CHAPTER 95

Undistorted Froude Model for Surf Zone Sediment Transport

by

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Abstract

Small scale movable bed wave tank experiments were carried out according to undistorted Froude model laws with the sediment fall time, H/wT, as the governing parameter for scaling the model sediment. Four questions addressed in this study included: (a) the ability to reproduce larger scale model results for both erosional and accretive conditions, (b) the effects of more realistic concave upward initial beach profiles instead of the more usual planar initial slopes, (c) the criterion for onshore-offshore sediment transport, and (d) the capability of the model to simulate post-storm recovery.

Based on a comparison with large scale results of Saville (1957), it was found that the model provided good agreement for erosive conditions. For accretive conditions, the results were less conclusive although the general patterns of profile change were similar. The final beach profiles resulting from concave upward initial profiles were found to be substantially different from those for an initially planar profile. It appears that the initially planar profile unrealistically affects the breaker type and results in a more pronounced longshore bar and offshore slopes that are steeper than found in nature. Tests conducted to evaluate the criterion separating onshore-offshore transport suggested a higher value of the fall time parameter, H/wT, than was originally proposed by Dean (1973); this is interpreted to be due to scale effects in most of the model data used in the original development. Tests to simulate post-storm recovery were affected by the presence of "reflection bars" associated with a partial standing wave system. The reflection bars appear to strongly affect the sediment transport limiting the post-storm profile recovery. The most effective recovery was induced by continually changing wave conditions to maintain the wave breakpoint slightly landward of the bar crest.

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Introduction

Simple and direct movable bed modeling laws are applied in a series of small-scale laboratory experiments on beach profile evolution. The basic criteria proposed by Dean (1985) and adopted in this study for modeling of surf zone processes are:

1) the model should be undistorted,

2) the model should be large enough to preserve the character of wave breaking processes and to avoid surface tension and viscous effects,

3) the scaling of hydrodynamic properties should be based on the accepted Froude criterion, such that the prototype to model length ratio, N_ℓ, and time ratio, N_t, are related as:

$$N_t = \sqrt{N_\ell} \tag{1}$$

4) The scaling of sediment properties should be based on preserving the fall time parameter, H/wT, where w is the sediment fall velocity, H is the wave height, and T is the wave period, such that the required fall velocity ratio, N_w, is given by:

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

The proposed requirements are not new and are not universally applicable since many prototype situations cannot be practically replicated at small scale with an undistorted model. The criteria attempt, instead, to build upon what concensus may exist among modeling laboratories, primarily through reliance on the fundamental Froude model laws and the fall time parameter. In the recently proposed scaling laws for coastal movable bed models of Vellinga (1978) and Hughes (1983), preserving H/wT has resulted in successful duplication of prototype events during highly erosive storm conditions. Noda (1978) has found that preserving H/wT produces closer similarity than when the ratio H/d is preserved. Kamphuis (1982) also concluded that modeling based on the fall time parameter eliminates most of the scale effects associated with attempting to geometrically scale quartz sand grain diameters. By further specifying that the model should be undistorted, ambiguous definitions of length and time scales are eliminated, unrealistic augmentation of gravity forces are avoided, and interpretation of all physical quantities are clarified.

Objectives and Procedures

The overall goal of the study is to evaluate the usefulness of the undistorted Froude model, with sediment scaled according to the fall time parameter, for simulating beach profile evolution under specific erosive and accretive wave conditions. In order to test the proposed model laws, several sets of experiments were conducted to address specific objectives.

The first objective is to examine the ability of the model law to reproduce actual prototype-scale beach profile evolution. For this purpose, two experiments were conducted to simulate full-scale experiments by Saville (1957). The second objective is to examine the evolution of concave initial beach profiles compared to profiles with linear initial slopes for the same erosive and accretive wave conditions. The third objective is to examine the criterion for onshore-offshore sediment transport determined by Dean (1973) based upon the fall time parameter, or equivalently, the wave steepness, H_o/L_o, and a fall velocity parameter, $\pi w/gT$. Ten experiments were performed and the results compared to Dean's criterion as well as to results of prototype-scale experiments of Saville (1957) and Kajima et al. (1982). The fourth objective is to simulate conditions of post-storm beach recovery. A reference storm-barred profile was generated by elevated water levels and erosive wave conditions, then five experiments were conducted by lowering the water and subjecting the storm-generated breakpoint bar to accretive wave conditions.

The laboratory experiments were conducted in the Air-Sea flume at the University of Florida Coastal and Oceanographic Engineering Laboratory. The flume is 37 m long, 1.2 m deep, and 0.86 m wide. The wavemaker can generate regular or random waves; however, all experiments were performed using regular waves. A motorized cart that runs along rails mounted to the top of the tank carries a capacitance-sensing bottom profiler that is capable of resolving sand bed changes to within 2 mm. The sediment used in the experiments was a fine quartz sand with a median diameter of 0.15 mm. The mean fall velocity of the sand was found to be 1.8 cm/sec as obtained from a settling tube analysis.

Due to length restrictions, only a sampling of the figures can be presented in this paper. Much greater detail is available in Kriebel, Dally and Dean (1986).

Results and Analysis

a. Model Verification

The first series of experiments was designed to verify that the undistorted Froude model could reproduce prototype-scale events. Prototype conditions were taken to be two full-scale experiments conducted by Saville (1957) in a large wave tank 193.5 m long, 6.1 m deep, and 4.6 m wide. Saville's experiments were conducted using a linear 1:15 beach slope with 0.4 mm sand having an approximate fall velocity of 5.6 cm/sec. Based on the undistorted Froude model laws, the prototype to model fall velocity and time ratios are 3.1 while the length ratio is 9.6.

Two experiments were conducted, one under erosive wave conditions, the other under accretive conditions. In the erosion test, Saville's wave period was 5.6 seconds while the wave height in the flat section of the wave tank was 1.6 m. In the small-scale model, the wave period and the wave height in the flat portion of the tank were 1.8 seconds and 0.167 m respectively. The model surf zone was on the order of 4 m wide and seemed large enough to permit realistic wave breaking and transformation free of noticeable surface tension or viscous effects.

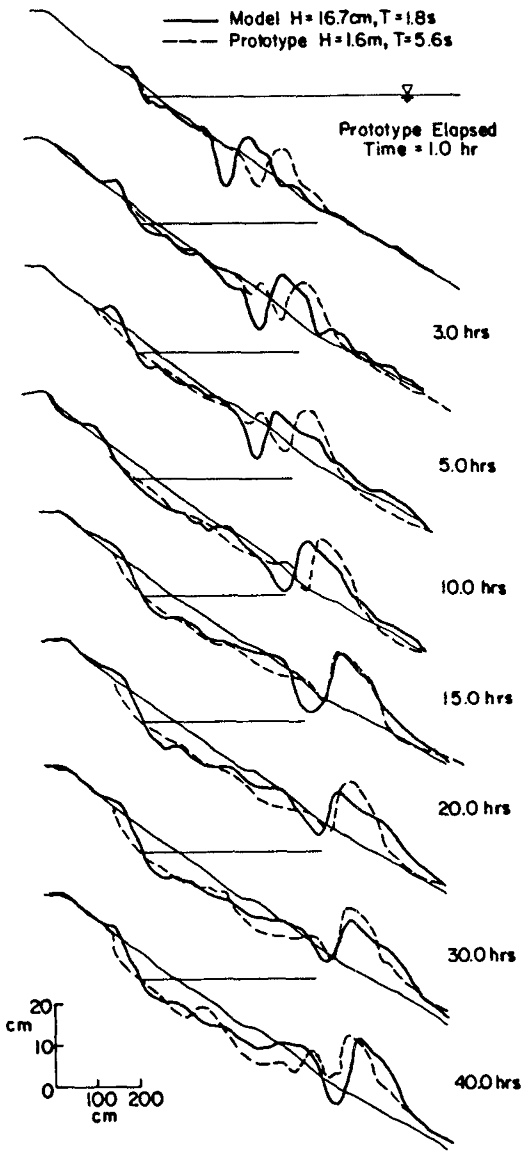

Figure 1. Beach Profile Evolution for Erosive Wave Conditions. Prototype Results Refer to Saville's (1957) Large-Scale Wave Tank Tests. Initial Planar Profile of 1:15 Slope.

In Figure 1, Saville's results are scaled according to the length scale and are compared to small-scale results. In general, the initial differences between the small- and large-scale model results are greater than at later times as equilibrium is approached. The final results at 40 hours are in good agreement and there is general similarity of the beach face slopes, the inner third of the surf zone, bar-trough geometries, and the offshore slopes. Offshore slopes in both model and prototype are approximately 1:5, and appear to be far steeper than natural offshore slopes.

In the second experiment, one of Saville's tests with constructive wave conditions was simulated. Saville's wave period and wave height in the flat section of the tank were 11.33 seconds and 1.28 m repectively. The required model parameters were $T = 3.67$ s and $H = 0.13$ m. Unfortunately, the wave generator in the model was not capable of generating a 13 cm wave at the required period, therefore, the maximum possible wave height of 8.5 cm was used. Results between model and prototype may then be compared in a qualitative sense only.

Figure 2 compares the profile evolution of the model and prototype. Despite the lack of similarity of wave heights, both profiles show the same general features with the building of a sizable berm and net onshore sediment transport. A problem encountered in the constructive wave test was severe wave reflection from the beach and re-reflection from the wave paddle. The reflection caused undulations or "reflection bars" in the outer profile, with bar crests located distinctly at the antinodes of the partial standing wave system. In Figure 2, three of these bars are noticeable over the offshore portion of the profile. The offshore bars seem to "lock up" sand and prevent effective onshore sediment migration from the toe of the slope to the berm as in the prototype.

b. Comparison of Results Using Concave Versus Linear Profiles

In an effort to achieve more realistic wave shoaling, wave breaking, and profile evolution, the 1:15 linear beach slope was abandoned in favor of a concave initial profile. As shown by Dean (1977), a profile shape which realistically represents non-barred profiles found in nature is:

$$h = Ax^{2/3} \tag{3}$$

where h is the depth at a distance x offshore and A is a slope parameter related to sediment fall velocity. Based on the initial experiments offshore slopes out to the breakpoint were fitted by an $Ax^{2/3}$ curve to establish a best-fit value of $A = 0.075\ m^{1/3}$. . The stable beach face slope was observed to be approximately 1:5. The new initial profile was therefore established with a 1:5 beach face slope to a point of tangency with the $Ax^{2/3}$ profile just below the still water level, beyond which the $Ax^{2/3}$ form was adopted.

For this initial profile, the same erosive and accretive wave conditions were repeated from the first experiments. The results corresponding to various elapsed times for the erosive case are shown in

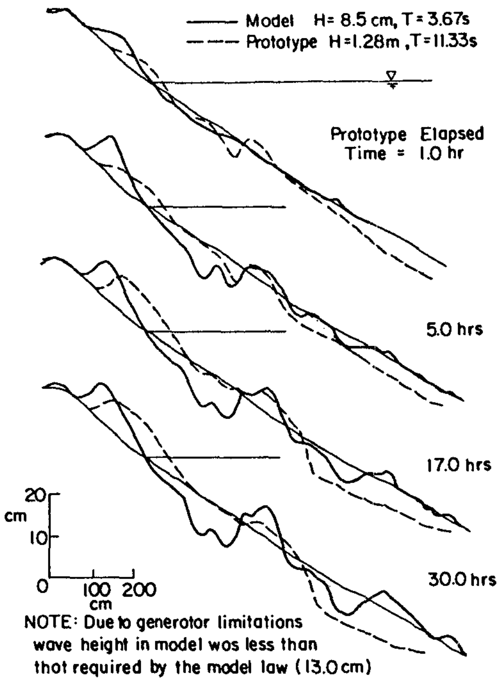

Figure 2. Beach Profile Evolution for Accretive Wave Conditions. Prototype Results Refer to Saville's (1957) Large-Scale Wave Tank Tests. Initial Planar Profile of 1:15 Slope.

Figure 3. Because of the mild offshore slope, waves broke in a spilling fashion during the first few hours of the test, in contrast to the plunging breakers observed in the 1:15 slope test. After 3 to 4 hours, waves began to plunge and a breakpoint bar became fully developed. From the beginning of the test, a broad symmetrical outer shoal grew steadily at a position well seaward of the breakpoint, seemingly due to increased sediment suspension over the rippled bed. As this bar grew, it began tripping waves in a spilling fashion between 10 and 11 hours. Waves then reformed before plunging on the inner bar, which moved shoreward due to the smaller reformed wave heights. Remarkably, the inner surf zone and beach face exhibited minor variation with only slight erosion over the test. It is noted that this offshore bar seems peculiar to this specific set of wave conditions and did not form under other erosive wave conditions.

In the case of low steepness waves beginning with an $Ax^{2/3}$ profile form, wave breaking was altered from surging-collapsing in the 1:15 test

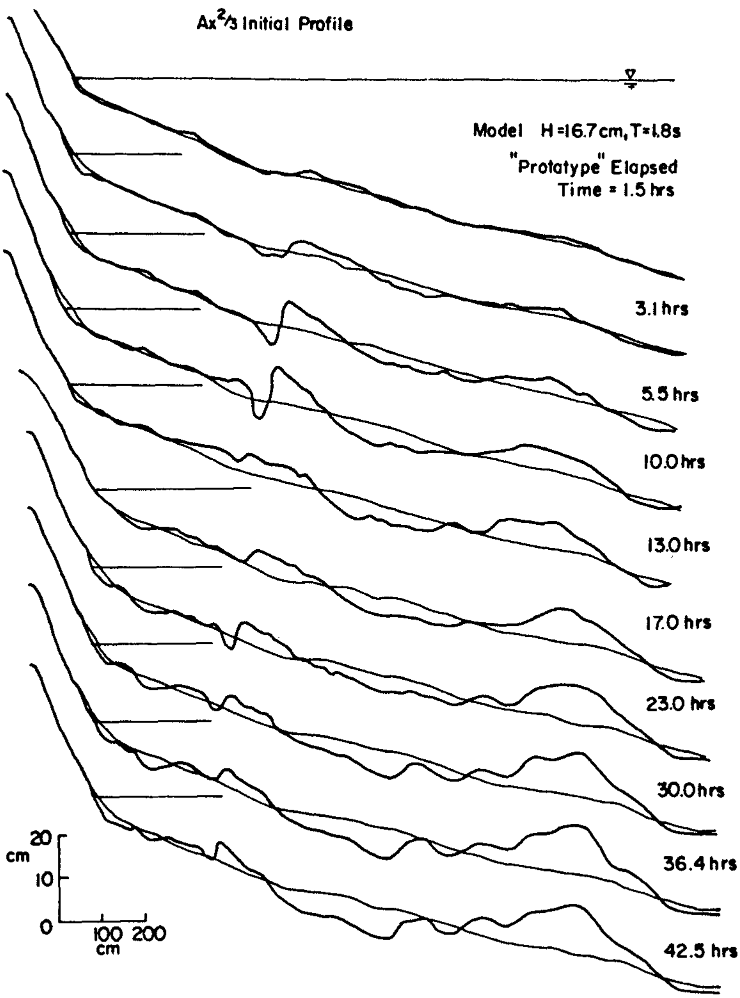

Figure 3. Evolution of Erosive Profile for $Ax^{2/3}$ Initial Profile.

to plunging. Only slight beach face accretion occurred but runup was nearly identical to the 1:15 test. The profile was dominated by multiple reflection bars and some cross-tank variations were present; however, little net onshore-offshore sediment transport occurred.

The effects of the initial profile form can be observed directly by superimposing the final profiles of the 1:15 and $Ax^{2/3}$ tests as shown in Figure 4. The most striking feature of the comparisons are the nearly identical beach face and inner surf zones despite the differences in initial profile forms and breaker type. Over the offshore regions the profiles are quite dissimilar, which may be attributed to different wave shoaling and breaking characteristics. To investigate further the role of bottom shape in wave transformation across the outer part of the profile, the breaker model by Dally, et al. (1985) was applied. Under erosive conditions for the initial profile of 1/15 slope, the model indicates rapid shoaling to an incipient breaker height of 19.8 cm at a mean water depth of 15.6 cm, i.e. $(H/h_b) = 1.27$, in accordance with the observed plunging breaker conditions. On the $Ax^{2/3}$ profile, the wave shoals very gradually until a height of 18.6 cm is reached in a mean water depth of 21.6 cm, $(H/h)_b = 0.86$, indicating a spilling breaker as observed at the beginning of the test. The same behavior is evident under accretive conditions. In general, wave shoaling and incipient breaking seem much more realistic on the $Ax^{2/3}$ profile as compared to the linear initial profile.

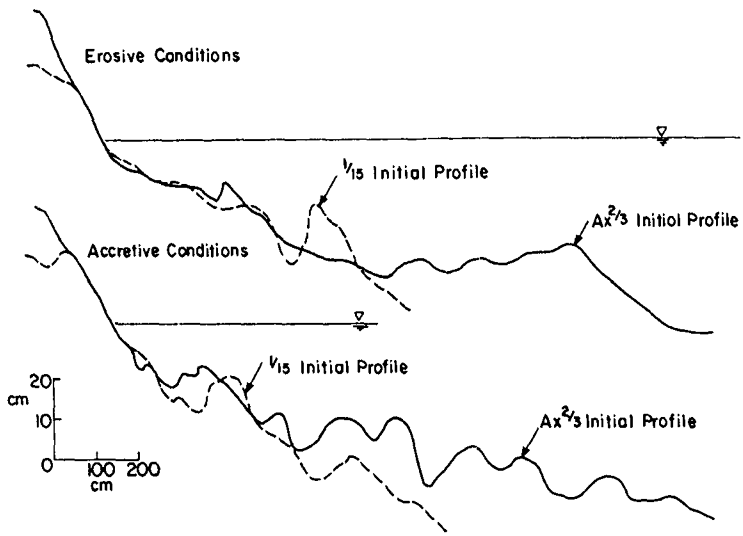

Figure 4. Comparison of Final Profiles Resulting from Planar (Slope 1:15) and $Ax^{2/3}$ Initial Profiles. (a) Erosive Conditions, (b) Accretive Conditions.

c. Model Experiments for Onshore-Offshore Transport

The major series of experiments was concerned with evaluating the undistorted Froude model against full-scale models for determining the criterion for the formation of storm or normal profile forms. Since the Froude model violates the Reynolds criteria, it was *a priori* expected that results of storm-normal profile tests would be skewed toward the formation of storm profiles, as it was found that onshore motion during constructive conditions is hindered by reflection problems while offshore motion under erosive conditions is enhanced by ripple-dominated suspension.

The framework adopted for the experiments was Dean's (1973) criterion for onshore-offshore transport:

$$\frac{H_o}{L_o} \begin{matrix} > \\ < \end{matrix} 1.7\,\frac{\pi w}{gT} \qquad \begin{matrix} > \text{ offshore (storm profile)} \\ < \text{ onshore (normal profile)} \end{matrix}$$

or

$$\frac{H_o}{wT} \begin{matrix} > \\ < \end{matrix} 0.85 \qquad \begin{matrix} > \text{ offshore (storm profile)} \\ < \text{ onshore (normal profile)} \end{matrix}$$

Ten combinations of deepwater steepness and the fall velocity parameter, $\pi w/gT$, were selected. Starting with the $Ax^{2/3}$ initial profile, wave conditions were run for the prototype equivalent of 6 to 12 hours. Profiles were found to exhibit three forms, characterized by net onshore transport, net offshore transport, or a mixed response with simultaneous formation of a berm and offshore bar.

The initial and final profiles from individual tests are shown in Figure 5 and the results for direction of transport are given in Table 1. In general, profile changes are not as dramatic as typically observed on linear initial profiles, presumably since the initial concave profile is in quasi-equilibrium. In Figure 6, the small-scale results are augmented by available full-scale experimental results of Saville (1957) and Kajima, *et al.* (1982) and plotted in the same format as Dean's original criterion. As found by Dean (1973), a line with a 45° slope seems to reasonably separate storm and normal profiles and is given by:

$$\frac{H_o}{L_o} = c_1\,\frac{\pi w}{gT}$$

or:

$$\frac{H_o}{wT} = c_2$$

where c_1 is found to be 4.0 to 5.0 and c_2, the critical value of the fall time parameter H/wT, is therefore 2.0 to 2.5. As expected, the undistorted Froude model exhibits slightly lower critical values than

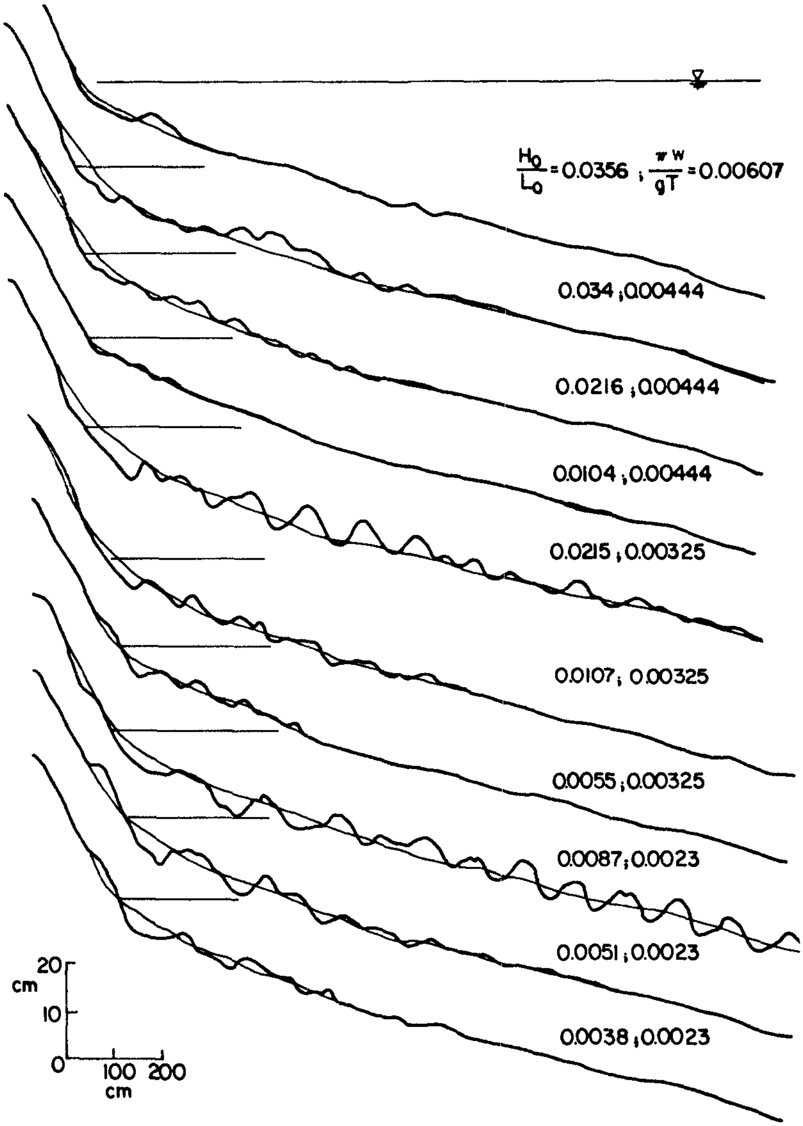

Figure 5. Final Beach Profiles for Test Series to Establish Criterion Separating Onshore and Offshore Sediment Transport. Initial $Ax^{2/3}$ Profile.

the full-scale experiments. The lower number in each range seems to represent the small-scale criterion while the upper number represents the approximate full-scale criterion, although more data is required to establish the criteria more exactly.

Table 1
Test Conditions and Results for Experiments
of Onshore-Offshore Criterion

H(cm)	T(s)	L_o(cm)	h/L_o	H_o	H_o/L_o	$\pi w/gT$	Profile Type
4.8	0.95	140.8	0.3268	5.01	0.0356	0.00607	storm
8.1	1.3	263.6	0.1745	8.86	0.0340	0.00444	storm
5.2	1.3	263.6	0.1745	5.69	0.0216	0.00444	mixed
2.5	1.3	263.6	0.1745	2.74	0.0104	0.00444	no change
10.3	1.8	505.4	0.091	10.94	0.0215	0.00325	storm
5.1	1.8	505.4	0.091	5.42	0.0107	0.00325	mixed
2.6	1.8	505.4	0.091	2.76	0.0055	0.00325	normal
8.8	2.5	974.8	0.0472	8.5	0.0087	0.0023	storm
5.2	2.5	974.8	0.0472	5.02	0.0051	0.0023	normal
3.9	2.5	974.8	0.0472	3.77	0.0038	0.0023	normal

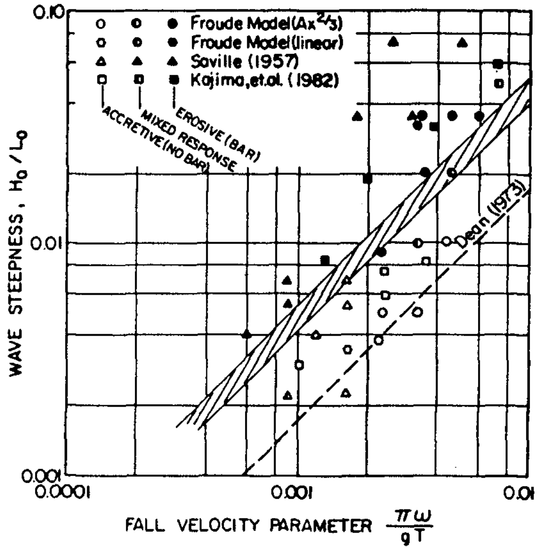

Figure 6. Conditions Separating Onshore and Offshore Sediment Transport Including Results of this Study, as well as Results of Prototype Scale Experiments of Saville (1957) and Kajima, et.al. (1982).

Reasons for the differences between the present criterion and Dean's original criterion are difficult to determine precisely but seem to be due to scale effects incorporated into Dean's original criterion. Other criteria for onshore-offshore transport also exhibit apparent scale effects from small to full scale. Kamphuis (1982) addresses possible scale-effects in small scale mobile bed models and attributes the greatest scale effects to the ratio of a characteristic length scale to the grain diameter, which governs bed roughness and bed geometry. He concludes, however, that it is impossible to determine the magnitude or source of scale effects with certainty. Despite the scale effects in the undistorted Froude model, results seem to agree reasonably with large scale results and are in much better agreement than other small-scale results with either unscaled sediment or unknown distortion effects.

d. Storm Bar Behavior Under Recovery Conditions

A final series of five experiments was designed to directly simulate the behavior of a profile, generated under storm wave conditions and an elevated water level, after the water level had returned to normal and lower steepness waves prevail. The storm profile was generated starting from the same $Ax^{2/3}$ profile used as the initial condition in the previous tests, except the water level was increased by 10 cm. The wave conditions of Saville's erosion test were then maintained for 3.87 hours to form a large breakpoint bar.

In this first test, the wave generator was set to maintain the erosive conditions with the water level returned to normal to see if any recovery would occur simply due to the drop in water level stranding the storm bar inside the new breakpoint. At the end of the test, nearly all traces of the storm bar had been eradicated and a new bar had formed offshore at the new plunge point that was identical to the initial bar. However, only a small berm has been constructed; and, on the whole, the beach face had not shown any signs of recovery and the inner surf zone had remained remarkably inactive.

The second test reduced the wave height so that the deepwater wave steepness was 0.01, while $\pi w/gT$ remained equal to 0.00325. This placed conditions in the recovery regime, according to Figure 6. This resulted in profile changes dominated by the formation of small scale reflection bars. For the first 3 hours the storm profile and bar retained their identity, with the reflection bars superposed on top. Ultimately, some material from the storm-generated bar moved landward to fill the trough and a small berm developed.

In the third recovery test, the deepwater steepness was reduced to 0.005, moving conditions further into the recovery regime. This produced a surging "breaker" at the toe of the beach face and substantial reflection. Energy conditions were so low that even after 8 hours, the original storm bar was still present. Except for a small transfer of material from the bar crest to trough, the storm bar was maintained much like a relict feature. A berm formed due to local onshore transport in the swash region.

In the fourth test, the deepwater wave steepness was returned to 0.01 while $\pi w/gT$ was reduced to 0.0023. According to Figure 6, this placed conditions in the transition between erosion and recovery. Wave conditions were such that the storm bar also caused breaking of the recovery waves, and as a result, much of the profile evolution consisted of a reworking of the bar material seaward. However, a substantial berm was constructed and fully developed within 3 hours.

In the fifth recovery test the deepwater steepness was reduced to 0.005, placing conditions within the recovery regime. The storm bar migrated landward over the first hour of the test and eventually stabilized at the breakpoint of the recovery waves. The berm grew until it stabilized at approximately 5 hours elapsed time, simultaneously with the appearance of reflection bars.

In a related experiment, using a linear initial profile, wave conditions were changed every 30 to 45 minutes to consistently maintain the breakpoint a few centimeters landward of the evolving bar. This test, shown in Figure 7, was the only test in which anything resembling complete shoreward bar migration onto the beach face was achieved. Apparently, under monochromatic wave conditions, complete bar migration requires "tuning" of the wave conditions toward smaller wave heights in order to continually promote the establishment of the bar landward of its previous position while ensuring that the previous bar is the source of sediment for the new bar.

Summary and Conclusions

Several sets of experiments were conducted to: 1) test a simple physical model scaling law for beach profile evolution, 2) investigate the effects of initial profile shape on profile evolution, 3) test the criterion of Dean (1973) for the formation of a storm profile versus normal profile, and 4) study the general behavior of a barred profile under recovery conditions. Only monochromatic waves were used in the experiments.

The model scaling law, based on Froude similarity and using sediment fall velocity as the controlling parameter, was found to reproduce beach profile evolution quite well under erosive conditions. Under constructive wave conditions simulation for portions of the profile seaward of the breakpoint is only moderately successful due to the improperly scaled boundary layer features and due to the persistent formation of fairly stable multiple bars associated with wave reflection.

For the same wave conditions, initial profile shapes of 1/15 planar slopes and $Ax^{2/3}$ produced dramatically different profile evolution and equilibrium shapes, especially offshore from the breakpoint. These differences are attributed to the different breaking behavior governed by different bottom slopes near the breakpoint. However, because depth limited breaking causes all waves to approach the same height regardless of incipient conditions, the inner surf zone and beachface showed remarkable similitude between the two tests. The concave profile was found to have more realistic wave shoaling and breaking characteristics and, on that basis, appears most useful for physical modeling.

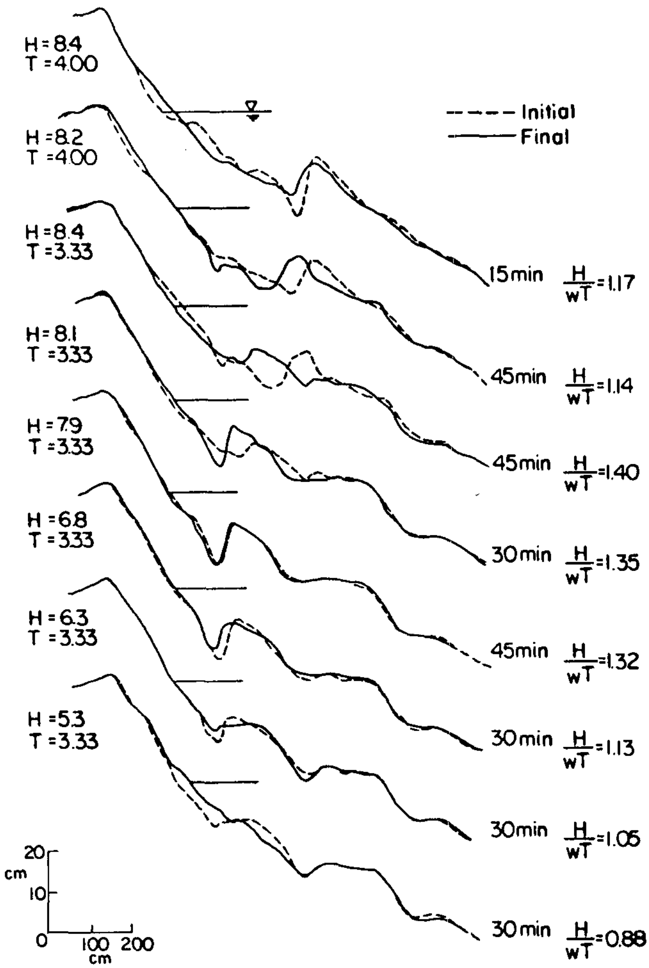

Figure 7. Beach Profile Recovery Resulting from Adjusting Wave Breakpoint to be Located just Landward of Bar Crest.

Model tests of the onshore-offshore criterion, when coupled with the prototype scale results of Saville (1957) and Kajima, et al (1982), resulted in a different criterion than that found by Dean (1973) based mostly on unscaled small-scale experiments. This criterion is more physically realistic, and the agreement of the undistorted Froude Model with prototype-scale experiments is satisfying but needs much additional model verification.

Direct simulation of a storm-barred profile with lowered water levels and constructive wave conditions indicates that onshore bar migration does not occur easily. Bar migration under monochromatic waves seems to require a specific set of finely tuned wave conditions such that the recovery breakpoint is always maintained just landward of the migrating bar. This can only occur due to a gradual reduction in wave height or due to changes in water depth due to tides.

Based on the undistorted Froude model, with monchromatic waves, beach recovery in qualitative or quantitative agreement with nature was difficult to attain. This is due to the aforementioned reflection problems, and scale effects in the bottom boundary layer and ripple formation. Preliminary tests with irregular waves were performed and seem useful for reducing wave reflection effects and for smoothing bottom ripples.

Acknowledgements

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