Coastal Engineering Technical Note

APPLICATION OF MOVABLE-BED PHYSICAL MODELS TO PREDICT STORM-INDUCED EROSION

PURPOSE: This note provides guidance and nomograms for determining if two-dimensional, movable-bed physical models can be used as a planning and engineering design tool to predict beach and profile erosion during storm events.

APPLICABILITY: This guidance is applicable to coastal erosion situations characterized by energetic wave conditions typical of the surf zone during storm events. Examples include beach and dune erosion during storms, beach fill response to a storm, and storm scour at the toe of a structure. The guidance provided in this note is not applicable to bedload-dominated flow situations such as dredge mound evolution and processes at a tidal entrance.

BACKGROUND: Movable-bed models can be performed to provide qualitative information about coastal sediment processes. However, determination of quantitative information for engineering use from small-scale movable-bed physical models has not been possible due to poor understanding of scaling relationships between model and field (prototype) conditions. This arises primarily because in most cases the sediment used in the model cannot be geometrically scaled by the prototype-to-model length scale without introducing significant cohesive effects. Recent research has provided various guidelines to minimize scaling problems by maintaining similarity of important physical parameters between model and prototype. Generally, the scaling guidance is dependent on the primary mechanism by which the sediment is being transported, i.e., scaling laws for bedload transport processes are different than scaling relationships for suspended transport processes. Because of this scaling difference, it is necessary to restrict movable-bed modeling activities to situations where one mode of transport is predominant throughout the modeled regime.

MOVABLE-BED SCALING CRITERIA FOR STORM-INDUCED EROSION: In the nearshore region, turbulent water motions play a greater role in mobilizing and transporting beach sands. Criteria for successful movable-bed physical modeling of hydrodynamic and sediment transport processes in the nearshore zone were suggested by Dean (1985) as the following:

a. Undistorted model with equal horizontal and vertical length scales.
b. Hydrodynamics scaled according to Froude similarity.
c. Similarity of fall speed parameter, H/wT, between model and prototype (H = wave height; T = wave period; w = vertical fall speed of the sediment).
d. Model is large enough to preclude significant viscous, surface tension, and cohesive sediment effects so that the character of the wave breaking is properly simulated.

Criteria a, b, and c result in the following relationships between prototype and scale model:

$$\frac{T_p}{T_m} = \frac{w_p}{w_m} = \frac{(L_p)^{1/2}}{(L_m)^{1/2}} \qquad (1)$$

where the subscripts p and m refer to prototype and model values, respectively, and

T - Time (wave period)
L - Length (wave height)
w - Sediment fall speed.

The scaling guidance provided by Equation 1 was recently verified in a mid-scale (maximum wave height 2 feet) laboratory tank at CERC. The experiment simulated an eroding sand berm fronting a sloping concrete revetment. The scaled model successfully reproduced profile development through time observed in a prototype-sized tank.

The main drawback to the above scaling guidance is that the length scale ratio (L_p/L_m) is uniquely dependent on the prototype and model sediment grain sizes. In the model the smallest grain size diameter that can be used without introducing cohesive effects is about 0.10 mm. This results in the requirement that fine-grained beaches in nature must be modeled in larger facilities because of the reduced length scale ratio. If only smaller tanks are available, then it is only possible to represent prototype behavior typical of coarser-grained beaches.

MOVABLE-BED MODELING APPLICATIONS: The assumptions used in formulating the movable-bed scaling relationships discussed above, coupled with limitations inherent in laboratory flumes, restrict application of this type of physical modeling to coastal sediment problems and processes that have the following characteristics:

a. The erosion process occurs in an energetic, turbulence-dominated region such as a surf zone.
b. Only short-duration events can be simulated, such as episodic storms.
c. Only erosion situations that indicate primarily onshore/offshore (2-d) sediment transport processes may be modeled (guidance is untested for three-dimensional case).

Within these constraints, the following situations may be candidates for a successful movable-bed physical model test:

- Onshore/offshore beach and dune profile response to storm events
- Initial beach fill adjustment at placement due to larger waves
- Beach fill response to storm events
- Short-term scouring at the toes of structures due to storms

On the other hand, many coastal sediment processes fall outside the characterization stated above. Situations that may not be physically modeled under the guidance provided in this Technical Note include the following:

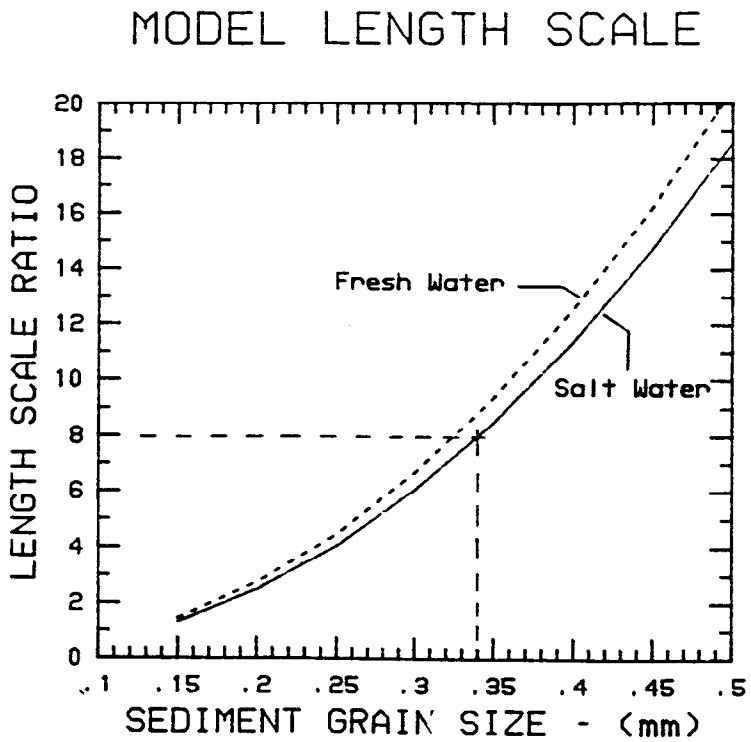

Figure 1. Nomogram for estimating movable-bed model length scale ratio. (Assumes model sediment grain size of 0.13 mm).

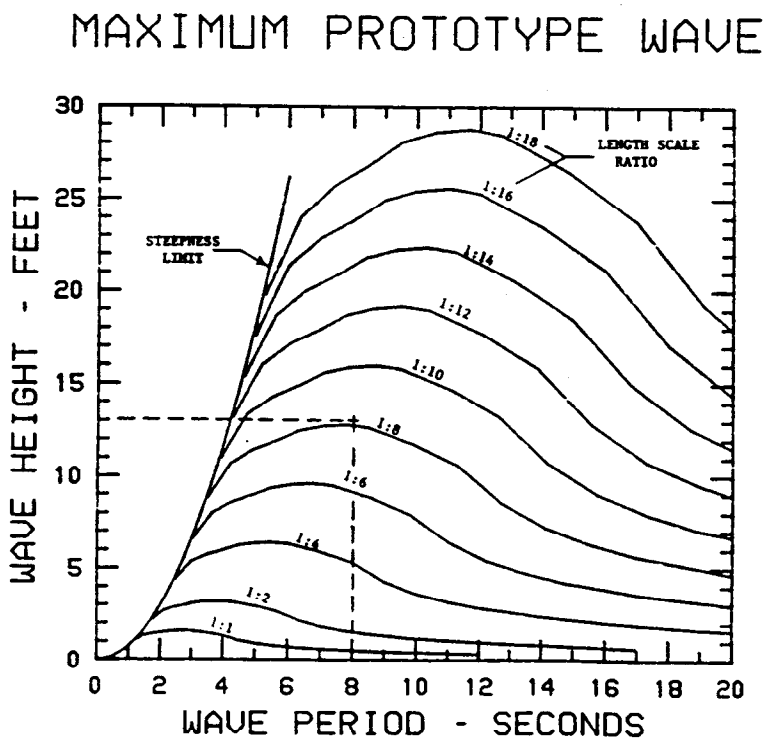

Figure 2. Monochromatic wave height capability at different length scale ratios.

- Long-term shoreline change may not be modeled. (This process is dominated by longshore sediment transport, and it is best modeled using established numerical modeling techniques verified by analysis of long-term geomorphological shoreline patterns as detailed in CETN II-7.)
- Three-dimensional sediment processes may not be modeled. (May be too expensive, present facilities are inadequate to examine fine-grained situations, and guidance is untested.)
- Longshore transport-dominated events, such as impoundment at a structure may not be modeled. (The time required for simulation would be too long, and the guidance is untested.)
- Current-dominated situations such as in the vicinity of an entrance may not be modeled. (Guidance untested for this situation.)
- Bedload-dominated transport such as dredge mound evolution in deeper water. (Requires different scaling relationships).

ESTIMATION OF PHYSICAL MODEL PARAMETERS: If a field problem is well characterized by items a through c of the previous section, and the process can be well approximated in two dimensions, then it may be feasible to employ movable-bed physical modeling as a tool for planning and design. However, it is still necessary to determine if existing CERC facilities can adequately accommodate a properly scaled field situation. This section provides a simple estimation technique for making this assessment. Because the facilities at CERC are periodically upgraded, consult with either of the CERC points of contact listed at the end of this Technical Note prior to making any final determinations.

Estimating Length Scale Ratio. The nomogram in Figure 1 can be used to provide a quick estimate of the appropriate length scale ratio for the physical model. The only requirement is specification of the mean sediment grain size (in millimeters) at the field site. Enter the figure on the horizontal axis with the grain size, and read the corresponding length scale ratio (L_p/L_m) on the vertical axis. Curves are provided for both fresh and salt water. This estimate assumes field conditions of quartz sand in water at 60 degrees Fahrenheit, and model conditions of quartz sand with mean grain diameter of 0.13 mm in fresh water at 60 degrees Fahrenheit. A more accurate method for calculating length scale ratio involves solving Equation 1 using sediment fall spped values obtained by the method detailed in CETN II-4. Field conditions with grain sizes larger than given on Figure 1 can be easily modeled provided that the main transport mode remains similar to the turbulence-dominated transport typical of energetic surf zones.

Estimating Maximum Water Depth. The deepest tank at CERC can accommodate a maximum water depth of 4 ft. This will correspond to a prototype maximum water depth determined by

$$\text{Maximum depth} = (\text{Length Scale Factor}) \times (4 \text{ ft}) \qquad (2)$$

Often it may be necessary to select a tank water depth less than the maximum to accurately represent a prototype situation. This is easily accommodated by either lowering the water level or by installing a false bottom in the wave tank.

Estimating Maximum Wave Conditions. The wave generating capacity for the deepest tank at CERC is presented on Figure 2 as a series of curves representing the equivalent prototype-scale wave conditions for a given length scale ratio. Using the length scale ratio determined from Figure 1, it is possible to estimate what prototype situations represent the maximum wave tank capability. The curves represent maximum monochromatic waves at maximum water depth. Irregular waves can be generated in the flume, and the maximum significant wave height will be slightly less than the monochromatic wave height estimated using Figure 2.

**********EXAMPLE**********

A beach fill project is proposed as one storm protection alternative for an ocean-front community. Design parameters for the project are as follows:

Beach fill median grain size diameter (d_{50}). 0.34 mm
Design significant wave height..... 10.0 ft
Design peak spectral wave period..... 8.0 sec
Water depth of specified design wave..... 50.0 ft

Can a movable-bed model be used to predict beach fill response to the design storm event?

Solution: First it is necessary to establish that the field problem adheres to the acceptability criteria provided by this note. Generally, beach fill response to storm events meets these criteria provided the assumption of dominant onshore/offshore sediment transport is not invalidated by specific site considerations, such as proximity to an inlet, river mouth, etc.

Estimation of Model Length Scale: Entering Figure 1, with a median sediment grain size of 0.34 mm in salt water, a prototype-to-model length scale of 8 is determined. This is illustrated on Figure 1.

Maximum Water Depth: From Equation 2 the maximum prototype water depth that can be reproduced in the physical model would be

$$\text{Maximum depth} = (8) \times (4 \text{ ft}) = \underline{32 \text{ ft}}$$

Design Wave Event at Maximum Water Depth: Because given design conditions are for a water depth of 50 ft, it is necessary to transfer the design wave event to a water depth that can be reproduced in the model. Then it can be compared to model wave capabilities. Using linear wave theory as given in the Shore Protection Manual (1984) to calculate shoaling, the design wave height in 50 ft depth transforms to a design wave height of

$$H_{mo} = 10.3 \text{ ft} \qquad \text{in 32 ft depth.}$$

Maximum Monochromatic Wave Height in Model: The curve labeled 1:8 on Figure 2 represents the maximum monochromatic wave condition that can be reproduced in the physical model. At a wave period of T = 8 sec,

$$H_{max} = \underline{13 \text{ ft}}$$

This indicates that the irregular wave condition representative of the design wave probably can be reproduced in the physical model.

HYBRID MODELING: Recent advances made in numerical modeling of cross-shore sediment transport processes enable the possibility of combining the best features of both physical and numerical modeling technologies to provide enhanced capability at lower costs. For example, the design problem of providing engineering estimates of the storm protection afforded by particular beach fill designs under different storm conditions would require extensive physical model tests to cover the multitude of cases. However, by conducting a small number of physical model tests, the movable-bed test results can be used to adjust empirical coefficients in a cross-shore sediment transport numerical model to reproduce the profile evolution observed in the physical model. The numerical model can then be used with greater confidence to examine the many possible storm wave and surge level combinations for each proposed beach fill design. The final product is reliable estimates on which to base cost/benefit analyses and for project design.

ADDITIONAL INFORMATION: For additional information contact Dr. Jimmy E. Fowler at *Jimmy.E.Fowler@usace.army.mil*. of the Coastal and Hydraulics Laboratory.

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