SWASH—GROUNDWATER—BEACH PROFILE INTERACTIONS

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ABSTRACT

Because features of an uninterrupted swash appear primarily dependent on only breaker height and beach slope, duration of an undisturbed swash can and often will exceed breaker period. When this situation occurs, collisions between successive swashes expend energy on the lower beach face thereby curtailing or inhibiting some uprushes. Magnitude of wave energy reflection and hence generation of leaky mode, nearshore standing waves appears in part to be conditional on the intensity of swash interaction. As a result, collisions between swashes can have a significant influence on nearshore and beach processes.

Swash and standing waves cause corresponding oscillations of the beach water table in the vicinity of the beach face by transmission mass flux through the saturated portion of the beach. As a result of low pass filter characteristics of the beach matrix, groundwater movement induced by lower frequency standing waves is the more significant of these two discrete frequency forcing functions. It is possible for these water table fluctuations to periodically alter the upper beach face environment so that sequential deposition and erosion result.

High frequency oscillations of beach elevation (on the order of 40 seconds or greater) have been measured on the upper and mid region of the beach face. These regular changes in sand level are produced by action of multiple swashes and appear to be the result of sequential deposition of material moved upslope as suspended load and subsequent erosion as this material moves downslope as bedload.

INTRODUCTION

Studies of the subaerial beach have had a pattern of examining sequentially higher frequency phenomena. Each level of temporal resolution (e.g. annual response, seasonal response, . . . , tidal cycle response) has supplied some further identification of relationships pertinent to the system. These studies, however, have not generally supplied information regarding the fundamental mechanics which govern this particular environment. Consequently, at times it may be possible to anticipate net response of the system (Harrison, 1969), but it has not been possible to state specifically why this response occurred. Fortunately, with the recent use of high speed photography (Miller, 1968; Nelson and Miller, 1974) and continuously recording electronic sensors (Machemehl and Herbich, 1970; Waddell, 1973), it is now possible to isolate some salient and fundamental characteristics and interactions of this dynamic environment.

One prior study which showed considerable insight into this environment was by Emery and Gale (1951) who made use of visual and photographic observations to infer qualitative interrelationships between incident waves, swash, and ground water. They described (1) small changes in beach water table induced by individual swashes, and (2) evolution of across beach swash profiles during the uprush-backwash cycle. Emery and Gale also noted that swash moved up the beach with a small, steep-faced front, and, that during backwash, it retreated in such a way that the swash mass thinned without significant changes in location of the leading edge until most of the water had moved down the beach face. In describing the combined shorebreak-uprush sequence Emery and Gale observed that smaller, high frequency breakers disappeared prior to moving up the beach face as swash. Because of this, they suggested that the beach acts as a filter which permits passage of only larger or longer waves. They also observed that the period of swash was always larger than that of input waves just seaward of the shorebreak. It was also noted that with gentler beach slopes there was a greater difference between periods of swashes and input waves.

Specific attempts have been made to establish the influence of groundwater on beach changes. Emery and Foster (1948) found that during ebbing tide, the water table near the beach face sloped seaward while during flooding tide the water table sloped landward. They indicate that response of the beach groundwater to tide was inversely proportional to the distance from the beach face. They reasoned that "vertical permeability (of the beach) must be lower than horizontal permeability because beaches contain thin alternating coarser and finer layers" (Emery and Foster, 1948, p. 648). Horizontal mass flux was associated with movement of the tidal wave through the beach matrix behind the swash slope.

Grant (1948) recognized that height of the groundwater table was related to whether the beach was prograding or eroding. The model which Grant presents for this relationship indicates that a dry beach facilitates deposition on the foreshore by reducing backwash flow velocity and thus prolonging existence of laminar flow. On a saturated beach, backwash is supplemented by outflow through the zone of effluent which makes backwash turbulent earlier in the cycle. Outflow also dilates sand grains in this region, which further encourages erosion.

Longuet-Higgins and Parkin (1962, p. 196) found that when an impermeable roofing-felt was inserted in the beach about 3 inches below the sand surface, "the waves quickly eroded the shingle overlying the roofing-felt but disturbed only to a lesser extent the shingle on either side." These investigators attributed these results "to the fact that over the roofing-felt, the backwash could not penetrate to a depth of more than three inches, and so, the backwash there was relatively undiminished."

Duncan (1964) investigated combined influences of semidiurnal tidal and ground water fluctuations on deposition and erosion in the swash zone. During flooding tide, sand that was deposited on the beach slope above the water table was taken from the region below the water table. This deposition was associated with loss of swash mass due to infiltration and consequent decrease in seaward acting momentum. As infiltration continued, the groundwater table elevated, thus causing the lower boundary of the zone of infiltration to migrate landward. There was also evidence of an associated outflow lower on the beach face. This outflow dilated sand grains to encourage further erosion on that portion of the slope. On the other hand, during falling tide, part of the zone of infiltration was removed from swash influence, and consequently little mass was lost to infiltration. Backwash was, in fact, enhanced by outflow of ground water causing a pad of material to move downslope until the profile approximated the initial low tide configuration.

Recently, Pollack and Hummon (1971) identified four beach zones based on both degree of saturation and on spatial and temporal changes of water content. The zones in order of occurrence down the beach face are (1) zone of dry sand, (2) zone of retention, (3) zone of resurgence, and (4) zone of saturation.

The zone of dry sand was influenced by swash action only during occasional tidal cycles. The zone of retention was influenced by swash for some period during all tides; therefore, sand in this region was never completely dry. During time of exposure, water content was controlled by gravity. This zone was porous and experienced a great deal of inflow and outflow. The zone of resurgence was characterized by intensive mass flux throughout the tidal cycle. This zone expands and contracts depending on the amount of circulation and the discrepancy between nearshore water level and the water table of the beach. The zone of saturation remained saturated under all conditions of tide and swash.

Common to these studies of beach ground water are two critical shortcomings: (1) the data were collected neither at sufficiently high resolution nor at sufficiently high frequency to allow for an insight into the actual physical mechanisms and (2) because the pertinent first-order parameters were not measured simultaneously, the real-time interaction between input waves, swash, groundwater, and beach changes could not be established. Furthermore, results from these studies were mostly qualitative.

SWASH AND INPUT WAVES

One of the fundamental interrelations of a beach system occurs between swash and groundwater; however, to understand this coupling, it is necessary to understand and characterize the natural swash process.

A normal isolated shorebreaking wave can reasonably be approximated by a bore configuration (LeMehaute, 1965). As a consequence of this similarity, work of Shen and Meyer (1962) provides a useful description of the mechanism of wave break at a shoreline, followed by the uprush and backwash of swash. Their analytical treatment, which evaluates the nonlinear long wave equations governed by conditions appropriate to a beach environment, produces predictions of some characteristics of an undisturbed swash mass as it moves up the active beach face.

Immediately prior to shorebreak, i.e. which is likened to initiation of bore collapse, the front of the wave is vertical. Following this initial condition there is a sequential disintegration of the bore configuration as the leading edge of swash moves up the beach face (Fig. 1). As the front edge moves upslope, the angle between the swash surface and the sand surface decreases. This has been described as the progressive thinning of the swash. Eventually, the leading edge reaches a maximum run-up and begins backwash. During

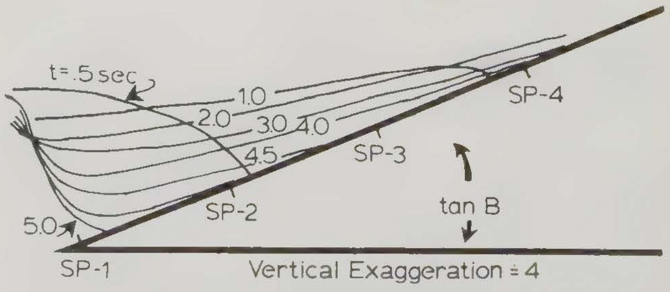

FIG. 1.—Swash geometry. Initial steep faced front (bore configuration) deteriorates by progressive thinning throughout the entire swash cycle. As a result, uprush and backwash have distinctly different flows.

this backswash phase, a swash mass continues to thin as the leading edge of the water mass moves down the beach face. It is important to realize that backwash flow is definitely not the reverse of uprush. There are distinctly different internal velocity fields during these two different phases of a swash cycle.

Observed and predicted histories of swash depth at several across beach locations are given in Figures 2 and 3. There is fair qualitative agreement between those predicted by Shen and Meyers (1962) as shown in Figure 2 and those observed by Waddell (1973) and shown in Figure 3. In Figure 3 the secondary depth maximum at approximately $T = 3$ secs, could be a secondary "retrogressive" bore as predicted by Shen and Meyer. This bore originates at midslope and propagates downslope while facing upslope.

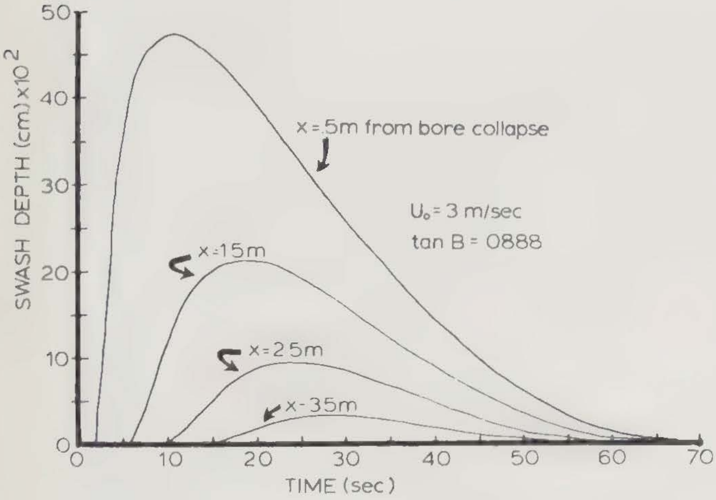

FIG. 2.—Predicted history of undisturbed swash depth. An initial rapid rise in water depth is followed by a more gradual decrease. Note that duration of inundation and maximum and average water depth decrease upslope.

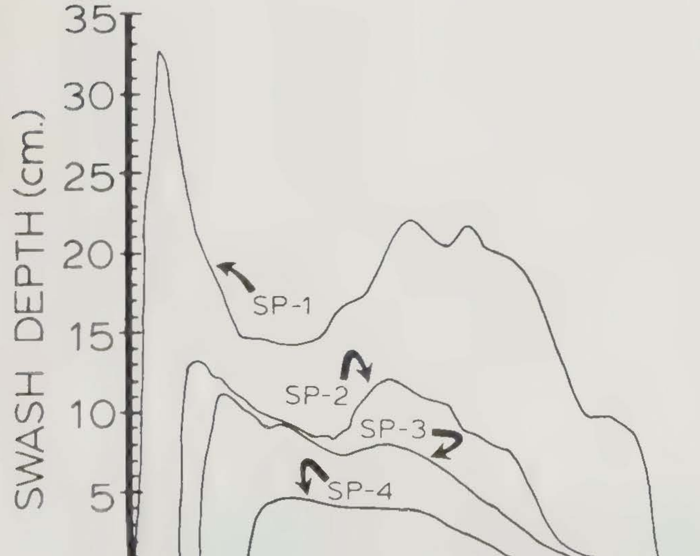

FIG. 3.—Observed history of swash depth. Qualitiative similarities with prediction are good. The secondary depth maximum following the initial rise to maximum water depth may be associated with a retrogressive bore. It is initiated at midslope and sequential moves downslope.

As given by Shen and Meyer (1962) and supported by my unpublished laboratory data, the path of the leading edge of an undisturbed swash is parabolic and approximated by

$$Xs(t) = \mu_0 t - (1/2g \tan\beta)\, t^2 \tag{1}$$

where $Xs(t)$ = location of leading edge relative to initial shoreline, $x = 0$; μ_0 = initial horizontal velocity of leading edge; g = acceleration due to gravity, $\tan\beta$ = slope of the swash slope, t = time. Note that the path of the leading edge is uniquely and completely determined by the initial energy conditions and the beach face slope. It should be noted that this development does not consider frictional effects and in many situations friction or apparent friction can be significant (Miller, 1968; Meyer, 1970).

As a result of the above equation (1) and an approximation of μ_0 in terms of breaker height, it is possible to determine swash duration, Ts, as a function of breaker height, Hb, for various beach slopes (Fig. 4),

$$Ts = \frac{6\, Hb^{1/2}}{g^{1/2} \tan\beta.} \tag{2}$$

In the evaluation of the governing equations which result in equation (2), it was assumed that only one swash mass acted on the beach face at any given time. Thus Figure 4 and equation (2) are only valid when collisions between successive swashes are not occurring, i.e., when the period of incoming waves is less than the duration of swash. Examination of Figure 4 indicates that for the range of beach slopes normally found, swash duration exceeds input wave period, and hence, interaction between swashes occurs. This is true even for many laboratory generated (monochromatic) wave fields. Consequently, any examination of processes or mechanisms active on a subaerial beach should incorporate a consideration of collisions between swashes (Kemp, 1960; Kemp and Plinston, 1968).

For a natural wave field which has a joint distribution of wave height and period, one of the most obvious consequences of interaction between swashes is that the upslope movement of selected swashes is curtailed or completely inhibited. This results in a distinctly higher energy

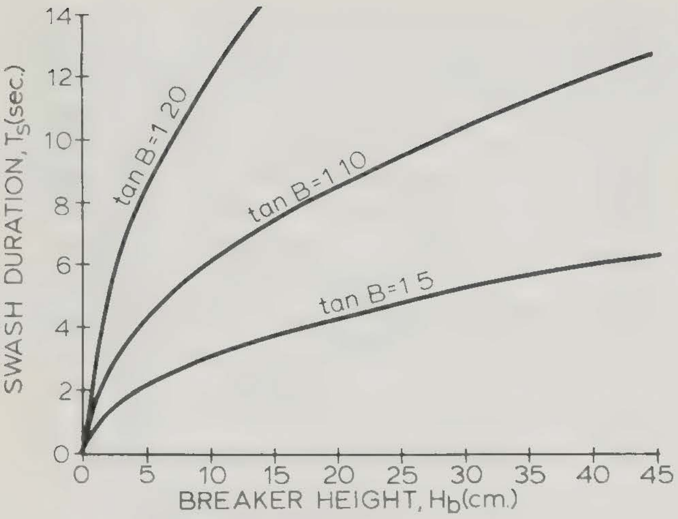

FIG. 4.—Graph of Equation 2 for various beach slopes. Examination indicates that only waves having long periods combined with low amplitudes can avoid producing collisions between swash masses.

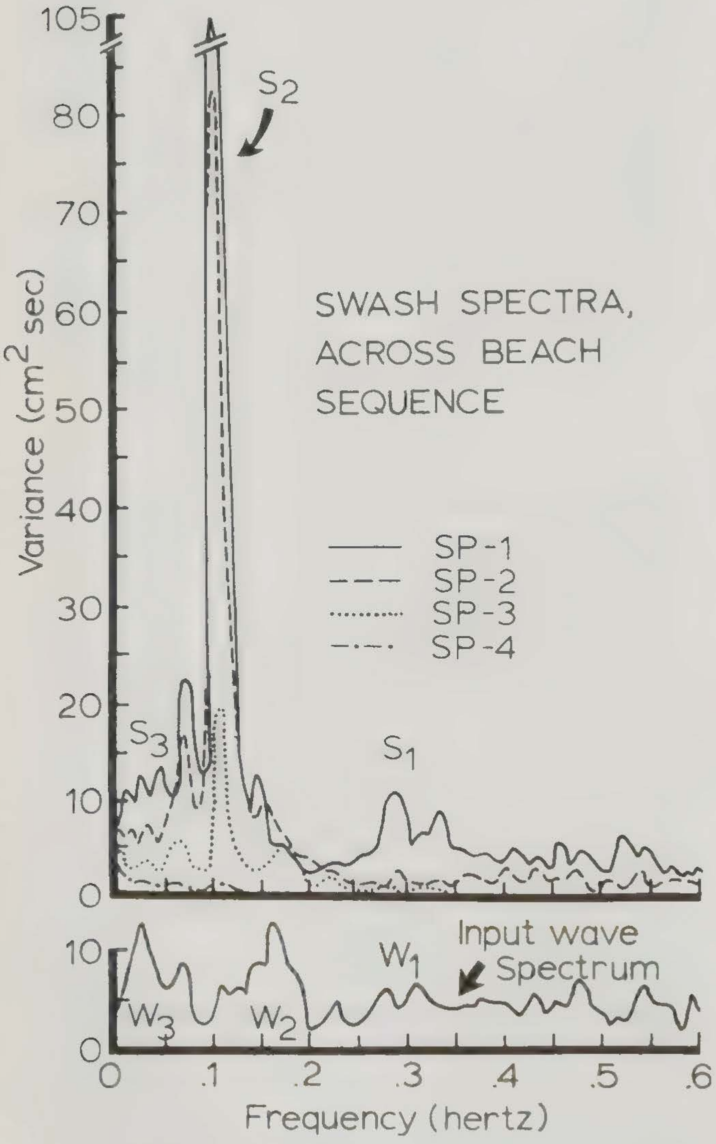

FIG. 5.—Variance spectra for input waves and associated swash. A low frequency shift of variance occurs across the shorebreak as the result of collisions between swashes.

environment at the base of the slope in addition to a distinct low frequency shift between average input wave frequency and the frequency associated with the average period between successive swashes. In terms of a systems function acting on a random input, shorebreak and interaction do not produce a high frequency attenuation function (linear lowpass filter) as suggested by Emery and Gale (1951) but, in fact, produce a nonlinear transfer of energy to lower frequencies. This becomes more obvious when examining the variance spectra for input waves and swash (Fig. 5). There are virtually no components of the incoming wave field having periods corresponding to that of the period between successive swashes.

Irrebarren and Nogales (1949) determined that significant incoming wave energy was reflected from a shoreline where the beach slope was greater than

$$\tan\beta = \frac{5.65\, Hb^{1/2}}{g^{1/2}\, T_{\text{input}}} \tag{3}$$

If the beach slope is less than that given by equation (3) a much reduced reflection of wave energy occurs. Because imperfect reflection of input wave energy can produce partial standing waves in the nearshore (Ippen, 1966), this critical beach slope, in fact, segregates those conditions producing significant nearshore standing waves from those which produce insignificant standing waves.

It was suggested by Irrebarren and Nogales (1949) that separation of these different reflection environments results from variation in the intensity of shorebreak. Similarities between equations (2) and (3) suggest that significant shorebreak coincides with initiation of interaction. Apparently, occurrence and intensity of swash-to-swash interaction can influence the generation of nearshore standing waves (Waddell, 1973). As will be shown, these nearshore standing waves can have a significant effect on the water table in the beach deposit.

GROUNDWATER

Fluctuations of the water table in the vicinity of the beach face have been identified over a wide range of frequencies. Tidal frequency response of groundwater has received the most intense discussion. Recently, several investigators (Dominck and others, 1971; Harrison and others, 1971) have developed one-dimensional computer simulations of the response of the water table in a beach matrix. These have been checked with field data and shown to be rather accurate. Waddell (1973) used continuously recording electronic sensors placed in a series of wells adjacent to

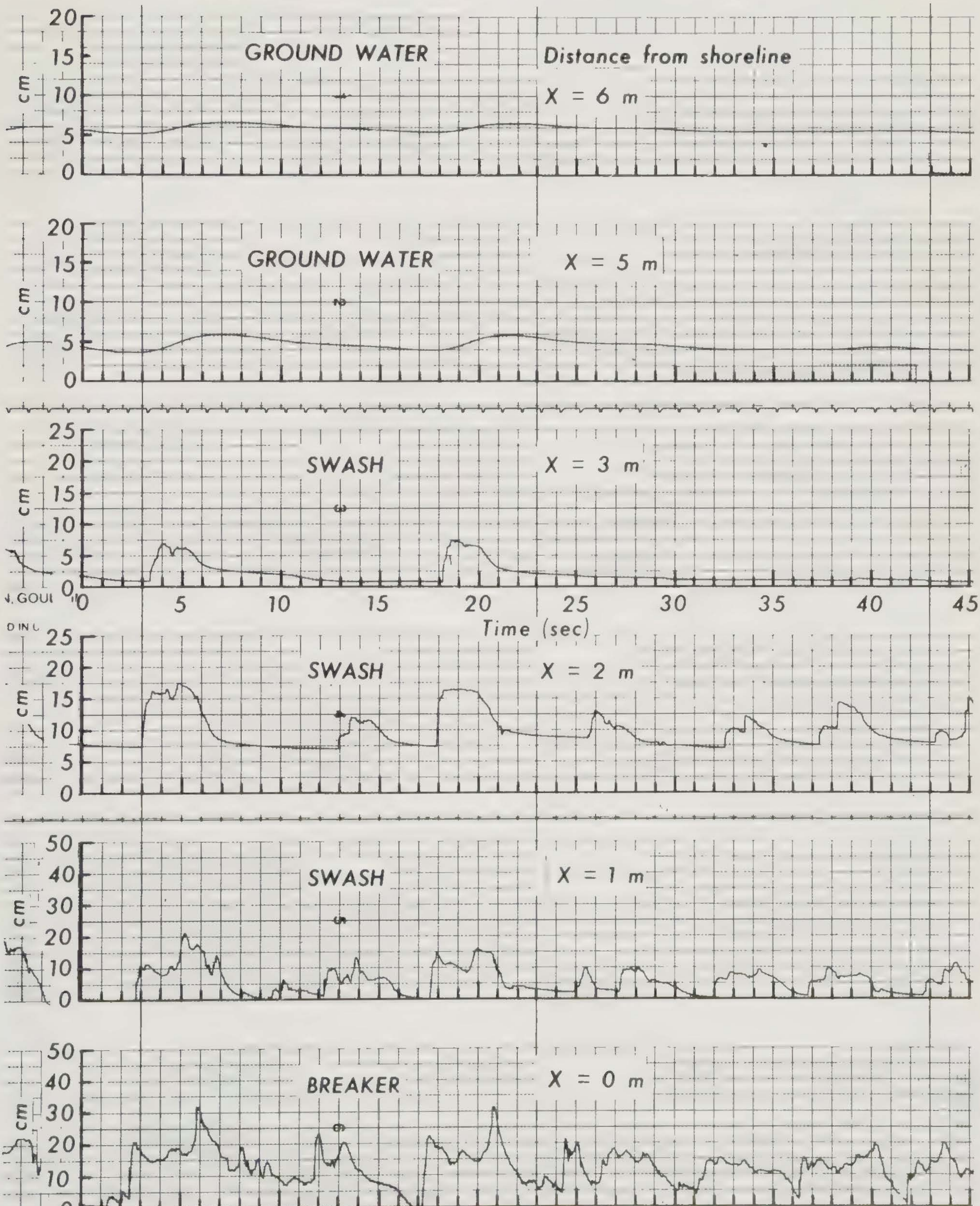

Fig. 6.—Examples of time series of water levels of breakers, swash and beach watertable. These data show groundwater responding to pressure from a swash while it is still at the base of the beachface.

the beach face in order to measure high frequency fluctuations of groundwater. These measurements support many of the statements of Emery and Gale (1951) regarding response of the water table to excitation by individual swashes.

Evidence of the response of a beach water table to individual swashes is seen in Figure 6 which shows simultaneous measurements of groundwater and swash depth. For these records, the water table intersects the beach face between swash probes #3 and #4 ($X = 2M$ and $X = 3M$) which were located two and three meters respectively upslope of the break point. At (Fig. 6) $t = 2.5$ sec, the leading edge of swash is at the base of the swash slope. At the same time, the water table in groundwater well #1 (*GW* #1) reaches a minimum and begins to increase. This increase continues until the swash is in the backwash phase.

While the leading edge of swash is downslope of the line of water table-beach-slope intersection, any increase in water table must be produced by mass flux through the saturated lower beach. After the leading edge reaches the water table, it is no longer possible to partition between water influx through the saturated beach face and infiltration into the nonsaturated beach face.

Variance spectra resulting from analysis of simultaneous time-series of nearshore water level, swash depth, and water table elevation provide further evidence of mass flux through the saturated beach surface (Fig. 7). There are two primary peaks in the input wave spectra: *W*2 which was associated with input swell, and *W*3 which was produced by a standing wave in the nearshore. The swash spectrum exhibits only one significant peak, *S*2, which is associated with the period between successive swashes. Note that the input wave spectrum has virtually no variance in the well defined frequency band of the swash peak. Also, the swash spectrum, obtained from measurements taken half way up the beach face (2 meters upslope from break point), contains virtually no variance at the frequencies which contain the nearshore standing waves. This suggests that these standing waves did not cause corresponding oscillations in the location of the swash zone. Instead, the influence of these standing waves was limited to the very lower portion of the beach face. If the influence of these longer period waves was limited to the base of the beach face yet was still able to induce water table oscillations, then it is apparent that this coupling and associated mass flux was transmitted through the saturated portion of the beach matrix.

Transmission of pressure through the beach matrix can be influenced by the sediment textures and fabric of the beach deposit. If there is a well defined coarse step deposit, then pressure could be transmitted more readily than in a homogeneous fine textured deposit. While this dependence on structure and texture can be important, the pattern of groundwater response is not totally dependent on it because such sequences of interaction between swash and groundwater have been observed in beaches having no apparent vertical structure and beaches having no well defined aquifers.

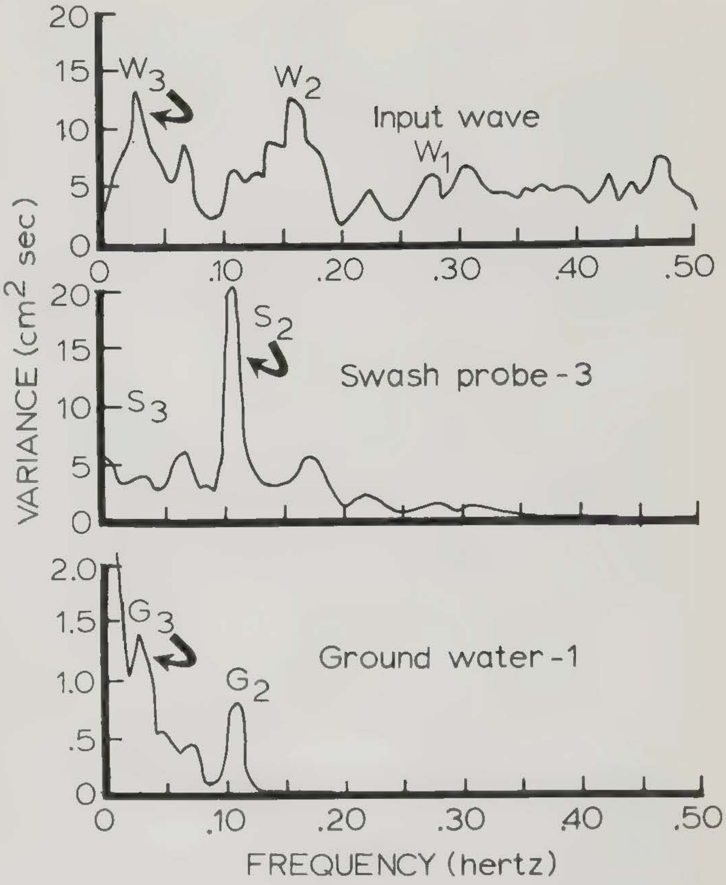

FIG. 7.—Spectra of input waves, swash and groundwater. Two peaks in groundwater spectrum correspond exactly to peak swash frequency ($f \cong 1$ hertz) and nearshore standing wave frequency ($f \cong 0.025$ hertz).

Examination of a transfer function between input wave spectrum and groundwater level spectrum shows that the beach matrix acts as a low pass filter (Fig. 8). In this particular example, despite input swell and standing waves having similar root mean square heights, influence of swell was completely attenuated at a location just landward of the swash slope (5 meters inland of the breakpoint) while standing waves could still produce significant water table fluctuations. Because groundwater oscillations attenuate with distance, the location of measurement of groundwater can influence the specific filter applied to the forcing function; however, all such frequency response functions should have general characteristics of a low pass filter which tends to accentuate longer period fluctuations.

In previously mentioned numerical modeling of

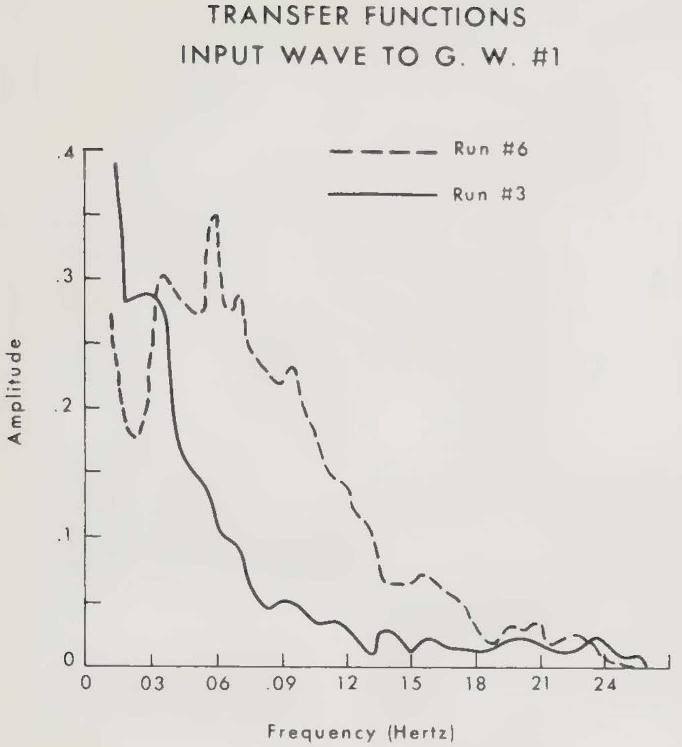

FIG. 8.—Representation of low pass filter characteristics of the beach matrix. During Run #6, the break point had migrated slightly further landward, thus the groundwater well was in closer proximity to the generating forces.

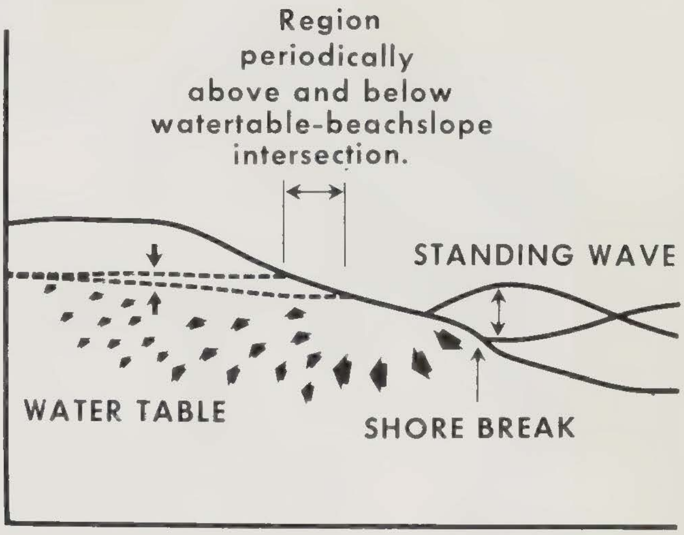

FIG. 9.—That portion of the upper half of a beach face which can be sequentially nonsaturated and saturated is illustrated.

tide induced water table movement, some discrepancies existed between predicted and observed elevations. These simulations however, considered only tidal period forcing functions, while field measurements, against which the models were evaluated, were taken at 10 or 15 minute intervals. As a result, observed elevations would include oscillations at a frequency not considered in the numerical model. Consequently, what appear as errors in prediction may in fact be the result of lack of resolution in the frequency domain. Specific differences which support this likelihood are that discrepancies between prediction and observation decrease away from the beach face, and that at each location the magnitude of this difference is of the same order as could be induced by nearshore standing waves.

All changes in groundwater level can cause a corresponding shift in the location of the line of intersection between the water table and swash slope. As the water table lowers, this line of intersection moves seaward and when it rises, the line of intersection moves landward. As a result of these water table fluctuations, there is a zone on the beach face which is sequentially saturated and unsaturated (Fig. 9).

A portion of a swash mass, when acting on a nonsaturated beach surface, infiltrates into the sand deposit which decreases the energy of the swash (Duncan, 1964; Nelson and Miller, 1974). This mass loss does not have to be large in order to affect the capacity for sediment transport by swash. During the entire cycle of swash, water depth normally decreases following the maximum (Fig. 3). Thus, near the location of maximum run-up, the swash depth is relatively shallow. Consequently, even a small loss of water due to infiltration can significantly decrease potential energy which becomes available to transport sediment downslope during backwash. Nelson and Miller (1974) found that losses due to infiltration become more critical as the waves become smaller or the beach slope lower.

A reduced mass of swash during backwash would tend to encourage deposition on the nonsaturated portion of the beach. If the beach face is saturated however, then mass loss would not be as great and the tendency for deposition would be reduced. Because of fluctuations of the water table, there can be a portion of the beach face which is alternately saturated and unsaturated which in turn, would suggest that this portion of the beach could alternately experience conditions encouraging deposition and discouraging deposition. If this is true, then measurement of sand levels on the swash slope should reveal a sequential rise and fall in elevations of the sand surface at frequencies similar to those for the water table fluctuations.

BEACH ELEVATIONS

Figure 10 shows a 6-hour record of sand level elevations which occurred at two locations, one meter apart, on the upper half of the swash slope. These records were made by electronically measuring exposed sand surfaces between successive swashes (Waddell, 1973). Obvious fluctuations of

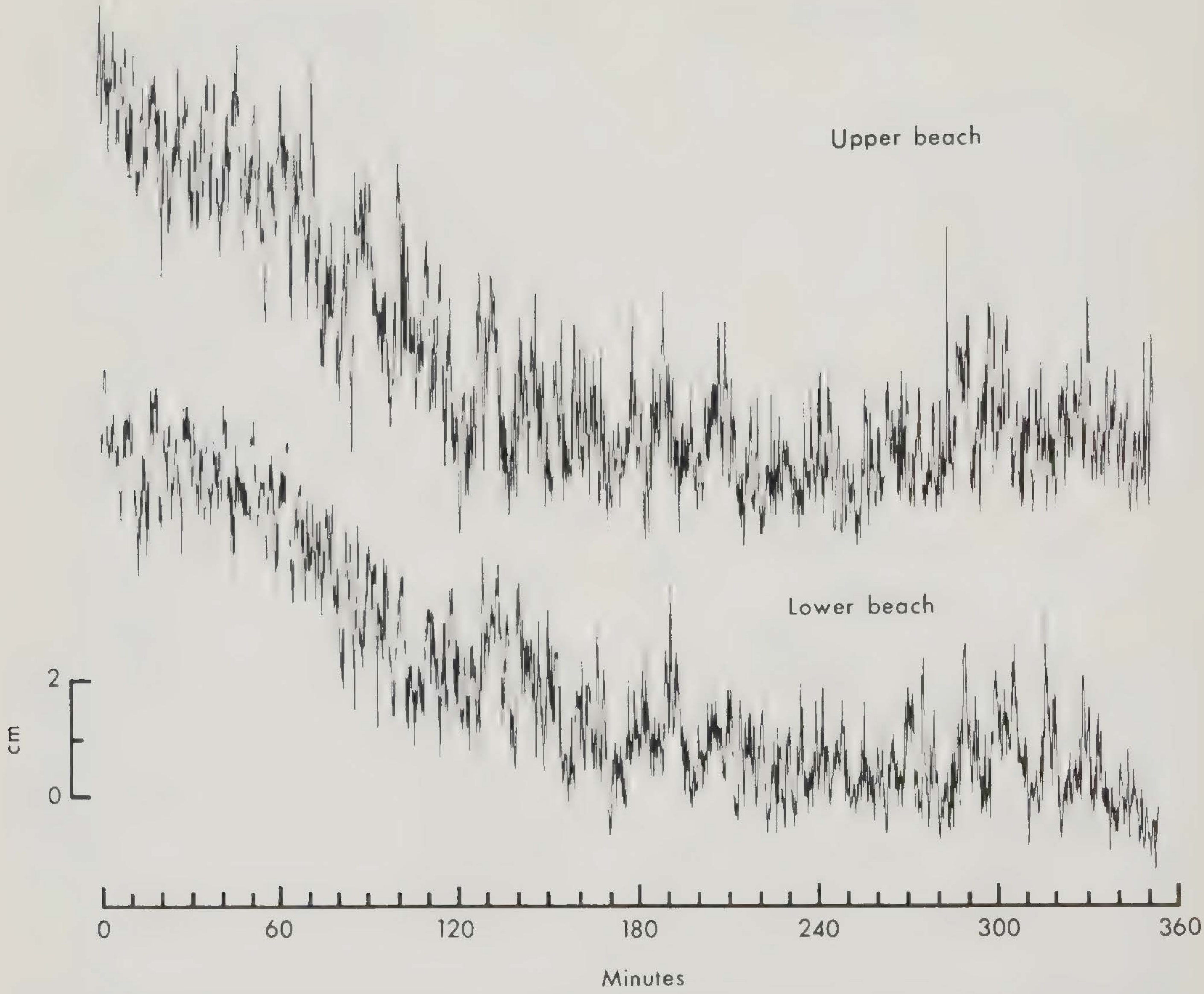

FIG. 10.—Sand level fluctuations at lower and upper beach stations. First three hours were erosional; latter three hours were approximately stable.

sand level occurred even during the 3-hour period of net erosion.

Visual examination of original time-series data indicates that the fluctuations in sand level were the result of multiple swashes causing deposition and subsequent erosion. Generally, these changes were composed of a gradual and sequential increase in sand level followed by a gradual decrease. The deposition and subsequent erosion was rather symmetrical about the time of maximum elevation. This is not to suggest that large changes can not be produced by an individual swash mass. On occasion, single swash elevation changes as large as 5 cm occurred. When such a large discontinuous change occurred, it was usually erosional.

Spectral analysis of these time-series indicates that virtually all sand level variation occurred at periods greater than 40 seconds, and thus, there was no evidence of a significant contribution of variance at the swash frequency (Fig. 11). Cross spectral analysis between the upper and lower beach stations indicates that at all frequencies beach elevation changes on the lower beach consistantly lagged behind elevation changes on the upper beach.

An explanation for these results was suggested by Waddell (1973) and subsequently supported, in part, by the laboratory work of Nelson and Miller (1974). Sand moves upslope as suspended load which Nelson and Miller found to be heavily concentrated in the highly turbulent leading portion of the uprush. Due to loss of capacity as a result of infiltration, a portion of this material remains on the unsaturated upper beach. The net accumulation seen in Figure 9 can be the result of repeated swash action. As groundwater level rises, a previously unsaturated portion of the slope

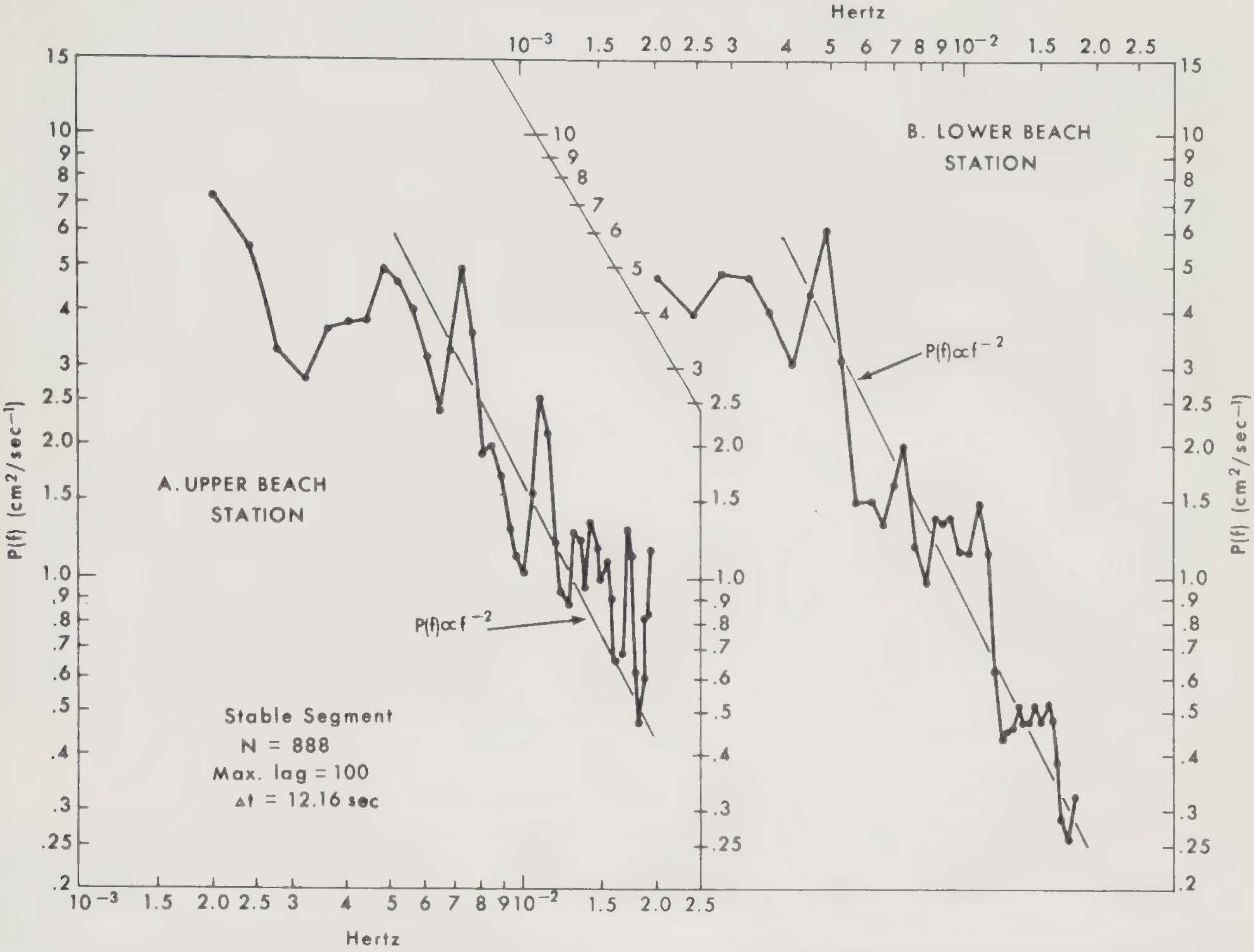

FIG. 11.—Variance spectra of sand level fluctuations during non-erosional segments. Straight line ($P \propto f^{-2}$) is the predicted slope of the spectrum using the development of Hino (1968) for sandwaves in unidirectional flow.

becomes saturated resulting in reduced local water loss, and hence, increased sediment transporting capacity. The undirectural backwash sequentially removes sediment and moves it downslope as bedload.

Another possible explanation for this sequential deposition and erosion is suggested by some of the conclusions of Nelson and Miller (1974). They suggest that low energy swashes tend to deposit while higher energy swash tends to have no net deposition. When this relationship is viewed in the context of swash interaction, it can readily be seen that for the upper beach face, swashes having intense interaction will generally be of lower energy while noninteracting swashes will be more likely to have characteristics of higher energy. As a result of this dependence, the pattern of swash-to-swash interaction can possibly induce depositional and erosional environments on the upper portion of the swash slope. It is possible to incorporate groundwater oscillations into this model because interaction inhibits energy reflection which does not encourage generation of standing waves and hence would encourage a lower water table. Minimal interaction encourages energy reflection which can create standing waves and hence tend to cause the water table to oscillate.

Obviously, any study using detailed measurement of sand levels on the active beach face as a parameter must consider these higher frequency variations. Survey accuracy of 0.5 cm is of limited use if measurements are taken at 10 minute intervals during which time elevation may vary 3 cm or more.

SUMMARY

Identifying some of the fundamental processes which are active on the subaerial beach requires laboratory and field measurements which permit resolution of high frequency interactions. Until recently such measurements were not available; however, several studies have identified some of the salient characteristics of swash and related phenomena (Shen and Meyer, 1962; Miller, 1968; Waddell, 1973; Nelson and Miller, 1974).

The fundamental mode of swash, i.e. an undisturbed swash cycle, is not the expected condition on most laboratory and natural beaches. Because of the dependence of swash duration on breaker height, collisions between swashes are to be expected. Evidence suggests that generation of standing waves in the nearshore may be intimately linked to the occurrence and intensity of interaction because increasing interaction decreases energy reflection.

These standing waves generate significant variations of the groundwater level in the vicinity of the active beach face. Although individual swashes do cause water table fluctuations, dampening of these impulses by the beach matrix limits higher frequency fluctuations to the immediate vicinity of the swash slope. Because of the low pass filter characteristics of the beach deposit, the water table variations induced by standing waves are of larger magnitude and are transmitted further into the beach.

Rapid changes of beach elevations on the upper half of the beach face have been measured. These variations occur such that a group of swashes produce a regular and sequential pattern of deposition and subsequent erosion. This pattern is produced by the collected influence of many swashes and is generally a regular pattern with large discontinuous changes in elevation being the exception.

To explain these regular elevation changes, a model which is consistent with other experimental data is suggested. Oscillations in groundwater level create a zone which is periodically saturated or nonsaturated. When nonsaturated, infiltration occurs which tends to encourage local deposition. When saturated, infiltration does not occur, deposition is not encouraged, and previously deposited material can be eroded. Material which is deposited is moved upslope as suspended load. Material which is subsequently eroded is moved downslope as bed load. In this arrangement, deposition and erosion would be the result of action by several swashes. It is possible that this downslope movement occurs as low amplitude sand waves which move successively further downslope with each eroding swash.

With the development and adoption of accurate and continuously recording instruments it is now becoming possible to realistically attempt to identify those mechanisms which result in observed beach morphologies. With this ability it may now be possible to learn in detail not only what is occurring, but, why many things occur which have long been recognized as characteristic of a beach. Only with this ability will beach systems truly be understood.

ACKNOWLEDGEMENTS

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