A Conceptual Fairweather-Storm Model of Beach Nearshore Profile Evolution at Duck, North Carolina, U.S.A.

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ABSTRACT


Limited long-term (decadal) beach-nearshore profile observations suggest that during fairweather conditions, the beach-nearshore slope gradually steepens while the shoreline remains relatively stable. The steepening process is terminated by an extreme storm event during which sand is carried offshore, the shoreline migrates landward and the beach-nearshore slope flattens. When the interval between storms is large, the profile approaches a maximum steepness and its susceptibility to erosion and shoreline recession is maximized. To test this conceptual fairweather/storm model, storm events were related to shoreline position, sediment volume and slope changes obtained from the high precision profile data at Duck, North Carolina. Beach-nearshore profiles have been collected for 10½ years at approximately biweekly intervals.

Four major groups of storms occurred during the observation period. They all caused an abrupt increase in the volume of the upper shoreface; in two cases there was a net volume gain to the overall profile. During intervening fairweather conditions, there was a steady onshore transport of sand from the upper shoreface while the total volume remained constant. Slope changes, determined by linear regression of the upper shoreface, support the conceptual fairweather/storm model. Inclusion of the more landward element of the profile was difficult due to the presence of bars. The shoreline at Duck was insensitive to these offshore changes due to the coarse grain size at the shoreline. However, other sites composed of finer-grained sediments might be expected to more sensitive to such changes. These results show that the fairweather/storm model may be a useful conceptual tool to examine medium- to long-term (years to many decades) beach-nearshore profile behavior.

ADDITIONAL INDEX WORDS: Slope, coastal erosion, sediment budget, shoreface.

INTRODUCTION

Storms and other high-energy wave activity in the nearshore zone tend to move sand offshore rapidly; the subaerial beach is eroded and the land behind the beach becomes more vulnerable to wave attack, erosion and flooding. During low-energy conditions, sand moves onshore and the beach undergoes a gradual accretion. Moreover, the onshore-offshore exchange of sediments is not confined to the surf zone where most beach profile studies have occurred, but extends across the shoreface and onto the inner shelf zone (NIEDORODA et al., 1985; WRIGHT et al., 1985).

Although data availability is limited, repetitive bathymetric surveys show that the shape of the shoreface is dynamic over long time scales (decades). BRUUN (1954) showed that the profile deepened along the Danish coast between 1874 and 1934. MOODY (1964) found that the shoreface on the Delaware coast steepened over a 33-year period (1928 to 1961), while the shoreline remained relatively stable. With the onset of an extreme storm, the notorious northeaster of 1962 (the Ash Wednesday storm), profile steepening terminated; the shoreface flattened and the shoreline retreated significantly. Subsequently, LEATHERMAN (1987) found that the profile at Ocean City, Maryland, which is immediately south of the area described by MOODY (1964), steepened from 1962 to 1978, a period without an extreme storm event.

These studies suggest a conceptual fairweather/storm model that describes how the beach-near-
shore profile undergoes long-term adjustments through time. Under fairweather conditions the beach-nearshore profile steepens toward some poorly defined maximum slope (To clarify the time scale in this study, the *fairweather condition* is defined as the period between extreme storm events and is based on a relative scale of storm intensity over the period of interest. The fairweather period is on the order of years to decades and includes less intense storms.) The long period of profile steepening is coupled with a relatively stable or even advancing shoreline. This steepening phase is terminated by an extreme storm event during which sand is carried offshore and the shoreline migrates landward. This beach recession provides sand which flattens the nearshore slope. It is hypothesized that periods without major storm activity are responsible for the steepening of beach-nearshore profiles. When the interval between major storms is large, the profile approaches a maximum steepness and its vulnerability to erosion and rapid shoreline recession is maximized. This model is similar to the Bruun Rule (BRUUN, 1962) in terms of profile translation through time but deals with relatively shorter time-scale profile response to storm and fairweather conditions compared to the long-term response to sea-level rise and an invariant profile shape with time. This model may help to explain the profile translation predicted by the Bruun Rule.

This study uses the highly accurate beach-nearshore profile data collected at the Field Research Facility (FRF) of the US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, located in Duck, North Carolina (Figure 1). To test the model, we examined volumetric and slope changes for different regions of the profile over a 10½ year period. While this period is shorter than the decadal periods over which the conceptual model is derived, it is hypothesized that if the model is valid the same behavior will be apparent in this high quality data set. However, the time scale of fairweather periods is shortened to years, based on a relative scale of actual storm intensity.

**PROFILE DATA**

Since 1981, the FRF has collected beach-nearshore survey data approximately biweekly along...
four profile lines (profiles 58, 62, 188, and 190), extending to about 9-m depth (Figure 2). Profile lines 58 and 62 which are separated by 90 m are located about 500 m north of the research pier, while profile lines 188 and 190 also separated by 90 m are located about 500 m south of the research pier, in both cases minimizing the local influence of the pier (Miller et al., 1983). Horizontal distances are measured relative to a baseline behind the dune system that runs nearly parallel to the shoreline. Elevation is referenced to the 1929 National Geodetic Vertical Datum (NGVD). Howd and Birkemeier (1987) and Lee and Birkemeier (1993) tabulated the profile data from 1981 to 1991 and discussed survey methods, error determination and correction, and survey accuracy in detail.

Because the dune at the FRF is relatively stable and because some of the surveys did not reach the designed offshore distance, the dune portion of the profile and short profile surveys were filtered from the data set. To maximize the number of usable surveys and to include as much offshore information as possible, the filtering criteria were set at 800 m (about -8.5 m). Because all four profiles behaved similarly, only the results from profile line 188 (248 surveys) are presented in this paper.

The profile configuration observed at the FRF varied from unbarred to triple-barred, depending on wave conditions and previous profile geometry. A double-barred profile with a narrow, well-defined inner bar and a broad outer bar was most frequently observed (Howd and Birkemeier, 1987;
Lee and Birkemeier, 1993). The envelope of all surveys of profile line 188 is shown in Figure 3. The vertical change of the profile is greatest from the shoreline to about 300 m seaward of the baseline, which is the zone occupied by the inner bar system most of the time. Farther seaward, profile variation is still significant due to the movement of the outer bar. The boundary between the inner bar and outer bar was subjectively selected using the profile envelope (Figure 3). The offshore tail of the profile envelope shows significant vertical variation but of a much smaller magnitude (max. range = 0.6 m at 800-m offshore). This zone (500–800 m) is defined as the upper shoreface, because it is seaward of the surf zone except during major storm events. The slope of the upper shoreface averaged 1:160. For the sediment volume calculations, different cross-shore zones were defined by distance: the subaerial beach from 70 m to the shoreline at the time of survey; the inner bar from the shoreline to 300 m; the outer bar from 300 to 500 m; and the upper shoreface from 500 to 800 m offshore (Figure 3).

STORM EVENTS

To address the impact of storms on profile changes over the period of record, a quantification of the relationship between intensity, duration and frequency of storms is required. Wave data was collected from a waverider buoy located in 18-m water depth 6 km offshore. A partial-duration series, which is commonly used in hydrology (Dunne and Leopold, 1978), was employed to determine the major storms that occurred during the study period. The partial-duration series consists of all events greater than some arbitrary base magnitude, usually the smallest of the annual-maximum series (i.e., the maximum significant wave height of each year in this study). Hereafter, wave height refers to the significant wave height, equal to 4 times the standard deviation of the sea surface time series. Note that the partial-duration series does not fit the extreme-value distribution, and therefore extrapolation is not possible (Dunne and Leopold, 1978).

The smallest wave height of the annual-maximum series was 2.7 m, occurring on 22 December 1983. The partial-duration series includes 56 storm events. The intensity of each storm was calculated by the energy-based wave power ($P$);

$$P = \frac{1}{16} \rho g \frac{H^2}{L} \text{T}$$  \hspace{1cm} (1)

where $\rho$ is seawater density, $g$ is gravity, $H$ is wave height, $L$ is wave length, and $T$ is peak spectral wave period. The wave power was integrated to obtain the total wave power during each storm. For the integration, storm duration was defined as the interval of time that wave height exceeded one meter. The 1-m criteria was arbitrary but reasonably ranks the intensity of storms which occurred during the study compared to other larger criteria. The relative intensity of each storm is shown in Figure 4(h). Four significant groups of storms (A, B, C and D) occurred, separated by fairweather periods. The groups of storms are defined by the rapid occurrence of storm events with more than one event exceeding a 4-m wave height. The longest duration of a group of storms was 145 days. The largest storm of the record (the so-called Halloween storm of late 1991) is not considered due to limited length of the subsequent time series.

BEACH-NEARSHORE PROFILE VARIATION

The beach-nearshore profile showed important changes through the study period (Figure 4(a)). Various zones of the beach-nearshore profile respond at different time scales (Lee, 1993). The shoreline position changes constantly in response to the changing wave and water level conditions. The shoreline position derived from the profile data generally displayed a seasonal fluctuation; it retreated in the winter but advanced seaward during the summer (Figure 4(b)). Superimposed on this annual cycle is the long-term accretion that began in 1987. The movement of the shoreline is highly correlated with the volume change of the subaerial beach ($r = 0.90$) (Figure 4(b) and 4(c)).
The inner bar is highly mobile under all wave conditions. Lippmann and Holman (1990) found that the inner bar was usually three-dimensional (84.7 percent of the time) and only became linear during storms. The cumulative inner bar volume change was well correlated to the subaerial beach volume ($r = 0.79$). However, the correlation of volume change between consecutive surveys was low ($r = 0.36$). This indicates significant short-term exchange of sand between these two zones but over the long-term their behavior is similar.

When storms affected the area, the inner bar moved offshore and sometimes became the outer bar if no outer bar was present (Figure 5(a) and Figure 4(a)). The outer bar, once formed by major storms, remained for long periods from several months to several years. The outer bar tended to migrate onshore, and decreased in amplitude, and ultimately disappeared after extended periods of low energy conditions as illustrated in Figure 5(b) (Birkemeier, 1985). When the outer bar was present, the inner bar oscillated within a maximum distance of 250 m.

The cumulative volume change of the outer bar had a moderate negative correlation with the combined subaerial beach and inner bar volume ($r = -0.56$). The correlation was performed using data from 1981 to 1986 in order to exclude the effect of the shoreline advance and associated increase of the overall volume which began in 1987. This may partly result from longshore transport onto the profile and from sediment exchange to the upper shoreface which cannot be resolved by a single profile.
An interesting aspect of the profile behavior is shown in the plots of cumulative upper shoreface volume change and total volume change (Figure 4(f) and 4(g)). The onset of the four groups of significant storms (A, B, C, and D in Figure 4(h)) induced a rapid increase in the upper shoreface volume, while two of the events (B and C) also increased the total volume.

This total volume increase indicates either onshore sediment transport from offshore or longshore transport and storage. Since similar behavior was also observed on profile line 62, some of the increase may have resulted from onshore transport, as argued by Larson and Kraus (1994). However, the longshore coverage of this profile data (1,000 m) is relatively small and the possibility of longshore transport increasing the volume along this entire frontage cannot be excluded. Therefore, no conclusive results on sediment source should be drawn from this data set.

At other times, the upper shoreface volume gradually decreased despite significant profile variability to landward (Figure 4(c) and 4(d)). Since the total volume was nearly constant during these times of fairweather and mild storm conditions (Figure 4(g)), the upper shoreface appears to feed sand onshore at a relatively steady rate. Similar onshore transport was observed by Wright et al. (1991) across the 8-m contour of the FRF during low and moderate wave conditions (wave height less than 1 m).

**SLOPE CHANGE**

To examine the applicability of the fairweather/storm conceptual model, the slope of the overall profile was first calculated by fitting the power
function curve (BRUUN, 1954; DEAN, 1977) to the actual survey points in a least-squares sense. The power function is;

$$Y = AX^m$$

(2)

where $Y$ is the depth at a distance $X$, $A$ is a coefficient, and $m$ is the exponent. The power function was utilized because it represents the overall steepness of beach-nearshore profile objectively. The time-varying exponent of the power function is presented in Figure 6(a).

The exponent varies considerably with time. The profile generally flattened during fairweather conditions and steepened after the four storm events, contradicting the fairweather/storm model. However, the exponent of the power function is sensitive to the shape of bars and troughs and this may have contributed to the result (Figure 6(b) and 6(c)).

The upper shoreface slope was calculated by using linear regression (Figure 7) to avoid problems associated with bar morphology. The resulting slope decreased steadily during fairweather conditions and steepened rapidly with each group of storm events. The steady flattening of the upper shoreface slope resulted from the onshore sediment movement from the upper shoreface discussed earlier. Therefore, the profile landward of the upper shoreface steepened between groups of storms which is in general agreement with the conceptual fairweather/storm model.

The movement of selected beach and bathymetric contours with time is shown in Figure 8. A similar trend to the upper shoreface volume change is apparent in depths greater than 4 m, including the groups of storms A, B, D and most particularly C. The movement of the contours decreases offshore, suggesting that this movement is partly related to movement of the seaward edge of the outer bar. Simply considering the distance between the NGVD and $-5$ m contours, where the two bars are present most of the time, defines a horizontal range of about 330 to 450 m (Figure 8), equivalent to a range of slopes of 0.011 to 0.015. These data suggest that a lull in major storm activity would allow further steepening of the profile to occur beyond that observed in this data set. The ultimate limit of such steepening remains uncertain.

The shoreline response to the storm groups (A, B, C and D) as predicted by the fairweather/storm model is not apparent in these data. This may be partly because of the coarse sediment commonly found on the subaerial beach and the trough of
SUMMARY AND CONCLUSIONS

This paper has used 10 1/2 years of high precision repetitive profile data (comprising 247 surveys) to examine a conceptual model of profile vulnerability to storms. The beach-nearshore profile underwent continuous changes during the study period. Four groups of major storms caused significant volume changes to the different crossshore zones, with a net addition of sediment to the system in two cases. During fairweather conditions, on the order of years, the total volume of sand was nearly constant and sediment was steadily transported onshore from the upper shoreface.

Important elements of the fairweather/storm model are consistent with the data from Duck. The nearshore slope appears to respond to the groups of storms that drive the medium term profile change (time scale of a year to a decade) in a manner consistent with the fairweather/storm model. However, the presence of bars complicates the detailed interpretation of the data. Given the near universal occurrence of bars, this difficulty of interpretation is probably a general problem.

Based on the response of the upper shoreface slope, the slope landward of the shoreface steepened during fairweather conditions and flattened with the onset of major storms. This is in general agreement with the fairweather/storm conceptual model. The lack of shoreline response at Duck

Figure 8. A time series showing the distance from the baseline for selected contours on profile 188. The four groups of storms are indicated.
does not invalidate the fairweather/storm model for the beaches composed of finer sediment. The coarse beach material and sediment gain into the local beach system during groups of major storms may play a role in the observed behavior at Duck. The data do indicate that the intensity and timing of major storm events have important effects on the beach-nearshore profile over a decade.

These results show that the fairweather/storm model may be a useful conceptual tool to examine medium-term (time scale of a year to a decade) beach-nearshore behavior. More widespread investigation of its applicability, particularly on beaches composed of fine- to medium-sized sand and with a long-term trend of erosion would be useful. In addition, further investigation of profile change over the longer time scale (decades) described by Bruun (1954), Moody (1964) and Leatherman (1987) in a wide range of settings would be valuable.

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LITERATURE CITED


