CHAPTER ONE HUNDRED THIRTY TWO

BEACH FORESHORE RESPONSE TO LONG-PERIOD WAVES

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ABSTRACT

A field experiment has been carried out to test the hypothesis that infragravity and lower frequency waves influence patterns of erosion and deposition on the beach foreshore. The data show coherent fluctuations in the foreshore sediment level which can be related to low frequency wave motions. The fluctuations have heights of up to 6 cm with typical time scales of 8 to 10 minute periods. They can be characterized in two ways: by the progression of the fluctuation up the foreshore slope (landward), and by the decrease in the root-mean-square (RMS) height of the fluctuations as they progress landward.

Analysis of runup time series obtained by time-lapse photography concurrent with the sediment level measurements reveals long-period waves of undetermined origin which are positively correlated with the sediment level fluctuations. This strongly suggests that the waves are responsible for forcing the sediment level fluctuations.

INTRODUCTION

Background

The beach foreshore is a complex environment. There are numerous physical processes which interact to produce the profile observed at any moment in time. The recent works of Bowen (1980), and Holman and Bowen (1982) demonstrate the role of infragravity (and longer) waves in determining surf-zone profiles, but no recent study has been made of the role of long waves in determining the foreshore profile. This paper reports on one aspect of such an influence.

Patterns of foreshore profile response to tidal fluctuations began to be reported after World War II. Grant (1948) hypothesized that the changes in beach foreshore saturation, due to either tides or storm surges, would cause distinctive changes in the profile. He reasoned that saturated beaches would be more apt to erode since backwash would be undiminished by percolation. On unsaturated beaches, backwash should be diminished by percolation and deposition would be favored. Emery and Foster (1948) studied the change in the

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foreshore groundwater profile over a tidal cycle and concluded that there was significant exchange of water between the runup and the beach, and that this exchange could influence patterns of erosion and deposition.

Duncan (1964) drew upon these conclusions and produced what has become accepted as the best conceptual explanation of foreshore profile change due to tidally induced changes in the beach groundwater. He found that the beach groundwater level lagged the rise in sea level. The foreshore should then steepen during flood tide as deposition occurs on the unsaturated upper foreshore and erosion occurs on the saturated lower foreshore. During ebb tide the opposite sedimentation pattern holds. The upper foreshore erodes due to the effluence of the groundwater lagging behind the falling tide. His field study supports this hypothesis as do the results of others (Strahler, 1964; Harrison, 1969).

Studies of small scale morphology on the beach foreshore have been carried out intermittantly. Tanner (1965, 1977) and Broome and Komar (1979) discuss the existence and formation of backwash ripples. These low-aspect ripples (wavelength of about 50 cm, height approximately 1 cm) can be formed under hydraulic jumps in the backwash on gently sloping beaches. They are not characterized by active migration.

Waddell (1973) conducted a study of the interaction between runup processes, beach groundwater and the sediment level response on the foreshore. He measured sediment level at two locations, one meter apart, on the upper foreshore of a low-energy, medium-sand beach. Simultaneously, he measured runup and the beach groundwater at a series of locations. He found significant fluctuations in sediment level and presented evidence that the oscillations were sandwaves progressing down the foreshore slope due to bedload transport in the backwash phase of the runup. Waddell (1976), referring to the same data, concluded that standing waves in the inner surf-zone were responsible for periodic fluctuations in the beach groundwater level. These groundwater oscillations created "a zone which was periodically saturated or nonsaturated." He then invoked Duncan's (1964) hypothesis and concluded that nonsaturation, or a low in the groundwater oscillation, encouraged deposition and that the subsequent saturation of the location lead to erosion, the result being the observed periodic oscillations. He did not explain how this theory could account for the apparent seaward progression of the oscillations.

Sallenger and Richmond (in press) conducted a field study in Monterey Bay, California with the aim of characterizing sediment level oscillations on a steep, coarse-grained, high-energy foreshore. They measured the sediment level at a series of locations that stretched across the upper two-thirds of the swash-zone, finding sediment level oscillations at periods of six to fifteen minutes occurring at locations above and below the mean swash position. They reported that the oscillations progressed landward during a period of net seaward transport, thus ruling out the possibility of lower flow regime bedforms such as sand waves. The width of foreshore monitored allowed them to show a landward decrease in the RMS height of the oscillations.

Goals

The purpose of this study was to test two hypotheses regarding foreshore sediment level oscillations with periods on the order of ten minutes. The first of these hypotheses is that infragravity or longer waves are capable of influencing the foreshore profile. The second hypothesis is that the profile response is not limited to the zone of intermittent saturation, groundwater fluctuations playing a lesser role than has been thought.

To test these hypotheses a field experiment was carried out on a high-energy, coarse-grained beach. The location chosen differed from that of Sallenger and Richmond (in press) in that it was on an open coast rather than within a major embayment known to have seiches. The goals of the field study were to document forcing (or non-forcing) of the sediment level oscillations by long period waves, to show that the oscillations are independent of any long term erosional or depositional trends on the foreshore, and that the oscillations are not directly related to the saturation of the foreshore.

EXPERIMENT SETTING AND METHODS

The field experiments were conducted during September 1981 and October 1982 at the U.S. Army Corps of Engineers, Coastal Engineering Research Center (CERC), Field Research Facility (FRF) on the outer banks of North Carolina near the town of Duck (Figure 1). The beach is interrupted only by piers for at least 50 km on either side. The nearest pier (belonging to the FRF complex) is 500 m from the experiment location. The surf-zone morphology in the region of the experiment is characterized by a single linear bar during conditions similar to those of the study periods. The average mid-foreshore slope during the studies was approximately 1:10. The foreshore is composed of medium to coarse sand with an average grain diameter of approximately 1 mm (Figure 2). During the two experiments the waves were oblique to the beach and had significant wave heights very close to 1 m as measured at a waverider buoy anchored in 20 m of water. There was little wind and waves were of the swell type. the tide range was approximately 0.9 m and semidiurnal. Figure 3 summarizes the environmental conditions surrounding the experiments.

On September 19, 1981, 19 stakes 1 cm in diameter and 1.5 m long were driven into the foreshore in the locations shown in Figure 4. The foreshore topography was dominated by a series of cusps, one of which is evident from the contours. The primary shore-normal line of eleven stakes had a spacing of 2.0 m.

In October 1982 an array containing eight shore-normal lines of stakes was established on the foreshore (Figure 5). The eight shore-normal lines were spaced 5 m apart. The second line from each

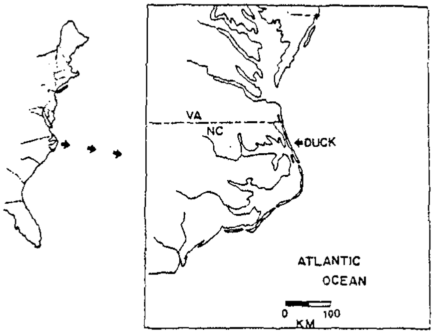


Figure 1. Location map. The field study was conducted at the Coastal Engineering Research Center Field Research Facility just north of the town of Duck, North Carolina. The beach is uninterrupted from Cheseapeake Bay to the north to Oregon Inlet to the south.

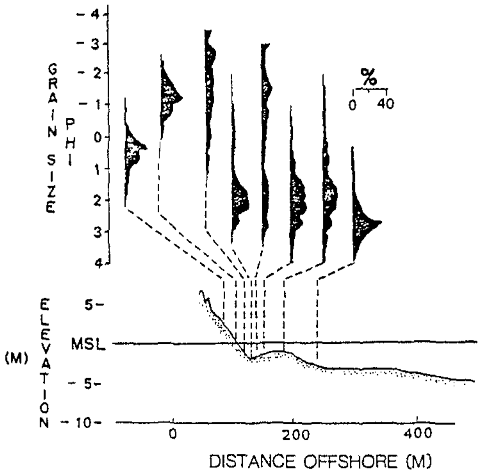


Figure 2. Grain size distribution. Cross-shore grain size distribution on a transect several meters south of the study site on 28 October 1982. The foreshore is composed of sand with an average diameter of approximately 1 mm. Data courtesy of Bill Birkemeier, CERC-FRF.

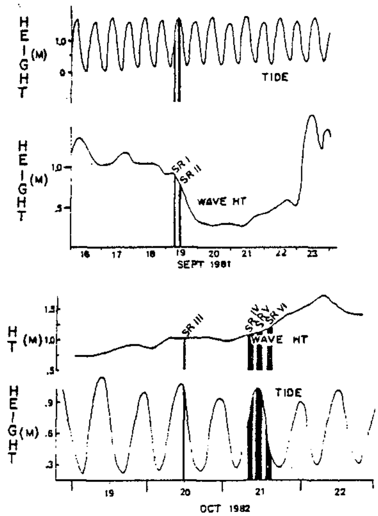


Figure 3. Environmental conditions. The significant wave height was measured by a waverider buoy in 20 m of water. The tides are semidiurnal and have a range of 0.75 to 1.3 meters.

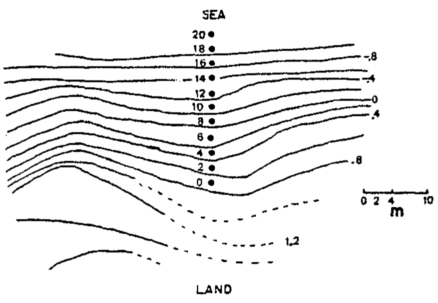


Figure 4. Foreshore topography and stake locations for the 1981 experiment (DS I and DS II). The primary stake transect was located in the trough of a cusp. The stakes are numbered according to their distance seaward from the landwardmost stake and are spaced at 2.0 m intervals.

end of the grid had shore-normal stake spacings of 2.5 m while the remaining lines had 5 m spacings. The foreshore contours show a remnant cusp in the backshore separated from the active, featureless foreshore by a well defined berm crest. A contour map of the surf-zone topography from 19 October 1982 shows a bar approximately 20 m from shore. The mapping, done by the FRF staff using their CRAB (Birkemeier et al., 1981), shows the bar to be linear along shore. There was little evidence to suggest that there was any appreciable change in the topography over the two day period.

Fluctuations in sediment level relative to the stake tops were measured using a modified meterstick. A hinged baseplate approximately 10 cm in diameter was affixed to one end of the meterstick to prevent penetration of the sediment surface. A moveable pointer was fitted to the meterstick and was used to determine the length of stake exposed. The stake tops were referenced to a known elevation using an infrared rangefinder. The resolution of the technique, employing different measurers and different metersticks was ± 1.5 mm in the upper swash-zone and ± 2.5 mm in the lower swash-zone. Resolution of the measurements made on stakes not subjected to runup was ± 0.5 mm. The differences are primarily due to the time available to make the measurement and the saturation of the sediment.

During both the 1981 and the 1982 experiments, time-lapse motion pictures were used to record the wave runup on the foreshore. This method allows for digitization of the runup at a series of longshore locations as well as the identification of the saturated portion of the foreshore. The results of a comparison of the film techniques and a dual-resistance wire runup meter are presented by Holman and Guza (1984).

The 19 September 1981 experiment consisted of two sixty minute segments, one centered on mid-flood tide, DS (Data Segment) I, the second centered on high tide, DS II. The stakes on the primary shore-normal line were measured to the nearest millimeter at approximately 48 second intervals. Measurements were made after the backwash cycle when the stake was either suberial or the velocity of the water covering the location was low. The landwardmost stakes were measured only after they had been exposed to runup action. The times at which the measurements were made were recorded to the nearest 0.2 minute (± 6 seconds).

The 1982 experiment consisted of one 35 minute segment near high tide on 20 October (DS III) and three 90 minute segments centered on mid-flood, high, and mid-ebb tides on 21 October (DS IV, DS V, and DS VI, respectively). Again, the stakes in a shore-normal line were measured at approximately 48 second intervals after the backwash cycle. Measurements were recorded to the nearest 0.2 minute. Stakes on the B-line (Figure 5) were those measured most frequently. The number of stakes measured varied according to the number of people measuring and the width of the swash-zone.

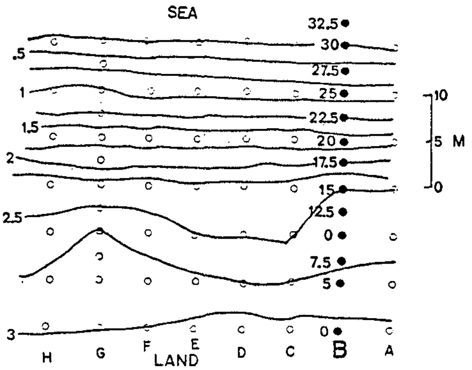


Figure 5. Foreshore topography and stake locations for the 1982 experiment (DS III to DS VI). The B line of stakes were those used in the study. The active portion of the foreshore was seaward of 17.5 m. A remnant cusp was perched landward of the berm crest. The foreshore is linear and has a slope of slightly greater than 1:10.

FIELD STUDY RESULTS

All the data show sediment level fluctuations superimposed on longer term trends. Figure 6 shows a representative set of time series of change in sediment level at a location versus time for the primary, shore-normal line of stakes. The stakes are numbered using their distance from the landward baseline, thus higher numbers refer to stakes further seaward. The trends are due either to the tidal cycle sedimentation patterns or to longer scale foreshore evolution such as changes related to storm cycles. On a shorter time scale, the fluctuations are periodic, and decrease in amplitude in a landward direction from a maximum height of greater than 6 cm to near zero. The stake locations on the lower foreshore show fluctuations occurring more rapidly than those at the upper, landward stakes. The fluctuations are visually progressive, and are coherent over at least 15 m in a longshore direction.

Statistical analysis quantifies these visual observations. The records were processed using linear interpolation to give time series with a constant interval of 12 seconds. The trend and mean were then removed so that they would not mask the analysis of the oscillations.

Figure 7 presents the relationship between root-mean-square (RMS) height and the distance from the top of the swash action for the 1982 data. The RMS heights of the fluctuations were computed as

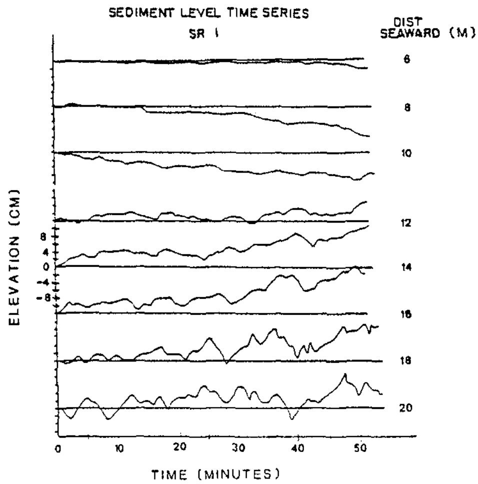


Figure 6. Sediment level time series, DS I. The time series are reported relative to the initial elevation at each location. Several things are obvious. There are trends in the records, the oscillations decrease in amplitude in a landward direction, and they seem to progress.

two times the standard deviation of the record. All segments show the landward decrease in the RMS height of the oscillations, which ranged from a maximum of > 4 cm at the seawardmost stake to near 0 cm for the landward stakes.

Crosscorrelation analysis was used to compare the detrended and demeaned time series. This analysis computes the correlation between two series of data at a series of lag times (Davis, 1973). It is not a frequency specific calculation as is the measure of coherence reported in association with cross spectral analysis. The lag associated with the maximum value in crosscorrelation is a measure of the shift of one series which results in the two series being most alike.

Figure 8 summarizes the results of the analysis as contour plots of crosscorrelation as a function of distance and lag time. Negative lags indicate that events at that location preceeded the events at the reference stake. The contours indicate a change from negative lags for stakes below the reference point to positive lags above. This indicates landward progression of the fluctuations.

The flood-tide data, DS I and DS IV, both show lags which indicate landward migration of the oscillations (Figures 8A and 8D). Adjacent stakes in the mid-forshore have crosscorrelation maxima ranging from 0.54 to 0.79 while stakes which are farther from one another have values which range from essentially zero to 0.43. The lowered crosscorrelation values between non-adjacent stakes are

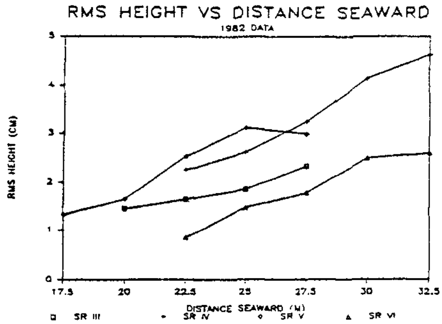


Figure 7. RMS heights of the sediment level fluctuations versus distance seaward for the 1982 data. Note the decrease in the RMS height in a landward direction for all the runs. The RMS height was computed as twice the standard deviation of the run.

primarily due to the loss of the high frequency oscillations present in the records obtained in the lower swash-zone.

The three high-tide segments also have maxima associated with landward migration of the fluctuations (Figures 8B, 8C, and 8E). Again, the values of the maxima are highest between adjacent stakes and decrease for non-adjacent stakes due to the loss of higher frequency fluctuations at the upper swash-zone locations.

Crosscorrelation was also used to compare the runup data to the sediment level fluctuations. Problems were encountered as the result of the large difference in the periods of dominant motion. The dominant runup period was near 8 seconds, while the dominant sediment level oscillations had periods from 2 to 8 minutes. Low pass filtering of the runup records helped alleviate this problem. Figure 9 shows the low-passed runup data along with the sediment level data for segment III. There are three obvious low frequency events in the runup time series that can be directly traced to the sediment level data. In all cases the lag associated with the best fit between the two types of series show motions in the runup preceed the motions in the sediment level records. This would have to be the case if the runup is forcing the sediment level response. In general, the crosscorrelation values are lower than those between adjacent stakes and sensitive to the characteristics of the filter applied to the runup time series. This is not surprising due to the assumed complexity of the transfer function between the runup and the profile response.

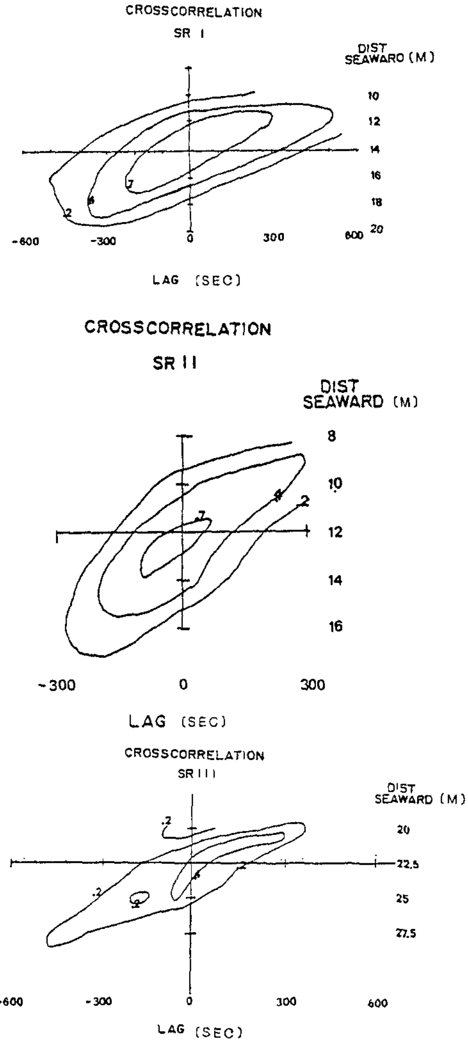
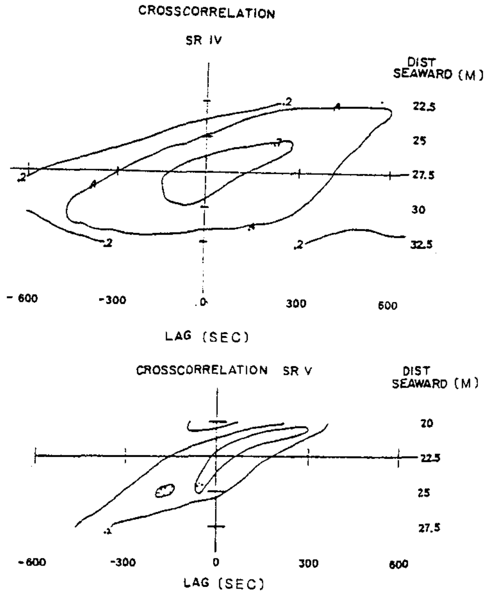


Figure 8. Crosscorrelation vs. time and distance. The crosscorrelation was computed between each time series and a reference time series from near the center of the section of the foreshore monitored during the experiment. Negative lags refer to shifting the reference series back in time, positive lags refer to forward shifts, thus the elongation of the contours from lower left to upper right indicates landward progres-



sion of the fluctuations. Values greater than 0.2 are significant at a minimum of 95% for all the plots at any lag shown. A: DS I, flood tide 19 September 1981. B: DS II, high tide 19 September 1981. C: DS III, high tide 20 October 1982. D: DS IV flood tide 21 October 1982. E: DS V high tide 21 October 1982. The results of DS VI were less characteristic and are discussed elsewhere (Howd, 1984).

Spectral analysis was done to allow specific frequency bands to be examined and compared between simultaneous records. Due to the record length containing as few as three cycles of the sediment oscillations, and the fact that the sampling interval allowed resolution of only those periods greater than 100 seconds, the technique was of limited use. The results are subject to considerable error.

Figure 10 shows a typical spectrum of runup. The distribution of energy is shown over a wider range of frequencies. As is typical for low wave conditions on a steep beach, the incident runup peak is clearly visible at 0.1 Hz. The dominant peak at approximately 0.0625 Hz is the subharmonic of the incident waves (f = 0.12 Hz). The reason for the difference between the incident wave frequency as recorded in the swash zone (f = 0.10) and in the inner surf zone (f = 0.12) is unknown but has been seen in other data from steep beaches (Sallenger, pers. comm.). Low frequency peaks are also present.

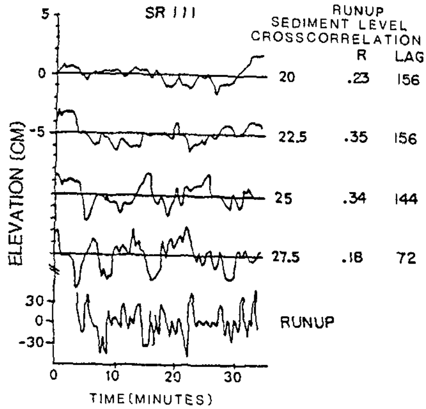


Figure 9. Detrended time series of sediment level and runup. The runup time series has been converted to a vertical excursion using the average foreshore profile and low pass filtered to exclude motions with periods of less than 70 s. The correspondence between the runup series and the sediment level time series at the seawardmost stake is obvious.

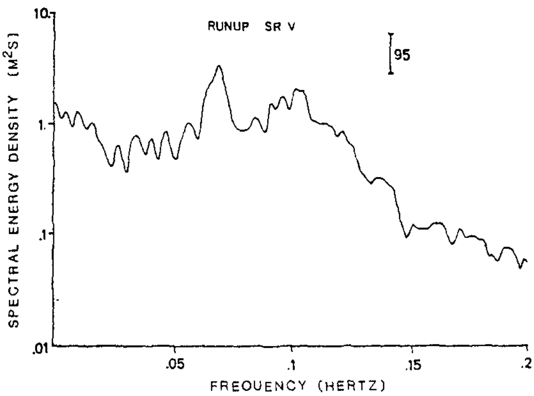


Figure 10. Runup spectrum, DS V. The spectrum shows the incident runup peak near a period of 10 seconds (0.1 Hz.), a peak at 16 seconds (0.0625 Hz.) thought to be the first subharmonic of the 8 second period incident waves (period measured in the surf zone), and several lower frequency peaks.

DISCUSSION OF FIELD DATA

The sediment level fluctuations maintain their form despite the high energy of the swash-backwash action. This suggests that the forcing of the shape must be continued past the initial formation of the features. The data show that sediment level oscillations do occur on the foreshore of a beach in apparent response to long period waves. The origin of the waves is unknown, but recent work bv Lanvon et al. (1982) documents the shoaling of shelf waves with similar periods on beaches in Australia.

The fact that the oscillations are present on all sections of the foreshore subject to swash action discounts the hypothesis presented by Waddell (1976) for the origin of these features. If Waddell's (1976) hypothesis were true, then on a foreshore of the steepness of the beach studied here, the long period wave would need to have an amplitude of greater than 1 m in order to force fluctuations of the saturation line that would extend over the range required. There was no evidence that such high-amplitude, low-frequency waves existed at the time of the study. The oscillations were also measured seaward of the lowest position of the saturation line. It should be noted that the beach on which Waddell did his study was of considerably lesser slope and a wave of smaller amplitude would be required.

An alternative explanation for the formation of the sediment-level oscillations is the formation of antidunes in the lower swash-zone. Antidunes form in supercritical flow, such as may occur during the latter stages of backwash. The migration of the form as an antidune is dependent on maintaining supercritical flow above the bedform. This could not be the case in the upper swash-zone. Furthermore, the direction of antidune migration is opposite to the direction of sediment transport. The observed oscillations migrate landward without regard for the direction of net sediment transport. So while antidunes may explain the initial formation of the oscillation, they do not explain the migration of the form on the foreshore.

A simulation model, presented elsewhere (Howd, 1984 and Howd and Holman, in prep), suggests that the sharp discontinuity in slope at the step-zone is necessary for the formation of the fluctuations. The existence of sharp discontinuities (apparently in equilibrium) in the foreshore slope in this area implies the existence of large local gradients in hydrodynamic characteristics. Thus small horizontal dislocations of the swash zone caused by infragravity waves may induce rapid response and slope adjustments, namely a perturbation which progresses upslope. Sallenger (personal communication) noted that in one experiment the step migrated landward past several of their stakes. The sediment level oscillations present prior to the passage of the step disappeared when the location became seaward of the step. This would suggest that the oscillations are generated in the lowermost foreshore near the vicinity of the step. The magnitude of the oscillation is related to the degree of disequilibrium, that is to the difference between the existing slope and the equilibrium slope, and to the time available for a response.

SUMMARY AND CONCLUSIONS

The primary objective of this field study was to document the influence of long-period waves on the beach foreshore profile. The data collected show such an influence. Oscillations of sediment level were recorded with maximum heights of up to 6 cm at time scales of 8 to 10 minutes. The oscillations decrease in amplitude as they migrate landward. Cross-correlation analysis showed the landward progression of the fluctuations and suggested that the oscillations in sediment level were the result of corresponding long period waves in the runup.

The fluctuations have been observed over the entire extend of the active swash-zone. Their occurrence below the zone of periodic saturation discounts the theory presented by Waddell (1976) for the origin of these features. An alternative explanation is based on disequilibrium conditions existing in the vicinity of the step-zone. The foreshore response to the disequilibrium is hypothesized to be the formation and migration of the observed fluctuations. It is obvious that the foreshore is capable of responding rapidly and in a very coherent manner to subtle changes in the dynamics of the swash-zone.

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