CHAPTER 186

VALIDATION OF MOVABLE-BED MODELING GUIDANCE

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Abstract

A 1-to-7.5 scale (midscale) movable-bed physical model was used to validate model scaling criteria selected as most appropriate for turbulence-dominated, erosion of sediment by waves. Two-dimensional flume tests successfully reproduced profile evolution observed in prototype-scale wave flume tests conducted in Germany under both regular and irregular wave conditions. For the case of regular waves, a sloping concrete revetment was exposed, thus validating the scaling guidance for use in studying scour at coastal structures. Comparisons between regular wave and irregular wave profile evolution indicated that best correspondence is achieved when the significant wave height equals the monochromatic wave height, although irregular wave profile evolution takes about twice as long.

Introduction

Physical models at reduced scale offer an alternative for examining coastal phenomena that are beyond analytical approaches. However, engineers must temper their enthusiasm for physical models by remembering the model's usefulness is directly related to the ability to understand the inherent lab and scale effects; and, when possible, to correct for these effects in the design and conduct of experiments.

Similitude relationships for modeling hydrodynamic phenomena are well established and thoroughly tested against prototype-scale data. Scaling effects in movable-bed models are not as well understood and are difficult to quantify.

A multitude of scaling relationships for modeling coastal sedimentary processes has been proposed over the years (see Hudson et al. 1979, and Kamphuis 1982 for overviews and lists of references). Hudson et al. (1979) give the basic philosophy for movable-bed scale modeling as fully understanding the physical processes involved and ensuring that the relative magnitudes of all dominant processes are the same in model and prototype. They also state, "This is an impossible task for movable-bed models ..." because of the complications of the fluid-sediment interactions, and thus it is necessary to attempt to reproduce the dominant process "...with the anticipation that other forces are small."

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Similar views are held by Dean (1985), who lists two major requirements in proper physical modeling of sand transport processes: (a) knowledge of the character of the dominant forces and (b) an understanding of the dominant response mechanisms of the sediment.

In the absence of fundamental knowledge of the dominant processes and associated sediment response necessary to develop scale relationships, movable-bed scale models can be used to investigate the effects of certain parameters in systematic ways to establish general behavior patterns (Gourlay 1980). Alternately, the researcher can abandon the idea of reproducing the dominant physical processes and instead attempt to maintain similitude of important observed engineering characteristics such as beach profile shape or longshore transport rates (Hudson et al. 1979).

Regardless of the approach taken to develop scaling relationships for movable-bed models, the nearly unanimous opinion among researchers is that it is important to verify the scaling laws by reproducing prototype-scale events. Preferably, the scale model should be validated using field data, but often this is not practical, and large-scale laboratory results must suffice. Only after validation can credence be given to the model results, and then only for situations which seem to be governed by the same processes that were assumed dominant in the validation.

The purpose of the research described herein was to verify previously suggested movable-bed scaling criteria for modeling turbulent wave-induced scour phenomena in small-scale movable-bed physical models. This verification involved model replication of the spatial and temporal evolution of a beach fronting a sloping revetment as observed in a prototype-scale flume experiment conducted using monochromatic waves. Because the sloping concrete revetment became exposed during the course of the experiment, the structural influence on the profile evolution made this case particularly germane to the study of scour at structures.

Further validation of the movable-bed scaling criteria was achieved by midscale model reproduction of profile evolution caused by irregular waves in the prototype-scale flume. In this case, no structure was exposed to complicate the profile evolution.

Selected Scaling Guidance

Generally, movable-bed modeling criteria can be divided into two broad categories based on the transport mechanism: bed shear-stress-dominated transport, and turbulence-dominated transport. The present research focussed on the latter case.

Historical Perspective

Many investigators have expressed opinions regarding the important physical parameters and scaling requirements to be considered in formulating guidance for movable-bed models of coastal sedimentary processes. Perhaps the most relevant requirement for modeling coastal scour, as well as nearshore beach dynamics, is to attain similarity of the equilibrium beach profile between prototype and model, particularly in the surf zone. Parameters that appear to correspond to features of the equilibrium profile are similarity candidates for developing scaling criteria.

In the nearshore region, turbulent water motions play a greater role in mobilizing and transporting sediment; and in this region there is increasing evidence that the dimensionless fall speed parameter, given as:

$$\frac{H}{wT} \tag{1}$$

where H = wave height, T = wave period, and w = vertical fall speed of the sediment, should be similar in both prototype and model.

The use of the fall speed parameter to characterize nearshore processes began in the late 1960's, and it was popularized by Dean (1973) when he incorporated it into an expression for distinguishing between swell and storm profiles. One physical interpretation of the parameter was given by Gourlay (1968) who pointed out that H/w represented "...the time taken for a sand particle to fall a distance equal to the wave height." If this time is large compared with the wave period, he reasoned the particle would remain in suspension and move as suspended load. Conversely, if the time is equal to or less than the wave period, then the sediment will move primarily as bed load. Hughes and Fowler (1990) summarize several of the research efforts that have lead to acceptance of the fall speed parameter for describing certain aspects of nearshore sediment processes.

Dalrymple and Thompson (1976) were among the first to propose movable-bed modeling criteria that maintained similarity between prototype and model values of the fall speed parameter. Kamphuis (1982) concluded that preservation of the fall speed parameter eliminates most of the scale effects associated with attempting to geometrically scale the grain size diameter of quartz sand. Vellinga (1982) and Hughes (1983) proposed different distorted model relationships; however, the undistorted versions were identical and conformed to that recommended by Dalrymple and Thompson (1976).

Dean (1985) reviewed previous movable-bed modeling criteria and considered the dominant physical mechanisms involved in surf zone sediment transport. He argued that the Shield's criterion need not be met in the surf zone because turbulence, not bed shear, is the dominant cause of sediment mobilization; and therefore, bed shear is not an important consideration above Reynold's numbers constituting the fully rough range. Dean made specific recommendations for successful modeling of surf zone processes:

a. Undistorted model (equal horizontal and vertical length scales).

b. Hydrodynamics scaled according to Froude similarity.

c. Similarity of the fall speed parameter between prototype and model.

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.

Dean (1985) argued that, in an undistorted model, the fall trajectory of a suspended particle must be geometrically similar to the equivalent prototype trajectory and fall with a time proportional to the prototype fall time. This is accomplished by ensuring similarity of the fall speed parameter between the prototype and the undistorted model.

The scaling recommendations of Dean (1985) were specifically tested in undistored, erosive movable-bed models by Kriebel, Dally, and Dean (1986) and by Vellinga (1986). Both studies documented success in reproducing prototype-scale profile development. Other acceptance of the scaling criteria is discussed in Hughes and Fowler (1990).

In conclusion, efforts aimed at reproducing surf zone profile response in small-scale movable-bed models during erosive conditions have converged on scaling criteria that preserves the parameter H/wT between prototype and geometrically undistorted model, with the hydrodynamics (waves primarily) being scaled by the Froude criterion. As Dean (1985) discussed, the model law preserves similarity in wave form, sediment fall path, wave-induced velocities, break point, breaker type, and wave decay (provided the model is large enough to preclude viscous and surface tension effects.) The bottom shear stress will not be correctly scaled using the fall speed parameter criteria because the bottom boundary layer and ripple formations are not reproduced. This will result in noticeable scale effects when wave breaking turbulence is **not** dominant in the domain being modeled.

Scale Relationships

The selected scaling guidance consists of simultaneously satisfying two scaling criteria in an undistorted movable-bed model. The first is the well-known Froude criterion for the hydrodynamics that results in the relationship

$$N_t = \sqrt{N_\ell} \tag{2}$$

where N represents the prototype-to-model ratio of the subscribed parameter, t is time, and ℓ is length. In deriving Equation 2, the gravity scale, N_g, was set equal to unity.

The second criterion requires maintaining similarity of the fall speed parameter between prototype and model, i.e.,

$$\frac{H_p}{w_p T_p} = \frac{H_m}{w_m T_m} \tag{3}$$

where the subscripts p and m represent prototype and model, respectively. Rearranging Equation 3 and expressing it in terms of scale ratios yields

$$N_H = N_w N_T \tag{4}$$

Recognizing in an undistorted model that $N_H = N_\ell$ and that the wave period will scale the same as the hydrodynamic time scale, the combination of Equations 2 and 4 results in the unique scaling relationships satisfying both criteria:

$$N_t = N_w = \sqrt{N_\ell} \tag{5}$$

Xie's Scaling Guidance

As mentioned, various parameters other than the fall speed parameter have been suggested for use in characterizing sediment transport processes. Xie (1981) conducted numerous small-scale movable-bed model tests to examine the scouring of bed material adjacent to a vertical seawall subjected to nonbreaking waves. After testing several parameters, including the fall speed parameter, Xie presented a criterion for distinguishing between the two scour patterns that depends on the grain size of the bed material and on the wave conditions. The criterion is based on the parameter

$$\frac{U_{max} - U_*}{w} \tag{6}$$

where U_{max} = horizontal component of the maximum orbital water particle velocity near the bed, U_* = critical velocity for incipient motion of the sediment, and w = sediment fall speed. High values of the parameter imply movement by suspension (turbulence-dominated), and low values correspond to bed-load-dominant conditions.

Xie (1981) suggested that similarity of the parameter given by Equation 6 should be maintained between prototype and model, but noted that this would be difficult at times because of the dependence of both U_* and w on grain size.

The scaling criterion derived from maintaining similarity of Xie's parameter in an undistorted Froude model requires that:

$$\left(\frac{U_{max} - U_*}{w}\right)_p = \left(\frac{U_{max} - U_*}{w}\right)_m \tag{7}$$

Rearranging Equation 7, using the notation for scale ratios, and noting that, in an undistorted Froude model, the scale for the water velocity will be the same as the time scale, Equation 7 becomes

$$N_* N_t = N_w = \sqrt{N_\ell} \tag{8}$$

where

$$N_* = \frac{\left(1 - \frac{U_*}{U_{max}}\right)_p}{\left(1 - \frac{U_*}{U_{max}}\right)_m} \tag{9}$$

In essence, the scaling guidance given by Equation 8 is a more generalized version of the guidance determined with the fall speed parameter (Equation 5). Equation 8 agrees with that given by Equation 5 if the scale ratio N_* is equal to unity.

Examining Equation 9, there are two conditions by which N_* could approach unity. The first is if $U_{max} \gg U_*$ in both the prototype and model. This would be representative of highly turbulent conditions, such as exist in the surf zone during energetic wave conditions; and in the limit it corresponds somewhat to the physical description given by Gourlay (1968) and Dean (1973) for a suspended grain falling through the water column under the influence of horizontal currents.

The other conditions leading to unit value for N_* is if the ratio U_*/U_{max} is kept similar between prototype and model. In general the investigator will be unable to satisfy both the fall speed scale and the grain size scale necessary to meet this condition. Even if possible, the scaling would be valid for only one specific hydrodynamic condition because U_{max} depends on wave period and wave height, whereas U_* is independent of wave height. This would hamper investigations using irregular waves, as well as studies in which numerous regular wave periods were of interest.

Applicability of Selected Scaling Criteria

The selected movable-bed scaling criteria given by Equation 5 are for undistorted Froude models where the sediment size is selected so that the fall speed parameter is held constant between prototype and model. Past experience with these and similar scaling criteria, coupled with the assumptions used in formulating the guidance, restricts application of this type of physical modeling to coastal sediment problems and processes that are chiefly erosional in nature, with the erosion occurring in an energetic, turbulence-dominated region such as the surf zone. Typically, the scaling is intended to replicate the short-term response of the sea bed to storm-induced waves. Examples of situations that may be candidates for modeling with the selected criteria include: beach and dune profile response to storm events, initial beach-fill adjustment to larger waves, beach-fill response to storm events, and storm-related short-term scour at the toes of structures.

Validation

All tests described in this paper were conducted in a 1.8-m-wide wave tank at the Coastal Engineering Research Center (CERC) during 1988–1989. Hughes and Fowler (1990) provide details on laboratory setup, experimental procedures, and detailed results.

Regular Wave Validation With Revetment

Movable-bed physical model tests conducted by H. Dette and K. Uliczka at the Großer Wellenkanal (GWK) facility in Hannover, Federal Republic of Germany (Dette and Uliczka 1987; Uliczka and Dette 1987; Uliczka and Dette 1988) served as the prototype-scale target conditions for reproduction at midscale. In the prototype experiments, sand with a median diameter of 0.33 mm was placed in front of a concrete structure with a slope of 1 on 4. The sand was molded to the same initial slope as the concrete structure shown by the long-dash line in Figure 1. Subsequent exposure of the solid revetment during testing makes this regular-wave case particularly useful for validation of movable-bed scaling guidance intended for modeling of scour processes.

The fall speed scaling relations of Equation 5 were used to determine the movable-bed model parameters. Fine quartz sand having a median diameter of 0.13 mm and specific gravity of 2.65 was used to simulate the 0.33-mm median-diameter prototype sand. The Froude scaling criterion was used to determine model wave period and the time scale for morphological development. Table 1 gives prototype and model experimental values and sediment fall speeds used to calculate the undistorted length scale ratio of 7.5 (prototype) to 1 (model).

Table 1: Prototype and Model Experiment Parameters

Parameter	Prototype	Model
Sediment Median Diameter	0.33 mm	0.13 mm
Mean Sediment Fall Speed	4.47 cm/s	1.64 cm/s
Wave Period	6.0 s	2.2 s
Wave Height	1.5 m	0.20 m
Water Depth	5.0 m	0.67 m
Horizontal Berm Width	11.0 m	1.47 m
Berm Thickness	2.67 m	0.36 m

The validation testing consisted of reproducing the experiment procedure used in the GWK during the prototype tests. Representative profile comparisons between prototype and model after equal numbers of waves (Froude scale for morphological development) are given in Figure 1. In these plots the model results have been scaled up to prototype dimensions using the length scale ratio of 7.5.

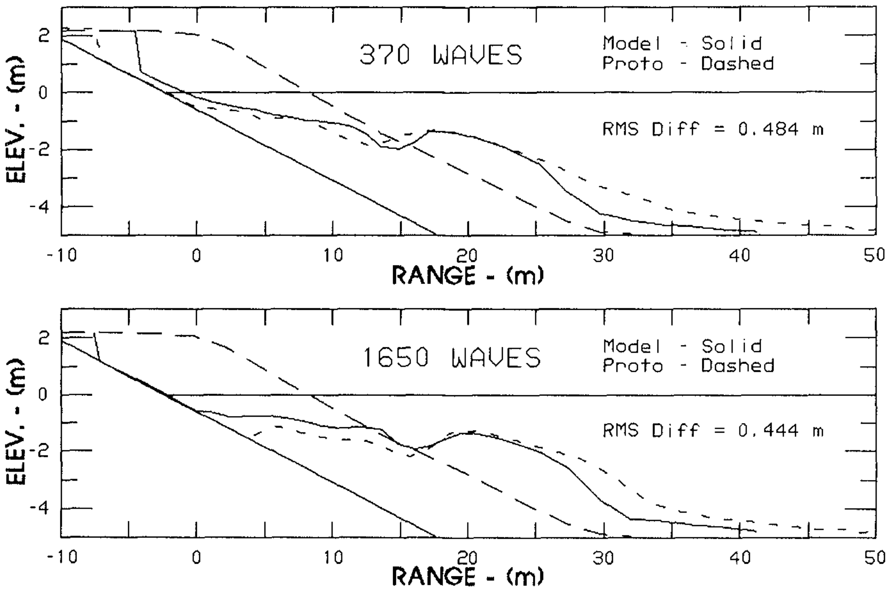

Figure 1: Prototype–Model Comparison, Regular Waves (RMS = root-mean-squared)

The profile comparison after 370 waves is relatively good, particularly in the surf zone and in the vicinity of the bar. The berm in the model was not eroded as much as in the prototype, and not as much sediment was moved to the region seaward of the breakpoint bar. An RMS (root-mean-squared) variation between profiles was calculated to be 0.49 m.

The center-line profile after 1,650 waves (Figure 1) represents the equilibrium condition for this test, and the comparison produced an RMS variation of 0.44 m. The model did not succeed in eroding the final portion of the berm on the upper portion of the revetment, and the model did not succeed in moving enough sediment to seaward of the breakpoint bar. Consequently, the scouring in the surf zone was not as severe as evidenced in the prototype.

The observed difference between prototype and model in the region offshore of the bar is most likely a result of the scaling relationship selected. This scaling relationship works best for regions dominated by turbulence-induced sediment transport. Because the model sand grains are not scaled according to the geometric length scale, they undergo a transition from suspended mode to bed-load mode of transport before this transition occurs in the equivalent prototype flow regime. With the selected scaling criteria, the bed-load mode of transport is not properly scaled in the model; consequently the model sand grains are at rest under scaled conditions that still result in offshore sediment transport in the prototype.

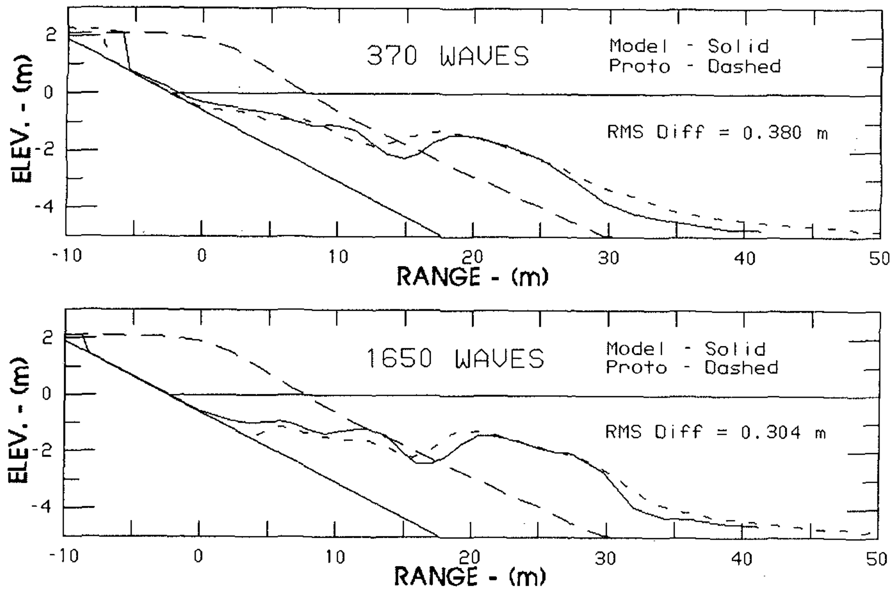

Figure 2: Prototype-Model Comparison, Waves Increased 10%

Figure 2 compares the prototype results to profiles obtained at midscale with the wave heights increased by 10% over the properly scaled value. As seen in Figure 2, better correspondence between prototype and model profiles resulted. The increased wave-induced water velocities in the offshore region appear to have transported sediment in the model to a greater offshore depth that more closely corresponds to the prototype. This increased *sediment demand* was met by the removal of more sand in the nearshore region; consequently, better profile reproduction, both in the final equilibrium and in the developmental stages, was achieved.

Table 2 gives values of Xie's parameter calculated at different water depths in the offshore region for the prototype (*Proto*), the basic validation model test (*Base*), and the model test with wave height increased by ten percent (*+10%*). Model values were calculated using the model depth equivalent to the prototype depth listed in the table. Columns 5 and 6 in Table 2 present the ratio of Xie's parameter in the prototype to that of the model. For the *Base* test, this ratio was always greater than one, approaching unity as the depth decreases. However, the ratio for the *+10%* test was nearer to unity over the range of offshore depths, and appears to be a reasonable compromise over the extent of the offshore portion of the profile.

The better comparison to prototype shown by the *+10%* test suggests a modification to the selected modeling criteria that includes a procedure for adjusting the scaled model wave height in such a manner as to achieve better similarity of Xie's parameter in the offshore regions of the modeled regime. This adjustment is dependent upon the wave period and should probably be limited to the more dynamically active portion of the offshore profile rather than being extended to full depth of closure.

Table 2: Prototype and Model Values of Xie's Parameter

Prototype	$(U_{max} - U_*)/w$			Ratio of Xie's Parameter	
Depth (m)	Proto.	Base	+10%	Proto/Base	Proto/+10%
5.0	20.86	18.15	20.42	1.15	1.02
4.5	23.57	20.84	23.33	1.13	1.01
4.0	26.83	24.09	26.83	1.11	1.00
3.5	30.89	28.09	31.19	1.10	0.99
3.0	36.12	33.33	36.80	1.08	0.98
2.5	42.23	39.42	43.36	1.07	0.97
2.0	51.83	48.97	53.67	1.06	0.97

Irregular Wave Validation Without Revetment

Prototype tests were also conducted in the Großer Wellenkanal using irregular waves that conformed to a JONSWAP spectrum. In these tests additional sand was added in front of the revetment so that the structure would not be exposed during profile development. The significant wave height and peak spectral period had the same prototype values as given in Table 1 for the regular wave tests. This prototype condition was reproduced as an additional midscale validation test. Every attempt was made to recreate the experiment in the same manner as it was conducted in the GWK. Representative profile comparisons between prototype and model after equal numbers of waves (Froude scale for morphological development) are given in Figure 3.

Reproduction of the irregular-wave prototype-scale flume experiment was considered to be very successful as indicated by the RMS differences shown in Figure 3. This further validates the selected movable-bed modeling guidance as being appropriate for energetic regimes of sediment transport. It is significant that close reproduction was obtained over the entire extent of the profile using properly scaled irregular waves. Recall from previously presented results that the regular wave tests suggested augmentation of the model wave height to provide a better correspondence of the Xie parameter between model and prototype. Because this was not required for the case of irregular waves, it is tentatively concluded that the natural variations within the irregular wave field were sufficient to assure correct redistribution of sediment over the entire extent of the modeled profile.

Irregular Wave Equivalence

Much of the established design guidance for sediment transport has been derived in part from laboratory tests conducted with movable-bed models using uniform, regular wave trains. For engineering design based on this guidance, the irregular wave condition which exists in nature is commonly represented by a single statistical wave height parameter that is taken as being equivalent to the regular wave height in the design formulae. Therefore, it is important to determine which irregular parameter best matches the regular wave parameter used to establish the design guidance.

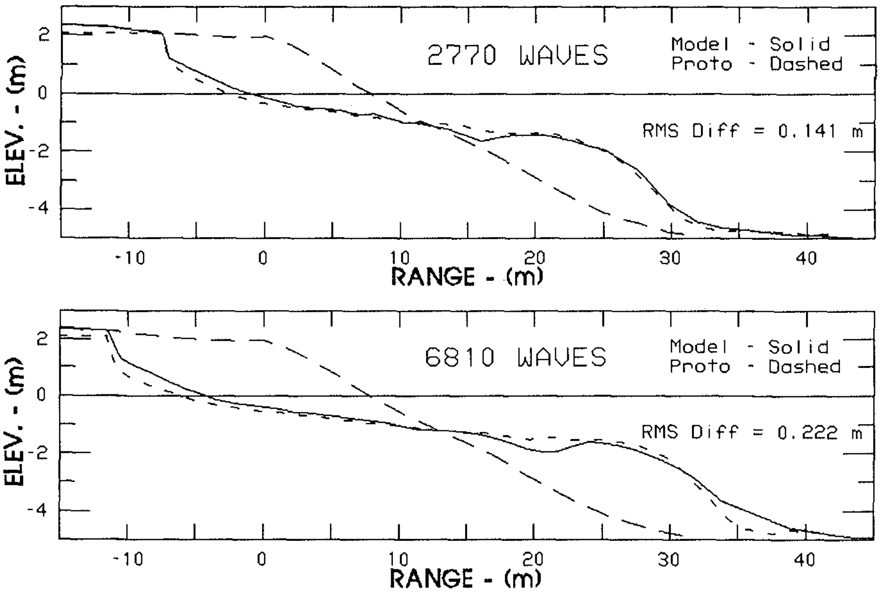

Figure 3: Prototype–Model Comparison, Irregular Waves

Midscale tests employing irregular waves were conducted using the initial revetment configuration shown in Figure 1. In one test the significant wave height was chosen so that the energy present in the irregular wave train was equivalent to the energy of the regular waves used in the validation test. This resulted in a value of $H_{1/3}$ about 41% greater than the regular wave height (H_{mono}). In the other test, $H_{1/3}$ was set equal to H_{mono}.

Irregular Wave Energy Equal to Monochromatic Wave Energy

The purpose of this test was to examine whether equivalent energy levels are necessary to obtain similar profile development between model regular and irregular wave physical model tests. Figure 4 compares the irregular wave case (solid line) with the regular wave test (dashed line). The irregular waves resulted in greater erosion of the berm area and also resulted in movement of the sediment farther offshore than in the regular wave case. The comparison after 1,650 waves also reveals a significantly different profile in the region of wave breaking and seaward of breaking.

Irregular $H_{1/3}$ Equal to Monochromatic Wave Height

Figure 5 compares regular-wave profiles with corresponding profiles from the irregular test with $H_{1/3} = H_{mono}$ after approximately the same number of waves (equal elapsed time of wave action).

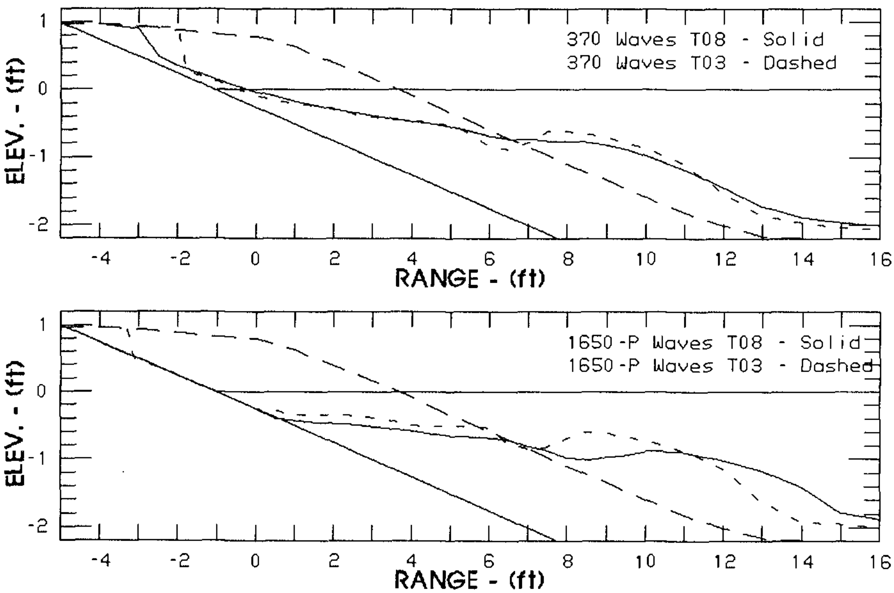

Figure 4: Irregular Wave Comparison, $H_{1/3}$ Equals 141% H_{mono}

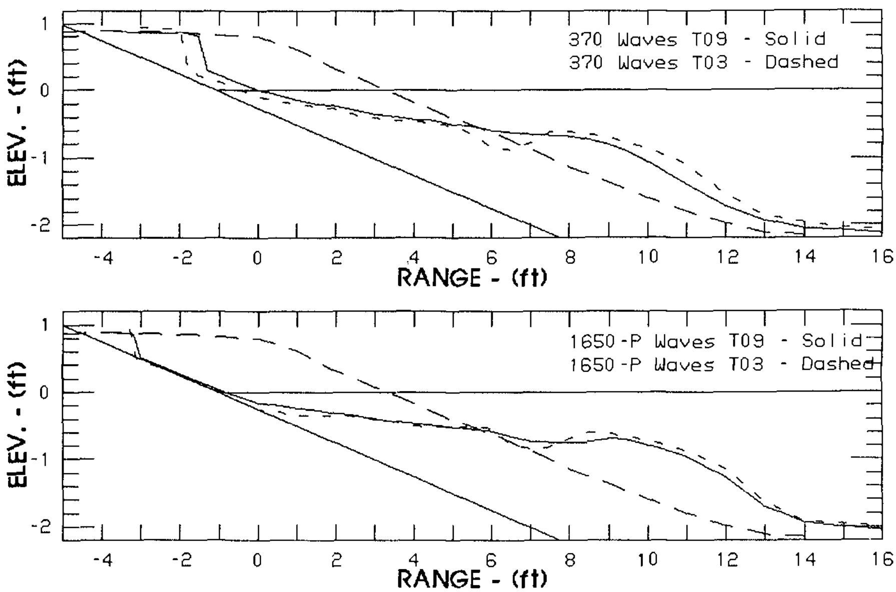

Figure 5: Irregular Wave Comparison, $H_{1/3}$ Equals H_{mono}

Generally, the irregular wave condition (solid line) produced similar erosional history as the regular wave case (dashed line), but at a slower rate. After the initial adjustment, evolution of the profile under irregular wave action was less than in the regular wave case, with the most noticeable region of difference being the berm recession. This observation follows the same trend as reported by Mimura, Otsuka, and Watanabe (1986) and Uliczka and Dette (1987). The irregular wave-induced profile reached a near-equilibrium state after 1,650 waves, which corresponds to the same response of the profile under regular wave action. The good comparison shown in Figure 5 indicates that best equivalence between regular and irregular waves is found when $H_{1/3} = H_{mono}$.

The time lag in profile development under irregular waves was estimated by comparing irregular and regular wave profile that had been shifted in time. Figure 6 shows irregular wave profiles (solid) compared to regular wave profiles (dashed) that developed in about half the time. The good comparison qualitatively supports morphological development taking approximately twice as long if equivalent irregular waves are used instead of regular waves.

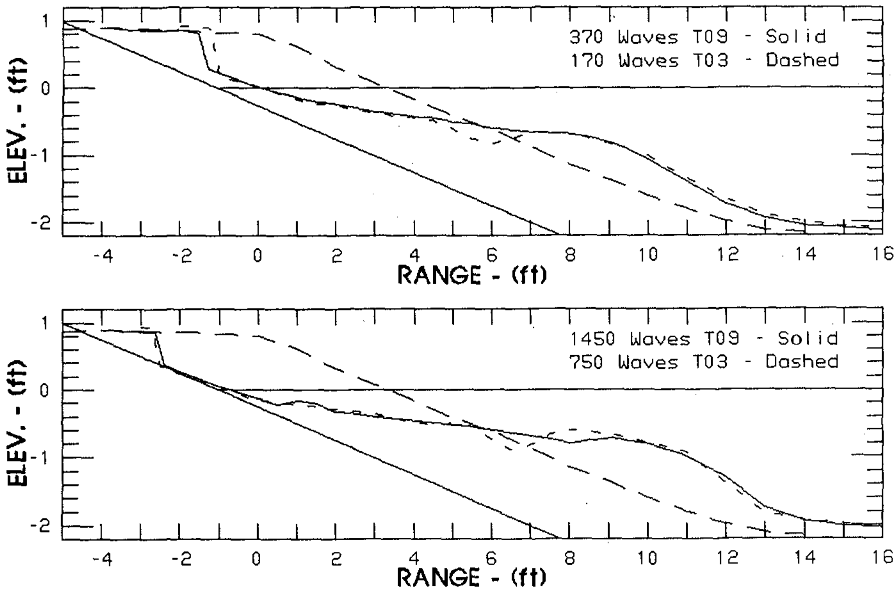

Figure 6: Time-Shifted Irregular Wave Comparison, $H_{1/3}$ Equals H_{mono}

Conclusions

Prototype-scale experiments conducted in the Großer Wellenkanal were reproduced at a prototype-to-model scale of $7\frac{1}{2}:1$ using both regular and irregular wave trains. The testing procedures were designed to duplicate those used in the GWK tests. Conclusions resulting from the midscale tests are listed below:

a. Mid-scale test results support preservation of the dimensionless fall speed parameter in an undistorted Froude model as a viable method of scaling models intended to replicate wave erosion under turbulence-dominated situations.

b. For tests involving regular waves, model designers should consider augmenting the Froude-scaled experimental wave height to provide better prototype-to-model correspondence of the Xie parameter in the offshore region. This correspondence should be limited to the more active portions of the offshore and need not extend out to closure depth.

c. Tests conducted using irregular waves do not require the augmentation described in (b) above.

d. Comparable profile development can be achieved between regular and irregular wave models when the irregular significant wave height, $H_{1/3}$, is equal to the regular wave height. Profile development will take approximately twice as long in the irregular wave model.

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