Coastal Engineering, 19 (1993) 151-162
Elsevier Science Publishers B.V., Amsterdam

Experimental investigation of wave propagation over a bar

S. Beji* and J.A. Battjes

Delft University of Technology, Department of Civil Engineering, Stevinweg 1, P.O. Box 5048, 2600 GA, Delft, Netherlands

(Received 6 March 1992; accepted after revision 30 June 1992)

ABSTRACT

Beji, S. and Battjes, J.A., 1992. Experimental investigation of wave propagation over a bar. *Coastal Eng.*, 19: 151-162.

Laboratory experiments have been performed to elucidate the phenomenon of high frequency energy generation observed in the power spectra of waves traveling over submerged bars. Wave breaking itself, even in the case of plunging breakers, is found to be a secondary effect in this process, contributing by dissipating the overall wave energy without changing its relative spectral distribution significantly. The dominant physical mechanism is the amplification of the bound harmonics during the shoaling process, and their release in the deeper region, resulting in the decomposition of these finite amplitude waves. The observations suggest the feasibility of numerical modeling of the harmonics generation and release in breaking waves on the basis of a model for nonlinear conservative (non-dissipative) wave-wave interaction, to simulate the evolution of the spectral shape, in conjunction with a (semi-empirical) model for the dissipation of the total energy due to breaking.

1 INTRODUCTION

Accurate estimation of wave conditions in the nearshore zone has always been a central issue in coastal engineering. Unlike deep water waves, shallow water waves are profoundly modified by the bottom topography. Refraction, diffraction, shoaling, and breaking are typical manifestations of this interaction. The subject matter of this study is concerned with spatial evolutions of steep waves propagating over a longshore bar. Frequent occurrence of wave breaking in such regions naturally suggests a link in this direction and requires an assessment of the role of wave breaking in this process.

Wave breaking can be viewed as a twofold manifestation: a pre-breaking stage with a sequence of ordered motions like wave steepening and nonlinear

---

Correspondence to: J.A. Battjes, Delft University of Technology, Department of Civil Engineering, Stevinweg 1, P.O. Box 5048, 2600 GA, Delft, Netherlands.
*Post-doctorate fellow. Permanent address: Cumhuriyet Caddesi No: 148, Kirklareli, Turkey.

0378-3839/93/$06.00

interactions, and a second stage which begins with the incipient wave breaking and assumes a rather chaotic appearance with eddying motions and turbulence. The latter stage is not completely disordered; the motion still has an irrotational part associated with the remaining wave motion but the vorticity-related flow and turbulence are significant. After breaking the wave either recovers its laminar nature and continues to propagate with a smaller amplitude or turns into a turbulent bore. The first case is observed when waves break over a nearshore bar, the second case is characteristic of waves breaking on a beach where the depth decreases at a rate sufficient to sustain turbulence (Peregrine, 1983; Battjes, 1988).

Generation of higher harmonics in waves propagating over submerged obstacles has long been known. Johnson et al. (1951) noted that over natural reefs the energy was transmitted as a multiple crest system. Jolas (1960) carried out experiments with a submerged obstacle of rectangular cross section and observed that the transmitted waves were noticeably shorter than the incident waves. In an experimental study investigating the performance characteristics of submerged breakwaters, Dattatri et al. (1978) pointed out rather complex forms of the transmitted waves, which indicated the presence of higher harmonics. Drouin and Ouellet (1988) and Kojima et al. (1990) reported their experimental results with immersed plates, the latter emphasizing the phenomenon of wave decomposition and associated harmonic generation past the obstacle. Quite recently, Rey et al. (1992) have reported similar results for laboratory waves passing over a bar.

Field measurements of Byrne (1969) and lately of Dingemans (1989) and of Young (1989) in nearshore regions with bar–trough type bathymetries show results similar to those obtained in the laboratory observations.

This investigation aims primarily at determining the role of wave breaking in the inherently nonlinear phenomenon of high frequency energy generation and transfer occurring in power spectra of long waves propagating over barred topographies. In this connection, the phenomena of de-shoaling and wave decomposition which take place in the deepening regions of the shoal are examined with the help of experiments conducted for both non-breaking and breaking waves passing over a bar.

The organization of the paper is as follows. Section 2 describes the experimental setup, the instrumentation, and the experimental program. Section 3 begins with some descriptive features of the experiments, referring to recorded surface elevations that capture the essence of the problem. Spectral evolutions for narrow-banded and JONSWAP type incident waves are presented next. The last section is devoted to discussion and concluding remarks.

2 DESCRIPTION OF EXPERIMENTS

2.1 Experimental setup

The experiments were carried out in the wave-flume of the Department of Civil Engineering, Delft University of Technology. The flume has an overall length of 37.7 m, width 0.8 m, and height 0.75 m. During the entire set of experiments the still water level over the horizontal bottom was 0.4 m.

The bottom profile selected for the experiments is shown in Fig. 1. A submerged trapezoidal bar was constructed, consisting of an upslope of 1:20 and a 2 m horizontal crest followed by a 1:10 downslope. The height of the horizontal plane section was 0.3 m above the bottom of the flume. The water depth in the deep region was 0.4 m and reduced to 0.1 m in the shallowest region above the horizontal part. At the end of the flume opposite to the wave generator, a plane beach with a 1:25 slope was present from previous experiments; it was left intact to serve as a wave absorber. Some coarse material was placed on the beach to reduce the reflection even further.

The flume is equipped with a hydraulically driven, piston-type random-wave generator. The control signal is provided via a dedicated personal computer, which is connected to a DA–AD converter that supplies the voltage input for the amplifier which in turn sends the amplified signal to the driver. The time series signals used by this computer were generated by using a software package developed at Delft Hydraulics. The package can generate random-phase time series corresponding to JONSWAP type spectra for various peak enhancement factors as well as monochromatic waves. It is also possible to create signals for custom-made spectra by entering the spectral heights at equally spaced frequency intervals.

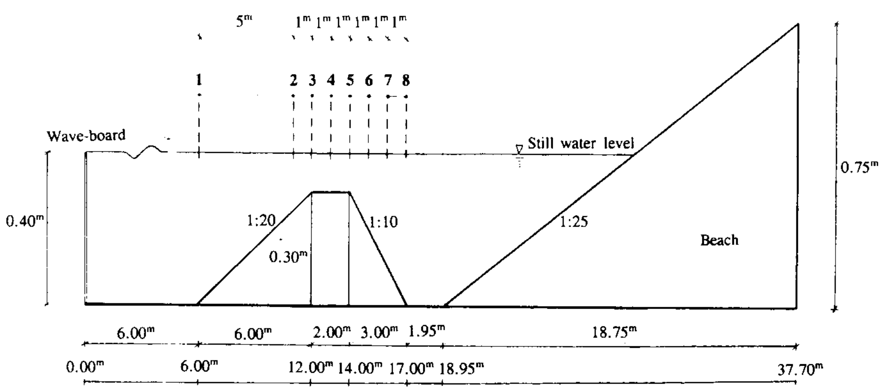

Fig. 1. Definition sketch of wave flume and locations of wave gauges.

2.2 Instrumentation

Measurements of the free surface elevations were made with parallel-wire resistance gages at 8 different locations as sketched in Fig. 1. One of these was placed in the constant-depth section, 6 m from the wave-board and right at the toe of the submerged trapezoidal bar. This gage served as the reference gage for the incident waves. The other gages were placed at 1 m intervals, starting at a distance of 5 m from the first gage and ending at the downslope toe of the trapezoid.

The wave gages were calibrated immediately before each run. Deviations from linearity were quite negligible; the correlation coefficients were almost unity as long as the minimum submergence exceeded 4 cm. This requirement was met at every station.

The gage signals were recorded by a personal computer which was loaded with data acquisition software. In each run, data were recorded simultaneously from 8 separate channels at a sampling frequency of 10 Hz, for a total of 9000 data points per channel. Also, for inspection purposes, incidental paper chart recordings were made but they were not used in the quantitative analyses.

2.3 Experimental program

In order to distinguish the individual effects of conservative (non-dissipative) nonlinear wave–wave interactions from those of wave breaking, it was essential to perform tests for both breaking and non-breaking waves. For this purpose three different wave conditions were aimed at: nonlinear but non-breaking waves, spilling breakers, and plunging breakers. The criteria for the type of breaking are to some extent subjective; therefore the selections were done simply by trial-and-error and personal judgement.

The depth-to-wavelength ratio of the incoming waves is an important parameter especially when the combined effects of nonlinearity and dispersion are considered. To explore the distinctly different aspects of low and high frequency waves, two rather extreme frequencies were selected: 0.4 Hz and 1.0 Hz, the former corresponding to the so-called long waves and the latter to the so-called short waves. After several trials the following wave heights were selected: 2.9 cm, 4.4 cm, 5.4 cm for 0.4 Hz, and 4.1 cm, 5.9 cm, 6.9 cm for 1.0 Hz. For the high frequency case the initial wave heights were larger because it was attempted to keep the nonlinearity parameter, ϵ=amplitude/water-depth, nearly the same in the shallowest region of the flume for both cases. Such a constant parameter is particularly useful for the comparisons.

Irregular waves with two different spectral shapes were realized: a JONSWAP spectrum and a custom-made, very narrow-banded spectrum. The latter was especially desirable for eliminating the smearing effects of a tail appearing in the higher frequency region of the input spectrum.

A total of twelve different combinations were realized: two different wave spectra, two different wave frequencies, and three different wave heights. In order to lower the statistical error in spectral computations it was decided to perform five different realizations (by specifying a different random seed number, which was an option in the software package of Delft Hydraulics) for each combination. Thus, the total number of runs for irregular waves were 60. It was also noticed that regular waves were providing quite valuable insight, hence six additional runs were performed with monochromatic waves. Overall the number of experiments performed was 66.

The analysis of the collected data was carried out with the use of a standard FFT package. Each record, containing 9000 data points, was divided into two parts, each part containing 4096 data points. In this process certain data points were discarded from either end of each record so that possible contaminations of the data due to transients were eliminated. Before applying the FFT, the 4096 data points were 10% cosine tapered; later, the spectral estimates were re-scaled to account for these taperings (Bendat and Piersol, 1971). Averaging in the frequency domain was done by merging 16 consecutive spectral density estimates. Since each record was divided into two segments and 5 different realizations, were used for each spectrum, the degree of freedom in the spectral estimates presented here is 320, and the corresponding statistical error is less than 8%.

3 RESULTS

3.1 Time domain records

Before presenting measured spectra of irregular waves it is worthwhile to recapitulate the quite different features of the long (f=0.4 Hz) and short (f=1.0 Hz) monochromatic waves as concluded from visual observations during the experiments and from inspection of chart recordings of surface displacements. See Figs. 2a and 2b for f=0.4 Hz and f=1.0 Hz, respectively.

The long waves, as they travel upslope, gradually lose their vertical symmetry and assume a saw-toothed shape. In this phase bound harmonics — primarily second harmonics — are generated by self interactions. Over the horizontal extension, where the waves are in a rather non-dispersive medium, the triplet resonance conditions are nearly satisfied (Phillips, 1960) and a very rapid flow of energy begins from the primary wave to the higher harmonics. This rapid energy flow coupled with the effects of amplitude dispersion generates the so-called dispersive tail waves traveling at nearly the same celerity as the primary waves. This phenomenon is reminiscent of the soliton formation behind a solitary wave, a subject which has been studied exten-

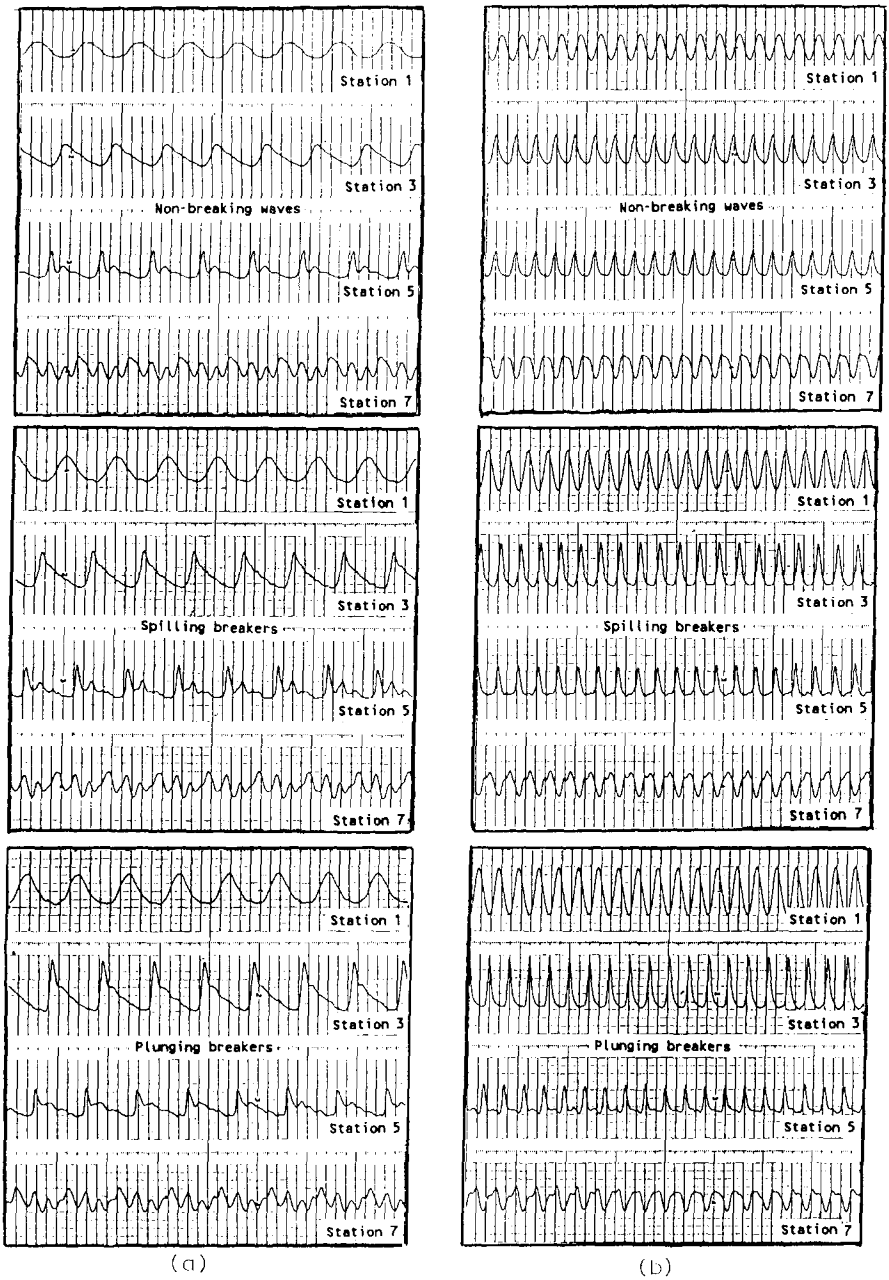

Fig. 2. Surface elevation records showing evolving (a) long waves (f=0.4 Hz) and (b) short waves (f=1.0 Hz).

sively. (See, for example, Tappert and Zabusky, 1971 or Johnson, 1973.) It is quite plausible to regard the dispersive tail waves as free since they now propagate at the celerity dictated by the total depth and their amplitude alone. This also explains their gradually increasing phase lag behind the still larger amplitude primary component. As these finite amplitude long waves and the following dispersive tails move into the deeper water — downslope — they decompose into several smaller amplitude waves of nearly harmonic frequencies. Such a decomposition, triggered by the de-shoaling* effect, appears to begin almost abruptly but the exchange of energy among different wave components, as the total potential energy is re-adjusted with increasing depth, continues at a high rate for several wavelengths. Finally an equilibrium is reached with the result that the initially narrow-banded spectrum is now a broad-banded spectrum.

Contrary to the long waves, the short waves do not develop any tail waves as they grow in amplitude but they keep their vertical symmetry and appear as higher order Stokes waves. Consequently, the wave decomposition in the deeper region is never as drastic as that of the long waves and only relatively smaller amplitude second order harmonics are released.

It is readily seen in Figs. 2a and 2b that wave breaking does not alter the characteristic wave form drastically so as to make it incomparable with its unbroken counterpart. This important point is further substantiated in the following section by comparing the spectral evolutions for different conditions of irregular waves.

3.2 Spectral evolution

As already indicated, irregular waves were generated with two different types of spectra. In the case of the custom-made narrow-banded spectrum, the primary wave energy at any given station remains separated from that of the higher frequency part generated by nonlinear interactions. Although it is not possible to tell, without resorting to higher-order spectra (bispectrum, trispectrum), whether these higher frequency components are bound or free, it is still quite enlightening to compare the spectral evolutions for different wave conditions. Figure 3 shows the power spectra for non-breaking, spilling, and plunging waves ($f_p = 0.4$ Hz) at three selected stations. It is important to note that the overall features of the spectral shape evolution do not differ appreciably for those three conditions. Further clarification is offered in Fig. 4 where the spatial variations of normalized potential energy of the total, the primary, and the higher frequency components are plotted. In computing the primary

*We have coined the word to indicate the physical process of wave propagation into deeper water that results in reductions in the potential energy consistent with increase in group velocity.

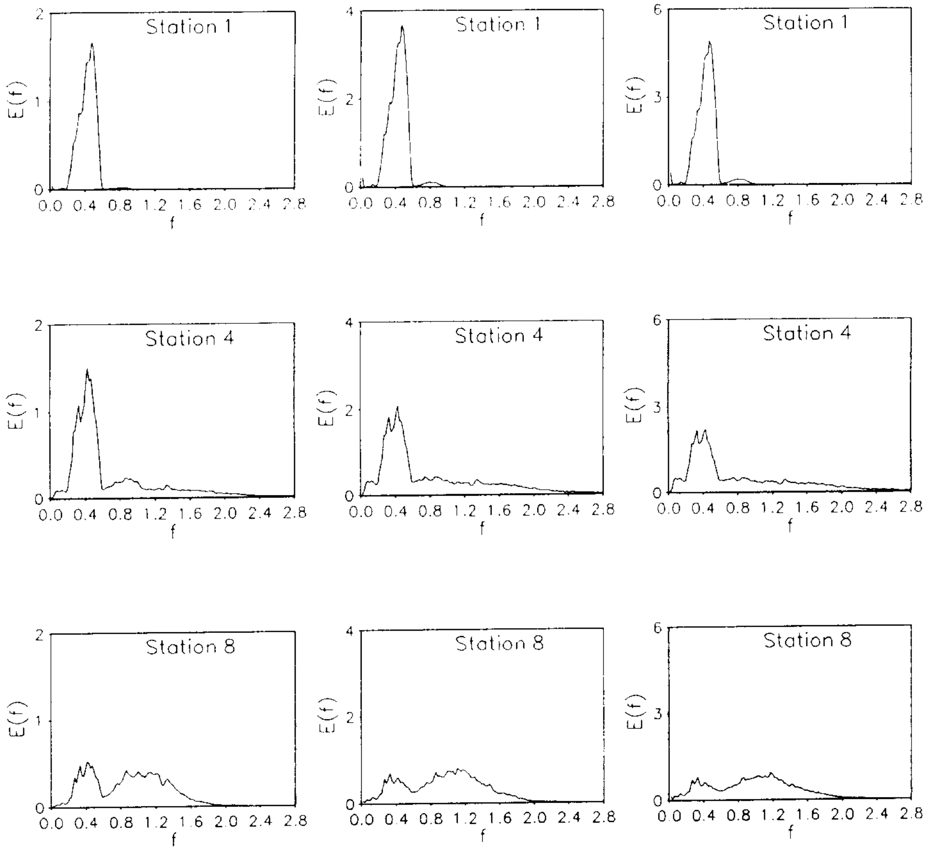

Fig. 3. Spectral evolutions for non-breaking (left), spilling (middle), and plunging (right) waves (narrow-banded spectrum, $f_p=0.4$ Hz); frequency unit is 1 Hz, spectral density unit is 1 cm^2/Hz.

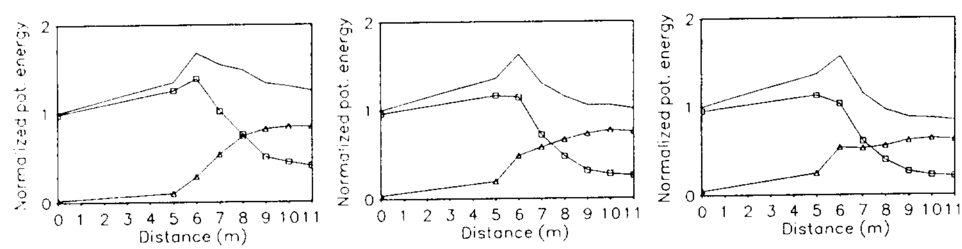

Fig. 4. Spatial variations of normalised potential energy for non-breaking (left), spilling (middle), and plunging (right) waves (narrow-banded spectrum, $f_p=0.4$ Hz). (——) Total, (□) primary, (△) higher frequencies. Distances are measured from the first station.

wave energy the range of integration is taken between 0.0 Hz and 0.6 Hz ($=1\frac{1}{2}f_p$) while for high frequency energy it is between 0.6 Hz and 2.5 Hz. The total energy is obtained simply by adding the two. In each case the energies are normalized with respect to the total measured at station 1. It can be seen that the high-frequency potential energy, relative to that in the primary frequency range, develops virtually independently of wave breaking.

In order to make direct comparisons of spectral evolutions for different wave conditions, spectral estimates obtained at stations 2, 4, 6, and 8 for JONSWAP type incident waves, for non-breaking and plunging breakers, are normalized and plotted together. The normalization is such that the total area under the spectrum for every case is unity. Figure 5 shows these comparisons. Obviously, the spatial evolution of the spectral shape is the same for breaking waves and for non-breaking waves. This was also observed in the case of narrow-banded incident waves.

As should be obvious from the qualitative descriptions given in § 3.1, the measurements with the short waves ($f_p=1.0$ Hz) revealed little spectral shape evolution over the obstacle. See Fig. 6. The spectral shape remains nearly in-

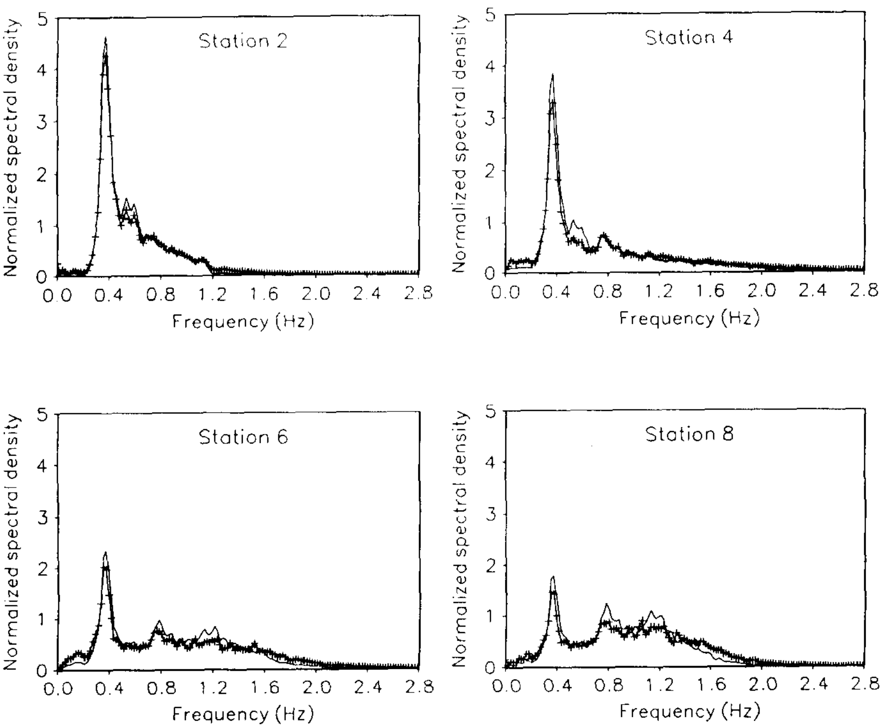

Fig. 5. Comparisons of normalized spectra for non-breaking and plunging waves at stations 2, 4, 6, and 8 (JONSWAP spectrum, $f_p=0.4$ Hz). (——) Non-breaking waves, (+) plunging breakers.

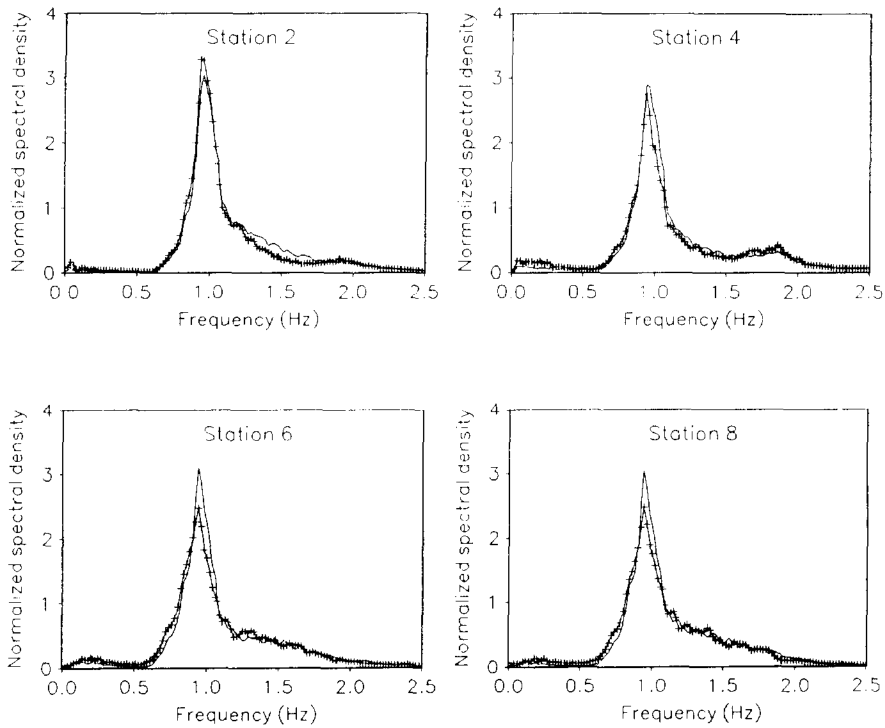

Fig. 6. Comparisons of normalized spectra for non-breaking and plunging waves at stations 2, 4, 6, and 8 (JONSWAP spectrum, $f_p = 1.0$ Hz). (——) Non-breaking waves, (+) plunging breakers.

tact over the entire region and only a relatively small amount of high frequency energy is generated. For this reason we shall not pursue this case any further.

4 DISCUSSION AND CONCLUDING REMARKS

The measurements analyzed here were obtained for a single bottom configuration and therefore due care should be observed in generalizing their implications. First of all the results are valid for mildly sloping bars rather than sharp, steplike bottom configurations where the incident wave transformations are abrupt and the contribution of reflected waves is no longer negligible. Another point concerns the existence of a horizontal bar crest. For the long waves generated in our experiments this section of the bar was a non-dispersive medium giving rise to triple resonant interactions. In the absence of such a shallow horizontal part, the amount of primary wave energy transferred to higher harmonics would have been less. Finally, wave breaking took place over the horizontal crest; there was no wave breaking before the shallowest region.

Keeping the above points in mind we draw the following conclusions from the analysis of the experimental data. The phenomenon of harmonic decoupling, which takes place as the waves propagate in the deepening water (downslope), resulting from the de-shoaling, plays a major role in the wave decomposition and in re-distributing the total energy among the primary wave and harmonics and thus determining the final spectral shape. It is therefore desirable to analyze the experimental data further with the help of higher order spectra. On the other hand, the generation of high frequency energy and its transfer among nearly harmonic wave components, due to the nonlinear interactions taking place in the course of waves' passage over the bar, is hardly affected by wave breaking which acts merely as a secondary effect by simply re-scaling the wave spectrum through overall energy dissipation. The practical implication of this observation from a modeling point of view is the apparent possibility of combining a weakly nonlinear non-dissipative model, such as a Boussinesq model, with a semi-empirical dissipation formulation for the total energy loss due to breaking, as given by Battjes and Janssen (1978), Battjes and Stive (1985) or Dally et al. (1984). The feasibility of Boussinesq modelling for the non-breaking wave conditions discussed here has been demonstrated by Battjes and Beji (1991) (see also Beji and Battjes, 1992). The inclusion of the effects of breaking is the subject matter of following work.

ACKNOWLEDGEMENTS

The financial support for this project was provided in part by the EC-MAST program within the framework of the WASP-project, contract number MAST-0026-C(MB). The authors thank M.W. Dingemans for helpful discussions and for pointing out some additional references.

REFERENCES

Battjes, J.A., 1988. Surf-zone dynamics. Annu. Rev. Fluid Mech., 20: 257–293.

Battjes, J.A. and S. Beji, 1991. Spectral evolution in waves traveling over a shoal. In: Proc. Nonlinear Water Waves Workshop, Bristol, pp. 11–19.

Battjes, J.A. and J.P.F.M. Janssen, 1978. Energy loss and set-up due to breaking in random waves. Proc. 16th Coastal Eng. Conf., Hamburg, Part 1, pp. 569–587.

Battjes, J.A. and M.J.F. Stive, 1985. Calibration and verification of a dissipation model for random breaking waves. J. Geophys. Res., 90: 9159–9167.

Beji, S. and J.A. Battjes, 1992. Numerical simulation of nonlinear wave propagation over a bar. J. Waterway, Port, Coastal Ocean Eng., ASCE, submitted.

Bendat, J. and A. Piersol, 1971. Random Data: Analysis and Measurement Procedures. Wiley Interscience, New York.

Byrne, R.J., 1969. Field occurrences of induced multiple gravity waves. J. Geophys. Res., 74(10): 2590–2596.

Dattatri, J., H. Raman, and N. Jothi Shankar, 1978. Performance characteristics of submerged breakwaters. Proc. 16th Coastal Eng. Conf., Hamburg, Germany, 3: 2153–2171.

Dally, W.R., R.G. Dean, and R.A. Dalrymple, 1984. A model for breaker decay on beaches. In: Proc. 19th Coastal Eng. Conf., Houston, TX, USA, Part 1, pp. 82–98.

Dingemans, M.W., 1989. Shift in characteristic wave frequency; some spectra in wave basin and in Haringvliet region, Tech. Rep., Part II, Delft Hydraulics, 56 pp.,

Drouin, A. and Y. Ouellet, 1988. Experimental study of immersed plates used as breakwaters. In: Proc. 21th Coastal Eng. Conf., Malaga, Part 3, pp. 2272–2283.

Johnson, J.W., R.A. Fuchs and J.R. Morison, 1951. The damping action of submerged breakwaters. Trans. Amer. Geophys. Union, 32(5): 704–718.

Johnson, R.S., 1973. On the development of a solitary wave over an uneven bottom. Proc. Cambridge Philos. Soc., 73: 183–203.

Jolas, P., 1960. Passage de la houle sur un seuil. Houille Blanche, 2: 148–152.

Kojima, H., T. Ijima and A. Yoshida, 1990. Decomposition and interception of long waves by a submerged horizontal plate. In: Proc. 22th Coastal Eng. Conf., Delft, Part 2, pp. 1228-1241.

Peregrine, D.H., 1983. Breaking waves on beaches. Annu. Rev. Fluid Mech., 15: 149–178.

Phillips, O.M., 1960. On the dynamics of unsteady gravity waves of finite amplitude, Part 1. The elementary interactions. J. Fluid Mech., 9: 193–217.

Rey, V., Belrous, M. and E. Guaselli, 1992. Propagation of surface gravity waves over a rectangular submerged bar. J. Fluid. Mech., 235: 453–479.

Tappert, F.D. and N.J. Zabusky, 1971. Gradient-induced fission of solitons. Phys. Rev. Lett., 27: 1774–1776.

Young, I.R., 1989. Wave transformation over coral reefs. J. Geophys. Res., 94: 9779–9789.