MODELING THE DYNAMICS OF A BAR SYSTEM AT DUCK, NC, USA

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ABSTRACT

The temporal evolution of nearshore bar topography forced by incident, wind-generated waves is predicted by a two-dimensional (2D) model. Predictions are compared with observed bathymetry from Duck, North Carolina, USA, acquired by the Field Research Facility (FRF) of the US Corps of Engineers over a period of 17 years (1980 - 1997). The model simulations presented are seen to approximate well the formation of the most frequently-observed shore-parallel bars at Duck as well as dynamic changes in their pattern caused by storm waves and varying mean water level.

1. INTRODUCTION

The two-dimensional model applied in the present work describes the temporal evolution of nearshore bar systems forced by incident, wind-generated waves (Boczar-Karakiewicz *et al.* 1987 and 1995). In this model, surface waves are described by simplified Boussinesq equations. Nonlinear wave forcing is transmitted through a wave-induced boundary layer to the bed, which is characterized by small-scale bed roughness. The model allows a finite-amplitude beach response which, in turn, feeds back to modify the wave field. At present, we consider the temporal evolution of the bed when it is forced by incident monochromatic and regular wave trains at the observed wind-wave peak-frequency. The energy is exchanged among the evolving wave modes as the wave propagates into shallower water. In the simulations presented, wave breaking and related undertow are not considered, though their incorporation is currently under development. Such simplifications allow the application of

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a model without free parameters. According to the model, distances between bar crests, the number of bars, their position and amplitude, at a given site, are scaled by naturally-occurring and site-specific units: the bar geometry is scaled by the incident wavelength, while the time of bar formation and their dynamics are scaled by the wave energy. These model predictions also explain changes in bar position in response to waves at high water levels induced by tides and storm surges.

Incident wave parameters and typically observed bed topographies are selected from field data in Section 2 and compared with model predictions in Section 3. General conclusions drawn from our work are set forth in Section 4.

2. FIELD DATA AND INITIAL MODEL PARAMETERS

In the present section, wave and bathymetry data from Duck, NC, spanning a period of 17 years (1980 - 1997) are analyzed. These data were acquired by the Field Research Facility (FRF) of the US Corps of Engineers in the following way: directional wave data were measured every 3 hours at a 10 m water depth, and bathymetry was carried out at least monthly.

In this report, a single line of cross-shore bathymetry is analyzed (#62 according to the FRF coordinates). This profile was chosen to represent the entire experimental area. It is located close to the northern extreme of the site to avoid the local topography effects of the piers. Measured data are scattered as shown in Figure 1 and no prevailing bar pattern is visible in the cloud of points. From this data, a featureless

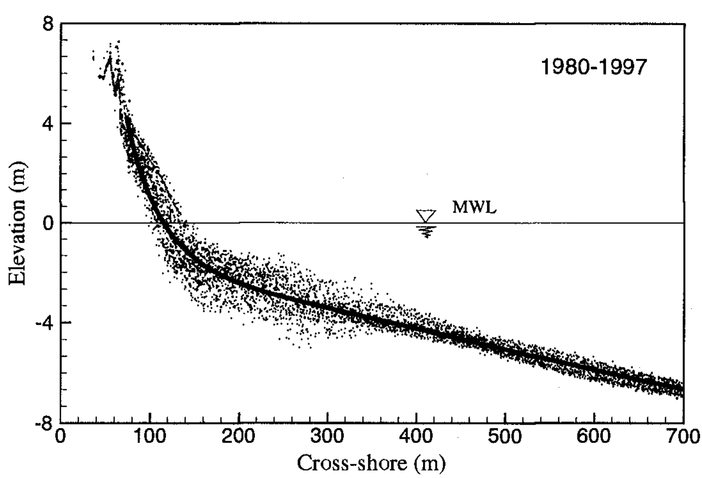

Figure 1: Foreshore morphology data at profile 62, Duck, NC, (1980-1997) and the featureless equilibrium profile

mean bed profile was determined (heavy line in Figure 1), by use of Dean's beach equilibrium formula with an additional function fitting observations lying in the very nearshore and on the upper beach. This profile was selected as the topographical input to the model calculations simulating bar formation in Section 3.

A subsequent, more detailed analysis of the topography observations was conducted to understand better the dynamics of the bed. First, the temporal sequence of profiles measured in the period 1980-1997 was animated. This interesting exercise revealed considerable temporal variability, and, occasionally, rapidly-changing bed configurations. These data suggested that metastable states exists which result from a longer sequence of wave events and not just from a single storm preceding the measured bathymetry. We proceeded by selecting from the temporal sequence of profiles (1980-97) several groups of typical bed types. The segregation criteria were based on morphological similarity, including the position of bar crests and number of bars. One among the selected groups of bed profiles is shown in Figure 2. This result confirmed conclusions from earlier work (see, e.g., Birkemeier 1984, Lippmann et al. 1993): the most frequently-observed bed profile at Duck is a two-bar system with bar crests at about 200 and 400 m relative to the FRF coordinates and the mean shoreline position at 100 m.

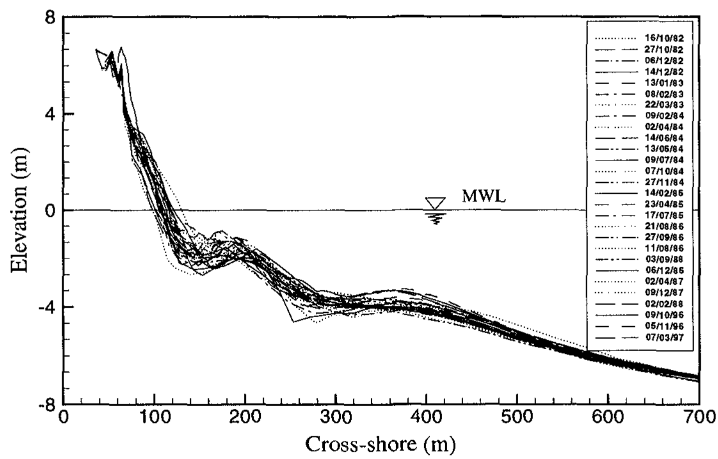

Figure 2: Typical two-bar system at Duck, NC, with indicated dates of data acquisition (based on measurements at cross-section 62)

However, during the period 1988-1995, a distinct one-bar topography (as shown later in Section 3) was predominant and the outer bar corresponding to the two-bar morphology seemed to be completely flattened out. Generally, in 17 years of measurements, the position of the nearshore bar crest varied over an interval of some 150 m, and the second offshore bar crest, when it existed, migrated about its mean 400 m position by $\pm$ 100 m.

Observations at Duck also show that every 8-9 years the previously mentioned "slow" changes in bar patterns are disturbed by episodic "anomalies" that occur at inter-seasonal cycles. During these anomalies, the bar crest positions change rapidly: for example, the inner bar may migrate 100 to 150 m in only a day or two (Birkemeier 1984, Holman and Sallenger 1993, Lippmann *et al.* 1993). These anomalous episodes are puzzling, especially in light of the metastability exhibited in Figure 2. In Section 3, we show a simulation of an anomalous event at Duck using our previously decribed model (see Section 1 and the references mentioned there). The observed wave environment pertaining to anomalies is now described.

In the predictions of the bar dynamics made in Section 3, the observed prevailing bar patterns, as seen in Figure 2, and the episodic change in the bar system are correlated with events in the local wave climate, in particular with single storms, or sequences of storms with and without a simultaneous water level change.

Input wave parameters, which are required by the model, are specified at the deep-water end of the nearshore zone by peak periods T_p, incident wave energy a^2 (where a denotes wave amplitude), and the mean water level. These data were obtained by analyzing the measured parameters of waves and waterlevels from 1980-1997 as presented in the format shown for the year 1990 in Figure 3.

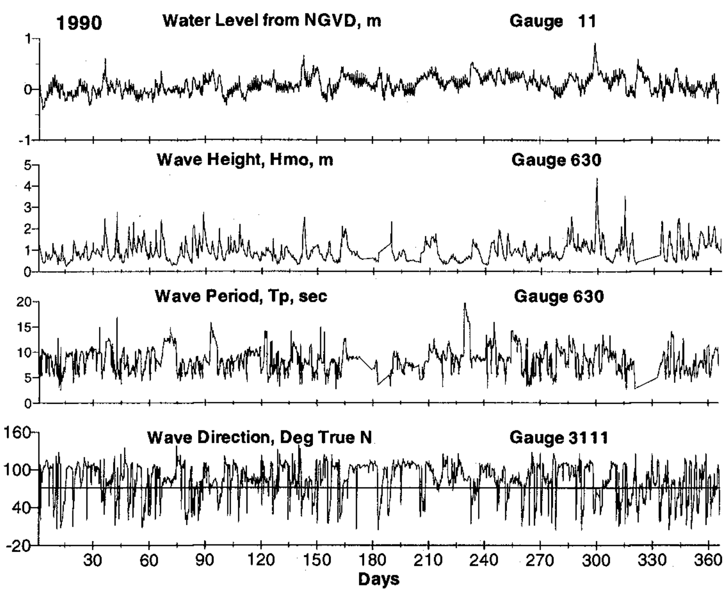

Figure 3: Observed wave and water level parameters at Duck, NC, in 1990

The analysis of data showed the wave climate at Duck to be, quite "noisy". Peak periods and related wave energy in incident waves vary irregularly during the year

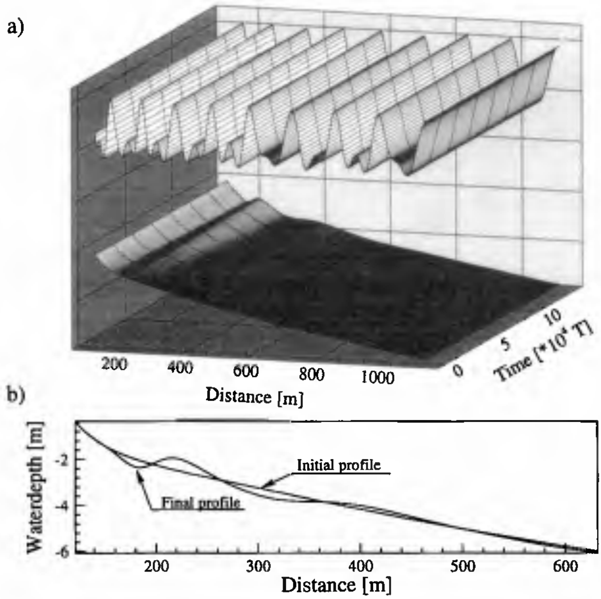

Figure 4: Prediction of the formation of the typical two-bar system by major storms (with T_p = 15s) at Duck, NC: (a) temporal evolution of the bar system from the featureless equilibrium profile, (b) initial and final profiles from (a).

with large differences between consecutive years. However, certain "seasonal" patterns could be discerned: extreme storm events and hurricanes occur predominantly in the autumn-winter season (with T_p from 12 s to 20 s); these stormy periods are followed by a summer season of moderate wave activity (T_p below 10 s). During the episodic anomalies mentioned above, there occur major storm events with water levels on the order of +1 m above the mean (see again Figure 3).

In the model predictions, the value $T_p = 15$ s was chosen to initiate simulations of major storm events both at mean and high water levels. Extreme storm events are represented by incident waves of period $T_p = 17.5$-s. On the other hand, summer waves are represented in the model by wave trains with $T_p = 10$ s.

3. PREDICTIONS AND COMPARISONS WITH OBSERVATIONS

Formation of the most frequently-observed two-bar system (Figure 2) by major storm events was simulated by the model with topographical input in the form of the mean featureless bed profile (heavy line in Figure 1) and deep-water incident wave parameters with peak period $T = 15$ s and wave amplitude $a = 1.5$ m. The temporal evolution of the seabed in the surveyed part of the nearshore is shown in Figure 4a

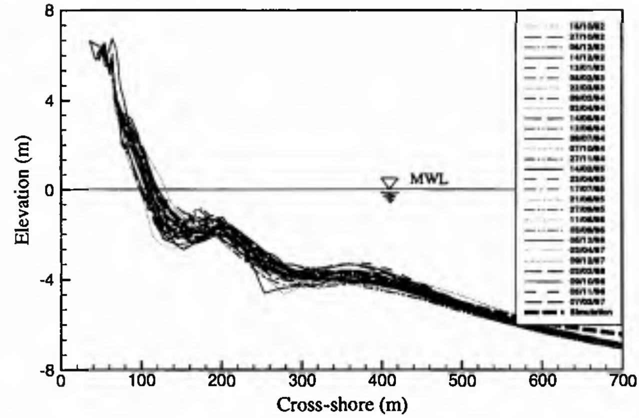

Figure 5: Comparison of predictions (heavy dashed line) and measurements of the most frequently-observed two-bar system at Duck, NC

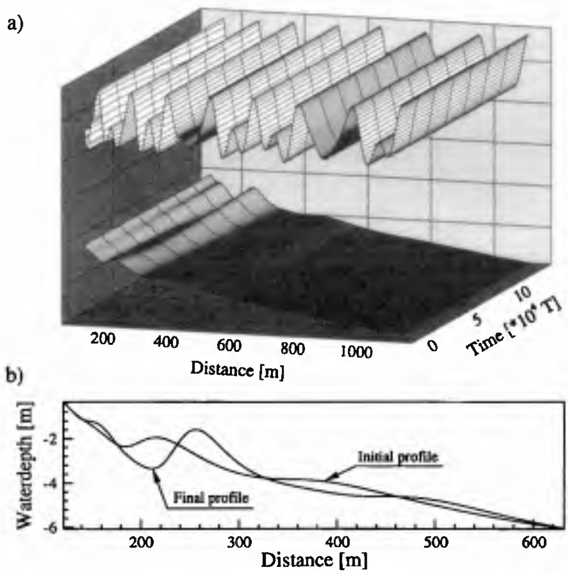

Figure 6: Prediction of changes from the typical two-bar system by extreme autumn-winter storms (with $T_p = 17.5$s): (a) temporal evolution of the new two-bar system from the original two-bar profile, (b) initial and final profiles from (a).

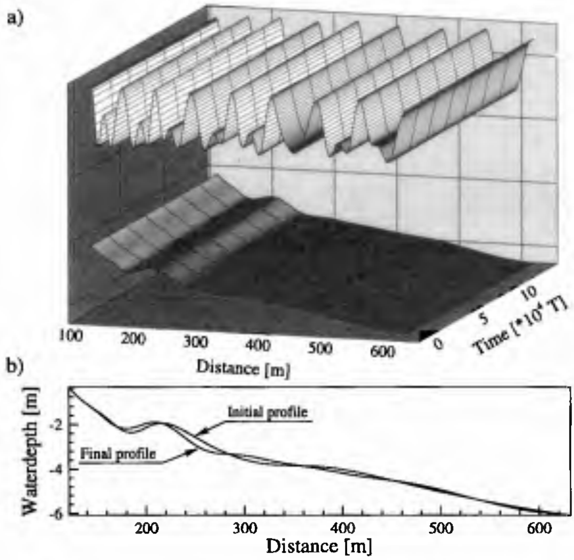

Figure 7: Prediction of changes from the typical two-bar system by moderate summer storms (with $T_p = 10$s): (a) temporal evolution to a one-bar system from the typical two-bar profile, (b) initial and final profiles from (a).

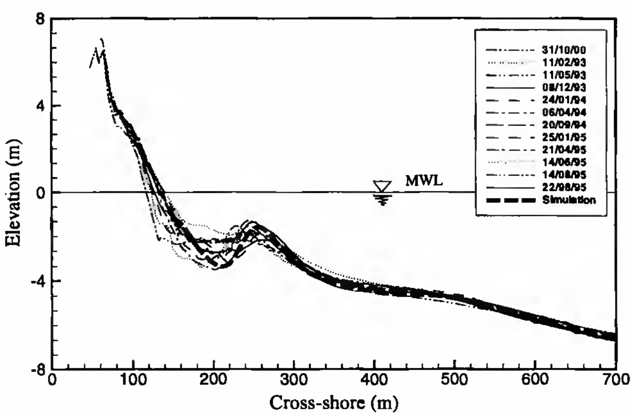

Figure 8: Comparison of predictions (heavy dashed line) and measurements of an observed two-bar system at Duck, NC (with bar crest positions at 250 m and 500 m).

and the initial and final profiles are depicted in Figure 4b.

In Figure 5, the heavy dashed line showing the predicted final bed configuration from Figure 4 is superimposed on observations from Figure 2. Comparisons of position, the number of predicted bars and their amplitudes are in quite good agreement with the 17 years of observations.

In the following simulations, the dynamics are initiated with the two-bar bed topography provided by the model, as depicted in Figures 4a and 4b. In the simulation shown in Figure 6a, the incident waves represent hurricane waves ($T_p = 17.5$ s). In a second calculation shown in Figure 7a, initiated with the same two-bar initial profile, the incident waves are moderate summer waves ($T_p = 10$ s).

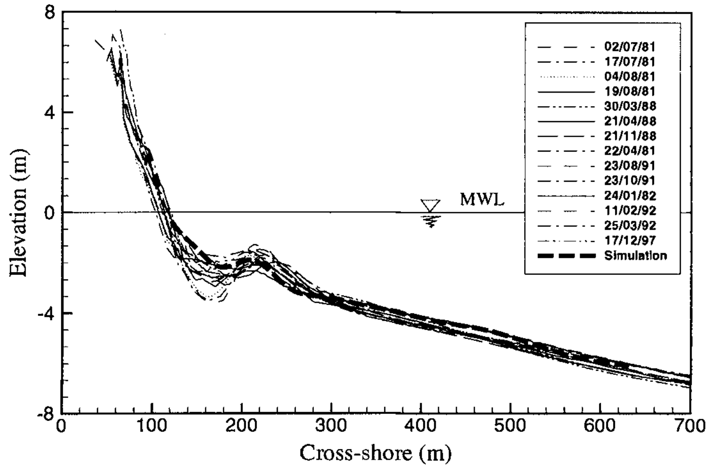

Figure 9: Comparison of predictions (heavy dashed line) and measurements of an observed one-bar system at Duck, NC (with the bar crest position at 220 m).

In both the cases shown in Figures 6 and 7, the model predicts the response of the frequently observed two-bar bathymetry to ambient hydrodynamic regimes representing simplified versions of winter ($T_p = 15$ s and 17.5 s) and summer ($T_p =$ 15 s and 10 s) wave activity. In the winter season (Figure 6a), the model predicts a transformation of the primary two-bar system via the migration of bar crests to new locations: the inner bar shifts from its 200-m position to a 250-m location; the outer bar migrates offshore by some 100 m from its mean 400-m position. In the first stages of the summer calculation (see bed profile at time $t = (2 \times 10^4)T_p$ in Figure 7), the post-storm two-bar system is only slightly changed by moderate waves ($T_p = 10$ s). However, the model also shows that at later stages of the calculation (a long-lasting period of moderate waves in a non-stormy year), the two-bar system goes over into a single bar system (see the final profile in Figures 7a and 7b).

In Figures 8 and 9, the final bed configurations from Figures 7b and 8b are superimposed on observations. Again, the comparison of predicted positions, number of bars and their amplitudes shows quite acceptable agreement.

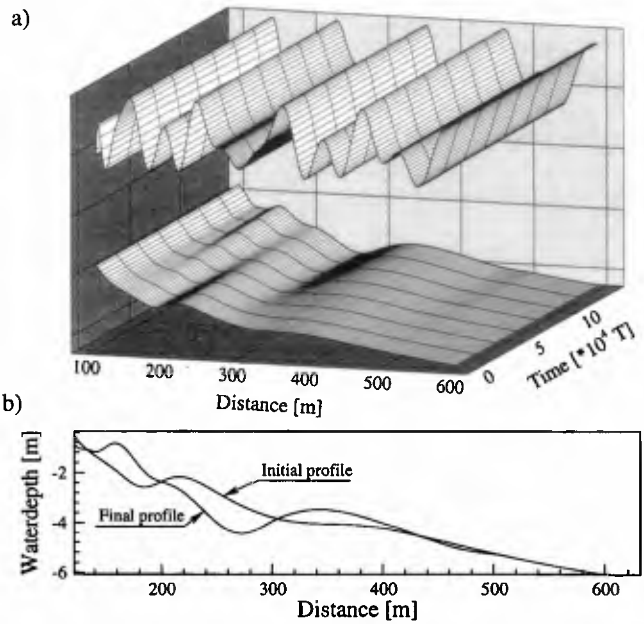

Figure 10: Prediction of an episodic change in the two-bar system at Duck, NC (a) migration of the post-storm profile under extreme waves (T_p = 15 s), accompanied by a 1.2-m surge above the mean water level, (b) initial and final bed profiles from (a).

The final simulation reported here was concerned with an "anomalous" situation wherein a storm with T_p = 15 s came on with a simultaneaos 1.2-m surge in the water level. As shown in Figure 10, the bottom response to extreme waves at this high water level was for the primary two-bar system to shift to a new position. In a period of two days, the outer and inner bar crests migrate some 100 m in the shoreward direction (compare the initial and final bed profiles in Figures 10a and 10b).

Comparisons of the predictions depicted in Figure 10 with observations are shown in Figure 11. During this episode, the calculation predicts a significant increase in the volume of the outer bar as measured at the site.

5. CONCLUSIONS

1. The model simulations presented here are aimed at approximating the temporal

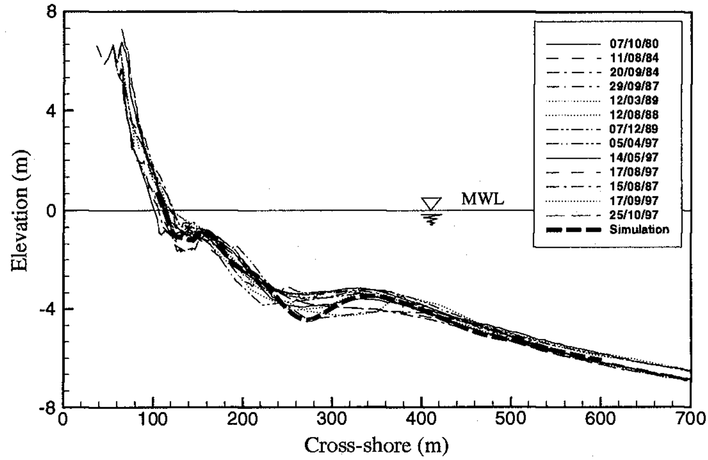

Figure 11: Prediction (heavy dashed line) and observations of episodic, nonstationary behavior of the two-bar system at Duck, NC.

evolution of the most frequently-observed shore-parallel bars at Duck and the dynamic changes in their pattern.

The following results were obtained.

- The predominant two-bar bed configuration is associated with forcing by large storms ($T_p = 15$ s) and the model approximates the observations, as shown in Figure 8.
- Predicted modifications of bar crest positions in the most frequently-observed two-bar system occur in the winter season during extreme storm events, as shown in Figure 7. The predicted bed configuration correlates well with observations (Figure 9).
- Predicted modifications from the most frequently-observed two-bar system to a single bar occur over several months of moderate storm activity, as seen at the site and illustrated in Figure 10.

2. The rapid and episodic response of the most frequently-observed two-bar system are predicted during extreme storm events accompanied by elevated mean water levels (Figure 10). Figure 11 illustrates the relation between model predictions and observed changes in bar morphology. These anomalous events occur on an abnormal cycle of several years duration. The one featured in our comparison was taken from 1989 data.

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REFERENCES

W.A. Birkemeier. 1984. Time scales of nearshore profile changes. *19th Proc.Int. Conf. Coast. Eng.*, ASCE, Houston, Texas, USA:1507-1521.

Boczar-Karakiewicz, B., J.L. Bona and D.L. Cohen. 1987. Interaction of shallow-water waves and bottom topography. *Dynamical problems in continuum physics, mathematics and its application*, J. L. Bona, C. Dafermos, J. Erickson & Kinderlehrer eds., Springer-Verlag, New York, NY, IMA Series in Mathematics and its Applications, **4**: 131-176.

Boczar-Karakiewicz, B., D.L. Forbes and G. Drapeau. 1995. Nearshore bar development in the Southern Gulf of St. Lawrence. *J. Waterways, Port, Coast. & Ocean Eng.*, ASCE, 129: 49–60.

Holman, R.A. and A.H. Sallenger. 1993. Sand bar generation: a discussion of the Duck experiment series. *Journal of Coastal Research*, SI(15): 76–92.

Lippmann, T.C., R.A. Holman and K.K. Hathaway. 1993. Episodic, nonstationary behavior of a double bar system at Duck, North Carolina, U.S.A., 1986-1991. *Journal of Coastal Research*, SI(15): 49–75.