CHAPTER 197

MOVABLE BED TIDAL INLET MODELS

by

Subhash C. Jain[1]

and

John F. Kennedy[2]

INTRODUCTION

Stabilization of tidal inlets is a major engineering problem that is frequently encountered in the development of harbors. The planning, design, and modification of these inlets under the dynamic conditions that generally characterize their surroundings is, at best, a complex and uncertain undertaking. Prediction of the sedimentary response of an existing inlet to artificial improvements and to changing environmental conditions, or of a new inlet to the expected ambient conditions, and the optimization of the layout in order to minimize undesirable accretion or erosion are major elements in the design of tidal inlets. Because of the complexity of the problem, movable bed hydraulic models aften are employed, despite the questions that surround their validity, to investigate these responses and to guide designs. The success of a movable bed hydraulic model depends upon the proper choice of similitude conditions and modeling criteria. Unfortunately, the conditions of similitude still are not well defined, as many of the phenomena constituent to the processes involved are yet to be elucidated adequately and formulated. Moreover, it is not possible to satisfy simultaneously all of the similitude conditions that arise. The required grain size and density of the model bed material, the current exaggeration that may be required, the effects of geometric distortion, etc. cannot be determined by straightforward computations. These must be chosen to obtain the most favorable balance between all relevant phenomena. The criteria of similitude generally are specified by experimenters who have previous experience with this type of model. The execution of a model studies of this type is, therefore, largely an "art" and entails major elements of subjectivity.

The Iowa Institute of Hydraulic Research, under contract to Coastal Engineering Research Center, U.S. Army Corps of Engineers, is presently (1976) conducting a study to evaluate the reliability and effectiveness of movable bed, tidal inlet, hydraulic models as predictors of prototype behavior. The main emphasis of this study is on comparison of model predictions with observations made in the prototypes, and evaluation of model performance in the light of: (i) the criteria of similitude adopted; (ii) the sedimentary material and instrumentation utilized in the models; (iii) the experimental procedure followed; (iv) the quality of the prototype data utilized in verification of the models; and (v) the degree and accuracy of model verification. The scope of this study is limited to those models in which the area of interest is composed entirely of movable material and not of just a thin erodible layer placed over a fixed bathymetry. In the United States these model studies

---

1 Research Engr., Inst. of Hyd. Res., Univ. of Iowa, Iowa City, Iowa, USA
2 Director, Inst. of Hyd. Res., Univ. of Iowa, Iowa City, Iowa USA

have been conducted only by Waterways Experiment Station (WES), U.S. Army Corps of Engineers, Vicksburg, Mississippi.

SIMILITUDE CONDITIONS - WHY?

Is it always necessary to satisfy certain dynamic similitude conditions in a coastal mobile bed model? It is generally possible to find by a trial and error procedure a combination of waves and currents in the model which will produce the known bed configuration and transport sediment at the desired rate to a certain scale. Why not then use the empirical approach; i.e., the trial and error procedure? To answer this question let us examine what L.F. Vernon-Harcourt (1892) reported long ago on movable bed technology. According to him, a model can be used successfully to predict the possible effects of proposed modification: (a) if the originally existing conditions can be reproduced in the model; and (b) if, moreover, by placing regulating works in the model, the changes that were brought about by the training works actually built can be reproduced. The first of these conditions, i.e., the satisfactory reproduction of the originally existing conditions, may be obtained using a suitable combination of waves and currents, determined by trial and error, in the model. There is, however, no guarantee that satisfactory reproduction would be obtained using the same combination of waves and currents when the constructed works are placed in the model; i.e. that condition (b) will be satisfied. This dilemma was encountered in a model study reported by Reinalda (1960). In his study, the model results were compared with the prototype data for the period before and after the construction of groynes along the coast in the vicinity of the Thyboron channel on the east coast of Denmark. The horizontal and vertical scales of the model were 1:250 and 1:40, respectively. Ground Bakelite with mean diameter of 1.8 mm and a density of 1350 kg/m^3 was used as sediment. The waves and currents were reproduced according to the Froude law. The sedimentological time scale was determined by comparing the rates of recession of the coastlines in the model and the prototype. Groynes were built in the model at locations and times at which prototype groynes were installed. The relationship between the sedimentological time scale in the model and the prototype time scale for both pre- and post-construction periods is shown in figure 1. For the period from 1874 to 1890 (before the construction of groynes) one year in the prototype corresponds to about 0.5 hours in the model, while after 1920 (following construction of groynes) one year in the prototype corresponds to roughly 2 hours in the model. The model, therefore, over-predicted the effectiveness of the groynes on the rate of recession of the shore-line by a factor of 4. Although the groynes in the model reduced the rate of recession of the shoreline as observed in the prototype, the rate of sediment transport in the model was not accurately reproduced in the model. It might have been possible, after numerous attempts, to find another combination of waves and currents which would have yielded the same time scale for both pre- and post-construction periods (although the probability of doing so is very small). But such a trial and error procedure is very time consuming and expensive. It can be applied only in those cases in which extensive prototype detailed data are available for comparison and model calibration.

The empirical approach, therefore, can be applied only in very few cases and with limited expectation of success. It follows that the realization of a satisfactory model can be achieved only by satisfying certain similitude conditions at the outset. As mentioned in the introduction, these conditions of similitude are still not well defined. A certain amount of experimentation to determine proper combinations of waves and currents and to calibrate each model will continue to be required to reproduce the prototype conditions satisfactorily, even if one has satisfied similitude requirements to the extent possible. But the refined procedure will certainly reduce the time required for model calibration. Moreover, the results from such models can be used with more confidence.

SIMILITUDE RELATIONS

Over the past several years many papers (Bijker, 1967; Fan and Le Méhauté, 1969; Yalin, 1971; Migniot, 1972; Kamphius, 1975) have been written on similitude requirements for mobile bed coastal models. Dimensional analysis generally has been used to derive the nondimensional quantities which must assume equal values in model and prototype for similitude to attain. Any dependent property, A, of the flow may be expressed in terms of the independent variables by the following relationship:

$$A = f[H,\ L(\text{or } T_w),\ \sigma_w,\ \theta,\ T_t,\ d,\ U,\ \rho,\ \nu,\ \rho_s,\ D,\ \sigma_g,\ X,\ g] \qquad (1)$$

in which

H	= wave height	Wave parameters
L	= wave length	
T_w	= wave period	
σ_w	= parameter to describe the distribution of wave heights and periods	
θ	= wave direction	
T_t	= tide period	Tide and current parameters
d	= flow depth	
U	= current velocity	
ρ	= density of water	fluid parameters
ν	= kinematic viscosity of water	
σ_s	= density of sediment particles	sediment parameters
D	= diameter of sediment particles	
σ_g	= parameter to describe the size distribution of sediment particles	
X	= some characteristic horizontal dimension	
g	= acceleration due to gravity	

Equation 1 may be expressed in dimensionless form as

$$\pi_A = \phi_A\{\frac{H}{d}, \frac{L}{d}, \sigma_w\, \sigma, \frac{T_t U}{X}, \frac{Ud}{\nu}, \frac{\rho_s}{\rho}, \frac{d}{D}, \sigma_g, \frac{d}{X}, \frac{U^2}{gD}\} \qquad (2)$$

which is so general as to be of practically of little practical use without simplification. It can be said at the outset, however, that it is neither possible nor essential to have the values of all the dimensionless quantities appearing in (2) equal in model and prototype. There is general accord (Fan and Le Méhauté, 1969; Yalin, 1971; Migniot, 1972; Kamphius, 1975) that the waves should be scaled according to the Froude law, with the scales for wave length and wave height equal to the vertical geometric scale. This condition insures proper wave breaking and refraction in the model (provided the model bottom topography is correct by modelled), but the wave reflection and diffraction are not reproduced correctly (because the wavelength is not scaled according to the horizontal length scale). Normally the currents also should be simulated according to Froude law. But the correct simulation of shear velocity, as discussed below, requires a certain exaggeration of the current velocity. The parameters σ_w and θ can be satisfactorily simulated in the model if the wave machine is able automatically to produce a continuous succession of irregular waves of different heights, periods, and directions. Though it is possible to simulate σ_g (by a crushing and sieving process), it is normally disregarded. It remains to simulate the other four nondimensional parameters: Reynolds number, $\mathbb{R}=\frac{Ud}{\nu}$; density ratio, ρ_s/ρ; ratio of flow depth to sediment size, d/D; and model distortion, d/X.

Froude similitude permits dynamically scaled representation of the mean hydraulic flow in the model but does not take into consideration the motion of the sediment. In order to define a suitable model bed material (sediment size and density) and a model distortion which will reproduce sediment motion in the model which is similar to that in the prototype, let us examine how the various sediment transport mechanisms are related to the dimensionless variables. It should be mentioned that the nondimensional parameters given in (2) are not unique. It is possible, at least in principle, to express these nondimensional variables in an infinite number of alternate forms. The form of the dimensionless parameters which should have the same values both in prototype and model to achieve similitude is not obtained by dimensional analysis alone, but requires also consideration of the physical processes involved.

For the satisfactory simulation of sediment motion in a tidal inlet movable bed model, it is desirable that the following conditions be satisfied in the model:

1. The general shape of the beach be conserved.
2. The condition of incipient entrainment of the sediment be correctly simulated
3. The rate of sediment transport be correctly reproduced.

It should be stressed that it may be neither possible nor necessary in some cases to satisfy all these conditions. It is hoped that the results of the study involving comparison between model and prototype which currently (1976) is underway at Iowa will determine which of these conditions must be fulfilled for acceptable similitude to be achieved. Unfortunately, the relationships among the various nondimensional variables which arise in the aforementioned conditions are not well formulated. Past investigators have used different relations and thus proposed different similitude conditions; these are summarized in a recent report by Kamphuis (1975). The following discussion is based upon the present state of knowledge of the roles of three conditions stated above.

Equilibrium Beach Profiles. A generally reliable relationship which will define the equilibrium beach profile in terms of independent variables has not been developed to date. Noda (1972) recently proposed some scale relations for equilibrium beach profiles, but Collins and Chesnutt (1975) concluded on the basis of their laboratory experiments that Noda's model laws predict only the shape of the foreshore region, and its general use was not recommended by them. Until a better relationship for the equilibrium beach profile is obtained, it is recommended that preliminary experiments in a two-dimensional wave tank be conducted to determine beach profiles using the selected model bed material and vertical and horizontal scales, for some characteristic model wave conditions. If the actual scale distorion of the resulting equilibrium beach does not agree that imposed in the wave tank experiments, it is necessary to adjust the imposed value of distortion until the values do agree.

Incipient Entrainment of Sediment. Presently only very limited experimental data are available on initiation of sediment motion by the combined action of waves and currents. The experimental information on initiation of sediment by currents or waves alone suggests that the initiation of sediment motion due to both waves and currents may be expressed by a relation similar to that of Shields (Vanoni, 1975) for steady unidirectional flows. The criterion for the incipient entrainment of sediment under the action of waves and currents can be expressed as

$$F_{*c} = f(\mathbb{R}_{*c}) \tag{3}$$

where

$$R_{*c} = \frac{U_{*c} D}{\nu}$$

and

$$F_{*c} = \frac{U_{*c}}{\sqrt{g\gamma' D}}$$

in which U_{*c} is the critical shear velocity, $\gamma' = \frac{\gamma_s - \gamma}{\gamma}$ is the apparent specific weight of the submerged sediment, and γ and γ_s are specific weights of the fluid and sediment, respectively. Both F_{*c} and R_{*c} are based on shear velocity, U_{*c}, which is a dependent variable. Equation 3 is not a suitable basis for a similitude condition unless U_{*c} is known for the model and the prototype. Valembois (1960) expressed Shields' relation in the modified form

$$G = f(R_{*c}) \tag{4}$$

where $G = \frac{\gamma' g D^3}{\nu^2}$, the so-called grain parameter, is obtained by dividing F_{*c}^{*} by $(R_{*c})^2$. It is proposed here, for want of a better alternative, that for the simulation of incipient entrainment of sediment, the value of grain parameter, G, should be equal in model and prototype. This gives the following similitude condition:

$$\lambda_{\gamma'} \lambda_D^3 = \lambda_\nu^2 \tag{5}$$

in which λ represents the scaling factor (value in model/value in prototype) for the quantity symbolized by its suffix. It is assumed that λ_g is unity.

Sediment Transport. Experimental data on sediment transport under the combined action of waves and current are also very limited. Recently Lin (1972) conducted some tests in a model basin to study sediment transport due to inlet currents and waves approaching the shoreline at an angle of 10°. He used dimensional analysis and his experimental results to express the sediment transport rate as a function of Froude number, bottom shear stress, friction factor, and wave steepness. Another experimental study on sediment transport by currents and waves was conducted by Bijker (1967). He expressed the rate of sediment transport by the following relation:

$$\frac{q_s}{U_{*c} D} = 1.95\, e^{-0.33 \frac{\gamma' g D}{\mu U_*^2}} \tag{6}$$

in which q_s is the volumetric sediment transport rate per unit width, U_* = shear velocity based on total shear stress due to both waves and currents, and μ is a "ripple factor". For correct simulation of the sediment transport in the model, the value of $\frac{\gamma' g D}{\mu U_*^2}$ should be the same both in the model and the prototype, i.e.,

$$\lambda_{\gamma'} \lambda_D = \lambda_\mu \lambda_{U_*}^2 \tag{7}$$

The scale of shear velocity can be written

$$\lambda_U = \lambda_{U_*} \lambda_C \tag{8}$$

where C is bed resistance coefficient. Assuming $\lambda_\mu \simeq 1$, as found by Bijker (1967) in his experients, the similitude condition for sediment transport becomes

$$\lambda_U = (\lambda_{\gamma'} \lambda_D)^{1/2} \lambda_C \tag{9}$$

Using (5), (8), and (9) it can be shown that

$$\lambda_{R_*} = 1 \tag{10}$$

where $R_* = \frac{U_* D}{\nu}$; that is if (5) and (9) are satisfied, then (10) is also satisfied. Equation 7 for $\lambda_\mu \simeq 1$ reduces to the similitude condition that the particle Froude number based on the total shear velocity must be the same both in the model and the prototype.

STUDIES CONDUCTED AT WES

Through 1975 WES had conducted seven movable bed model studies of tidal inlets. Each study was conducted on an *ad hoc* basis, in that no general similitude requirements or modeling criteria were followed. The waves and currents requried to produce satisfactory bed configurations were obtained by a trial and error procedure. Wave heights were exaggerated as much as possible without causing wave breaking to occur at entirely wrong locations. Two prototype hydrographic surveys conducted some time apart were used for model verification and calibration. A model distortion of five was adopted in all model studies. Sands with mean diameters ranging from 0.2 mm to 0.25 mm was used as a model bed materials in all models except the Galveston Harbor Entrance Model, in which coal with specific gravity of 1.4 and a median diameter of 1.4 mm was utilized. The WES studies have utilized plunger-type wave generators, which are adjusted manually to generate regular waves of desired height and period. In all model studies, waves were generated from one or more fixed directions. The bed configurations in the model were recorded manually using sounding rods graduated to 1 ft (prototype). Tides were produced using automatic tide generators.

For the verification of the movable bed models, fill and scour maps, both for prototype and model, were prepared and compared. In some studies the dredging volumes also were used in the model verification. If the general pattern of fill and scour in the model was similar to that in the prototype, the model was considered to have been satisfactorily verified. This "eye-ball" comparison of the scour and fill patterns involves, of course, a strong element of subjectivity.

A PROPOSAL FOR QUANTIFICATION OF MODEL VERIFICATION

It would be very useful to have a quantitative measure of the performance of movable bed tidal models. Some of the quantitative indicators being considered in the Iowa study are the following.

Let S_j be the total amount of scour and F_j be the total amount of fill over the jth profile during a given time Δt (see figure 2). Let Q_j be equal to $(S_j - F_j)$; thus Q_j is a measure of the net sediment transport across the jth profile in the given time. It is also a measure of the average depth change over the jth profile.

The degree to which the change in bed elevation along at a given profile or at a given point in the model is related to that in the prototype can be expressed by the correlation coefficients

$$R_S = \frac{1}{N-1} \sum_{j=1}^{N} \frac{(S_{jm} - \bar{S}_{jm})(S_{jp} - \bar{S}_{jp})}{\sigma_{Sm}\,\sigma_{Sp}} \qquad (11)$$

$$R_F = \frac{1}{N-1} \sum_{j=1}^{N} \frac{(F_{jm} - \bar{F}_{jm})(F_{jp} - \bar{F}_{jp})}{\sigma_{Fm}\,\sigma_{Fp}} \qquad (12)$$

$$R_Q = \frac{1}{N-1} \sum_{j=1}^{N} \frac{(Q_{jm} - \bar{Q}_{jm})(Q_{jp} - \bar{Q}_{jp})}{\sigma_{Qm}\,\sigma_{Qp}} \tag{13}$$

and

$$R_D = \frac{1}{\sum_{j=1}^{N} M_j - 1} \sum_{j=1}^{N} \sum_{i=1}^{M_j} \frac{(D_{ij} - \bar{D}_{ij})_m (D_{ij} - \bar{D}_{ij})_p}{\sigma_{Dm}\,\sigma_{Dp}} \tag{14}$$

in which D_{ij} is the change in the bottom elevation at a point (i,j) within the given time interval (figure 2), σ is the standard deviation of the quantity symbolized by the subscript, the overbar denotes the average value, and the suffixes m and p denote model and prototype, respectively,

If the model results were in perfect agreement with the prototype data, the correlation coefficients in (11) thru (14) would be unity. This would be too much to expect from a model with a high value of R_D, but the values of the other correlation coefficients in (11), (12), and (13) must be high (approaching unity) before a reasonable verification of the model can be said to have been achieved.

A CONCLUDING REMARK

In conclusion the writers take this opportunity to invite identification of other model prototype studies and other methods of analysis that could be used in the Iowa investigation of tidal inlet models.

ACKNOWLEDGEMENT

This work is a result of research sponsored by the U.S. Army Coastal Engineering Research Center under Contract DACW72-76-C-0003.

REFERENCES

Bijker, E.W., "Some Considerations about Scales for Coastal Models with Movable Bed", Delft Hydraulic Laboratory, Publication No. 50, 1967.

Collins, J.I. and Chesnutt, C.B., "Tests of the Equilibrium Profiles of Model Beaches and the Effects of Grain Shape and Size Distribution", Proc. of the Symposium on Modeling Technique, San Francisco, Calif., Sept. 1975.

Fan, L.N., and Le Méhauté, B., "Coastal Movable Bed Model Technology", Tetra Tec., Report No. TC-131, 1969.

Kamphuis, J.W., "The Coastal Mobile Bed Model", C.E. Research Report No. 75, Queen's University, Kingston, Ontario, Aug 1975.

Migniot, C., "Representation Des Transports et Des Depots de Sediments Dans Des Modeles Reduits Maritimes", Journee Technique sur la Simulation en Hydraulique Maritime, Moth Division Hydraulique, Paris, Mar 1972.

Migniot C., Orgeron, C., and Biesel, F., "LCHF Coastal Sediment Modeling Techniques", Proc. of the Symposium on Modeling Techniques, San Francisco, Calif., Sept. 1975.

Noda, E.K., "Equilibrium Beach Profile Scale-Model Relationship", Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE, Vol. 98, No. WW4, Nov. 1972.

Reinalda, R., "Scale Effects in Models with Littoral Sand-Drift", Delft Hydraulic Lab., Publication No. 22, Sept. 1960.

Valembois, J., "Etude Sur Modele du Transport Littoral Conditions de Similitude", Proc. Seventh Congr. on Coastal Engineering, Vol. 1, Hague, Netherlands, Aug. 1960.

Vanoni, V.A., *Sedimentation Engineering*, ASCE - Manual and Reports on Engineering Practice, No. 54, 1975.

Vernon-Harcourt, L.F., "Improvement of the Maritime Portion of Rivers Including Their Outlets", Proc. 5th International Congress of (Inland) Navigation, 4th Section, 10th Question, Paper 51, 1892.

Yalin, M.S., *Theory of Hydraulic Models*, MacMilan, London, 1971.

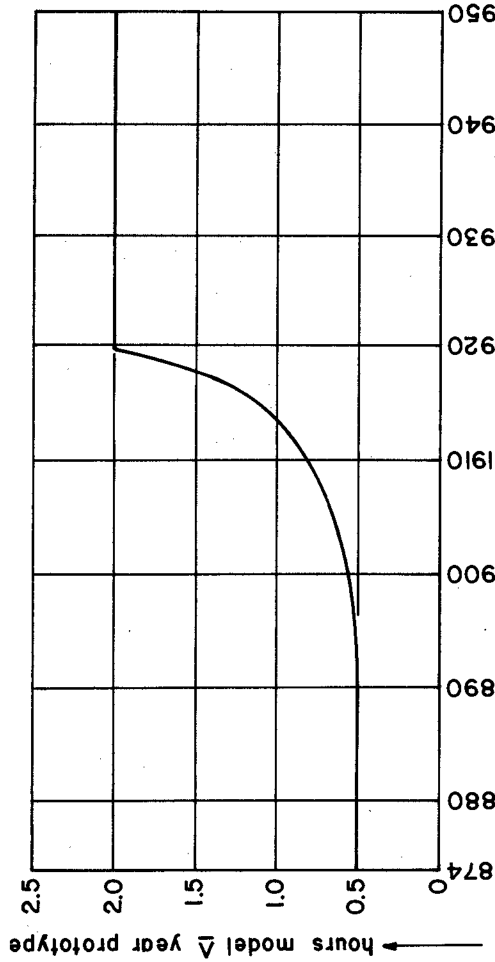

Figure 1 – Curve for the time scale

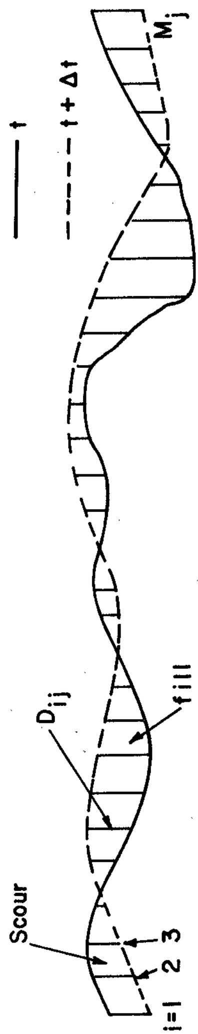

Figure 2 – jth cross-section profile