CHAPTER 170

DYNAMICS OF LONGSHORE BARS

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ABSTRACT: This paper presents empirical predictive expressions describing the cross-shore movement of linear nearshore bars, based on intensive analysis of survey data from Duck, North Carolina. The analysis centers on 300 beach profile surveys taken at approximately 2-week intervals for the continuous period from 1981 to 1989, together with accurate measurements of the wave conditions. The geometry and dynamics of bars derived from the surveys are related to wave characteristics, and criteria previously developed by the authors to predict beach erosion and accretion are found to be applicable to bar movement if a multiplicative empirical coefficient in each criterion is modified. The results indicate that onshore movement of bars is more probable than previously estimated. The implication is that linear bars formed of dredged material are more likely to move onshore to nourish the surf zone and beach than previously thought.

INTRODUCTION

The beach is a dynamic system that resists inundation and erosion by storage of material on the foreshore and dune complex and by storage of sand in the offshore in longshore bars. Bars also reduce erosive energy entering the surf zone by breaking the higher incident waves. Sediment moves between the shore face and bars according to the wave and water level conditions, grain size of the beach material, and other factors. During storms, characterized by higher waves and water levels, sediment moves from the beach face and, possibly, dunes to form bars, whereas under lower waves bars tend to lose volume and move onshore to resupply the surf zone and beach. Sediment also moves alongshore in a direction mainly controlled by the angle of the incident waves. In the present study, only cross-shore sediment transport processes are considered.

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In recognition of the positive effects of bars for promoting beach growth and protecting beaches, nourishment projects have been performed to construct bars or "nearshore berms" from dredged material with the intent of the placed bars to either serve as a wave break and/or to supply or "feed" the beach with material (McLellan 1990, McLellan and Kraus 1991). Engineering motivation for the present study is the need for quantitative criteria for predicting the movement of material placed to serve as an active or feeder berm. In order to derive such criteria, extensive analysis of field data on the characteristics and movement of natural sand bars was carried out, as described further in Larson and Kraus (1992).

In this study, the dynamics of longshore bars were determined from field data and related to the prevailing waves. Depth to bar crest, maximum bar height, bar volume, location of bar center of mass, and time dependencies of these quantities, as well as speed of bar movement, were calculated for a large number of profile surveys made on fixed lines at Duck, North Carolina, at the Field Research Facility (FRF) operated by the Coastal Engineering Research Center (CERC), U.S. Army Engineer Waterways Experiment Station.

The analysis procedures adopted rely on two assumptions; first, the profile change admitted to this study must be dominated by cross-shore transport, meaning that longshore homogeneity exists, and, second, short-period incident waves are the direct and dominant sediment-transport driving mechanism. Engineering studies have long recognized the appearance of three-dimensional patterns in beach morphology in the surf zone (Hom-ma and Sonu 1962). Intensive high-resolution beach profile surveys (Howd and Birkemeier 1987) and inference of morphology through long-term remote sensing (Lippman and Holman 1990) at the FRF indicate that bars tend to become linear (two-dimensional) during storms and rhythmic (three-dimensional) 5 to 16 days following the peaks of storms. Care was taken in the present study to identify potential occurrences of three-dimensionality, mainly through comparison of shapes of the profiles at different survey lines and through censoring of the data by imposing threshold values to consider only larger change. Although incident waves may be one contributing mechanism to the mean flow, other forcing mechanisms such as the tide and wind-generated currents also enter in the total mean flow. Thus, during times of mild wave conditions in particular, correlations between bar movement and incident waves, such as sought in the present study, may be weak and should be viewed with caution.

DATA EMPLOYED

Beach profile data collected at the FRF were analyzed to provide information on the spatial and temporal properties of natural longshore bars located in the nearshore (depth less than 15 m). The beach profile was surveyed at a nominal 2-week interval along four shore-normal lines from 1981 to 1989, where each survey extended from a base line behind the dune out to a water depth of about 9 m. All depths in this paper are referenced to the National Geodetic Vertical Datum (NGVD), which lies 6.7 cm below mean sea level at the FRF. The locations of the four profile lines, numbered 58, 62, 188, and 190, are given in Howd and Birkemeier (1987). Typically, between 20 to 50 distance-elevation pairs were recorded in each survey, and the total number of surveys during the studied period varied between 250 and 300, depending on the profile line. The surveys were usually carried out to a water depth exceeding the depth of profile closure (Birkemeier 1985). The profiles were surveyed using the Coastal Research Amphibious Buggy (CRAB), which has an accuracy in elevation on the order of 5 cm.

The wave data used in this study were taken by a waverider buoy located in 18-m water depth seaward of the FRF research pier. Wave height was obtained as energy-based significant wave height calculated as four times the standard deviation for a 20-min water level record. The wave period was determined as the period corresponding to the peak in the energy spectrum. Wave height and period were typically recorded every 6 hr but more frequently during the end of the 9-year observation period, for which hourly values are available. The influence of water level was not included in this study, because its period of variation was significantly shorter than the time elapsed between surveys, and the variation in most cases was almost symmetrical about the mean value.

BASIC PROPERTIES OF PROFILE CHANGE

Profile Shape

The average profile was computed for each line from all surveys for the period 1981 to 1989. Because individual survey points were taken at varying distances from the baseline, (linear) interpolation was employed between measured points to derive the average profile. Also, maximum and minimum depths recorded at any point were determined across shore together with the standard deviation of elevation. These quantities indicate the profile variability during the measurement period and the areas along the profile where the most active sand transport occurred. Fig. 1 displays the average profile and the aforementioned quantities for Line 62, for which the largest number of surveys exists (in total 300).

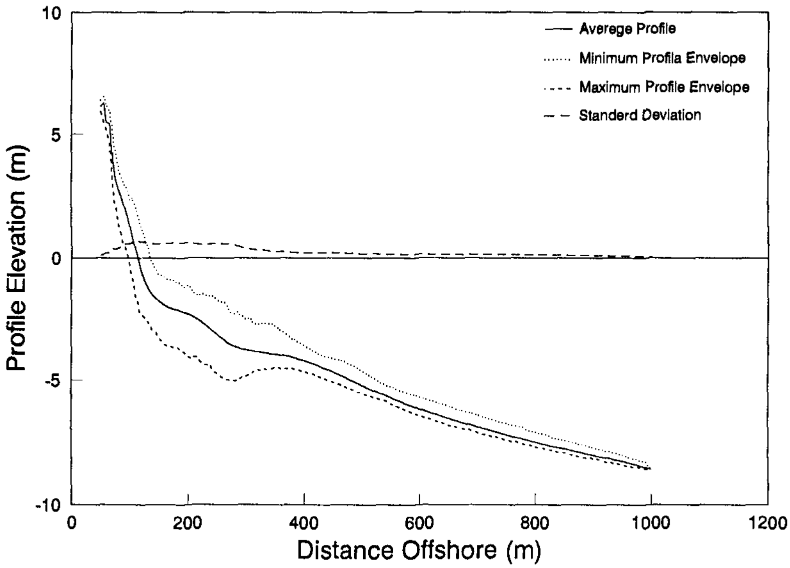

Fig. 1. Average profile and profile variability for Line 62

Average profiles of the four survey lines were similar, having a steep foreshore joining a gently sloping profile at a small distance seaward of the shoreline. Because longshore bars are usually present at the FRF, the average profiles are influenced by these features, and the computed average profiles have two regions where the beach gradient is not monotonically decreasing, related to the inner and outer bars commonly observed at the FRF. The inner bar in shallower water closer to shore is almost constantly exposed to breaking waves, whereas waves break at distances from the shoreline out to about 400 m (depth between 4 and 5 m) for all survey lines, representing the region of most active sand transport.

The average profile was compared to theoretical equilibrium profile shapes. The modified equilibrium profile equation employed in this study is (Larson 1991),

$$h = A\left[x - x_s + \frac{1}{\lambda}\left(\frac{D_o}{D_\infty} - 1\right)\left(1 - e^{-\lambda[x - x_s]}\right)\right]^{2/3} \tag{1}$$

where h is depth, A is a shape parameter, x is distance from the baseline, x_s is the location of the shoreline from the baseline, D_o and D_∞ are, respectively, the equilibrium wave energy dissipation per unit water volume in the inshore and offshore, and λ is a characteristic (decay) length at which D_o approaches D_∞. The term containing the factor $1/\lambda$ augments the original equilibrium profile equation $h = A\,(x - x_s)^{2/3}$ derived by Dean (1977) and describes a trend of decreasing grain size with distance offshore. The equilibrium profile equation of Dean was least-square fitted to the average profile, determining the optimum value of the shape parameter as 0.09 $m^{1/3}$, with root-mean square error in deviation in depth of $\Delta h_{rms} = 0.20$ m. The corresponding median grain size is 0.20 mm according to an empirical curve given by Moore (1982).

In the offshore, agreement between the Dean equilibrium profile and average profiles is satisfactory (Fig. 2); however, close to the shoreline the original equilibrium profile equation provided a poor fit, because the average profile is considerably steeper in this region. The larger beach gradient at the shoreline owes to the coarser grain size found near the shoreline. The typical median grain size on the foreshore at the FRF is 1.0 mm, whereas the grain size in the offshore region of the profile approaches 0.1 mm (Howd and Birkemeier 1987). The trial and error best-fit of eq. 1 used the previous shape parameter and $D_o/D_\infty = 3.3$ and $\lambda = 0.039$ m^{-1}, with $\Delta h_{rms} = 0.15$ m. The modified equilibrium profile equation well accounted for fining of sediment across the profile and achieved a better overall description of the average or equilibrium shape of the profile.

Definition of bars

In order to describe and quantify bar formation and movement, a consistent definition of a bar feature is needed. Previous investigations involving laboratory profiles have defined bars with reference to the initial profile (Larson and Kraus 1989). Areas along the subaqueous part of the profile where material accumulates with respect to the initial profile were defined as bars. Crossings between a specific profile and the initial profile defined the beginning and the end of the bar. However, in the field, such a definition is not operational due to the absence of an unambiguous "initial profile," and thus a different method must be employed. In the present study, several methods were tested for defining bars, and, after evaluation, the modified equilibrium profile equation was found to give the most reliable reference profile for definition of a bar and was employed in the following analysis. As an example of how bars were defined, Fig. 3 illustrates a surveyed profile at Line 62 together with the modified equilibrium profile least-square fitted to the 9-year average profile.

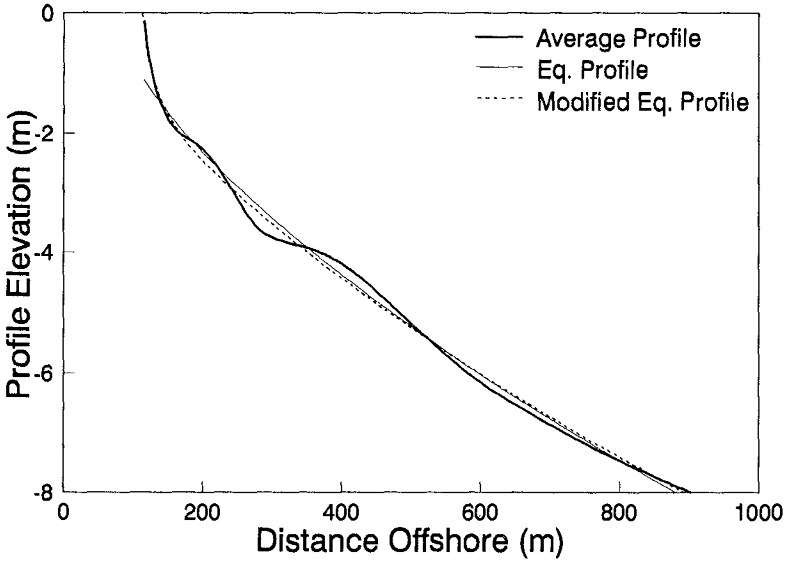

Fig. 2. Average profile at Line 62, equilibrium, and modified equilibrium profiles

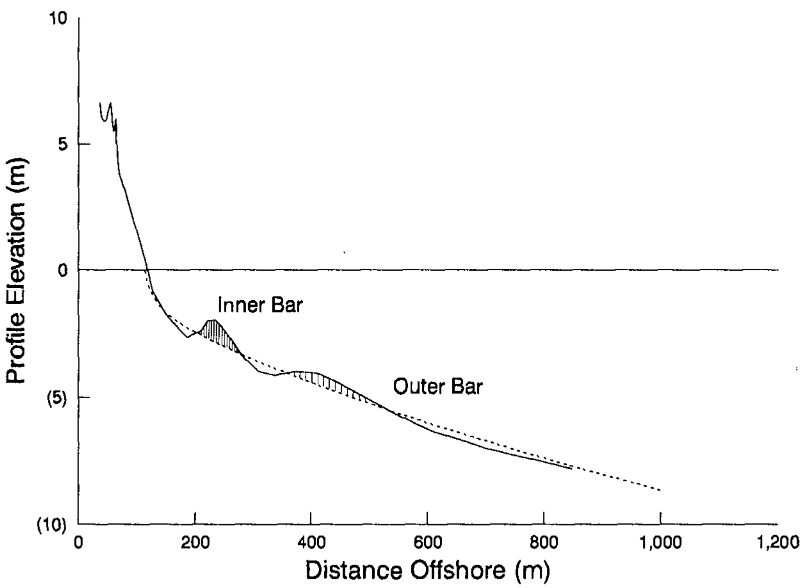

Fig. 3. Definition of longshore bar extent using the modified equilibrium profile equation (hatched areas represent bars)

Volumetric Profile Change and Contour Movement

To determine and characterize the long-term beach evolution at the FRF, the time-variation in subaerial sand volume above selected elevation contours was calculated. Over the 9-year interval encompassed by the data set, the subaerial portion of the beach at the FRF displayed a slight trend of accretion, especially at Line 62, indicated primarily by a long-term increase in the sand volume above NGVD. Strong seasonal variations, including those attributed to large storms, were superimposed on this trend, with the subaerial sand volume mainly lying below the average value during the first half of the measurement period, and above it during the second half. Fig. 4 displays the variation in the volume of sand above NGVD as a function of time for Line 62. Time is given in consecutive days starting at 810101, and the sand volume is referenced to the average volume, 104 m^3/m, above NGVD from a point located 66 m seaward of the FRF baseline. The 66-m location was the minimal distance seaward common to all profile surveys.

Analysis of volumetric profile change and contour movement showed that the FRF beach accreted somewhat above NGVD for the measurement period, but no long-term change in the subaqueous portion of the beach was detected. Survey lines located north of the FRF research pier (Lines 58 and 62) experienced slightly more accretion than those south of the pier (Lines 188 and 190). The increase in subaerial sand volume is probably due to sand transport by wind. A stable subaqueous beach profile indicates no long-term differential in the longshore sand transport or no significant loss of material to the offshore. Thus, the profile data from the FRF provides a good basis for analysis of natural longshore bar properties because the data set is, on the average, not strongly influenced by a longshore bias. However, short-term longshore variations could still influence profile evolution, and identification of possible times of longshore nonuniformity required tedious visual inspection of the plotted profile surveys.

BAR PROPERTIES

Because the four profile survey lines displayed similar long-term behavior, analysis of bar properties was focussed on survey Line 62. The largest number of surveys (300) was available for Line 62, and this line was judged to exhibit the most representative bar response. Each profile survey was visually examined for bar features, and shoreward and seaward boundaries of the bar were determined from the crossings between a profile and the modified equilibrium profile. The following properties were calculated for every identified bar from each profile survey: V_b = bar volume, l_b = bar length, h_c = minimum bar depth, z_m = maximum bar height, x_{cg} = location of bar center of mass, and $\Delta x_{cg}/\Delta t$ = speed of bar movement, where t = time. Fig. 5 schematically illustrates these bar properties for a typical profile survey from the FRF data set (inner bar shown).

Inner Bar

Short-term variability in bar properties was considerably greater for the inner bar because it was frequently located in the breaker zone, experiencing significant sand transport and influence of beach change on a shorter time scale than the outer bar. A distinct inner bar was identified in 200 of 300 surveys, and statistical quantities were computed for bar properties (Table 1). Disappearance of the inner bar was primarily due to welding to shore or to offshore movement until the inner bar became or merged with the outer bar. Thus, minimum and maximum values in Table 1 depend on determination of when the inner bar welded on to the shore or joined with the outer bar as it moved offshore, respectively.

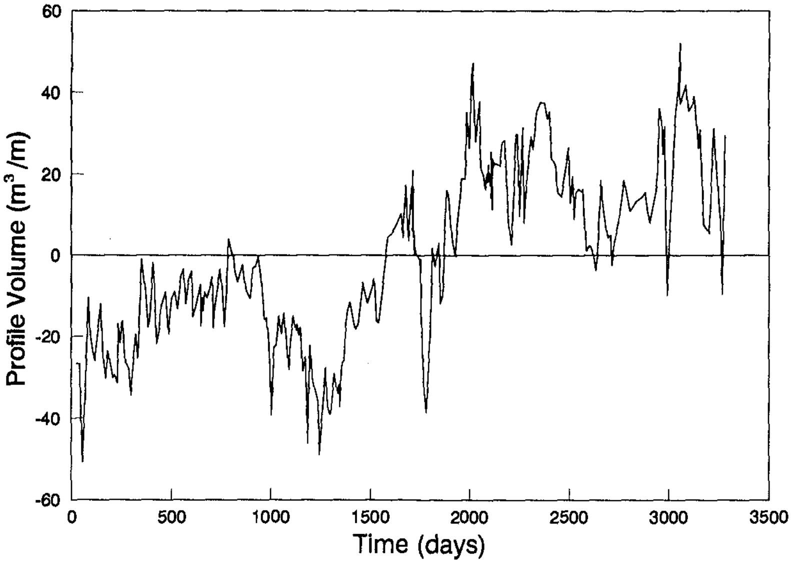

Fig. 4. Temporal variation in subaerial sand volume above NGVD at Line 62

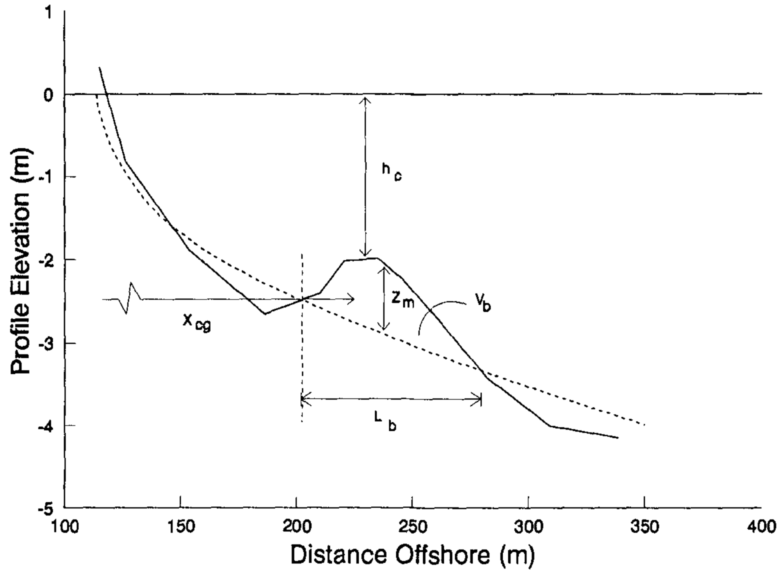

Fig. 5. Definition sketch of bar properties calculated for each survey

Table 1. Statistics for Inner Bar Properties					
Property	Mean	Minimum	Maximum	Q_{25}*	Q_{75}*
Depth to crest, m	1.6	0.6	2.5	1.3	1.9
Bar height, m	0.9	0.2	1.4	0.7	1.0
Bar volume, m^3/m	42	6	98	27	55
Bar length, m	95	35	280	65	100
Bar mass center, m	215	150	330	195	230
* Q_{25} and Q_{75} denote limits for which 25 % and 75% of the values are below, respectively.					

The average depth to bar crest was 1.6 m, implying a mean breaking wave height of about 2 m, as estimated from an empirical expression given by Larson and Kraus (1989). Bars in large wave tank (LWT) experiments with monochromatic waves (Larson and Kraus 1989) display marked similarities with the inner bar, although bars in the field tend to be smoother due to shifting of forcing under random waves and varying water level. Thus, inner bar volume is similar to that found in LWT experiments, whereas maximum bar height is considerably lower in the field. Fig. 6 illustrates volume of the inner bar with time, in which time periods when no bar existed have been left blank. Change in bar volume was used to derive a time scale for the inner bar by the fractal box-counting method (Larson and Kraus 1992). A break point occurs in the box-counting curve for a box size of about 60 days, which is interpreted as the typical duration between events that move the inner bar offshore.

Outer Bar

A distinct outer bar was identified for 221 profile surveys, and statistical quantities were computed for the bar properties (Table 2). During extended periods of low waves, the outer bar moved slightly onshore simultaneously with flattening, to finally disappear. The outer bar disappeared as an identifiable morphological feature by flattening before it moved a significant distance onshore. In comparison with the geometric properties of the inner bar, variability of the outer bar is significantly smaller. This is because once the outer bar has formed, it is only exposed to wave breaking and large sand transport during severe storms, and transport induced by non-breaking waves produces less rapid change in bar properties.

Table 2. Statistics for Outer Bar Properties					
Property	Mean	Minimum	Maximum	Q_{25}*	Q_{75}*
Depth to crest, m	3.8	1.3	5.1	3.4	4.1
Bar height, m	0.4	0	1.4	0.27	0.6
Bar volume, m^3/m	45	0	120	20	67
Bar length, m	170	25	280	150	200
Bar mass center, m	410	200	520	390	440
* Q_{25} and Q_{75} denote limits for which 25 % and 75 % of the values are below, respectively.					

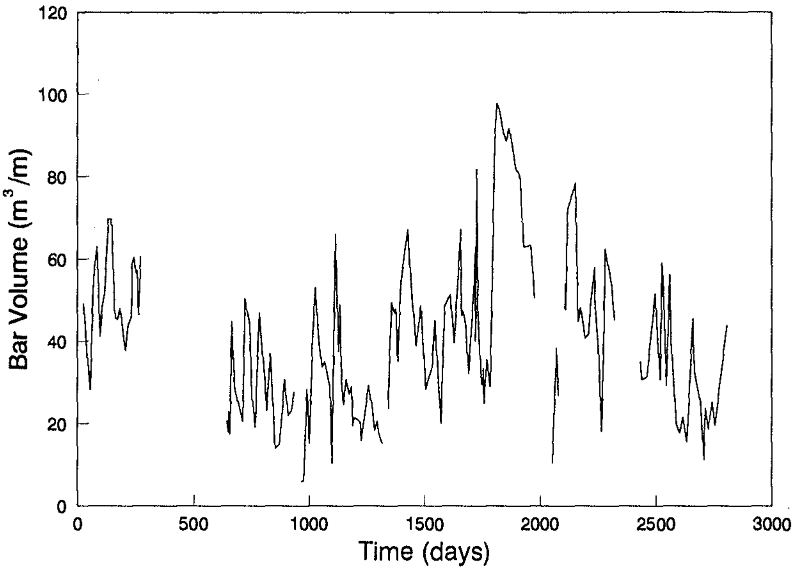

Fig. 6. Volume of inner bar as a function of time

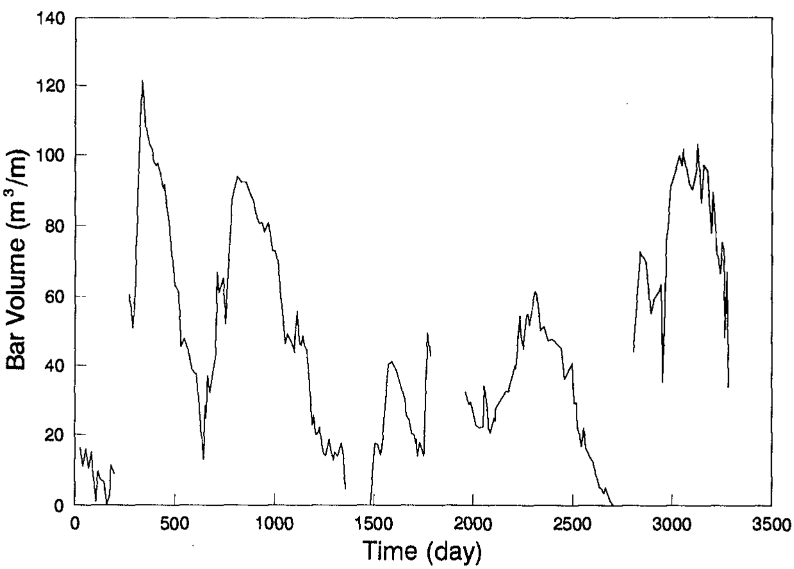

Fig. 7. Volume of outer bar as a function of time

The average depth to bar crest of the outer bar was 3.8 m, which indicates the presence of individual breaking waves with heights on the order of 4 to 5 m associated with modifications of the outer bar. Volume of the outer bar is shown in Fig. 7 as a function of time, displaying regular, long-term variations, where the bar grows rapidly to maximum size after which it decreases in volume at a lower rate until it flattens completely. Comparison of Figs. 6 and 7 illustrates the different time scales in responses of the inner and outer bar to wave forcing in the nearshore. Box-counting analysis of change in outer bar volume produced a break point in the box-counting curve corresponding to 120 days. Thus, the inner bar moves offshore at least every second month, whereas about four months at most separate wave events that move the outer bar seaward.

Bar Speed

The speed of bar movement was determined for the inner and outer bar as the distance Δx_{cg} the bar center of mass moved between two consecutive surveys divided by the time Δt between the surveys. However, because bar movement may be rapid, particularly during storms (Sallenger, Holman, and Birkemeier 1985, Sunamura and Maruyama 1987, Larson and Kraus 1989), values obtained underestimate bar speed through the assumption that the movement is constant during the time between surveys. A storm with a typical time scale of days that moves a bar offshore would produce rapid bar movement not apparent in the calculation if surveying is done with a longer time interval. If the bar is located outside the region of breaking waves, however, profile change is more gradual under non-breaking waves, and the estimated bar speed should be more accurate.

Onshore and offshore bar movement were analyzed separately, and the inner (outer) bar moved onshore on 99 (122) and offshore on 92 (90) occasions. The average speed of onshore bar movement was 1.5 (0.6) m/day and the maximum onshore bar speed was 8.7 (6.1) m/day for the inner (outer) bar. Corresponding values for offshore bar movement were an average speed of 2.9 (1.1) m/day and a maximum speed of 18.0 (15.2) m/day. The outer bar exhibited considerably lower average speeds than the inner bar, both for onshore and offshore movement, whereas the maximum values were comparable. The average bar speed for the outer bar was approximately one third that of the inner bar. Because the inner bar is more frequently subjected to breaking waves than the outer bar, the average speed of movement is greater for the inner bar. However, if waves broke on the outer bar, the speed of movement was comparable to that of the inner bar, as shown by the similar maximum bar speed for the inner and outer bar.

RELATIONSHIP BETWEEN BAR AND WAVE PROPERTIES

The average significant wave height for the entire measurement period was 1.1 m, and the average peak spectral wave period was 8.4 sec based on 29,098 individual recordings. Measurements of the incident wave angle were not available for the full 9-year observation period, and in the simultaneous analysis of bar and wave properties the influence of this variable was not quantified. Deep-water wave quantities were calculated from linear-wave theory including shoaling and omitting refraction. Wave quantities were determined from the time period preceding a specific profile survey, and averages were formed for the full record starting from the previous survey.

Larson and Kraus (1992) summarized the results of the correlation analysis between bar and wave properties, covering (1) the correlation between geometric bar properties and wave quantities, (2) the correlation between change in geometric bar properties and wave quantities, and (3) distinguishing between onshore and offshore bar movement. The largest correlation was found between change in the geometric properties of bar volume, maximum bar height, and mass center location, and the fall speed parameter or wave steepness, with correlation coefficients of typically 0.5 to 0.8.

Several criteria were derived to predict onshore and offshore movement of the inner and outer bar. To determine the direction of bar movement, and thus the net direction of the sand transport across the bar, both change in bar volume and change in the location of bar center of mass were examined. Use of bar volume as an indicator of transport direction assumes that bar growth is associated with offshore movement, whereas a decrease in bar volume is caused by onshore movement. In the final analysis for deriving the criteria, a simultaneous increase in bar volume and offshore movement of the center of mass were required as indicators of offshore transport and similarly for onshore transport. A threshold value of 5 m^3/m on bar volume change was imposed to eliminate events with minor change that were expected to be sensitive to measurement limitations.

The parameters examined to distinguish onshore and offshore bar movement were: wave steepness H_o/L_o, dimensionless fall speed H_o/wT, wave height over grain size diameter H_o/d_{50}, and a Froude number based on grain size $Fr = w/(gH_o)^{1/2}$, where H is wave height, L is wavelength, T is wave period, w is fall speed, d_{50} is median grain size, g is acceleration due to gravity, and the subscript o refers to deep-water conditions. Wave heights and periods associated with the significant wave were taken as the means over the analysis interval. Similar analyses have been performed by Larson and Kraus (1989) primarily for the LWT data sets and limited field data (not examining the Froude number), and by Kraus, Larson, and Kriebel (1991) for the LWT data and an extensive field data set of primarily qualitative observations of beach erosion and accretion (and including the Froude number). The strategy for obtaining the criteria was to plot the data in a diagram encompassing two non-dimensional parameters and subjectively fit a line that best separated onshore and offshore bar movement. In the choice of parameter combinations, at least one parameter contained a variable that characterized the sediment (w or d_{50}).

$$\frac{H_o}{L_o} = 3.92 \cdot 10^{-5} \left[\frac{H_o}{wT} \right]^3 \tag{2}$$

$$\frac{H_o}{L_o} = 4.5 \cdot 10^{9} \left[\frac{H_o}{D_{50}} \right]^{-3} \tag{3}$$

$$\frac{H_o}{wT} = 2.34 \cdot 10^{5} \left[\frac{w}{\sqrt{gH_o}} \right]^2 \tag{4}$$

Acceptable distinctions between onshore and offshore movement of both the inner and outer bar could be obtained by eqs. 2 to 4. The same exponents are obtained for the non-dimensional quantities as were noted in earlier work, but the constant multipliers have smaller values. This means that application of previous criteria for overall beach response to sand movement in the offshore produces conservative estimates for prediction of onshore sand transport of a bar. The two parameters in eq. 4 may be obtained from the parameters in eq. 2 (Kraus, Larson, and Kriebel 1991); however, the form of eq. 4 is convenient because the wave height appears inversely in the respective parameters, giving a more visually distinct separation of onshore and offshore bar movement. Reasonable predictions are also given by the simple one-parameter criteria: $H_o/wT = 7.2$, $H_o/D_{50} = 6{,}400$, and $w/(gH_o)^{1/2} = 0.0055$. Figs. 8 and 9 show H_o/wT versus $w/(gH_o)^{1/2}$ used to distinguish between onshore and offshore bar movement for the inner bar and outer bar, respectively. Criteria developed for the overall response of the beach typically focus on beach evolution in the surf zone, where wave breaking prevails. The tendency for material to be transported onshore is much greater under the action of non-breaking waves in comparison with breaking waves.

CONCLUDING DISCUSSION

Considerable information on the dynamics of natural longshore bars was obtained from a 9-year record of accurate beach profile surveys made at an average 10-day interval. Availability of data from four survey lines allowed judgement of three-dimensionality which would violate the analysis procedures, and correlations were improved by imposing censoring criteria on combined bar movement and volume. The analysis proceeded by defining bar position from a modified equilibrium profile that accounts for fining of grain size with distance offshore. The analysis covered an inner bar in 2-m depth and an outer bar in 4-m depth, which were tracked through 300 profile surveys.

For the inner bar, average depth to crest was 1.6 m, average maximum bar height 0.9 m, and average bar volume 42 m^3/m. Average speed of the inner bar was 1.5 m/day for onshore movement and 2.9 m/day for offshore movement, with maximum recorded speeds of 8.7 and 18.0 m/day, respectively. Fractal box-counting analysis showed that the typical maximum duration between wave conditions that moved the inner bar offshore was 2 months.

For the outer bar, average depth to crest was 3.8 m, average maximum bar height was 0.4 m, and average bar volume was 45 m^3/m. Although the outer bar had, on average, a volume comparable to the inner bar, the maximum height was considerably lower, producing a much more gentle bar shape. Average speed of the outer bar was 0.6 m/day for onshore movement and 1.1 m/day for offshore movement, with maximum recorded speeds of 6.1 and 15.2 m/day, for onshore and offshore movement, respectively. The typical maximum duration between wave conditions that moved the outer bar offshore was about 4 months.

Criteria previously developed by the authors to predict beach erosion and accretion were found to be applicable to bar movement if a multiplicative empirical coefficient in each criterion was modified. The results indicate that onshore movement of bars is more probable than previously estimated. The implication is that linear bars formed of dredged material are more likely to move onshore to nourish the surf zone and beach than previously thought.

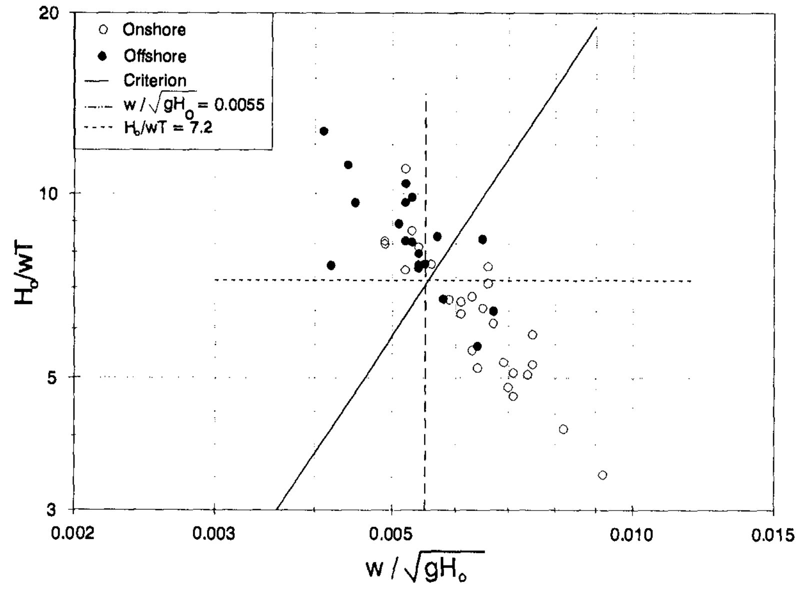

Fig. 8. Cross-shore movement of inner bar predicted using $w/(gH_o)^{1/2}$ and H_o/wT

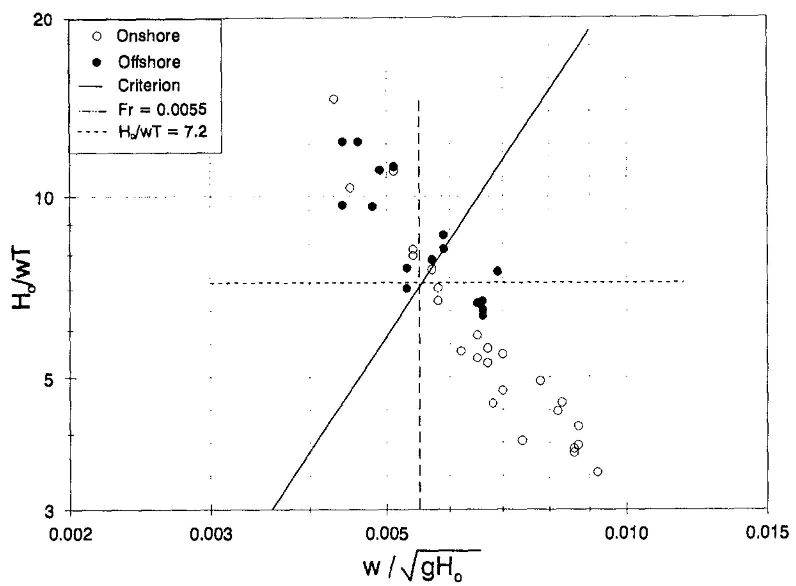

Fig. 9. Cross-shore movement of outer bar predicted using $w/(gH_o)^{1/2}$ and H_o/wT

Comparison of bar properties from the surveys at a North Carolina beach and results from experiments carried out in large wave tanks indicates similar geometric and dynamic properties (direction of movement and celerity) of bars in the laboratory and in the field. Thus, data sets from large wave tanks are of considerable value for investigating the fundamentals of cross-shore sediment transport and bar movement.

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