# CHAPTER 274

## WAVE GROUPS IN A BARRED NEARSHORE

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## ABSTRACT

Observations of waves and sediment movement in coastal zones have shown evidence of groupiness in the wave field associated with episodic events of high sediment concentration above the sandy bed. These observations raised the question about the role of wave groups on large-scale coastal sand bars. The present study addresses this question. Analysis is based on data from a lacustrian experimental study site located in Nottawasaga Bay, Lake Huron, Ontario, Canada. The results of field measurements provided initial and boundary conditions for numerical simulations of wave-seabed interactions under waves and wave-groups. Model predictions are compared with observations. The conclusions suggest that nonlinearly modulated wave trains may potentially form and modify sand bars in coastal zones due to large-scale spatial variation in the nonlinear structure of these waves. However, strong irregularities in observed wave groups and related episodic sediment concentration events suggest that these groups do not represent an effective factor in the 'slow' process of sand bar formation.

## 1. INTRODUCTION

In deep ocean, with limited breaking, wave groups can be described by superposition of linear wave components or by applying nonlinear modulation instabilities. Medina and Hutspeth (1990) have shown that linear algorithms describe observed wave groups in a water depth greater than 10 m with satisfactory agreement. Battjes and Vledder (1984) supported this conclusion for the surf zone.

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However, in the linear approach, waves are assumed to be a Gaussian process, with independent components of the wave field. In earlier studies, it also has been assumed that upon initial breaking, wave groups vanish, except for a small zone surrounding the mean breakpoint.

These assumptions were shown not to be valid in shallow coastal zones. List's quantitative study (1991, 1992), using the concept of wave group envelope, has confirmed that groupiness decreases rapidly through the surf zone, and is sensitive to initial wave breaking. However, he also proved that the degree of groupiness does not become negligible, even in a saturated surf zone. His analysis revealed that groupiness of unbroken waves remains constant over a wide range of incident wave conditions from fairweather swells to storm seas. That observation contradicts the intuitive concept of groupiness resulting from the superposition of sinusoidal waves of similar frequency. According to the linear concept, an increase of spectral bandwidth should result in decreased groupiness.

Laboratory tests and numerical simulations carried out with wave shoaling over a beach of constant slope allowed experimentations with nonlinear wave groups in a simpler environment than a natural coast. A set of such experiments has been conducted in the wave basin of the Hydraulics Laboratory of the National Research Council of Canada (Nwogu 1993). Bichromatic linear waves were generated at the deep-water end of a 1:25 sloping concrete beach. The time series of water surface elevation were measured at two locations: at the toe of the slope and at the initial breaking location. A numerical model based on Boussinesq equations simulated hydrodynamics in the experiment. Comparisons of model results and observations showed good agreement and explained the nature of nonlinear transformations in the initial modulated train composed of sinusoidal waves. When these waves approach shallow water, their shape changes into a complex nonlinear form. The nonlinearity in an individual wave profile increases with decreasing water depth, due to a transfer of energy from the two fundamental frequencies of the incident biharmonic wave train into respective higher harmonic modes. A small amount of energy is also transferred to a low-frequency group-bound wave. That energy increases with decreasing water depth.

The results of a similar numerical study based on a KdV equation with variable coefficients describe the nonlinear evolution of a single group of modulated sinusoidal waves propagating over a gently-sloping beach (Talipova *et al* 1995). Nonlinear and dispersive effects in this group lead to recurrent energy transfer between the fundamental and the higher harmonic components. The initial wave group evolves with increasing distance into a strongly nonlinear wave packet. At a distance of several tens of wavelengths from the deep-water end, the initial modulation changes shape. Higher waves are shifted to the front of the packet due to frequency dispersion. Nonlinearity causes the appearance of secondary crests in the individual waves of the packet. Therefore, it is not

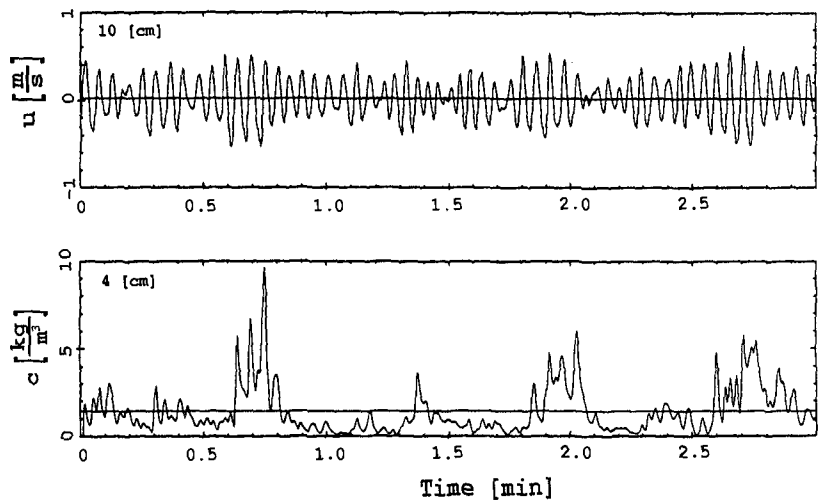


Figure 1: (a)Cross-shore velocity (at 0.10 m above the bed), (b) suspended sediment concentration (at 0.04 m above the bed).

clear how to relate the number and position of waves in the packet with the number of sinusoidal waves in the initial group.

Examples of numerical simulations and laboratory experiments with idealized wave groups show how their properties result from nonlinearity and dispersion of the shallow-water environment. On a natural coast, wave group behaviour is even more complex because of the presence of several flow components.

Observations of waves and sediment movement in coastal sites (Greenwood *et al.* 1992) show evidence of groupiness in the wave field associated with episodic events of high sediment concentration above the sandy bed. A typical record of nearbed velocities and suspended sediment concentration is shown in Figure 1. These observations raised the question about the role of wave groups on large-scale coastal sand bars.

The present study addresses this question and concentrates on the role of wave groups in sand bar formation and dynamics. Our analysis is based on observations from an experimental study site presented in Section 2. Numerical simulations of wave-seabed interactions under waves and wave-groups are presented in Section 3. Model calculations are carried out with initial data from the field experiment. Predictions are compared with observations from the experimental site. The conclusions are formulated in Section. 4.

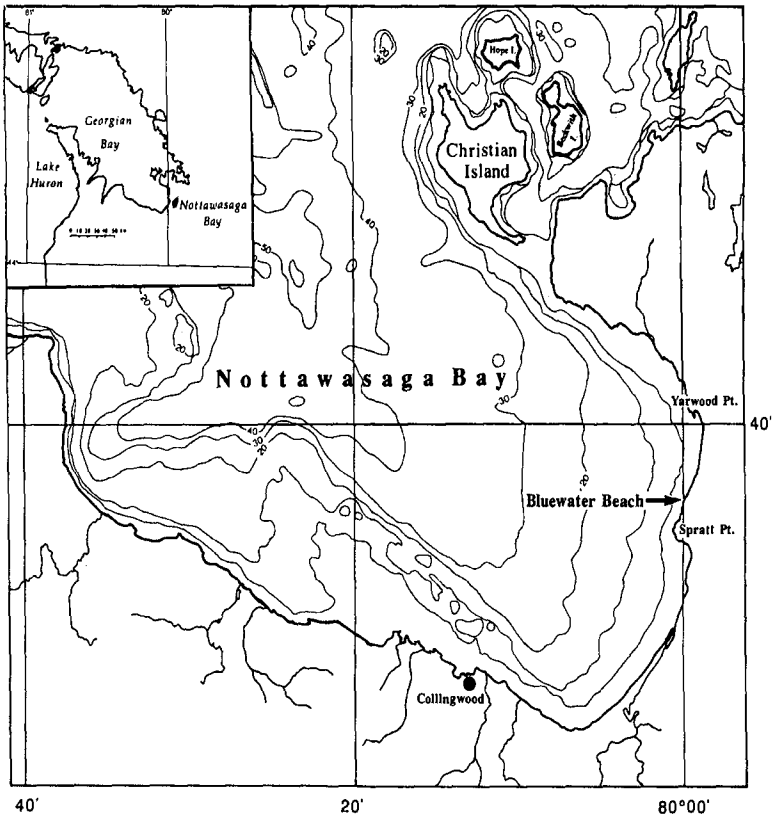


Figure 2: Field site, Bluewater Beach, Nottawasaga Bay, Ontario, Canada.

## 2. THE EXPERIMENTAL SITE AND FIELD OBSERVATIONS

The study site (Bluewater Beach, Nottawasaga Bay, Lake Huron, Ontario, Canada) is located in a narrow bay, as shown in Figure 2. Incident wind-generated storm waves arrive to the nearshore zone from a narrow window and impinge on the beach from the shore-normal direction. Under such conditions, we may apply our two-dimensional morphological model in calculations presented in Section 3. In the chosen site, surface hydrodynamics are simpler than on ocean coasts as they are not affected by tidal flows.

The study site has a barred shoreface (see Fig. 3 for the location of sensors used in measurements). The typical multibar shoreface from Figure 3 is not static. In 1987, a beach survey revealed a one-bar profile ( Fig. 4a), which transformed into a multi-bar profile in the following year (Fig. 4b).

Field measurements of waves and sediment concentrations at Bluewater Beach analyzed by Osborne and Greenwood (1992) have shown that the lo-

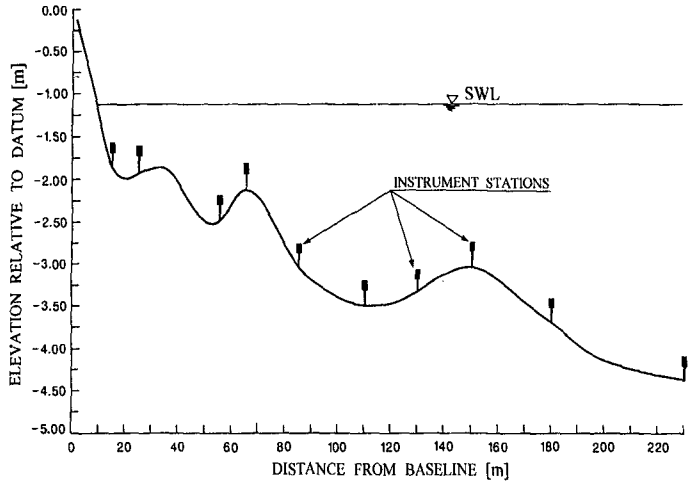


Figure 3: Typical shoreface profile and sensor deployment (pressure sensors, electromagnetic current meters, optical backscatter sensors (OBS)).

cal time-varying suspended sediment flux is a response to high-frequency wind-wave oscillatory currents, low-frequency waves and quasi-steady currents (undertow). The relative importance of these transport components varies spatially and temporally in association with variability in incident wave energy. In contrast to a non barred shoreface, where variations of transport components are strongly controlled by monotonically-decreasing local water depth, across a barred shoreface sediment fluxes are constrained by position with respect to the bars.

Co-spectral analyses of cross-shore velocities and sediment concentrations reveal that grouped, nonlinear shoaling waves induce large onshore sediment transport rates at wind-wave frequencies. However, simultaneously, net offshore-directed transport at low frequencies was also observed. This offshore sediment flux compensates onshore currents induced by grouped waves. During extreme storms, the group-bound long wave could potentially dominate the net oscillatory component of suspended sediment transport and, consequently, displace sediment in the offshore direction.

Additional complexity at a barred foreshore results from waves breaking over a bar crest and waves reforming in the bar trough. Observations show that, typically, outside the surf zone, the re-suspension of sediment under groups of large waves is coherent with the offshore phase of low-frequency modulation of the velocity field due to the presence of wave groups and the group-bound, forced long wave.

However, landward of the zone of wave breaking, on the bar crest and on the upper lakeward slope, the wave-group structure was observed to be diminished.

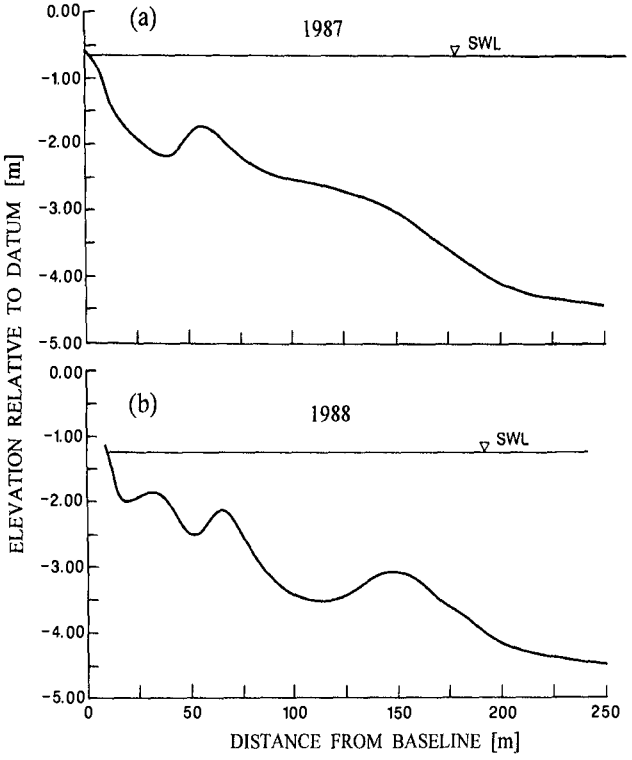


Figure 4: Shoreface profiles at Bluewater Beach in 1987 and 1988.

Here, low-frequency waves were still evident, which suggests the presence of edge waves or reflected long waves. These waves may contribute to observed high sediment concentrations and to the observed morphodynamic response under highly energetic conditions.

Observations have also shown that bar topography exerts an important constraint on both the magnitude and direction of transport by oscillatory and mean currents. The bar crests experienced the largest oscillatory currents and greatest levels of turbulence induced by wave breaking. Surprisingly, however, the net suspended sediment transport rates were minimal, near balance, between the mean transport rate directed offshore by undertow and the net onshore oscillatory transport rate controlled by asymmetric waves at or close to breaking. The oscillatory transport rates at wind-wave frequencies decreased with increasing water depth both landward and lakeward of the bar crest.

According to the interpretation of reported spatial changes in suspended transport rates, it has been concluded that spatial variation in sediment transport does concur with bar morphodynamics that resulted from the monitored storm event. After the storm, the inner bar migrated landwards. However,

the lower lakeward slope did not show any erosion despite large and persistent sediment flux gradients and net offshore transport.

The reported results of observations analyzed by Osborne and Greenwood (1992) were concluded by a statement that the net oscillatory sediment transport rate induced by low-frequency waves increases both landward and lakeward of the breaker zone on the bar crest, as does the mean sediment transport rate. Additionally, it was shown that the low-frequency group-bound wave transports sediment offshore. However, it could only be inferred that the secondary low-frequency wave may transport sediment onshore because observations did not provide quantitative data on the structure of the low-frequency wave and about its role in the maintenance of the bar form.

The results of field data analysis presented above show that surface hydrodynamics and related sediment fluxes are extremely complex in a barred foreshore. With available technology and analytical methods applied in the study of Osborne and Greenwood (1992), it is, at present, impossible to discriminate between the contribution of wave groups to sediment transport from the contribution of the remaining transport components active in the nearshore. In their conclusion, Osborne and Greenwood also pointed out that the spatial variation of suspended sediment transport rates correlated only partially with observed changes in bar morphology.

The numerical modeling presented in Section 3 allowed us to investigate the influence of wave groupiness on bar dynamics in idealized, simple conditions. Wave and topography data from field measurements at Bluewater Beach were used in initial and boundary conditions required in the model, and in the experimental verifications of model predictions.

## 3. METHODOLOGY OF NUMERICAL SIMULATIONS

We present three sets of numerical experiments investigating wave-bed interactions in a coastal environment. In these experiments, surface hydrodynamics are induced by wave trains at wind-wave frequencies characterizing the wave climate at Bluewater Beach. In the first set of calculations, model predictions were carried out with incident nonlinear waves without any group-like modulation. In the remaining calculations (set 2 and set 3), wave-bed interactions were induced by modulated wave trains with some properties of groupiness observed in the coastal wave field.

In the analysis presented, quasi-steady flows (undertow) and low-frequency group-bound waves are not considered. The first simplification is sustained by observations from Bluewater Beach (Osborne and Greenwood 1992). The results of these observations show that despite evidence of steady flow contribution to sediment transport, the changes seen in bar morphology correlated only partially with measured transport rates. The second assumption is based on conclusions from the DUCK'85 field experiment. In this experiment, low-frequency group-bound waves and other secondary, low-frequency flows were

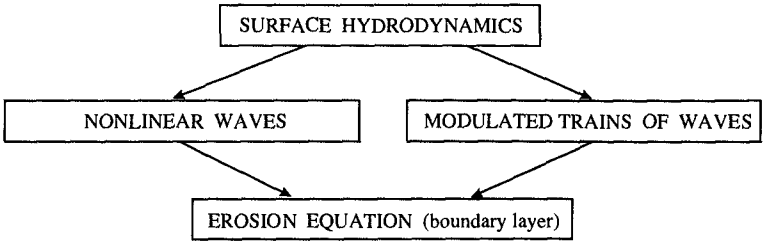


Figure 5: Schematical presentation of modeling non-modulated and modulated wave trains.

shown to contain lower energy levels than oscillations at wind-wave-induced frequencies (List 1991).

To predict the spatial and temporal evolution of the bed morphology under waves, we applied our two-dimensional morphological model (see, e. g., Boczar-Karakiewicz *et al.* 1995). In this modular model, the surface wave induces a nearbed flux of sediment, resulting in a deformation of the underlying seabed. For nonlinear incident, non grouped waves, surface hydrodynamics are described by a simplified Bussinesq equation (Boczar-Karakiewicz *et al.* 1987). To simulate incident trains of wave groups we have modified the original description of the surface wave. In this simulation, group-like modulations in the incident wave train result from superposition of two waves of similar frequency. The original and modified approaches are shown schematically in Figure 5. In all calculations, incident wave conditions are given at the deep-water end of a two-dimensional coastal zone. The initial topography, a uniform featureless slope, corresponds to mean slopes observed at Bluewater Beach (broken line in Fig. 6c).

In the first set of calculations, we analyzed the morphological response to incident nonlinear waves without any group-like modulation (Fig. 6). The spatial evolution of the surface wave (Fig. 6a and 6b) and the temporal change of the underlying bed from the initial featureless slope (broken line in Fig. 6c) to a final multibar profile (heavy line in Fig. 6c) are predicted for an extreme storm event. This event is simulated in the model by a train of regular waves with period $T$ ($T = T_p = 6.9$ s), where $T_p$ denotes the peak period of extreme storms at Bluewater Beach. (In the results presented, the amplitudes of harmonic wave components are non-dimensionalized by the amplitude of the incident wave.)

The temporal evolution of waves and morphology is shown in more detail in Figure 7. The morphological time scale $\tau$ (Fig. 7a) characterizing the formation of a multibar morphology from an initially featureless slope is of the order of hundreds of thousands of wave periods. The comparisons presented in Figure 7b show satisfactory agreement between the predicted and observed number of bars and bar-crest locations.

For a sequence of incident waves simulating a typical season (extreme winter

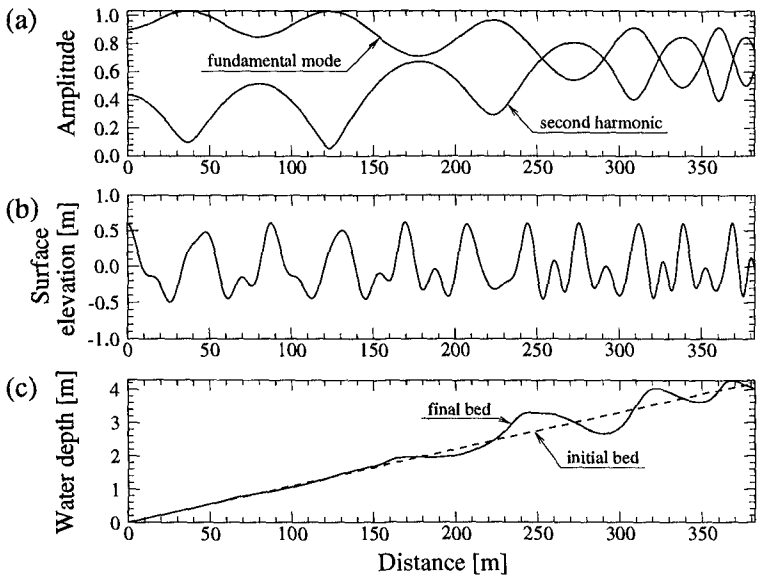


Figure 6: Prediction of wave and morphology evolution under nonlinear waves without group-like modulation (simulation of an extreme storm event with $T_p$ = 6.9 s): (a) amplitude of the two first harmonic modes, (b) free-surface elevation, (c) initial and final bed.

storms followed by moderate summer wave conditions, with $T_p$ = 6.9 s and $T_p$ = 3.5 s, respectively), the model correctly reproduces the observed seasonal variability of the shoreface morphology that transforms from a multiple bar profile into a single bar, as observed at Bluewater Beach (Fig. 3; see also Boczar-Karakiewicz and Jackson 1991, Boczar-Karakiewicz *et al.* 1995).

In the second set of calculations, we simulated the linear effects of groupiness on coastal morphology. In this calculation presented in Figure 8, the group-like modulated wave train (Fig. 8a) propagates over the featureless mean slope of Bluewater Beach (Fig. 8b) without interacting with the underlying bed. A similar result is obtained for an initial multibar bed profile which remains unchanged under a train of linear wave groups (see again Fig. 8b). The amplitude modulation in the train of linear wave groups at $x$ = 100 m is shown in Figure 9. Modulation results from a superposition of two waves of similar frequency, derived from the peak period, $T_p$ = 6.9 s, of extreme storm events observed at Bluewater Beach.

In the third set of calculations shown in Figure 10, surface hydrodynamics are again induced by a group-like modulation (in the frequency band of extreme storms at Bluewater Beach). In contrast to previous experiments with linear wave groups (set 2), we have imposed spatial, nonlinear energy flow between

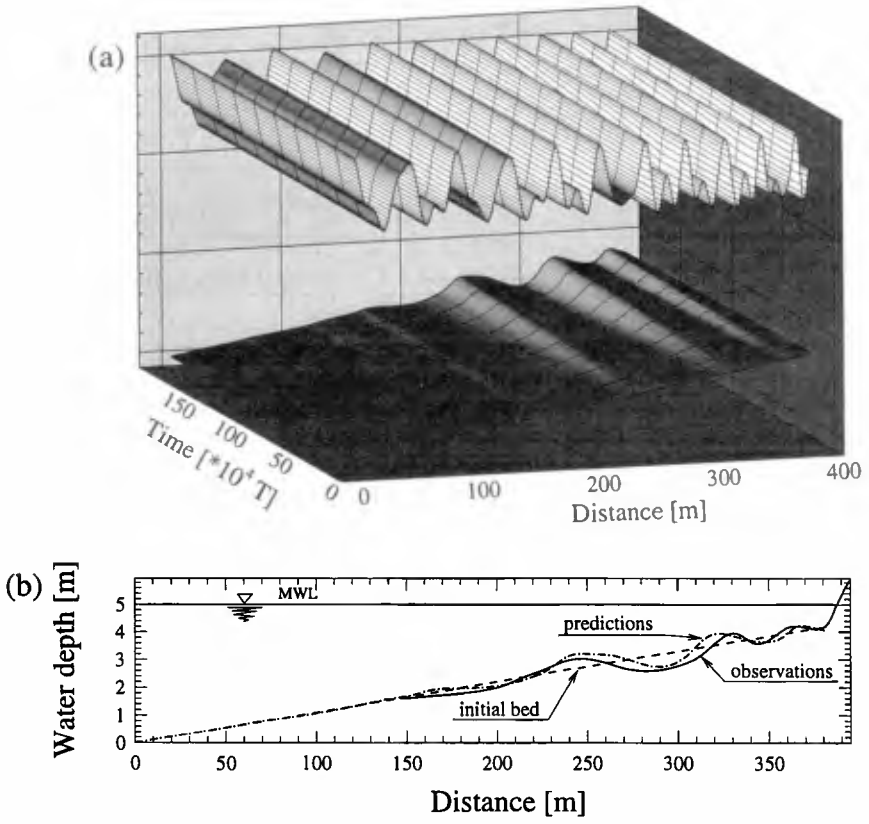


Figure 7: Prediction of morphology evolution under nonlinear waves without group-like modulation (simulation of an extreme storm event with $T_p = 6.9$s): (a) temporal evolution of waves and morphology, (b) predicted and observed multibar morphology.

fundamental modes of the incident wave train in the present simulation (see Fig. 10a). This pattern results from the solution of approximated Boussinesq equations (Fig. 5; Boczar-Karakiewicz *et al.* 1987). The spatial view of the resulting surface elevation is shown in Figure 10b. The velocity field of simulated wave groups generates nearbed sediment fluxes that gradually deform the underlying bed. Eventually, at time $\tau$ ($\tau = 10^4 T_p$), the initially-featureless, uniform slope (broken line in Fig. 10c), evolves into an equilibrium configuration (solid line in Fig. 10c). In the deeper part of the shoreface (at 0-260 m, Fig. 10c), the initial featureless slope remains nearly intact. In the shallower part (at 260-380 m in Fig. 10c), the initial bed deforms into multibar morphology. The spatial distribution of bar crests correlates with the nonlinear pattern of the imposed energy exchange among fundamental modes of the wave group

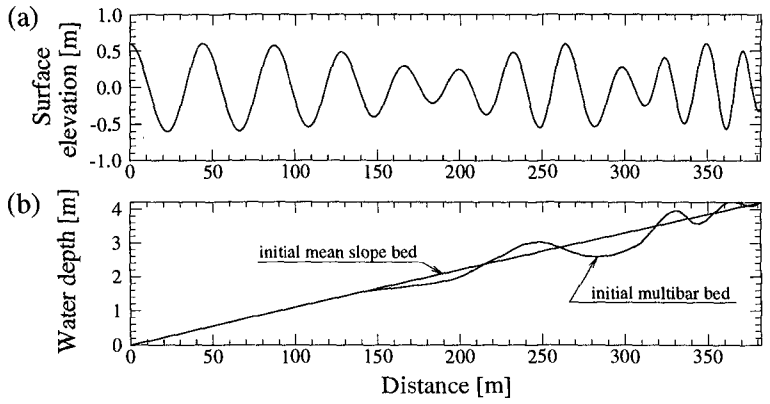


Figure 8: Evolution of waves and morphology under group-like modulated wave train (linear case): (a) free-surface elevation, and (b) shoreface morphology.

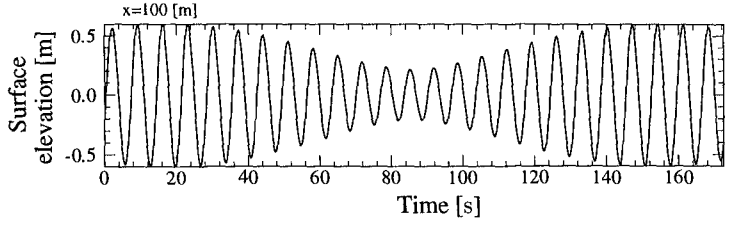


Figure 9: Time history of the incident bimodal wave train (linear case)

(Fig. 10a).

Figure 11 shows, at three chosen locations indicated in Figure 10c, the time history of surface elevation in nonlinear simulation. These records indicate strict periodicity in the time domaine, $T$. In contrast, velocity records from field measurements show evidence of pronounced temporal irregularity in observed wave groups (see again Fig. 1a). The reported results of model calculations suggest that large-scale morphology in coastal zones responds to the passage of nonlinear waves. In both nonlinear cases considered (set 1 and set 3), a rhythmical bed configuration is generated by waves characterized by large-scale nonlinear modulation in their amplitudes. The process of bar formation (Fig. 6 and Fig. 10) and bar transformation (Fig. 4) lasts over time denoted by $\tau$ in Figure 6. This morphological time scale $\tau$ is several orders of magnitude lower than the hydrodynamical scale $T$, characterized by the wave period of the incident wind wave.

In contrast, the large-scale coastal morphology (featureless uniform slope and a multibar profile) does not respond to the passage of trains of linear wave groups. This conclusion explains observations reported from the study

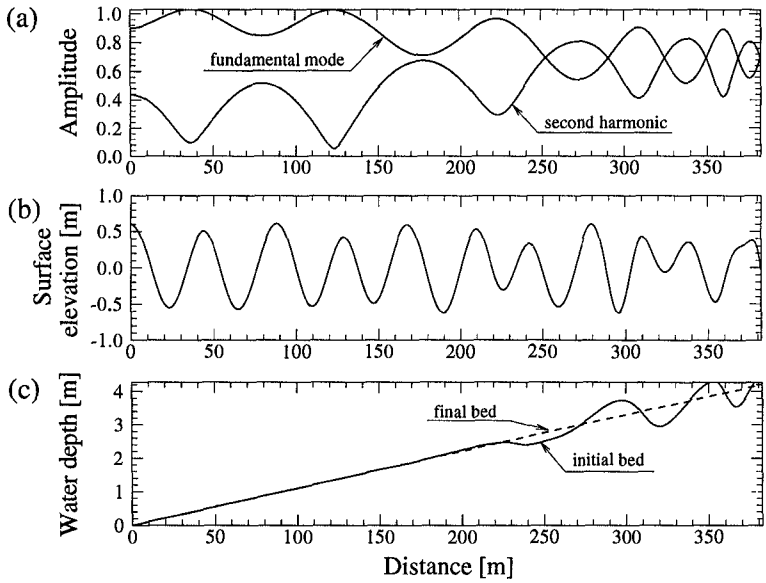


Figure 10: Evolution of waves and morphology under a group-like modulated wave train (nonlinear case): (a) initial spatial modulation of wave amplitudes, (b) free-surface elevation, and (c) shoreface morphology.

site according to which the deeper lying outer bar and the lakeward slope of the inner bar were unaltered during the monitored moderate summer storm (with peak period waves $T_p = 3.5$ s). During this storm, part of the unaltered underwater beach was located in a deep-water region for both the incident peak period wave and for observed wave groups related to summer wave conditions (see, e.g., Fig. 8).

## 4. CONCLUSION

1. Model predictions show that nonlinearly-modulated wave trains may potentially form and modify sand bars in coastal zones. These morphological changes are correlated with large-scale spatial variation in the nonlinear structure of these waves.

2. The predictions presented with strictly periodic nonlinearly-modulated waves suggest that sand bars are formed over time scales in the order of hundreds of thousands of wave periods. Velocity records from Bluewater Beach reveal strong irregularities in observed wave groups and related episodic sediment concentration events. Therefore, on natural coasts, these irregular wave groups do not represent an effective factor in sand bar generation.

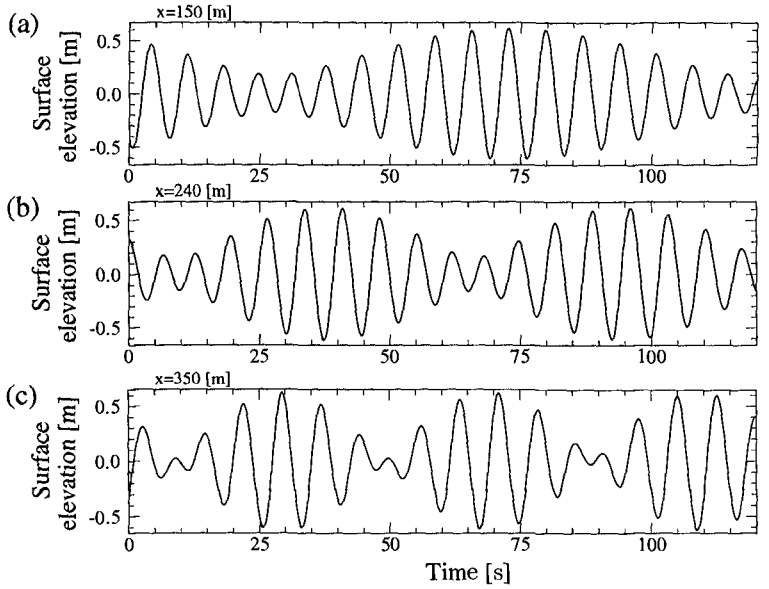


Figure 11: Time history of the shoaling group-like modulated wave train (in three chosen cross sections of the shoreface indicated in Fig. 10).

3. Predictions and observations show that trains of linear wave groups do not interact with the large-scale nearshore morphology.

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