 3. In special cases the distortion ratio could be as high as 10. In harbor and estuary models greater distortion is permitted due to the relatively small prototype sand slopes and very mild water surface slopes. The choice of scales and bed materials for movable bed models is largely based on the experience and judgment of the modeler. At the Waterways Experiment Station coal dust is frequently chosen as the bed material. Model velocities ranging between 0.3 and 1.0 ft/sec are required to simulate bed material movement. This velocity criteria is used to select a vertical scale. The slope of the model is then determined using the Manning's equation with a roughness coefficient of 0.018 for coal dust. The horizontal scale is determined from

$$Xr = Yr / Sr \qquad (6\text{-}4)$$

The time scale governing the fluid flow in the model will probably be different from the time scale governing sediment movement. This means that the hydrograph applied to the model will have to be reduced by model operation. During the model verification process, adjusted historical hydrographs are run through the model until historical bed changes can be reproduced. The adjusted hydrograph may require different time scales for low discharges than high discharges because of the nature of the model bed material. For instance, coal dust moves rapidly from little movement to violent movement with small increases in tractive force so that the time scale would be increased for low stages and decreased for high scale in order to simulate prototype bed movement. The verification of the movable bed model is very important due to the absence of quantitative similarity. Once the model and its operations is adjusted so that it accurately reproduces known bed configuration changes, then there is ground for confidence in model predictions of future events.

6-5. <u>Numerical Models.</u> The computer program HEC-6 "Scour and Deposition in Rivers and Reservoirs" is used throughout the Corps of Engineers to set up numerical models of river systems. The application, data requirements, and theory behind this program are discussed at length in the references [24], [52], and [51]. Numerical models, like physical models, must be verified and calibrated if they are to be effective predictors in river systems. It may be tempting to feed data into a computer program such as HEC-6 and consider the results as reliable. However, mobile boundary computer Programs are not simple extensions of fixed boundary hydraulics, as numerous complex factors are involved which are not fully understood. Verification and calibration are essential to demonstrate the programs are simulating the prototype.

6-6. <u>Calibration.</u> Ideally, any quantitative analysis should be based on predictive equations that have been calibrated and verified. The calibration process consists of taking known physical conditions and adjusting coefficients and representative values needed for the one dimensional average approximations to reproduce measured changes. After the predictive equations have been calibrated, the model should be verified by testing the behavior against data not used in the calibration. That step is not always possible, and when it is, careful attention to the boundary conditions are required. That is, do not expect to reconstitute specific field measurements with a model which has a general calibration. Moreover, do not expect to reconstitute a specific period using representative boundary condition developed from some other flow record.

6-7. Prediction. Models that have been calibrated can then be used to predict future conditions with a degree of certainty that is as reasonable as the predicted, future boundary conditions will permit.

6-8. Interpretation of Results. Results from numerical as well as physical models should be interpreted by comparing the results from a plan test with those for a base condition. The base condition is the predicted future with no project. All input data should be the same in the two runs except the variable being tested. For example, deposition and degradation due to a dam should be compared with sedimentation in that reach of river if no dam is built to determine problems resulting from the dam. Therefore, the Base Test Conditions would come from simulating sedimentation for the entire length of stream in the study area during the project life for a no dam condition. The Plan Condition would be determined by installing the dam and re-running the simulation. The impact of the dam is determined by comparing those two results.

6-9. Scour and Deposition in Rivers and Reservoirs (HEC-6). The most commonly used movable bed computer program for 1-dimensional computations is HEC-6. This program is designed to analyze scour and deposition by modeling the interaction between the water-sediment mixture, sediment material forming the stream's boundary and the hydraulics of flow. It simulates the ability of the stream to transport sediment and considers the full range of conditions embodied in Einstein's Bed Load Function plus silt and clay transport and deposition, armoring and the destruction of the armor layer. It has no provision for simulating the development of meanders or specifying a lateral distribution of sediment load. The program can be used to determine both the volume and location of sediment deposits in reservoirs. Degradation of the stream bed downstream from dams can be determined. Long term trends of scour and deposition in a stream channel as a result of channel modification can be simulated. Channel contraction required to either maintain navigation depths or diminish the volume of maintenance dredging can be studied, but not in the detail obtainable from movable-bed physical model studies. The influence that dredging has on the rate of deposition can be simulated, and scour during floods can be investigated.

6-10. Open Channel Flow and Sedimentation (TABS-2). This is a 2-dimensional, finite element calculation of the Reynold's form of the Navier-Stokes equation for hydraulic parameters, linked, by a similar solution, with the convection-diffusion equation for sediment transport using an uncoupled computation scheme. All non-linear terms are present allowing the computation of eddys and separation zones. Like HEC-6, this system of computer programs is available for Corps Wide use. It is maintained and supported by Waterways

Experiment Station. More information on TABS-2 is available in reference [67].

6-11. CORPS. The Waterways Experiment Station maintains a system of computer programs for hydraulic design. The system is called CORPS which stands for Conversationally Oriented, Real-time Program Generating System. It is documented in the Waterways Experiment Station report by that same name, [66].

a. Scope. These programs cover the range of problems presented in Hydraulic Design Criteria: spillways, stilling basins, outlet works, locks, closed conduit flow, open-channel hydraulics, stable channel design, and sediment transport. However, new programs are added in response to field office requests so use the on line documentation system for current information.

b. Access. Access to CORPS is available via the district's computer, the Corps wide contract computer service or the Waterways Experiment Station computer. Access information can be obtained from the district Automatic Data Processing (ADP) contact, the Waterways Experiment Station ADP Center or the Chief, Hydraulic Laboratory, Waterways Experiment Station.

c. Documentation. Once on line the following information can be acquired:

(1) Description of "CORPS."

(2) Listing of the available programs by category,

(3) Brief description of any of the programs in the system,

(4) Execute demand for any of the programs.

d. The sediment group. One of the groups in the CORPS system is sedimentation. Sediment transport, flow resistance over movable beds, stable channel design, riprap design, and particle settling velocities programs are available with several examples being shown in the following list.

H0011 KINEMATIC VISCOSITY OF WATER, EFFECTS OF TEMPERATURE

H0910 COMPUTATION OF PARTICLE FALL VELOCITY BY SHAPE FACTOR

H0920 TOTAL SEDIMENT TRANSPORT RATE IN SAND BED STREAMS BY COLBY'S METHOD

H0921 BED-LOAD TRANSPORT IN RIVERS BY EINSTEIN'S PROCEDURE

H0922 TOTAL SEDIMENT LOAD BY MODIFIED EINSTEIN PROCEDURE

H0923 BED LOAD TRANSPORT RATE BY MEYER-PETER MULLER'S METHOD

H0924 COMPUTATIONS OF SEDIMENT DISCHARGE IN RIVERS BY SHEN AND HUNG'S METHOD

H0925 TOTAL SEDIMENT DISCHARGE BY YANG'S METHOD

H0926 SAND DISCHARGE BY TOFFALETI'S METHOD

H0941 STABLE CHANNEL DESIGN

H9110 FLOW RESISTANCE OVER MOVABLE BEDS BY EINSTEIN'S METHOD

H9111 FLOW RESISTANCE BY THE METHOD OF WHITE, PARIS AND BETTESS

H7010 RIPRAP REQUIREMENTS FOR OPEN CHANNELS

H7220 EROSION AT CULVERT OUTLETS AND RIPRAP REQUIREMENTS

e. Category "A." Each program has been checked to be as foolproof as possible in compliance with Category "A" quality control. Documentation, prepared according to Category "A" standards as established by the Office, Chief of Engineers (OCE), is available for each program.