CHAPTER 23

THE EFFECT OF WAVES ON THE PROFILE OF A NATURAL BEACH

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ABSTRACT

A 60-day field study was conducted on a selected natural beach in which the beach profile was measured daily and the waves incident upon the profile were recorded continuously. Beach and wave parameters derived from the field data were empirically combined to yield: (a) quantitative relationships between the change in the profile and the average deep-water wave steepness and wave power over a lunar day (24.8 hours) given the profile at the beginning of the period, (b) equilibrium profiles for different values of wave steepness, (c) an empirical relationship between wave steepness and wave power which agrees well with theory, and (d) rates at which the beach profile approached equilibrium for given initial conditions of non-equilibrium. Using the relationship developed between beach change and wave steepness, hindcasts were made of the day-to-day sand elevation at a selected location near the middle of the profile and were found to agree fairly well with the observed sand level.

INTRODUCTION

Observations made daily or on a shorter term basis show that natural sand beaches change sensitively in evident response to changing wave conditions, but in a complex way. This paper reports on a successful attempt to establish a quantitative relationship between daily changes in the profile and the waves incident upon a selected beach. The development of this relationship is a very preliminary step toward the ultimate development of methods for making daily synoptic forecasts of the behavior of natural beaches given predicted or observed wave conditions and knowledge of the tides and the sand properties.

The beach where this field study was conducted is a long, gently curving strand named Del Monte Beach, which is located in the southern end of Monterey Bay, California. A brief review of its environmental characteristics is given here before proceeding.

Del Monte Beach is a stable beach and has remained in very nearly the same location since the earliest hydrographic survey of 1851. The

profile across the beach and through the surf zone characteristically lacks a well-defined berm and offshore bars, and is fairly simple most of the time. Seaward of the surf zone the bottom slopes evenly across the continental shelf. The beach in the vicinity of the profile studied is uniform laterally for some distance, except for subdued cusps that frequently occur on the upper beach. The material composing the beach is well-sorted medium to fine siliceous sand having a mean grain diameter of 2 ϕ (0.25 mm).

The predominant waves on the beach are moderate to long period swell usually having narrow frequency spectra. The beach is partially sheltered from the Pacific Ocean in such a manner that waves entering the bay from all open ocean directions refract so as to arrive with their crests parallel or nearly parallel to shore. Littoral drift is negligible most of the time, and beach profile changes involve essentially offshore-onshore transport of sand. The tides are of the mixed type and have a diurnal range of 5.3 feet. Meteorologically induced water-level variations are negligible.

It may be seen from this description that the beach selected for study is a natural laboratory where beach response to changing wave conditions may be investigated under relatively simple environmental conditions.

BEACH OBSERVATIONS

The beach and wave information used in this study were collected over a 60-day period in February and March 1967 by Harlett (1967) along a permanently established profile. The profile, shown in Figure 1, consists of a line of 20 railroad rails driven into the sand at approximately 10-foot intervals extending from the rear of the beach to the lowest tide level.

Beach profiles for every day of the study were constructed from measurements of the sand level against the rails. The latter were made at the time of lowest tide each day when the beach exposure was greatest, and accordingly at a sampling interval of one lunar day or 24.8 hours. The observation times during the study are marked by dots on the tide curve in Figure 2.

Synchronization of the observation times with the diurnal lunar tidal cycle may be seen in Figure 2 to result in a very nearly repetitive tidal sequence between successive observations as well as tide levels that differ only slightly from one sampling time to the next. It thus appears probable that this choice of sampling interval tends to filter out the effect of the tides and thereby to amplify the effect of changing wave conditions in producing the observed profile changes.

Waves were recorded continuously during the field study, except

Figure 1: PERMANENT PROFILE ON DEL MONTE BEACH
The front edge of the foam line is at Rail 8.

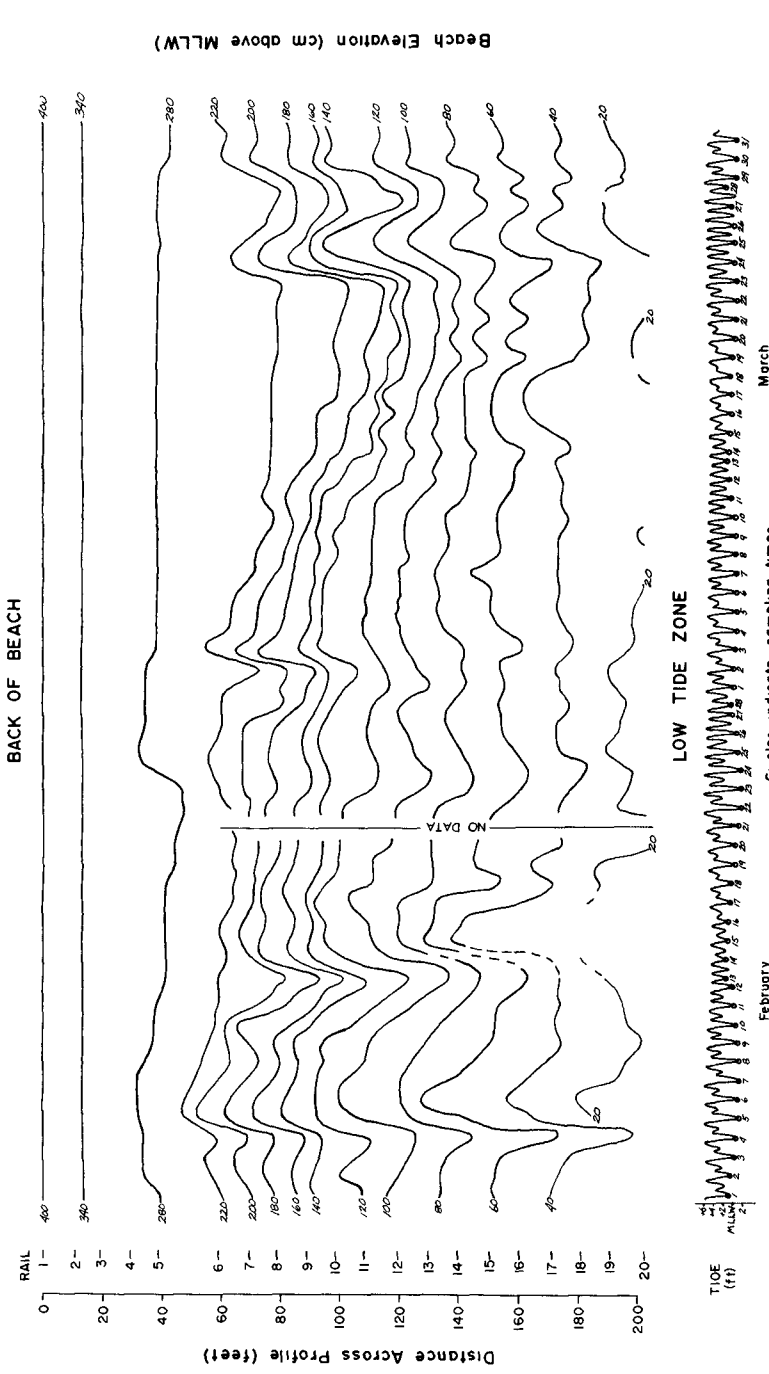

Figure 2 BEACH PROFILE TIME SERIES

for the first five days, using a pressure sensor located 600 feet directly seaward of the rails. The analog records were analyzed manually for significant height and dominant period. The waves observed during most of the study were low swell with periods in the range from 8 to 20 seconds. The wave height exceeded three feet on only one occasion, and most of the time was under one foot.

Deep-water wave height, which was used to calculate deep-water wave steepness and wave power, was computed from the recorded height in shoal water using linear wave theory. Application of the linear theory appears valid in view of the relatively narrow frequency spectrum evident in the swell most of the time.

Sand samples collected from the uppermost thin skin of the beach surface were also obtained daily across the profile along with the measurements of the sand level. Information on the textural properties of the sand are not presented in this paper but may be found in Harlett (1967). It is of interest to record here only that the phi mean grain diameter during the field study ranged between extreme values of 1.6 and 2.3 ϕ.

The field study was limited to the exposed intertidal portion of the beach above the lowest daily tide level because of the practical difficulty of making measurements in the surf zone. A wave-tank study by Rector (1954) and a field study by Eubanks (1968), who extended his profile measurements through the surf zone on this beach, show that the intertidal section of the profile behaves very differently from the section that lies seaward of the approximate low tide level and that it should be studied as a separate beach unit.

OBSERVED BEACH PROFILES

The daily profiles for the 60-day period are presented in Figure 2 in the form of a time series. The curves in the figure represent contours of beach elevation above MLLW. The contour interval is 20 cm except near the rear of the beach where it is 60 cm. Seaward movement of the contours with time represents accretion and shoreward movement denotes erosion. Spacing of the contours is inversely proportional to the beach slope. For reference to the tides, the elevations of the principal tidal datum planes are: MLLW = 0.0 cm, MSL = 83 cm, and MHHW = 159 cm.

Perhaps the most obvious feature to strike the eye in this figure is the constant change that occurs in the profile. During the two-month period the change in sand level from one day to the next amounted to 6 cm or more somewhere on the profile. This was the case even during extended periods when the incident wave heights recorded did not exceed 0.5 feet

(10-13 February, and 5-10, 12-23, 26-28 March). The rear portion of the beach where the contours remain stationary with time was not reached by waves during the study.

To the observer walking on this beach, the profile on most days is quite smooth to the eye. Examination of the figure shows, however, that the beach does not usually erode or accrete in a simple way. At times the entire profile in the intertidal zone changed fairly uniformly, particularly when the change was large (as from 4 to 5 February), but most of the time the change tended to be localized along the profile. On several occasions there were as many as five separate zones of minor cut and fill across the profile.

Changes in the profile are by no means random, however, as evidenced by the patterns of cut and fill that may be seen. Focusing attention on the five prominant sequences of cut and fill, it may be noted that erosion rates were ordinarily greater than accretion rates. The extreme values measured were 61 cm and 44 cm per 24.8 hours, respectively. On the other hand, significant cutting usually lasted only one day and never more than two, whereas accretion ordinarily occurred more or less continuously over a series of days. These prominant cycles of erosion and accretion were found to occur in response to the arrival of prominant wave trains propagated from individual wind areas. Another feature of interest, which was observed in an earlier field study of this beach (Rohrbough, Koehr, and Thompson, 1964), is that cutting sometimes begins on the upper beach with fill on the lower beach (as from 23 to 24 March), but ordinarily within a day a reversal occurs and the upper beach accretes while the lower beach erodes.

It is evident that this beach reacts sensitively to the waves arriving upon it. It appears that the reaction is in the form of constant profile readjustments to continuously changing wave properties, which in turn are superimposed in an endless variety of combinations on the regularly changing tide levels.

PROFILE CHANGES RELATED TO WAVE PARAMETERS

In the belief that it should be possible, in view of the comparatively simple beach and wave conditions normally prevailing on Del Monte Beach, to quantitatively relate the observed daily profile changes to the incident waves, a systematic effort was made to find representative parameters that incorporate time changes in the beach and the waves and to combine these successfully.

Two waves parameters of several that were investigated proved to show a good correlation with the profile changes, namely deep-water wave

steepness, γ, and wave power, P. The selection of steepness as a parameter is of interest particularly because of its demonstrated relationship to various wave characteristics such as wave mass transport, breaker height, breaker type, and wave runup. Wave power was adopted as a parameter upon the suggestion of D. L. Inman in the discussion of this paper following its presentation at the London conference. With respect to beach profile changes and the offshore-onshore sand transport that is implied, wave power has obvious dynamic significance whereas wave steepness does not. Steepness on the other hand conveys a sense of wave age which power does not.

It is of interest to observe that both of these parameters incorporate the two fundamental wave properties, height and period, and that steepness tends to stress the influence of wave period ($\gamma \propto HT^{-2}$) whereas power stresses wave height ($P \propto H^2T$). It may be noted that neither parameter has a discrete value for every H-T combination since a range of H-T pairs can yield the same value. Finally, it will be recognized that wave steepness has a definite upper limiting value which is determined by wave stability whereas the value of wave power has no such upper limit.

The relationship found between beach changes and wave steepness will be considered first.

Wave Steepness

The relationship to be presented between beach parameters and wave steepness was arrived at on the basis of assumptions derived from the results of wave-tank studies conducted by others and from subjective examination of the field data collected in this study. These assumptions are (a) that real ocean waves (wave spectra) having a specific set of properties would produce a characteristic equilibrium profile on this beach if the waves were to remain constant with time (note the laboratory studies by Watts, 1954), (b) that this beach tends constantly to readjust its profile so as always to approach the equilibrium profile associated with the wave conditions prevailing at the moment, and (c) that the response of the profile to changing wave conditions is sufficiently rapid that the profile assumes the hypothetical equilibrium profile at all times to a first approximation.

It was concluded from these assumptions that if, at a given point on the beach, the sand elevation at a given time is higher than the equilibrium elevation associated with the wave conditions prevailing during the

interval immediately following, the beach should cut in order to approach the equilibrium profile for those waves. Conversely, if the elevation is initially too low the beach should fill. From this reasoning an empirical relationship was established between the following beach and wave parameters.

h_i the initial beach elevation at a given point on the profile (elevation above MLLW at the beginning of a 24.8-hour sampling interval)

Δh change in the beach elevation over the 24.8-hour sampling interval at that point

$\overline{H'_o/L_o}$ the average unrefracted deep-water wave steepness during the 24.8-hour sampling interval ($\overline{\gamma_o}$).

H'_o is the deep-water significant wave height computed from the recorded waves and uncorrected for refraction, and L_o is the deep-water wave length. Both quantities were calculated from linear wave theory using the observed dominant period. The average steepness for a given sampling interval was obtained by averaging the values of H'_o/L_o at the two consecutive observation times. This method of integrating the wave characteristics over a sampling interval is obviously gross but yielded good results. No wave data were used for periods of very low waves because of difficulty of analyzing the records.

The relationship established between the selected beach and wave parameters is illustrated in Figure 3 for the arbitrarily chosen location on the beach occupied by Rail No. 10, which is near the mid-point of the daily swash zone. In the graph the negative the positive values of Δh represent cut and fill in centimeters. The curve of $\Delta h = 0$ cm is of particular interest because it can be considered to represent the equilibrium elevation of the beach over the range of wave steepnesses shown. Application of the graph is best indicated by means of an example. If the sand level at Rail 10 is observed to be 160 cm above MLLW and the wave steepness averaged over the following 24.8-hour interval is 0.001, then a drop in the sand level of 20 cm may be expected over the interval.

Figure 3 indicates that when wave properties are averaged over a suitable time interval, the beach can be shown to cut with an increase in wave steepness and to build with a decrease. The figure thus confirms empirically the often made statement to this effect. The figure also reveals that very high sand levels are produced only by swell of very low steepness, and suggests that the lowest sand level possible is that given by the equilibrium elevation associated with storm waves of limiting steepness.

Graphs similar to that in Figure 3 have been constructed for other rail locations, and the information contained in each for the equilibrium condition has been extracted and combined to produce Figure 4 in which is shown a family of equilibrium profiles for the range of wave steepnesses observed. The equilibrium profiles are seen to have a gentle upward curvature. The profile is not completed on the upper part of the beach between Rails 1 and 7 because of the sparsity of beach change observations due to less frequent wetting.

Wave Power

The wave power arriving at the surf zone per unit length of beach for the case of simple waves having a zero breaker angle can be shown to be

$$P = \frac{\rho g}{16} \frac{g}{2\pi} (H_o')^2 T \qquad (1)$$

where ρ is the density of sea water, g is the acceleration of gravity, and H_o' and T are as defined above. As pointed out earlier refraction is such that waves arrive on the beach most of the time with little or no wave angle.

Wave power, when computed using this equation and averaged over the 24.8-hour observation interval in the same manner as the deep-water wave steepness, was found to display a similar relationship to the beach parameters as that shown in Figure 3. Similar conclusions regarding cut and fill as related to wave-power can also be drawn. The wave-power relationship is presented in Figure 5. Wave-power graphs for other rail locations along the profile have not been constructed.

Relationship Between Wave Steepness and Wave Power

An empirical relationship between the average values of wave steepness and power was obtained for the condition of equilibrium at Rail 10 by combining data from Figures 3 and 5, and is shown in Figure 6.

The trend of the beach elevation values (h) on the curve indicates that the maximum height to which waves can build the beach at this location is limited by a building rate that approaches zero as the wave power approaches zero, and also by the length of time over which waves of very low steepness can prevail. Thus, the highest beach levels are evidently constructed during long intervals in which only very low swell arrive on the beach. This explains the general observation that the longest intervals of low swell on this and other beaches on the Pacific Coast of the United States normally occur in the summer and that

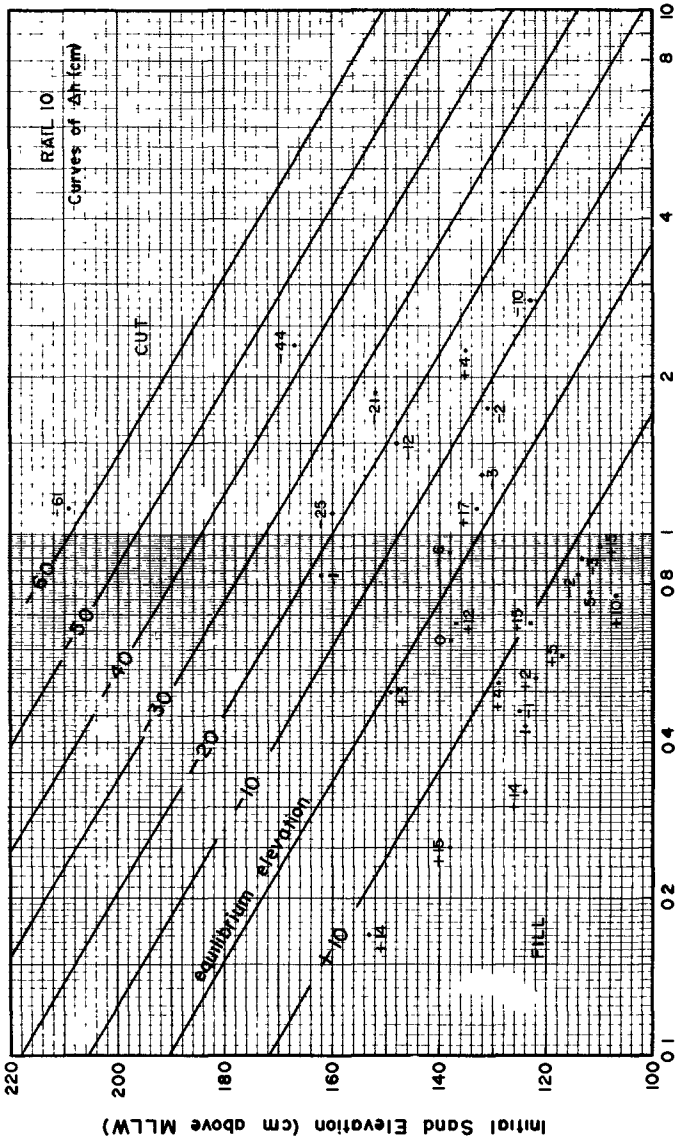

Figure 3: SAND LEVEL CHANGE RELATED TO WAVE STEEPNESS

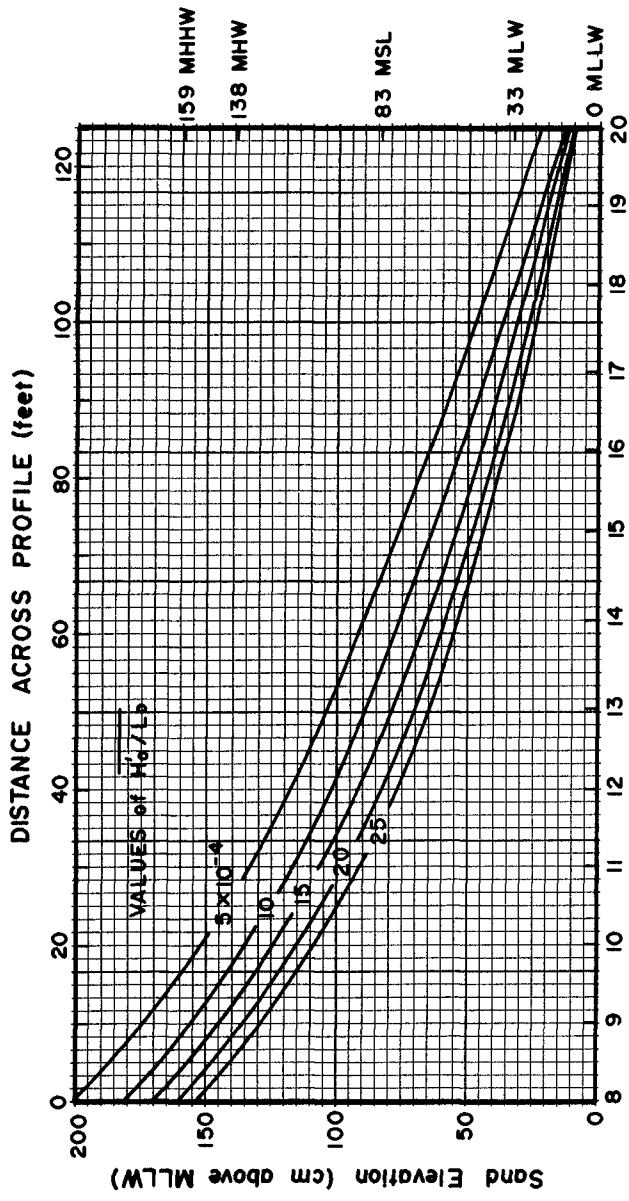

Figure 4: EQUILIBRIUM PROFILES FOR WAVE STEEPNESSES OBSERVED

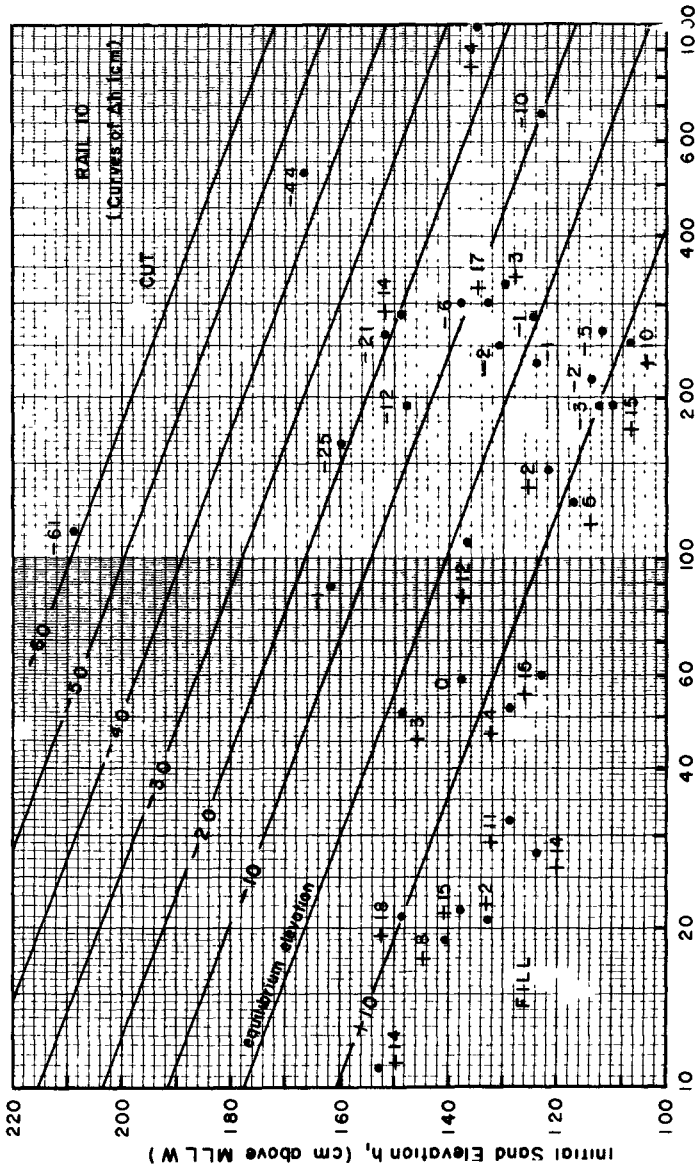

FIGURE 5: SAND LEVEL CHANGE RELATED TO WALL POWER

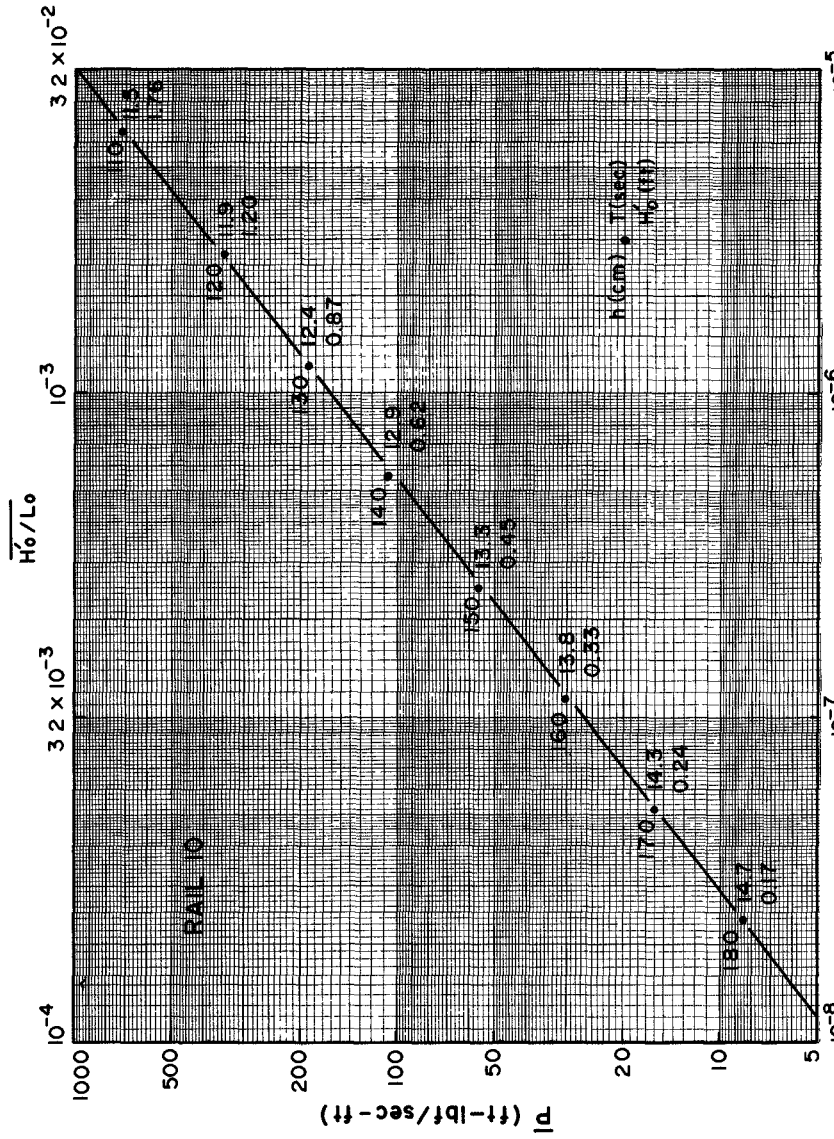

Figure 6: WAVE STEEPNESS vs WAVE POWER for the EQUILIBRIUM CONDITION

it is in this season that the beach usually acquires the most sand. The period of prolonged beach building that may be seen in Figure 2 in the month of March coincided with an interval of very low swell generally under 1/2 foot in height.

The lowest beach levels, on the other hand, are seen to occur with large waves of maximum steepness. The minimum elevation to which waves can be expected to lower the beach is clearly determined by the wave power available since exponentially increasing amounts of power are required according to Figure 6 to produce the incremental lowerings of the profile shown by the beach elevation values on the curve. The minimum elevation is also determined by the length of time that waves of exceptional height can persist.

An independent relationship between wave power and wave steepness can be derived mathematically through multiplication of Equation (1) by $(L_o'/L_o)^2$, where $L_o = \frac{g}{2\pi} T^2$:

$$P = \frac{\rho g}{16} \left(\frac{g}{2\pi}\right)^3 \left[\frac{H_o'}{L_o}\right]^2 T^5 = 537 \left[\frac{H_o'}{L_o}\right]^2 T^5 \left(\frac{\text{ft-lbf}}{\text{sec-ft}}\right) \quad (2)$$

If T is solved for in this equation by inserting the associated values of $\overline{P}$ and $\overline{H_o'/L_o}$ from Figure 6, values of the period are obtained which are plotted in the figure. The values of H_o' shown in the figure were obtained by introducing these T values and the associated values of $\overline{P}$ into Equation (1). The pairs of H_o' - T values presented in the figure evidently represent average wave conditions that would maintain the beach in equilibrium at Rail 10 for different values of average wave steepness and power.

The form of Equation (2) indicates that the empirically derived curve in Figure 6 is not a straight line but obeys the 5th power of T. If the curve is treated as a straight line, however, and is equated with Equation (2) a value of T = 11.8 sec is found. The reasonableness of this value, which is characteristic of the wave periods measured during this study, indicates unexpectedly good agreement between the empirical and theoretical relationships between $\overline{H_o'/L_o}$ and $\overline{P}$.

Equilibrium Condition for Limiting Wave Steepness

The condition of limiting wave steepness at which the dominant waves become unstable in the real ocean is assumed here to occur when $H_o'/L_o = 0.10$. For this steepness value the lowest equilibrium elevation

of the beach that can be expected at Rail 10, and the extreme wave conditions required to produce this level, are estimated as follows:

$\overline{P} = 2.4 \times 10^5$ ft-lbf/sec-ft
$T = 8.5$ sec
$H_o' = 37.2$ feet
$h = 15$ cm above MLLW

$\overline{P}$ was derived from Figure 6 by extrapolation to the limiting steepness, T was obtained from Equation (2) using the limiting values of $\overline{P}$ and $\overline{H_o'/L_o}$, and H_o' was obtained from Equation (1) using $\overline{P}$ and T. The beach elevation obtained by extrapolation of Figures 3 and 5 to the limiting values of power and steepness were 16.7 cm and 13.5 cm, respectively, giving an average of 15 cm.

The value obtained for the deep-water wave height is particularly interesting because it is identical to that hindcasted by Bixby (1962) for the most severe storm occurring over a 50-year period off Monterey. A wind speed of 40 knots or greater blowing for a sufficient length of time would be needed to produce waves of this height. In order to lower the beach level approximately to the equilibrium elevation would require that these or equivalent wave conditions have a duration on the order of two days or more according to considerations presented in the next section, which appears to be a possible but exceedingly rare event off Monterey.

TIME TO REACH EQUILIBRIUM

The rate at which the beach at Rail 10 would approach equilibrium if the wave conditions remained constant with time can be derived from Figure 3. Examination of this figure shows that the beach profile, if initially out of adjustment, does not reach the equilibrium state in one observation interval but approaches it rapidly during the first interval and increasingly more slowly during successive intervals.

If, for example, the sand level was measured at Rail 10 and found to be 210 cm and the wave steepness during the succeeding 24.8 hours averaged 0.001, then the beach should cut 60 cm during the interval and come to a new level of 150 cm. If the same wave conditions prevailed the beach should cut 12 cm, 3 cm, 1cm, and 1/2 cm during successive observation intervals and finally stabilize at an elevation of 133 cm, or 77 cm below the initial elevation. Thus, 78% of the total cut would be accomplished during the first interval. By the end of the second, third, and fourth intervals the cut would amount to 91%, 97%, and 99% of the total. Of course ocean waves do not remain constant over such lengths of time except in limited geographical areas.

It may be noted from Figure 3 that the rate of adjustment of the sand level for a given value of Δh is independent of the wave steepness. Thus if $\Delta h = -60$ cm the graph indicates that the sand level should fall 78% of the total drop expected for equilibrium regardless of the wave steepness during the interval.

The time required for the beach to approach equilibrium under uniform conditions at Rail 10 may be seen in Figure 7. The figure, constructed from the information in Figure 3, shows the rate of change of the sand level toward the equilibrium elevation for different initial relative beach elevations at Rail 10. It indicates, for example, that if the beach elevation at time zero is 40 cm above the equilibrium level then the elevation expected after 10 hours would be 21 cm above the equilibrium elevation. It also shows that the beach should approach equilibrium 50% of the way after 11 hours, 75% after 25 hours, and 90% after 42 hours. The percentage rates of cutting may be seen to be significantly more rapid than the rates of upbuilding. It is interesting to note here that in wave tank studies Watts (1954) found an essentially stable profile to be formed after 40 hours of test time.

These high response rates, when coupled with the observation that individual swell trains arriving during this study had durations of commonly 2 to 4 days, indicate that every train of swell should induce a beach-change sequence of the same duration. Whether or not this was the case is difficult to tell because of the coarseness of the sampling interval used.

The rate at which the beach approaches equilibrium at other points along the profile has not been determined.

BEACH PROFILE HINDCAST

Figure 3 can be used as a profile forecasting graph by virture of the fact that if the sand elevation at Rail 10 is measured and the wave conditions during the following 24.8-hour interval are forecasted or observed, the expected change in sand level is obtained.

Accordingly, a test was performed in which the sand elevation was hindcasted daily from this graph using the beach and wave data collected during the 60-day study. In this test each day's forecast was based on the observed sand level of the day before. The hindcasted beach heights are shown in Figure 8 along with the observed heights. It may be seen that the hindcast is best when significant cut occurs and poorest when the profile is near equilibrium or the beach is building. The agreement between the hindcasted and the observed beach elevation, of course, gives a measure of

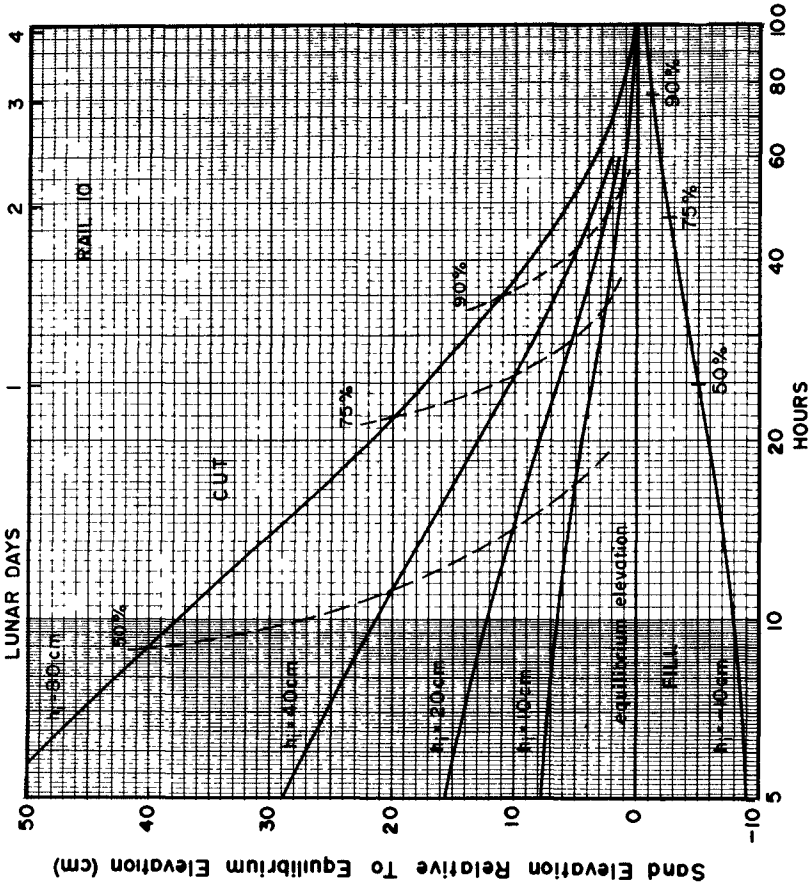

Figure 7: TIME TO REACH EQUILIBRIUM

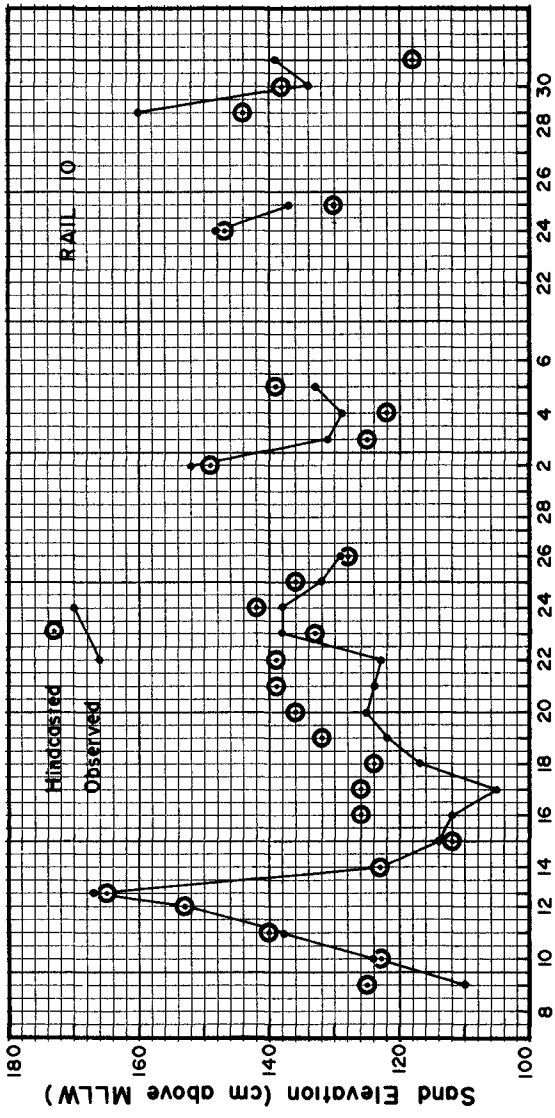

Figure 8: SAND LEVEL HINDCAST

the closeness of fit of the curves in Figure 3 to the basic data. The agreement is in general reasonably good.

A second test was also performed in which, beginning with an initial beach elevation on a given day, each day's sand level was hindcasted from the previous day's hindcasted sand level. This running hindcast, the results of which are not shown, proved somewhat less satisfactory than the first forecast. It was found that if a fictitious sand level falling within the working area of the graph is used as an initial value and each successive hindcast is based on the previous day's hindcast, the sand level immediately begins to approach the hindcast produced by the second test and after several days becomes identical with it.

It is evident that the accuracy of a beach forecast depends critically upon the accuracy of the wave information used. Fortunately, because of the rapid response of the beach profile to changing wave conditions, a poor forecast of the sand level caused by an error in the wave data would not be propagated long and would largely die out after one day.

DISCUSSION

The wave records were analyzed at intervals of 1/2 to 3 hours and therefore provided essentially continuous information on height and period with time. These data reveal a series of wave trains which arrived one after another and sometimes simultaneously. In view of the short-term variations exhibited, the use of wave steepness values at a one day interval gave unexpectedly good results. Inspection of the wave data shows, however, that a once daily sample represents the trend of the wave properties reasonably well most of the time. It appears that the sampling interval for both wave and beach data should not be much longer than one day, otherwise resolution of the information becomes poor rapidly.

The equilibrium profiles shown in Figure 4 were developed for swell having heights of mainly one foot or less. Consideration of the shape of the profiles leads to the conclusion that waves of the same steepness but different height must produce equilibrium profiles of different absolute configuration. In this regard Saville (1957) concluded from laboratory experiments that the deformation of a beach under wave attack is as much a function of absolute wave size as of wave steepness.

The present study is also limited to swell having a moderate to narrow frequency range, and the response of the beach to waves having wide frequency spectra has not been examined. It should be remarked, in this regard, that wave tank experiments described by Watts (1954) revealed no significant difference in the equilibrium profiles produced by waves of

variable period compared with constant period, except for a certain sand size used in the tests.

The equilibrium profiles of Figure 4 integrate the effects of the wave conditions that prevailed during the 60-day field study and are therefore composite profiles. The profiles are also presented in the figure as being rigidly fixed in space relative to the rails. It is probable, however that they migrate landward and seaward with the seasons and through the years due to net changes in the volume of sand on the beach with time. Additional field measurements will be required to determine how the shape and position of equilibrium profiles vary over a winder range of wave and beach conditions than was encountered in this short field study.

The daily range of the tide was several times larger than the wave height and runup during most of the study. Accordingly, it appears that the general shape of the profiles in Figure 4 significantly reflects the local tidal characteristics. On the other hand, the day-to-day changes observed in the profile, as stated earlier, are presumed to show little tidal influence because the profile measurements were made in phase with the tides. For a pertinent laboratory study dealing with the effect of tide on the formation of equilibrium profiles the reader is referred to Watts and Dearduff (1954)

No attention has been directed here to possible effects on the profile of variations in the textural parameters of the sand, but it appears from the obvious reaction of the profile to the incident waves that grain-size variations have a very minor influence by comparison.

ACKNOWLEDGMENT

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