CHAPTER 121

PRACTICAL SCALING OF COASTAL MODELS

by

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ABSTRACT

In this paper the practical design of coastal mobile bed models is considered. The semi-theoretical approach expressed by the author in earlier publications (9,10,11,12) is extended and used to classify and design coastal models. Fixed bed coastal models are discussed first to form a basis for the argument. Subsequently, mobile bed models are classified according to criteria of dynamic similarity satisfied in their design and scale effects present in their operation. Basic scale laws are next derived for all classifications of coastal models. This is done for both inshore and offshore models, the distinction being brought about by adjusting the velocity scales for unidirectional (and long wave) motion. Time and sediment transport scales are next derived and some well known models are compared. The presence of bedform and model distortion is also treated. The work is compared with that of other authors.

FIXED BED COASTAL MODELS

For fixed bed short wave models (12) the basic model scales, where distortion is allowed, are

$$n_H = n_L = n_d = n_z = n_a = n$$

$$n_u = n_t = n_T = n^{1/2} \qquad (1)$$

$$n_x = n_y = Nn$$

Here n is the model scale (prototype over model value) and N is the model distortion. The subscripts refer to wave height (H), wave length (L), depth of water (d), vertical scale (z), wave orbital amplitude (a), orbital velocity (u), time (t), wave period (T), and the horizontal scales $(x$ and $y)$. Where no subscript appears, n refers to the basic (vertical) scale. Here it is considered that water is used as the fluid medium, i.e. the scales for gravity, fluid viscosity and density are unity.

When motion within the boundary layer is of interest the model behaviour must be rough turbulent (9). For this case additional scales may be derived (9,10,11) using boundary layer equations and a number of assumptions.

Work by Riedel et al (22) and Kamphuis (14) on shear stresses below waves has further shown that for rough turbulent flow, i.e.

$$\frac{\hat{v}_* k_s}{\nu} > 200 \quad \text{and} \quad \frac{k_s}{a_\delta} > 0.01 \tag{2}$$

$$\frac{\hat{v}_*^2}{\hat{u}_\delta^2} = 0.2 \left(\frac{k_s}{a_\delta}\right)^{3/4} \tag{3}$$

Their research indicates that this expression is also approximately valid in the transition region

$$15 < \frac{\hat{v}_* k_s}{\nu} < 200 \tag{4}$$

Here v_* is the shear velocity $(= \sqrt{\tau_o/\rho})$, τ_o is the shear stress at the bottom, ρ is the fluid density, k_s is the "sand grain" bottom roughness, ν is the kinematic viscosity of the fluid, a_δ is the wave orbital amplitude at the bottom, u_δ is the wave orbital velocity at the bottom and $\hat{}$ denotes the maximum value.

Equations 1 and 3 yield a practical shear stress scale

$$n_{\hat{\tau}_o} = n\, N_{k_s}^{3/4} \tag{5}$$

where N_{k_s} is the roughness distortion normally necessary in practical models

$$N_{k_s} = n_{k_s}/n \tag{6}$$

The effect of distortion of roughness is quite considerable. Equation 5 is of importance when determining friction losses for waves travelling substantial distances in models as well as when determining shear stresses on a mobile bed.

For the laminar boundary layer, experimental evidence (14,22) shows that

$$\frac{\hat{v}_*}{\hat{u}_\delta} = \frac{1}{RE^{1/4}} \tag{7}$$

where RE is the wave Reynolds Number ($= \hat{u}_\delta\, a_\delta / \nu$) . This expression yields

$$_w n_{\hat{\tau}_o} = n^{1/4} \tag{8}$$

In this case the bottom material has no effect and the scale may be thought of as a result of the scaling down of the waves only - hence the subscript w . If for rough turbulent flow the waves only are scaled down, i.e. the bottom material remains the same, then Eq. 5 reduces to Eq. 8.

For the unidirectional (and tidal) flow aspects of a coastal model the following scales may be derived (9,10)

$$\begin{aligned} n_U &= n^{1/2} \\ n_x &= n_y = {}_\ell n_L = Nn \\ {}_\ell n_T &= {}_\ell n_t = Nn^{1/2} \\ n_f &= n_S = N^{-1} \end{aligned} \tag{9}$$

Here U is the average flow velocity, f is the friction factor and S the surface slope. Subscript ℓ refers to long waves.

The friction factor scale requires a total shear stress which is a function of model distortion, in order to achieve correct current patterns in the model

$$_\ell n_\tau = n\, N^{-1} \tag{10}$$

where τ is the shear stress required for unidirectional (or tidal) flow. If a logarithmic velocity profile is assumed, an expression for the shear stress on the bottom may be found.

$$_\ell n_{\tau_o} = n_U^{\,2}\, N_{k_s}^{\;1/4} \tag{11}$$

Equations 10 and 11 may be satisfied simultaneously by making $N_{k_s} = N^{-4}$.

This would, however, totally destroy any reasonable wave simulation near the bottom. Thus for combination models, combining short waves and unidirectional flow (or long waves), additional roughness in the form of vertical roughness strips must be supplied. For the model, the additional shear stress required is

$$\tau_a = \tau - \tau_o = \frac{\tau_p}{n} \left(N - N_{k_s}^{-1/4} \right) \tag{12}$$

where τ_p is the prototype shear stress.

Most model studies assume inherently that the velocity scales are equal to the shear velocity scales so that velocities may be used in model analysis, rather than shear velocities or shear stresses. Examination of Eqs. 1, 5, 9 and 11 indicate that normally this is incorrect since

$$n_{\hat{v}_*} = n_u N_{k_s}^{3/8} \quad \text{and} \quad {}_{\ell}n_{v_*} = n_U N_{k_s}^{1/8} \tag{13}$$

MOBILE BED COASTAL MODELS

CRITERIA FOR DYNAMIC SIMILARITY

In mobile bed models the upper region, the boundary layer, the bottom configuration and the sediment motion must be modelled simultaneously. The criteria for dynamic similarity in modelling mobile beds have been discussed earlier (9,10,11) and may be summarised as

$$n_{R_*} = \frac{n_{v_*} n_D}{n_\nu} \tag{14}$$

$$n_{F_*} = \frac{n_\rho n_{v_*}^2}{n_{\gamma_s} n_D} = \frac{n_\rho}{n_{(\rho_s - \rho)}} \cdot \frac{n_{v_*}^2}{n_g n_D} = 1 \tag{15}$$

$$\frac{n_{\rho_s}}{n_\rho} = 1 \tag{16}$$

$$\frac{n_{a_\delta}}{n_D} = 1 \tag{17}$$

where R_* is the grain size Reynolds Number, F_* the densimetric Froude Number, D the particle size, ρ the fluid density, ρ_s the particle density and γ_s the underwater specific weight $= (\rho_s - \rho)g$.

MODEL CLASSIFICATION

It is impossible to satisfy Eqs. 14 through 17 simultaneously but for $R_* > 2$ it would not be unreasonable to drop Eq. 14 (10, Fig. 1). This would result in a scale effect at low shear velocities, i.e. at flow reversals. The type of model where Eq. 14 only is ignored will be called the "Best Model" (BM) for ease of reference and in Table 1, the criteria satisfied and the scale effects present if criteria are not satisfied may be found for this type of model.

Unless the prototype particle size is very large, it is impossible to satisfy Eq. 17. The model material resulting from Eq. 17 would become too small and the mode of material transport would change from bed load to suspended load transport. This is unacceptable and Eq. 17 is out of necessity quickly ignored. Two possibilities now present themselves. The first is the use of sand as a model material. This meets Eq. 16, but now Eq. 15 cannot be quite satisfied, while for most practical purposes Eq. 14 cannot be satisfied either. The scale effects resulting from the disregard of Eqs. 14, 15 and 17 for this "Sand Model" (SM) may be found in Table 1. It may be noted that unless the prototype transport is very small, adjustments need not be made in connection with F_* .

The second possibility is to ignore Eq. 16 resulting in a model with lightweight material. It is now possible to satisfy Eqs. 14 and 15 simultaneously. This model will be referred to as a "Light Weight Model" (LWM). Ignoring Eq. 16 involves additional scale effect shown in Table 1.

Because scale selection for LWM is rather restricted, laboratory studies may be carried out, still counting on the fact that for $R_* > 2$, Eq. 14 may be ignored. This type of model will be referred to as the "Densimetric Froude Model" (DFM) since only Eq. 15 is satisfied, ensuring that F_* is correct.

Finally, all too often, the last step is taken and none of Eqs. 14 through 17 are satisfied. This will be referred to as the "Nothing Model" (NM). In this case it is often ensured that sediment transport does occur in the model, by artificial means such as exaggerating wave heights and current velocities. This simply ensures that F_* in the model is greater than critical. Any similarity between model and prototype is strictly forced by adjusting model quantities until the model approximates prototype situations.

SCALE LAWS FOR SEDIMENT MOTION OVER FLAT BED

Consider first the sediment motion over a flat mobile bed. For this case, Kamphuis (13) states it is not unreasonable to assume that

$$n_{k_s} = n_D \tag{18}$$

TABLE 1

MODEL CLASSIFICATION

CRITERIA	CRITERIA SATISFIED					SCALE EFFECT (if criterion is not satisfied)
	BM	SM	LWM	DFM	NM	
$n_{R_*} = 1$	x	x	√	x	x	transport is not similar at low velocities and velocity reversals
$n_{F_*} = 1$	√	x	√	√	x	initiation and transport of material may now be totally different in model and prototype, requiring extensive adjustment
$n_{\frac{\rho_s}{\rho}} = 1$	√	√	x	x	x	particle ballistics are no longer correct. particle motion above water at the shore is incorrect
$n_{\frac{a_\delta}{D}} = 1$	√	x	x	x	x	transport scale varies with depth

For BM , Eqs. 5, 11 and 15 to 18 yield the scales for D , γ_s , $\hat{\tau}_o$ and ${}_{\ell}\tau_o$, if it assumed that equations developed for flow without sediment transport are valid for flow with sediment transport. This is not an unreasonable assumption since in most cases the sediment transport is purposely kept small to prevent suspension of the bottom material.

It may be seen that for the Froude velocity scale (= $n^{1/2}$) , the shear stress resulting from unidirectional (or long wave) motion is scaled down the same as the shear stress from wave motion. The current pattern condition (Eq. 10) may be satisfied by additional roughness similar to the fixed bed model, however, this model meets the additional requirement that bottom shear stresses from wave and current motion are scaled down the same. This is summarised in the first line of Table 2, cols 1 to 6.

For SM Eqs. 5, 11, 16 and 18 yield the second line (cols 1 to 6) in Table 2. It must be noted that the shear stress scales resulting from waves and currents may now be forced equal only by adjusting the velocity scale for unidirectional flow (col 5) which will be no longer Froudian. The current pattern condition, Eq. 10 may once again be satisfied by added roughness (col 6).

In most cases, however, the condition of simultaneously correct bottom shear and correct current patterns cannot be brought about simply by adding roughness (τ_a becomes negative). In this instance, the model may be distorted (col 7) to achieve shear and current similarity. But for mobile bed models the maximum distortion must normally be rather small as a result of other considerations such as stability of slopes and positions of beaches (19). This means that col 7 often is not a feasible solution and, either the bottom shear stress scale for unidirectional (or long wave) flow is made the same as the bottom shear stress scale for the short wave portion of the model (col 5), resulting in an incorrect current pattern or the current pattern can be forced to be correct (col 8) causing unequal shear stress scales at the bottom. This is done by adjusting the velocity scale for unidirectional (long wave) action.

Inherent in this adjustment is a philosophical decision that a coastal model is a waves model with currents and long waves added, i.e. adjustable to give the required similarity. This is not the same philosophical decision as made by Fan and Le Méhauté (4).

For inshore areas, e.g. in a littoral drift study, the shear resulting from wave motion normally greatly exceeds the shear from current action. To model these areas correctly, the governing velocity scale would need to be as in col 8. In offshore areas, e.g. around deep-sea gravity structures, where material is moved by combined wave and current action, the velocity scale should be as in col 5. Distortions normally do not matter in these latter studies and exact current patterns can be brought about by baffles. In either case, the answer will be slightly incorrect because of a scale effect resulting from not modelling either current patterns or shear stresses correctly as well as from ignoring Eqs. 14, 15 and 17 (discussed earlier). For convenience these two types of models will be labelled Inshore Models (IM) and Offshore Models (OM) .

TABLE 2

BASIC SCALE LAWS

					For $_{\ell}n_{\tau_o} = n_{\hat{\tau}_o}$ SHEAR FROM CURRENTS = SHEAR FROM WAVES	For $_{\ell}n_{\tau_o} = {}_{\ell}n_{\tau} = n_{\hat{\tau}_o}$ SHEAR FROM CURRENTS = SHEAR FROM WAVES CURRENT PATTERNS CORRECT		For $_{\ell}n_{\tau_o} = {}_{\ell}n_{\tau}$ CORRECT CURRENT PATTERN
MODEL TYPE	n_D (1)	n_{γ_s} (2)	$n_{\hat{\tau}_o}$ (3)	$_{\ell}n_{\tau_o}$ 2) (4)	n_U (5)	τ_a (6) or	or N (7)	n_U (8)
BM	n	1	n	n	$n^{1/2}$	$\frac{\tau_p}{n}(N-1)$	-	-
SM	* 1)	1	$n^{1/4}\,n_D^{3/4}$	$n^{3/4}\,n_D^{1/4}$	$n^{1/4}\,n_D^{1/4}$	$\frac{\tau_p}{n}(N-n^{3/4}\,n_D^{-3/4})$	$n^{3/4}\,n_D^{-3/4}$	$\frac{n^{5/8}}{N^{1/2}\,n_D^{1/8}}$
LWM	$n^{-1/11}$	$n^{3/11}$	$n^{2/11}$	$n^{8/11}$	$n^{5/22}$	$\frac{\tau_p}{n}(N-n^{9/11})$	$n^{9/11}$	$\frac{n^{7/11}}{N^{1/2}}$
DFM	*	$n^{1/4}\,n_D^{-1/4}$	$n^{1/4}\,n_D^{3/4}$	$n^{3/4}\,n_D^{1/4}$	$n^{1/4}\,n_D^{1/4}$	$\frac{\tau_p}{n}(N-n^{3/4}\,n_D^{-3/4})$	$n^{3/4}\,n_D^{-3/4}$	$\frac{n^{5/8}}{N^{1/2}\,n_D^{1/8}}$
or								
DFM	$n\,n_{\gamma_s}^{-4}$	*	$n\,n_{\gamma_s}^{-3}$	$n\,n_{\gamma_s}^{-1}$	$n^{1/2}\,n_{\gamma_s}^{-1}$	$\frac{\tau_p}{n}(N-n_{\gamma_s}^{3})$	$n_{\gamma_s}^{3}$	$\frac{n^{1/2}\,n_{\gamma_s}^{1/2}}{N^{1/2}}$
NM	*	*	$n^{1/4}\,n_D^{3/4}$	$n^{3/4}\,n_D^{1/4}$	$n^{1/4}\,n_D^{1/4}$	$\frac{\tau_p}{n}(N-n^{3/4}\,n_D^{-3/4})$	$n^{3/4}\,n_D^{-3/4}$	$\frac{n^{5/8}}{N^{1/2}\,n_D^{1/8}}$
					OM			IM

1) * *denotes free choice*

2) long wave shear stress for Froude velocity scale $n_U = n^{1/2}$

For LWM, Eqs. 14 and 15 express a relationship between v_*, D and γ_s and Eqs. 5, 11 and 18 yield the third line in Table 2. Columns 6 and 7 are now very unlikely and it is imperative to make a choice between modelling the bottom shear stress resulting from unidirectional (or tidal) flow correctly or modelling current patterns correctly. Similar relationships for DFM and NM have been derived.

Table 2 shows that in most cases a choice must be made with respect to correct bottom shear and correct current patterns. For correct bottom shear resulting from unidirectional (or long wave) flow (i.e. a deep water sediment transport model) - OM condition,

$$n_U = n^{1/4} \; n_D^{1/4} \tag{19}$$

while for correct current patterns (inshore models) the IM condition is

$$n_U = n^{5/8} \; N^{-1/2} \; n_D^{-1/8} \tag{20}$$

PRESENCE OF BEDFORM

The above discussion refers totally to mobile bed models with a flat bottom. Many models and almost all prototypes have bedform, in the way of ripples and dunes, on the bottom. In the absence of research results on shear stresses resulting from bedform below waves, it is assumed that as in unidirectional flow

$$\tau_\Delta = \frac{\rho U^2 \Delta^2}{\Lambda d} \tag{21}$$

where Δ is the height and Λ the length of the bedform, while τ_Δ is the shear stress resulting from bedform presence only. Mogridge (17) has found that for waves

$$n_\Delta = n_\Lambda = n \quad \text{for} \quad \frac{\rho \hat{u}_\delta^{\,2}}{\gamma_s D} < 40 \tag{22}$$

This results in a shear stress scale for a model with bedform of

$$n_{\tau_\Delta} = n_U^{\,2} = n_u^{\,2} = n \tag{23}$$

This is the same as the flat bed (or grain) shear stress scales in BM, but it is considerably greater than the shear stress scales in the other models where the grain size is distorted. Thus grain shear is certainly exaggerated in these models relative to the shear generated by the bedform. The total shear is of course a combination of the two. In models where the bedform generated shear predominates, it will be possible to use additional roughness strips (as in BM) and to satisfy the current pattern and shear conditions simultaneously.

Under waves, results obtained by Inman and Bowen (6) and Carstens et al (2) indicate that Eq. 21 underestimates the actual shear stresses by at least one order. This does not necessarily mean that Eq. 23 is incorrect. Until accurate shear stress measurements over bedform under waves have been made, Eq. 23 must be used.

This leaves one further problem. On a bed with bedform the direction of sediment transport must be the same in model as in prototype. This depends a great deal on the phase difference between the rise of the eddies from the lea of the bedform and the main orbital motion. A number of papers have been written on this subject and an interesting recent discussion may be found in Ref. 7.

SEDIMENT TRANSPORT AND TIME SCALES

Most coastal mobile bed models are built to determine coastal morphology in the future. For this it is necessary to determine sediment transport scales and time scales for bed morphology.

From Ref. 11 it may be seen that the relationship for flat bed sediment transport under two dimensional wave action is

$$\frac{q_s}{v_* D} = \phi \left(R_* , F_* , \frac{\rho_s}{\rho} , \frac{a}{D} , \alpha \right) \tag{24}$$

where q_s is the volume of material transported per unit width and α is the asymmetry of wave motion. Normally α is the same in model and prototype if Eq. 1 is satisfied.

The sediment transport scale may then be derived as

$$n_{q_s} = m \, n_{v_*} \, n_D \tag{25}$$

where the scale effect m is a function of all the dimensionless ratios of Eq. 24 ignored in the model design, as well as of the bedform present in model and prototype.

Normally in offshore coastal models, the sediment transport is governed by the wave motion rather than the currents (i.e. the currents modify the transport resulting from wave action) and thus Eq. 25 can be considered an adequate approximation of the sediment transport scale. The corresponding time scale may be derived as

$$n_{t_s} = \frac{N\, n^2}{m\, n_{v_*}\, n_D}\; n_{(1-p)} \tag{26}$$

where p is the material porosity, i.e. volume of voids over total volume. Both n_{q_s} and n_{t_s} are given in Table 3 as a function of model type.

To obtain a sediment transport scale for littoral transport in a nearshore coastal model, it is postulated that the waves stir up the material and the nearshore current pattern moves it along. Using the approach first used by Bagnold (25) and assuming wave shear stress and unidirectional velocities interact, the scale for littoral drift is

$$n_{Q_\ell} = M\, N\, n\, n_{\hat{\tau}_o}\, n_U\, n_{\gamma_s}^{-1} \tag{27}$$

The time scale for coastal morphology may be derived as

$$n_{t_m} = \frac{N\, n^2\, n_{\gamma_s}}{M\, n_{\hat{\tau}_o}\, n_U}\; n_{(1-p)} \tag{28}$$

Here M is the scale effect for littoral transport which is a function of all the parameters ignored from Eq. 24. In addition M includes the non-similarity of fall velocity, but more importantly, M includes the non-similarity of wave climate. When a survey is made of some model studies performed, one quickly recognises that the sediment transport and time scales are defined very subjectively. The model wave climate may vary from monochromatic waves from one direction to several waves from several directions. These represent all sorts of prototype wave climates from short term monsoon conditions to many years of net transport where the gross transport is in both directions.

Both the littoral drift and time scales are given in Table 3 as a function of model type. Table 4 gives a comparison of scales for a limited number of models. It may be seen that M is very sensitive to the similarity of wave climate.

SCALES DERIVED BY OTHER AUTHORS

For fixed bed models, there is general agreement among the various authors, but for mobile bed models certain differences in basic philosophy are evident.

Valembois (23) derives scales for mobile bed motion which are similar to LWM without the substitution of Eq. 18.

TABLE 3

SEDIMENT TRANSPORT AND TIME SCALES

MODEL TYPE	OFFSHORE MODEL (OM)		INSHORE MODEL (IM)	
	n_{q_s}	n_{t_s}	n_{Q_ℓ}	n_{t_m}
BM	$m\ n^{3/2}$	$N\ n^{1/2} \cdot \frac{n_{(1-p)}}{m}$	$M\ N\ n^{5/2}$	$N\ n^{1/2} \cdot \frac{n_{(1-p)}}{M}$
SM	$m\ n^{1/8}\ n_D^{11/8}$	$\frac{N\ n^{15/8}}{n_D^{11/8}} \cdot \frac{n_{(1-p)}}{m}$	$M\ N^{1/2}\ n^{15/8}\ n_D^{5/8}$	$\frac{N^{3/2}\ n^{9/8}}{n_D^{5/8}} \cdot \frac{n_{(1-p)}}{M}$
LWM	m	$N\ n^2 \cdot \frac{n_{(1-p)}}{m}$	$M\ N^{1/2}\ n^{17/11}$	$N^{3/2}\ n^{16/11} \cdot \frac{n_{(1-p)}}{M}$
DFM	$m\ n^{1/8}\ n_D^{11/8}$	$\frac{N\ n^{15/8}}{n_D^{11/8}} \cdot \frac{n_{(1-p)}}{m}$	$M\ N^{1/2}\ n^{13/8}\ n_D^{7/8}$	$\frac{N^{3/2}\ n^{11/8}}{n_D^{7/8}} \cdot \frac{n_{(1-p)}}{M}$
or DFM	$m\ n^{3/2}\ n_{\gamma_s}^{-11/2}$	$N\ n^{1/2}\ n_{\gamma_s}^{11/2} \cdot \frac{n_{(1-p)}}{m}$	$\frac{M\ N^{1/2}\ n^{5/2}}{n_{\gamma_s}^{7/2}}$	$N^{3/2}\ n^{1/2}\ n_{\gamma_s}^{7/2} \cdot \frac{n_{(1-p)}}{M}$
NM	$m\ n^{1/8}\ n_D^{11/8}$	$\frac{N\ n^{15/8}}{n_D^{11/8}} \cdot \frac{n_{(1-p)}}{m}$	$\frac{M\ N^{1/2}\ n^{15/8}\ n_D^{5/8}}{n_{\gamma_s}}$	$\frac{N^{3/2}\ n^{9/8}\ n_{\gamma_s}}{n_D^{5/8}} \cdot \frac{n_{(1-p)}}{M}$

TABLE 4

COMPARISON OF COASTAL MODELS

MODEL	Ref	n	N	n_{γ_s}	n_D	TYPE	n_U	n_{t_m}	n_t	M	COMMENTS
Cobourg	15	60	3.33	55	.14	NM	$n^{1/2}$	$\frac{133,000}{M}$	21,000	6.4	25 minutes = 1 year waves from one direction wave height exaggerated by 2 thin layer of bed material
Durban	8	100	3	1	1	SM	$n^{1/2}$	$\frac{950}{M}$	2,200	.43	4 hrs = 1 yr 4 different waves in cyclical pattern
									65	14.6	4 hrs = 65 hrs waves from one direction
Newcastle	16	100	2	1	1	SM	$n^{1/2}$	$\frac{630}{M}$	1,825	.35	3 days = 12 - 17 years two different waves from same direction
Scheveningen	3	25	6	1	1	SM	2.5	$\frac{670}{M}$	730	.91	12 hrs = 1 yr waves from one direction
									440	1.53	20 hrs = 1 yr waves from two directions
Thyborøn	20	40	6.25	4.71	.11	NM	$n^{1/2}$	$\frac{15,500}{M}$	17,500	.90	prior to 1900 80 hrs = 16 years
									4,400	3.5	after 1900 80 hrs = 40 years
Visakhapatnam	5	80	3.75	4.18	.71	NM	$n^{1/2}$	$\frac{5,200}{M}$	1,375	3.8	150 mins = 143 days during monsoon
									3,300	1.6	40 mins = 92 days during monsoon

Bijker (1) specifies four similarity conditions which may be reduced to Eqs. 10 and 15 plus the condition that the shear velocity scale is the same as the orbital velocity scale. The last condition would appear to be incorrect except for BM .

Fan and Le Méhauté (4) satisfy Eqs. 14 and 15 like in LWM , but use the unidirectional (or long wave) considerations as basic and assume all roughness to be bottom roughness (i.e. no vertical roughness elements). This causes a coastal model to be an extension of a unidirectional flow model (waves are added). In this paper it is argued that a coastal model is a waves model and the unidirectional portion is adjusted to suit the wave conditions. This is a little more realistic since the wave shear stresses normally dominate and unidirectional (long wave) components can then be adjusted to yield an inshore model (current patterns correct) or an offshore model (shear stresses the same for unidirectional and wave phases). Fan and Le Méhauté also propose a morphology time scale which differs considerably from Eq. 28.

Yalin (24) differs from the present analysis only in the extent of the argument (he also deals mainly with LWM). He proposes a distortion equal to n .

ACKNOWLEDGEMENTS

The author is very grateful for the financial support of the National Research Council of Canada. He is indebted to Drs. Mogridge, Riedel and Paul for their meticulous research and he thanks Dr. Yalin for our fruitful discussions.

REFERENCES

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

2. Carstens, M.R., Neilson, F.M. and Altinbeck, H.D., "Bedforms Generated in the Laboratory under an Oscillatory Flow", *Coastal Engineering Research Centre,* Technical Memo 28, U.S. Corps of Engineers, Washington, 1969

3. Delft Hydraulics Laboratory, private communication

4. Fan, L.N. and Le Méhauté, B., "Coastal Movable Bed Scale Model Technology", *Tetra Tech.* Report No. TC-131

5. Ince, S. and Jamieson, W.W., Internal Report, *National Research Council,* Ottawa, 1972

6. Inman, D.L. and Bowen, A.J., "Flume Experiments on Sand Transport by Waves and Currents", *Proceedings 8th Coastal Engineering Conference*, Mexico, 1963, pp 137-150

7. Inman, D.L. and Tunstall, E.B., "Phase Dependent Roughness Control of Sand Movement", *Proceedings 13th Coastal Engineering Conference*, Vancouver, 1972, pp 1155-1171

8. Jordaan, J.M., "Study of Durban Harbour Silting and Beach Erosion", *Proceedings 12th Coastal Engineering Conference*, Washington, 1970, pp 1097-1116

9. Kamphuis, J.W., "Scale Selection for Wave Models", *Queen's University C.E. Report No. 71*, 1971

10. Kamphuis, J.W., "Scale Selection for Mobile Bed Wave Models", *Proceedings 13th Coastal Engineering Conference*, Vancouver, 1972, pp 1173-1196

11. Kamphuis, J.W., "Sediment Transport by Waves over a Flat Bed", Engineering Dynamics of the Coastal Zone, *The Institution of Engineers of Australia*, Sydney, 1973, pp 228-233

12. Kamphuis, J.W., "Wave Models with Fixed Bed", *Waterways, Harbours and Coastal Engineering Journal, A.S.C.E.*, Vol. 99, WW 4, Nov. 1973, pp 471-483

13. Kamphuis, J.W., "Determination of Sand Roughness for Fixed Beds", Accepted for publication to *Journal I.A.H.R.*, 1974

14. "Wave Friction", To be published

15. Le Méhauté, B. and Collins, J.I., "A Model Investigation of Cobourg Harbour", *Queen's University Civil Engineering Report No. 17*, Kingston, 1961

16. Lucas, A.H. and Anderson, P.G., "Newcastle Harbour Entrance Shoal Wave Model and Sand Tracing", *Engineering Dynamics of the Coastal Zone*, Sydney, 1973, pp 89-98

17. Mogridge, G.R., "Wave Generated Bed Forms", *Queen's University*, Ph.D. Thesis, 1973

18. Noda, E., "Coastal Movable-Bed Scale-Model Relationship", *Tetra Tech* Report No. TC-191

19. Paul, M.J., Kamphuis, J.W., and Brebner, A., "Similarity of Equilibrium Beach Profiles", *Proceedings 13th Coastal Engineering Conference*, Vancouver, 1972, pp 1217-1236

20. Reinalda, R., "Scale Effects in Models with Littoral Sand Drift", *Delft Pub No 22*, 1960

21. Riedel, H.P., "Direct Measurement of Bed Shear Stress under Waves", *Queen's University*, Ph.D. Thesis, 1972

22. Riedel, H.P., Kamphuis, J.W., and Brebner, A., "Measurement of Bed Shear Stress Under Waves", *Proceedings 13th Coastal Engineering Conference*, Vancouver, 1972, pp 587-604

23. Valembois, J., "Etude sur Modele du Transport Littoral Conditions de Similitude", *Proceedings 7th Coastal Engineering Conference*, The Hague, 1961, pp 307-377

24. Yalin, M.S., *"Mechanics of Sediment Transport"*, Pergamon Press, London, 1971

25. Yalin, M.S., *"Theory of Hydraulic Models"*, MacMillan, London, 1971