CHAPTER 62

PHASE DEPENDENT ROUGHNESS CONTROL OF SAND MOVEMENT

by

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ABSTRACT

Experiments with wave motion over asymmetrical "ripple-like" forms show that the difference between a net sand transport in a down-wave versus an up-wave direction is related to a subtle phase dependent mechanism associated with the intensity of vortex formation in the lee of the form. Artificial roughness modules have been developed, consisting of arrays of asymmetrical forms resembling natural ripples. The asymmetry of the forms causes an intense vortex to form in the lee of the steep face. This vortex traps and suspends sediment, which when the orbital motion reverses its phase, is lifted above the roughness element and carried in the new direction. Thus, the direction of the net sand transport is dependent upon the relation between the steep face of the roughness element and the phase of the orbital velocity; the net transport being in the direction of the orbital velocity that is out-of-phase with the maximum vortex formation.

INTRODUCTION

Progressive waves traveling over a sand bed usually produce sand ripples that are almost symmetrical in profile. This wave action over horizontal beds, in the presence of the Longuet-Higgins bed drift current, produces a net sand transport in the down-wave direction. However, experiments with waves and currents showed that asymmetrical sand ripples could cause a change in the direction of sand transport so that the net transport is opposite to the drift current and the direction of wave propagation.

Investigation of this phenomena indicates that the difference between a net sand transport in a down-wave direction versus an up-wave direction is related to a subtle phase dependent mechanism associated with the intensity of vortex formation in the lee of the ripple crest. Artificial roughness modules have been developed, consisting of arrays of asymmetrical forms resembling natural ripples. The asymmetry of the forms coupled with the oscillatory flow causes large vortices to be generated on the steep side of the crest and smaller vortices to be generated on the gentle side of the crest. These different sized vortices suspend differing amounts of sand or sediment, which when the orbital motion reverses its phase, is lifted above the roughness element and carried in the new direction. Since the larger vortex suspends a greater amount of sediment, the direction of the net sand transport is dependent upon the relation between the steep face of the roughness element and the phase of the orbital velocity: the net transport being in the direction of the orbital velocity that is out-of-phase with the maximum vortex formation. This differential vortex formation and sediment suspension is depicted in Figure 1.

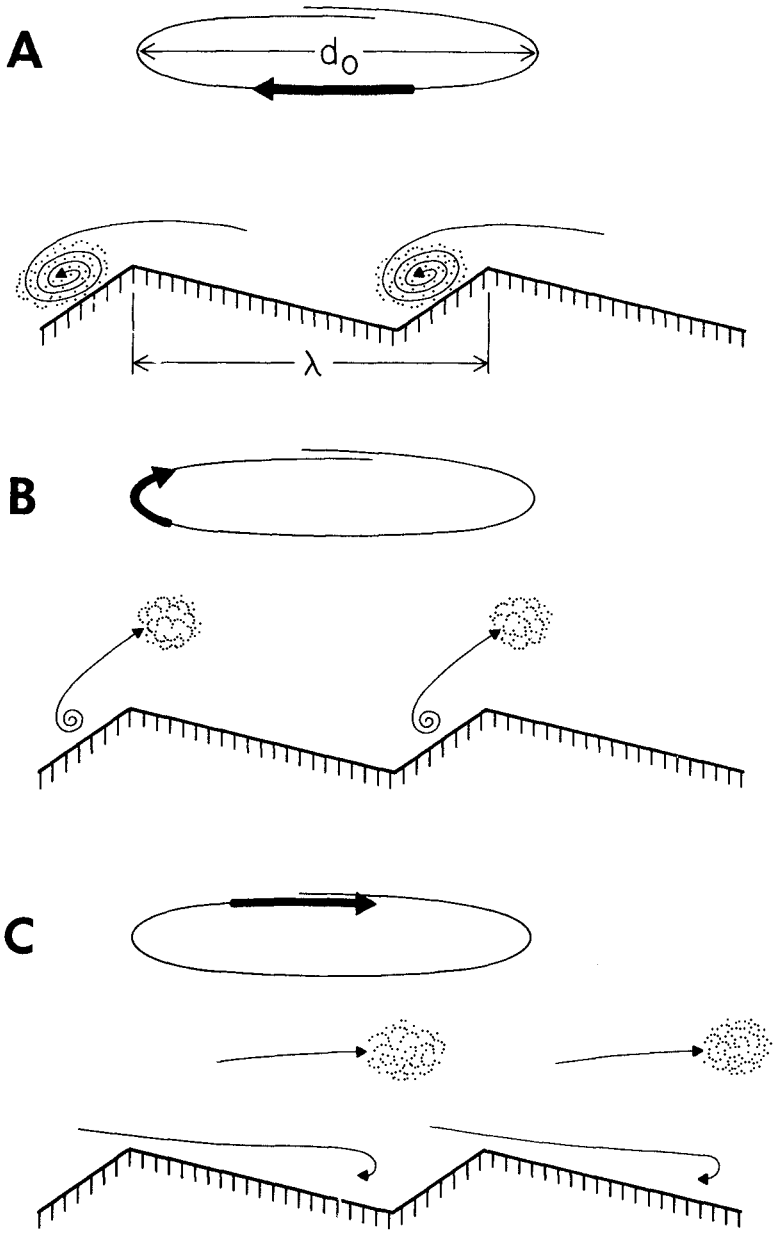

Figure 1. Asymmetrical bottom forms under oscillatory wave motion showing differential vortex formation and sediment transport. Wave travels from left to right.

It is well known that oscillatory ocean surface waves produce horizontal and vertical water particle motions in the water column which have been found to affect the bottom sediment to depths in excess of 52 meters (Inman, 1957). One of the more common effects of this motion is to form sand ripples, which in the absence of extraneous currents are generally symmetrical in profile.

The formation of vortices in the lee of the ripple crests has been described as early as 1884 (Darwin, 1884) and 1910 (Ayrton, 1910). Good photographic evidence of vortices was obtained by Bagnold (1946), and many studies have been conducted since. However, most of these studies have been conducted with standing waves or oscillating beds, which give flow conditions that differ in some respects from those of progressive waves. The oscillatory flow is seen to form the vortex over symmetrical ripples with the vortex being released into the water near the bed as the flow reverses (Figure 2). This alternate formation and release of vortices leads to the existence of a vortex sublayer near the bed under oscillating flow. This vortex sublayer is a zone of two dimensional vorticity rotating about axes that are parallel to the ripple crests. Figure 3 shows this vortex formation over symmetrical sand ripples.

Inman and Bowen, 1963, while studying the transport of sand in a wave flume with a superimposed current, found that for certain combinations of wave and current speed, the sediment could be made to move in an up-wave and up-current direction. That is, in opposition to the direction of wave propagation and flow of current. It was argued that this direction of sediment transport was caused by differing amounts of sediment suspension due to differential vortex formation. This differential vortex formation was caused by the asymmetrical form of the ripples. The asymmetry of the ripples was due to the unidirectional current superimposed upon the velocity field of the wave.

The following series of demonstrations were performed to illustrate the capability of the phase dependent roughness mechanism in controlling the net movement of sand. A roughness form in two segments with five identical asymmetrical wavelengths in each segment was used. The segments were arranged to form a test section as shown in Figure 4. For the first arrangement, particles were placed on the down-wave end of the test section. The direction of particle transport was out-of-phase with the intense vortex formation and the particles moved up-wave and off of the forms. In the second arrangement, the forms were turned around, and the particles were placed on the up-wave end of the test section and the particles moved down-wave and off of the forms. In the third arrangement, only the up-wave form was turned around and a group of particles was placed in the center of the forms. Approximately one-half of the particles moved up-wave and the other half of the particles moved down-wave, both groups of particles moving completely beyond the forms. For the fourth arrangement, both forms were turned around and particles were placed at both ends of the test section. In this case, both groups of particles moved toward the center of the test section and remained in the center.

This series of demonstrations showed that: (1) the direction of transport is not determined by currents in the wave tank; and (2) end effects are not important in determining the direction of motion of the particles. From these results, it may be stated that the direction of motion of the sediment is determined by the orientation of the asymmetrical forms.

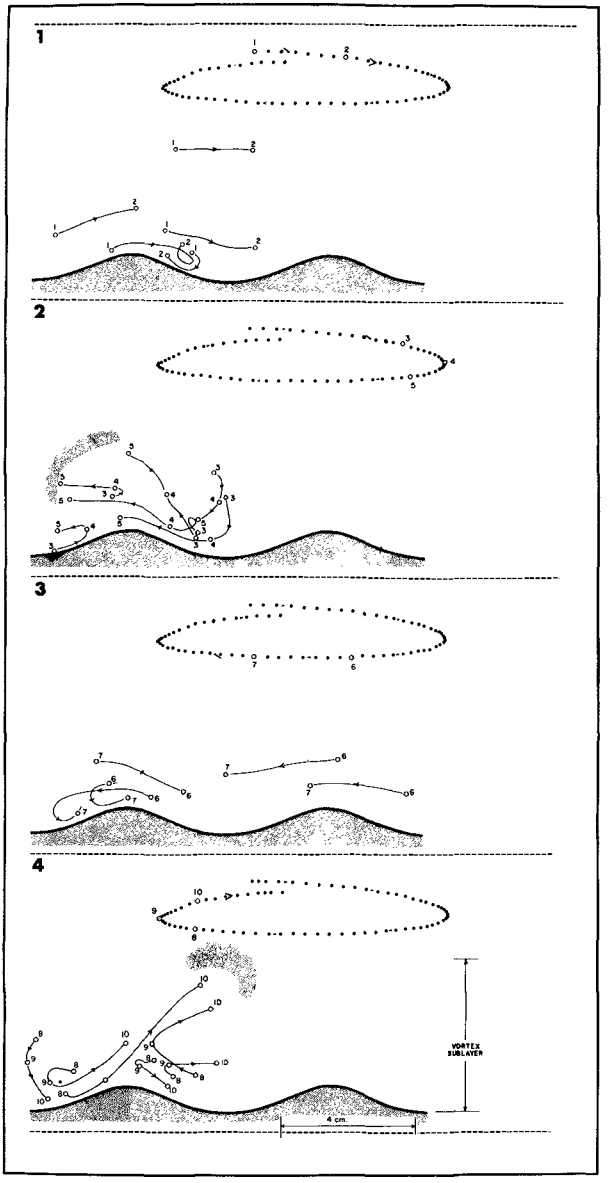

Figure 2. Particle trajectories over a rippled bed showing the height of the vortex-sublayer (after Inman and Bowen, 1963).

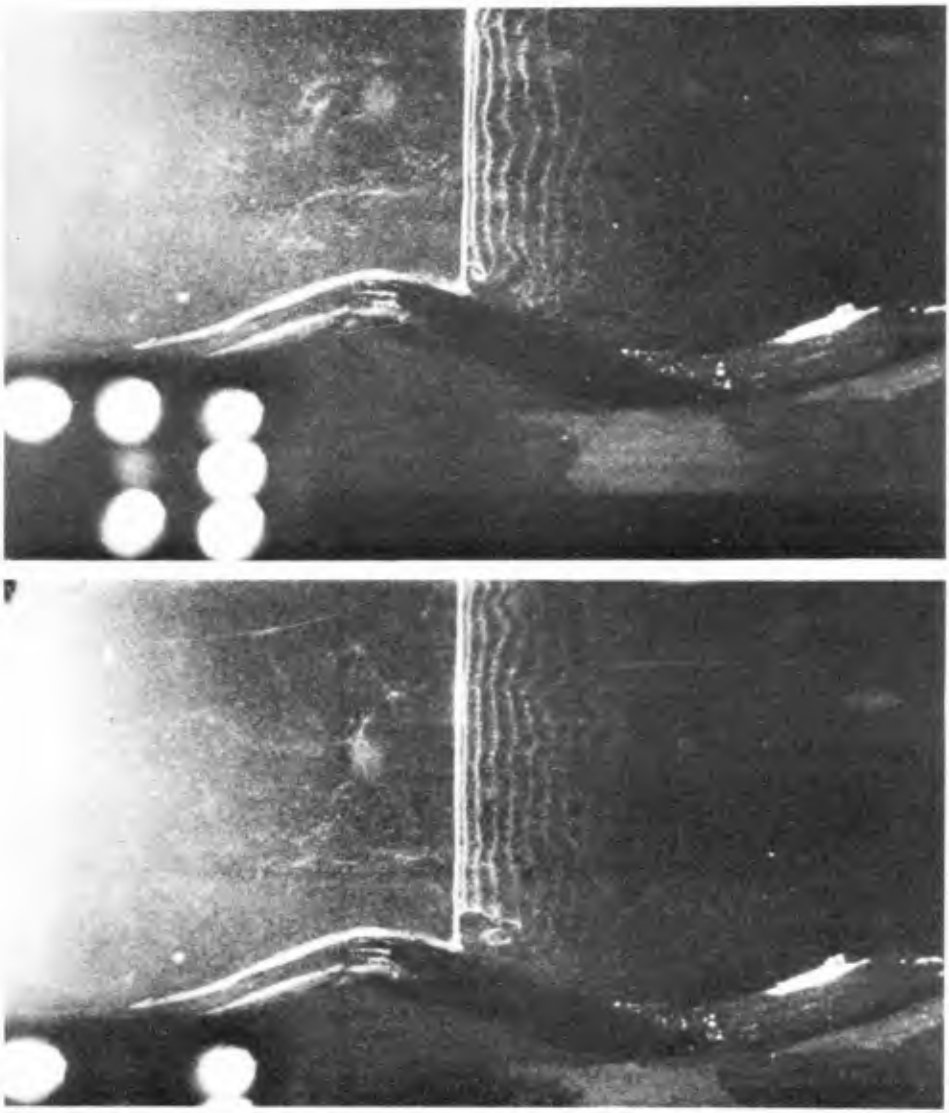

Figure 3. Vortex formation over symmetrical ripples, using the hydrogen bubble technique (note counting lights in lower left portion of figure). The wave form travels from left to right. Upper picture taken at a phase of 40 degrees, lower picture taken at a phase of 55 degrees, wave crest passage denotes zero degrees phase.

TYPICAL EXPERIMENTAL CONDITION

Water Depth	$h = 160$ cm
Wave Period	$T = 3.4$ sec
Wave Height	$H = 21$ cm
Orbital Displacement	$d_o = 24$ cm
pvc, $\rho = 1.5$ gm/cm^3 acrylic, $\rho = 1.1$ gm/cm^3	Tracers Used

ROUGHNESS DIMENSIONS

Wavelength = 10 cm Height = 1.5 cm

Asymmetry: 7.5 cm; 2.5 cm

Waves Propagate from Left to Right

Direction of Particle Transport is Shown by the Arrows

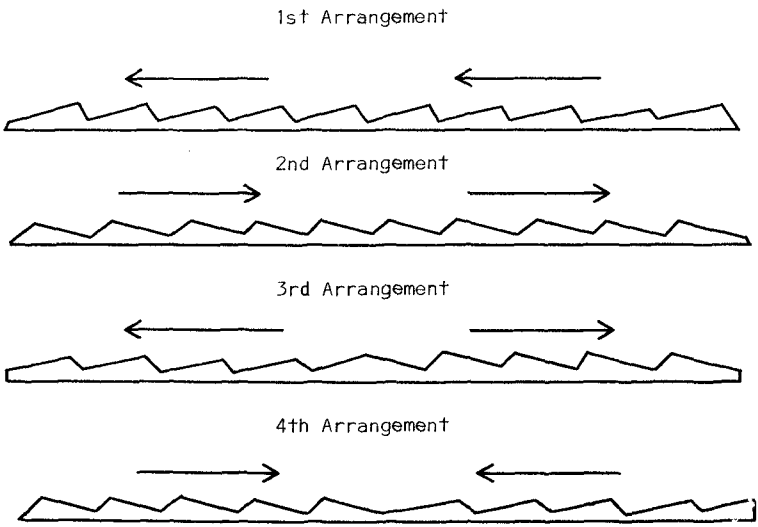

Figure 4. Laboratory demonstration of the capability of phase dependent roughness elements to control the direction of sediment transport. In each case the wave traveled from left to right.

EXPERIMENTAL PROCEDURE

In order to investigate the up-wave movement of sediment and the effect of asymmetrical ripples on this sediment transport, tests were conducted in a laboratory wave tank which is 45 m long, 2.5 m wide and 2.5 m deep. Water depths of 1.7 m were used throughout the testing program. The wave tank is equipped with a hinged paddle wave generator and a 1 in 8 slope at the far end to minimize reflection. The laboratory tests were conducted to take advantage of the benefits of good control and ease of measurements. Later tests on a full scale basis were carried out in the near-shore zone.

The tests in the wave tank were scaled to the prototype scale by using the ratio of water particle orbital diameter, d_o, to the wavelength of the asymmetrical roughness form, λ. For Airy wave theory the parameter $d_o/2\lambda$ is equal to the wave Strouhal number

$$\frac{u_m}{\sigma\lambda}$$

where $u_m = \pi d/T$ is the maximum horizontal component of the orbital velocity near the bed, $\sigma = 2\pi/T$ is the radian frequency, and T is the wave period. This scaling has been found to be a relevant parameter for naturally formed symmetrical ripples.

The first series of tests consisted of the construction of asymmetrical roughness elements and the study of the direction of particle motion caused by the wave induced flow over the forms. The testing method consisted of placing particles on the roughness forms and studying their direction of motion. Three types of particles were used: polyvinylchloride, PVC, with a density of 1.5 gm/cm^3; acrylic, with a density of 1.1 gm/cm^3; and, beach sand, with a density of 2.5 gm/cm^3. The beach sand was used in order to check that erroneous results were not being introduced by the usage of the larger and less dense synthetic particles. In all cases, the three types of particles behaved in a similar manner. The demonstration described in the introduction of this paper was first conducted during testing of the asymmetrical forms with these particles.

Once the nature of the movement of the particles was determined for various wave conditions and asymmetrical roughness elements, experiments were next conducted to study the nature of the vortex formation over the forms and the subsequent movement of these vortices. The vortices were studied using two flow visualization techniques; dye injection, and hydrogen bubble generation from a fine platinum wire. The dye injection technique proved most useful in determining the location and time of formation of the vortices and in following the path of the vortices after they were ejected from the surface of the roughness elements. The hydrogen bubble technique proved useful in studying the size and rotational characteristics of the vortices.

Motion pictures were taken of both visualization techniques. The pictures were correlated with the water surface motions by the use of timing lights in the field of view of the camera. The output of the timing lights also appearing on the strip chart of the analog record of the surface waves. The motion pictures were then analyzed frame by frame to study the motion and rotation of the vortices. Figure 5 shows a vortex generated over the steep side of one of the asymmetrical roughness elements.

Figure 5. Large vortex formed over steep side of asymmetrical roughness element. Wave form travels from left to right.

EXPERIMENTAL RESULTS

From the particle motion studies, it was found that for low values of steepness of the forms, where steepness is defined as form height/form wavelength, η/λ, the particle motion was always out-of-phase with the orbital motion causing the most intense vortex. That is, for steepnesses of about 0.15 to 0.2, the particles always moved in a direction opposite to that faced by the steep side of the roughness forms. For greater steepness values, the higher orbital velocities caused breakdown of the system and particle transport in the direction faced by the steep side of the forms.

It should be noted that the phase dependent mechanism is valid over the same range of steepnesses that are found for natural sand ripples. Figure 6 presents the results from these tests. The solid characters represent points where the direction of particle transport was as predicted by the phase dependent mechanism, while the x's represent conditions for which the particle transport was in the direction opposite to that predicted by the phase dependent mechanism.

The reversal of particle transport direction for forms with higher steepnesses was due to vortex destruction over the steep side of the ripple form. For forms with low steepness, the vortex remains well formed during the orbital motion causing it, with the consequence that the vortex is able to raise the sediment as a plume and move it up into the higher layer of reversed orbital motion (Figures 1 and 2). However, for forms with higher steepnesses the higher velocity flows caused a plaining off and destruction of the vortex on the steep side, and hence a degradation of its ability to suspend sediment. While vortices were destroyed over the steep side, the vortex over the gentle side remained well formed during the entire orbital motion. For these greater steepnesses, the vortex over the gentle side suspended more sediment than the vortex over the steep side, hence reversing the direction of preferred transport.

In unidirectional flow, vortex formation in the wake of an obstacle is due to an adverse pressure gradient caused by the presence of the obstacle. This adverse pressure gradient leads to reversed flow in the boundary layer near the obstacle, which in turn ultimately leads to the vortex roll-up observed in the lee of the obstacle. In oscillating flow there is an additional source of adverse pressure supplied by the pressure field of the oscillating fluid itself. As the velocity field passes through a maximum in one direction, it starts to be retarded by a pressure gradient in the opposite direction from that of the current velocity. This is due to the fact that under progressive waves, the pressure field has a phase lead of 90 degrees over the velocity field. Thus, under oscillating flow conditions, the phenomenon of vortex formation is optimized. The presence of asymmetrical roughness forms causes an intensification of the vortex over the steep face and minimizes the vortex over the gentle face. Thus, in oscillatory flow under progressive waves the difference in the relative intensities of the vortices determines the direction of net sediment transport.

ENGINEERING APPLICATIONS

Upon completion of the laboratory phase of the investigation, it was decided to test a 2 meter by 2 meter square array of asymmetrical roughness forms in the nearshore zone under natural wave conditions. Using Figure 6

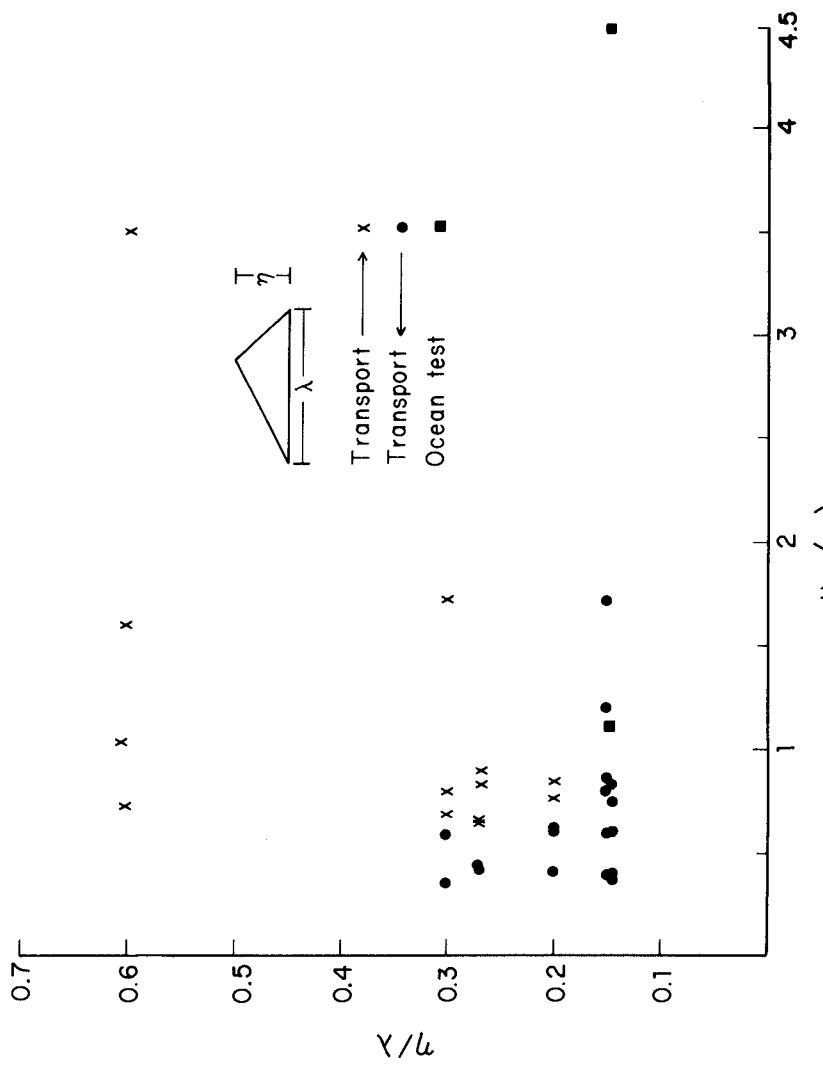

Figure 6. Transport behavior as a function of ripple steepness, η/λ, and wave Strouhal number.

as a design criterion, and a typical Southern California summer wave condition of 9 second period with wave heights of about 0.75 m, the test roughness forms were constructed with a wavelength of 40 cm and a wave height of 6 cm. This set of roughness and wave parameters corresponds to a steepness of 0.15 and a wave Strouhal number of 1.0 (Figure 6).

The roughness elements were cast with Portland cement concrete with an added 2.5 cm base for strength. Figure 7 shows the array of roughness forms just prior to installation in the nearshore environment. In addition to the asymmetrical roughness forms, two forms were cast which had the same wavelength as the asymmetrical forms, but were symmetrical in form. These forms were placed in the same locality as a control for the tests. The forms were placed in 6 meters of water, and metal rods were implanted on either side of the array in an on-offshore direction. Measurements were taken on the rods to ascertain the amount of sand loss or gain on each side of the array. The results of two weeks of observations on the array are presented in Figure 8.

The array was first arranged so as to move sediment in the offshore direction. After 24 hours in place the array had developed a pit on the inshore end of the array and had a mound on the offshore end of the array. Thus indicating that the array was having the intended effect even in this limited scale. Observations were continued for the next 6 days, with the maximum depth of the pit on the onshore side of the array attaining a depth of 13 cm below the level of the sand when the array was first installed. At the end of this one week period, the two symmetrical forms were completely buried with the crests of the ripple forms being 3 cm under the surrounding sand level. The asymmetrical array had no sand on top of it. The top portion of Figure 8 illustrates the effects of the array on the surrounding sand level.

The array was next arranged so as to move sediment in the onshore direction. After 24 hours in place, there was a 4 cm deep depression on the offshore side of the array with little noted change on the onshore side of the array. After 48 hours there were depressions on both sides of the array, with the depression on the offshore side of the array being some 2 cm deeper than the onshore side depression. It would seem that the effect of the array was not as pronounced when it was aligned in this direction. A possible explanation for the apparent lack of effectiveness in transporting sand in an onshore direction, is that at this time of year, the local beaches are accreting and sand is naturally moving toward shore (Inman and Bagnold, 1963). This sand transport rate would be sufficient to overshadow the effects of the asymmetrical array. However, when the array was arranged so as to move sediment in an offshore direction, it apparently prevented the onshore movement of sand from taking place. When the asymmetrical array was turned around, the symmetrical forms were uncovered and placed on level sand. Again within 3 days, the symmetrical forms were completely buried. The results of the second trial with the array are shown in the lower half of Figure 8.

From the preceeding discussion of the laboratory and field tests of phase dependent roughness elements, it seems likely that the phenominon is valid and should be further tested to determine the extent of its usefulness in sediment control in the nearshore zone. Along these lines, plans are underway to construct an array of roughness elements approximately 300 meters along the shore and 3 to 4 meters wide in the on-offshore direction to test their effect in preventing the loss of sand from the beach that naturally occurs during the winter storms.

Figure 7. Photograph of the phase dependent roughness forms used in the field test

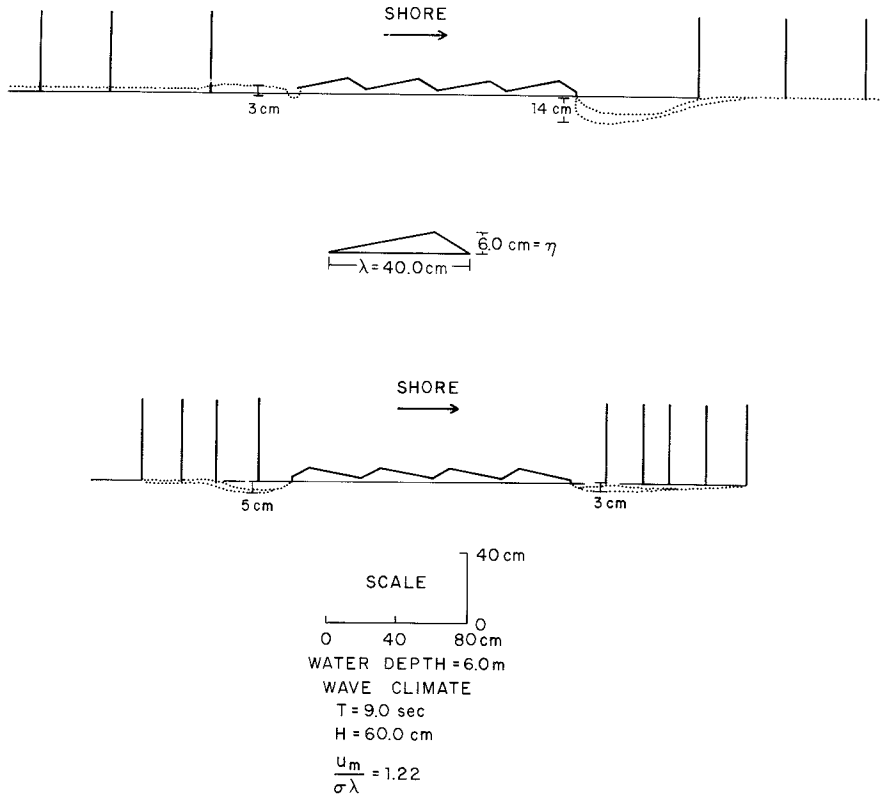

Figure 8. Results of field test in water depth of 6 meters adjacent to Scripps Institution of Oceanography Pier.

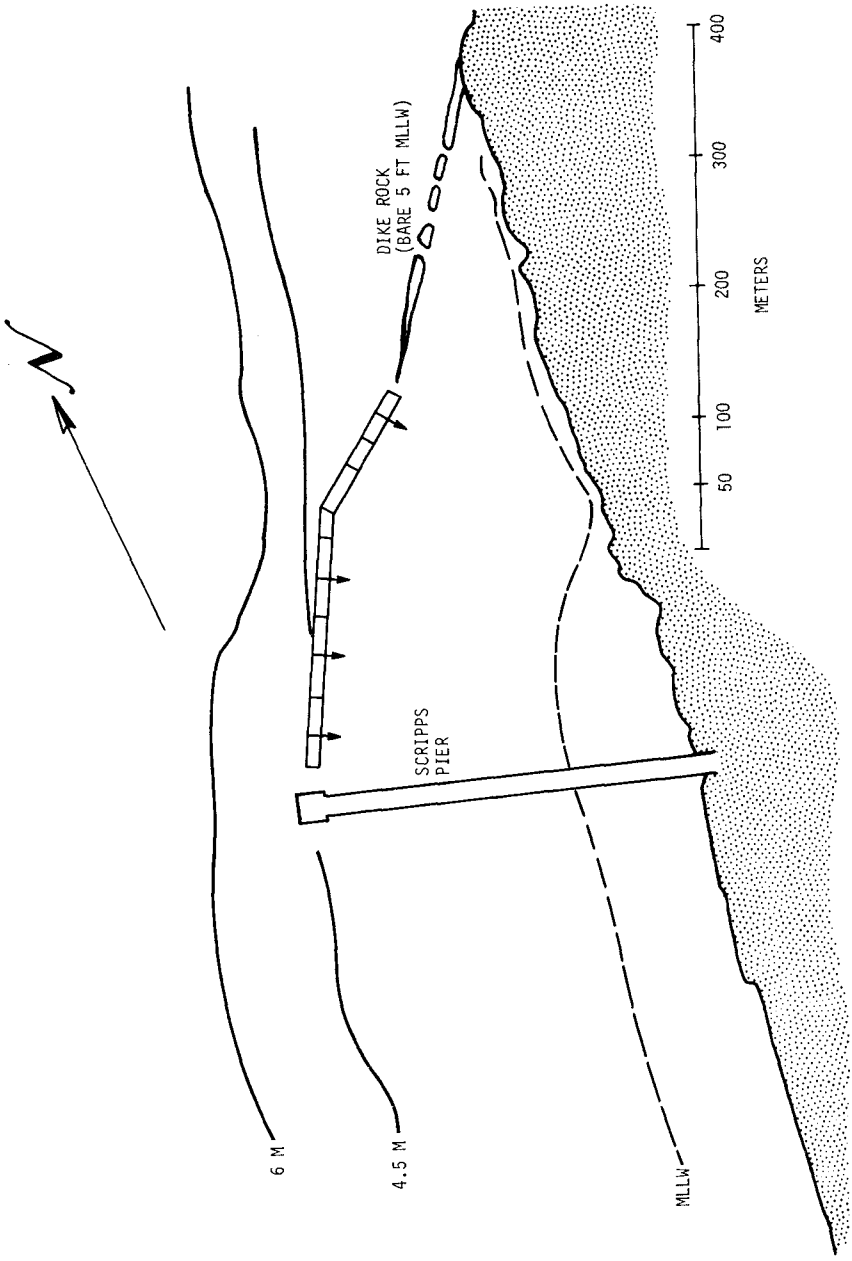

Figure 9. Proposed full scale ocean test off Scripps Beach.

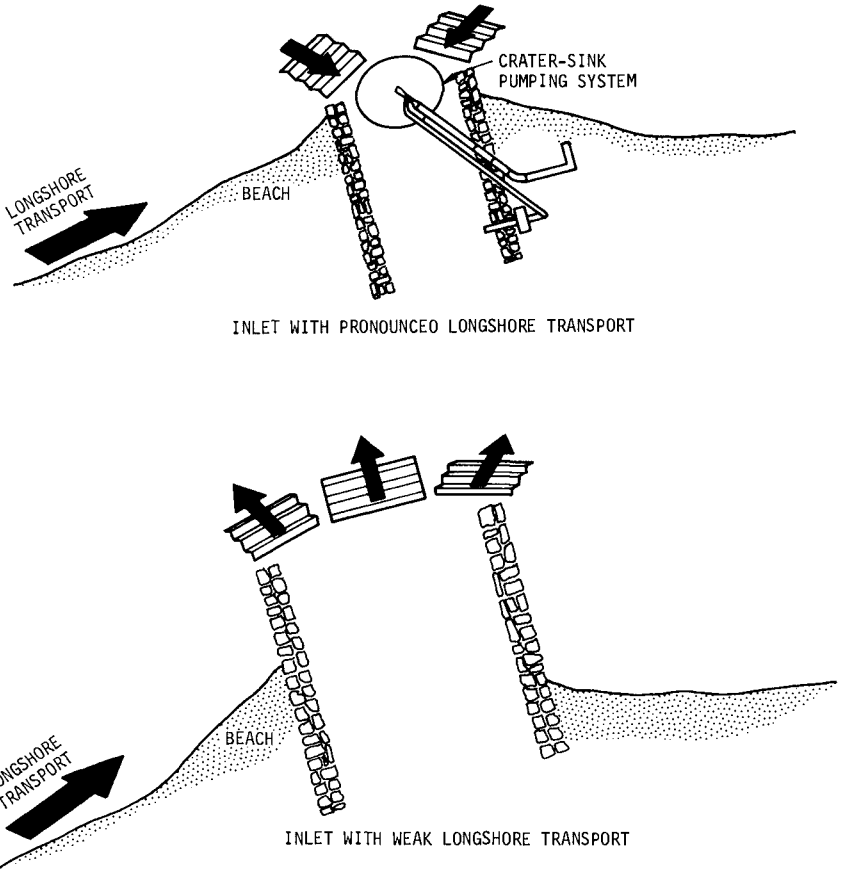

Figure 10. Possible applications for phase dependent roughness elements.

The area to be tested is a strip of beach just north of the Scripps Institution of Oceanography which is terminated by the presence of a rocky headland which will act as a barrier to "close" off one end of the experiment. The array is to be aligned with the 5 to 6 meter contour which has been found to be an area of equilibrium in terms of the seasonal on-offshore movement of sediment. In an effort to counteract the scouring effect which was present along the ends of the small test array, the 300 meter array will be placed atop a type of plastic filter cloth which will allow the passage of water, but not the passage of sand through its weave. Figure 9 is a plan view of the proposed test site showing the location and length of the test array of phase dependent roughness elements. To test the effectiveness of the system for controlling sediment movement, bottom profiles will be measured in the area of the array and also to the south of the pier to detect any differences in sand level between the "controlled" and "uncontrolled" strips of beach.

In addition to the management of beach erosion shown in Figure 9, several additional applications of phase dependent roughness elements are suggested. These are shown schematically in Figure 10. The first application is used in an area of pronounced longshore drift in which sediment continually gets around the end of a channel maintained by a jetty. The phase dependent roughness elements can be used to direct the sediment toward a dredge or crater-sink pumping system, (Inman and Harris, 1970) to increase the efficiency of the overall system in keeping the harbor entrance open.

For areas of less pronounced longshore drift, the phase dependent roughness elements could be placed at the ends of jetties to prevent the formation of a bar at the entrance to the jetty. The longshore transported sediment would be moved away from the entrance, where it would be available for longshore transport past the end of the jetty.

Present plans call for the construction of the nearshore test elements out of concrete. However, it may be possible to construct movable elements so that the roughness form could be changed as the wave conditions change, thus keeping the roughness elements operating in their most efficient range (Figure 6).

ACKNOWLEDGMENTS

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