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Dynamics of a Transient Wave Group Breaking on a Beach

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Abstract

New experimental data are presented on the dynamics of a transient wave group breaking on a beach. The transient group is tracked during shoaling and wave breaking, together with the long waves forced during those processes. High spatial sampling enables novel resolution of the evolution of the wave envelope during breaking and the correlation between the envelope and the long waves. The data show a strong dynamic long wave setup in front of the group in shallow water. The amplitude of the dynamic setup is likely to be a function of beach slope, and larger on steeper beaches.

Introduction

Wind and swell gravity water waves propagate towards the coastline in groups of high and low waves which shoal in shallowing water and eventually break on beaches. As a result of the dispersive nature of gravity waves, the groups are transient and evolve in space and time, with wave focusing potentially leading to the formation of extreme waves [1]. In addition to the formation of extreme waves, the focusing of wave energy and the wave height variation within the group forces low frequency long waves that propagate with the wave group [9]. In sufficiently shallow water the short waves within the group break at different depths, leading to further free long wave generation [12,4]. In both cases the shoreward propagating long waves may reflect at the shoreline and subsequently propagate offshore, which is how they were first identified by Munk [10] and Tucker [13].

The present paper considers this issue and presents a detailed analysis of the wave breaking process and the long waves forced by a large transient wave at the breakpoint. Carefully controlled laboratory experiments allow the direct identification of the incident and radiated long waves and this avoids difficulties associated with the analysis of non-linear shoaling waves and breaking waves. High data resolution enables direct identification of the relationship between the spatial variation of the short wave envelope and the long wave surface slopes, and this is consistent with radiation stress theory [9]. Cross-correlations between the long wave motion at different cross-shore locations suggest that the radiated long wave is generated in the surf and swash zones. A brief review of previous work follows, with the experimental setup and analysis techniques summarised in Section 3. Section 4 presents and discusses the experimental data, followed by final conclusions in section 5.

Background

Long waves in the coastal zone are frequently termed surf beat as a result of their correlation with the breaking process [10,13], and are significant since they can modify the incident wave field and strongly influence sediment transport patterns. Much recent research has considered long wave forcing by regular wave groups and random waves on sloping beaches and clarified the forcing mechanisms [5,2,4]. Similarly, recent work has presented detailed analyses of the non-linear mechanics of transient wave groups in uniform depth [1,8] and such waves may now form the basis for design conditions for offshore structures. However, studies on the propagation of transient wave groups over a sloping bed are much more limited, particularly during shoaling and wave breaking. Watson et al. [14] presented some results from numerical studies and limited comparisons with experimental data. Hunt [6] investigated the propagation of focused wave groups over a sloping bed and identified long wave generation in the surf and swash zones, but did not consider the long wave generation process in detail. Unfortunately, limitations on the wave generation technique also made it difficult to examine critically the long wave behaviour.

The identification of the details of wave breaking and long wave forcing for a particular set of experimental wave conditions is not trivial and complicated by a number of factors. These include the correct generation of non-linear waves and the absorption of radiated waves at the wavemaker in laboratory experiments (see section 3). Further, the analysis usually requires separation of the incident and reflected wave trains, for which no rigorous method exists for non-linear waves on a sloping bed.

In the present paper, we take advantage of the transient nature of the wave group and long wave to overcome these difficulties. The incident and radiated long waves are well separated in time, except very close to the shore, and can be identified directly in the time domain. In addition, high spatial sampling enables resolution of the instantaneous cross-shore structure of the short wave envelope and the long wave at sequential time intervals. This allows us to track the short wave breaking and the resulting long wave in space and time, which could only otherwise be achieved with an exact time-domain numerical model for shoaling and breaking transient waves.

Experimental Setup

The experiments were carried out in a wave flume 18m long, 0.9m wide, with a working water depth, h, of 0.8m (Figure 1). A plane beach (gradient β=0.1) starts 5.65m from the wave paddle. The origin of the horizontal co-ordinate, x, is taken as the intersection of the still water line with the beach face, positive onshore. Waves were generated by a hydraulically driven wedge type wave paddle using second order generation for long waves [3] and a digital feedback system that absorbs up to 60% (in amplitude terms) of waves radiated from the far end of the flume for frequencies at 0.1Hz, rising to over 90% above 0.4Hz.

Data were collected simultaneously from an array of five surface piercing resistance type wave gauges, mounted on a carriage above the flume, and a run-up wire within the swash zone. The absolute accuracy of these wave gauges is of order ± 1mm, with a relative accuracy better than ± 0.2mm. Further details of the wave flume, wave generation system and the instrumentation may be found in Baldock and Huntley [2]. Time-series data were collected from a total of 38 cross-shore locations, with the spatial separation between measurement positions varying between 0.2-0.6m offshore of the outermost breakpoint, reducing to 0.1-0.2m in the surf zone.

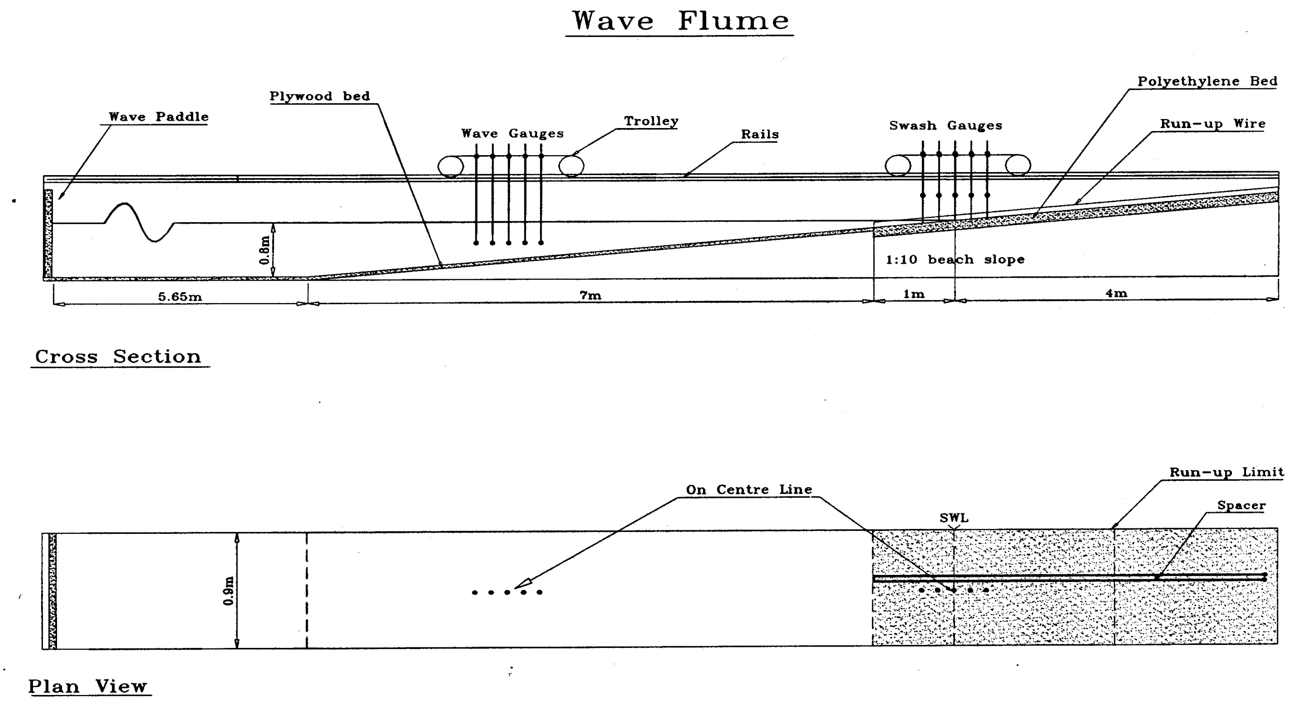


Figure 1. Wave flume and instrumentation.

The present paper examines data from a single transient focused wave group generated from a "top-hat" frequency spectrum. The central, upper and lower frequency limits for the 30 primary (linear) wave components of the spectrum were 1Hz, 1.2Hz and 0.8Hz, respectively, with a total group amplitude, A, defined by the linear sum of the amplitudes of the primary wave components and equal to 50mm. Long wave frequencies are defined as $f<0.4$Hz, with the long wave components obtained by Fourier filtering the measured surface elevation data. Linear wave theory was used to focus the wave energy to generate a group dominated by a single large transient wave, so that a well developed large plunging breaker occurred 1.5-2m from the still water shoreline. At this location, the crest-trough height measured in the time domain just prior to breaking was 125mm. The smoothed short wave envelope was calculated from a Hilbert transform of low pass filtered ($f<1.5$Hz) surface elevation data [11].

Results

Figure 2 shows the evolution of the focused wave group over the sloping bathymetry, together with the expected propagation path of the group centre, based on the linear group velocity. During propagation the energy is focused within a smaller region of space and time in comparison to the initial energy density at $x=-11$m, $t=25$s. In shallow water ($x>-3$m) the group travels faster than expected from linear theory, a result of the highly non-linear waves generated during focusing and shoaling. This is illustrated further on figure 3, which shows the surface elevation of the wave envelope (a measure of the local energy density). Prior to wave breaking at $x\approx-2.2$m, the transient group is fairly symmetric about the main crest, both in the time domain and in space. After breaking, the majority of the short wave energy is dissipated or transferred to other frequencies within a distance of approximately 1m, or about 1 wavelength of the short waves.

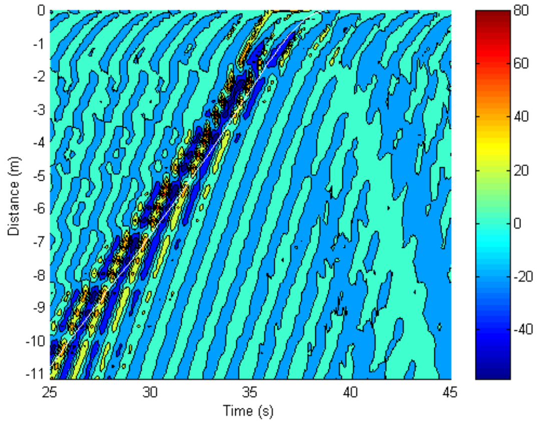


Figure 2. Space-time evolution of a focusing transient wave group. Colour bar on right indicates water surface elevation in mm. White line indicates expected propagation path based on group velocity.

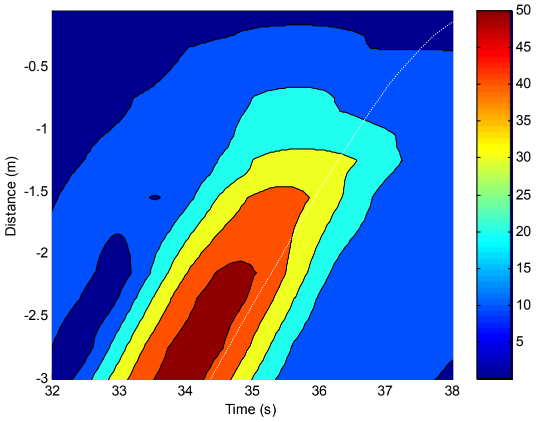


Figure 3. Space-time evolution of short wave envelope. Colour bar on right indicates elevation in mm. White line indicates expected propagation path based on group velocity.

During propagation of the wave group, energy is transferred to lower frequency bound long waves through radiation stress forcing [9]. These travel with the group, shoaling in shallow

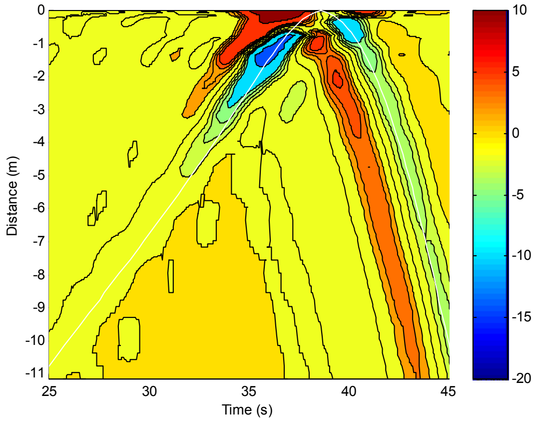


Figure 4. Space-time evolution of the low frequency (f<0.4Hz) surface elevation. Solid white lines indicate the expected shoreward and seaward propagation paths determined from the group velocity and the wave celerity, respectively.

water, and are frequently reflected from the shore as free waves after short wave breaking [4]. This is illustrated on figure 4, which shows the space-time evolution of the low frequency (f<0.4Hz) component of the surface elevation. A long wave trough propagates with the group as expected, and appears to reflect from the beach at t≈38s and propagate offshore at the free wave celerity. However, the notable feature in figure 4 is the dynamic setup or long wave preceding the group. Initially, this becomes significant in amplitude outside the breakpoint, at x≈-3m., and subsequently grows very rapidly just before and after short wave breaking. This growth is consistent with high radiation stress gradients due to the wave height variation across the group. Further time-varying radiation stress gradients are induced by breaking [12]. This wave reflects from the beach at t≈36s, again propagating offshore with the celerity of a free wave. Of particular interest is that the bound long wave (trough) decreases significantly in amplitude during the reflection and radiation process, while the dynamic setup (crest) is largely unchanged in amplitude. This is considered further below. The radiated long waves propagate offshore, where they can be recorded without interference from the short wave group at a later time (figure 5). Note that on this figure the long waves are plotted on the right hand scale.

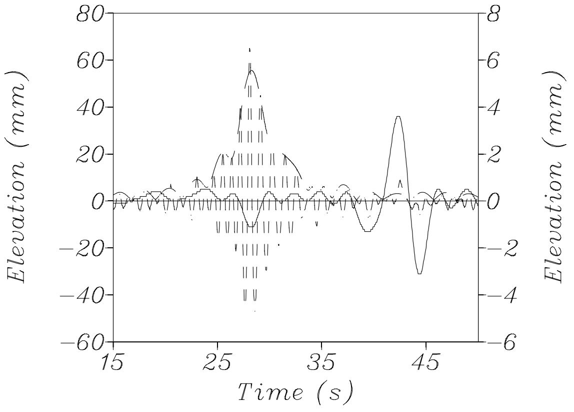


Figure 5. Wave group surface elevation and radiated long wave at x=-7.95m. – – – –, surface elevation; — —, envelope; ——, long wave (rhs).

Cross-correlations between the low frequency motion offshore (x=-11.15m) and that further shoreward are shown on figure 6. In this instance the long wave signal in the nearshore leads that further offshore, whereas Janssen et al. [7] observed the opposite on a much more mildly sloping beach under random wave conditions. The difference is that Janssen et al. [7] observed a reflected bound long wave that originally propagated from offshore to onshore, and then back. In contrast, these data show a new long wave generated through the shoaling and breaking process, reflected from the beach and then propagating offshore. Furthermore, the original incident bound long wave trough visible in figure 4 shows little correlation with the long waves observed further shoreward or at lags greater than zero. This implies that the original bound long wave is only a weak component of the overall radiated long wave. This analysis is complicated by the rundown that follows the large uprush at t≈36s (figure 4), which may well generate an offshore propagating long wave which is dominated by a wave trough [14]. It is therefore not possible to exactly determine if the radiated wave trough visible for t>40s on figure 4 is a reflection of the incident bound wave present at x=≈-3m, t≈34s. Indeed, weak autocorrelation at positive lags in the measured signal at x=-3m suggests that the radiated trough is strongly modified by the rundown.

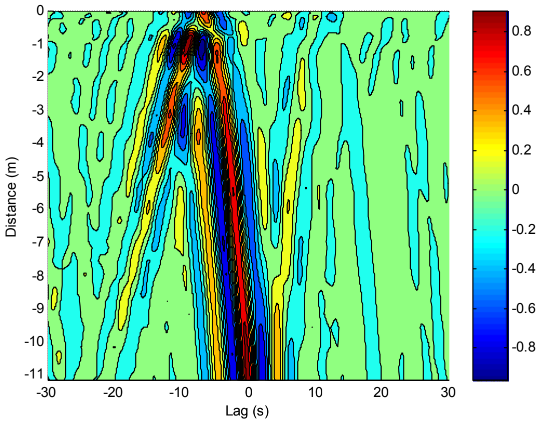
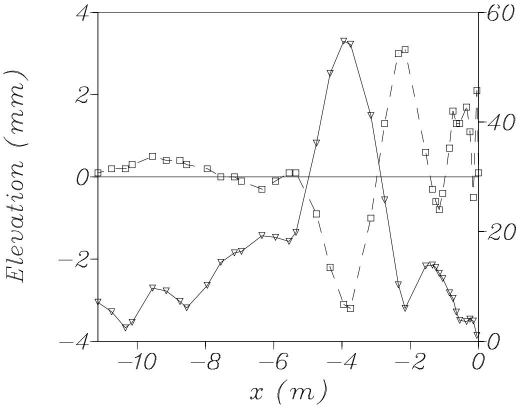


Figure 6. Cross-correlation between the low frequency motion at x=-11.15m and that further shoreward.

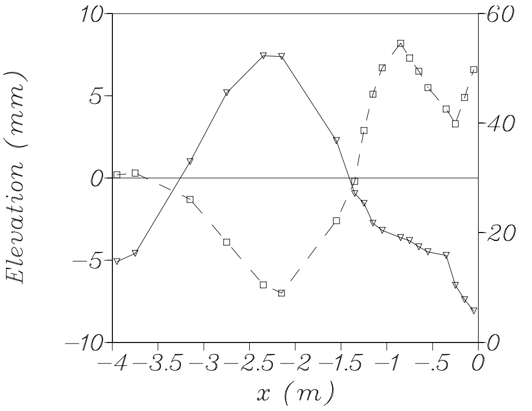
The high spatial sampling allows resolution of the instantaneous cross-shore structure of the short wave envelope and long wave. This novel experimental data is illustrated on figures 7a-c at three different times during the propagation of the wave group across the beach. Figure 7a&b show the group and long wave structure in the lead up to short wave breaking, while figure 7c shows the structure after breaking. In each case, the short wave envelope is plotted on the right hand scale. Prior to breaking, the gradients in short wave height lead to spatial variations in radiation stress which force the bound long wave (visible at x=-4m) as well as some dynamic setup in front of the group (x=-2m). Note that the changes in surface slope of the long wave exactly correspond with changes in gradient of the short wave envelope and hence radiation stress, in agreement with radiation stress theory.

In shallower water, after breaking, a similar correlation is evident between the short wave envelope and long wave slope until the long waves reflect at the shoreline and the incident waves can no longer be identified easily. However, these data show the dynamic setup in front of the group is similar in amplitude to the incident bound long wave, which has not been observed on mildly sloping beaches, but is consistent with long wave forcing by random waves on the same beach [2].

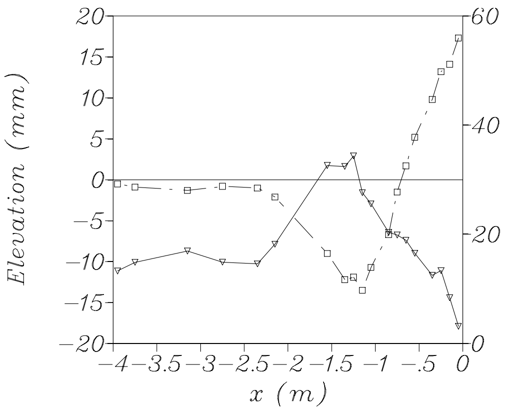
This appears to be a combination of two factors. Firstly, on mildly sloping beaches wave breaking is more gradual, with breaking spread over a broader surf zone, and this leads to smaller radiation stress gradients overall. Secondly, to generate the large dynamic setup requires large radiation stress gradients in very shallow water. This is possible on a steep beach, where wave breaking occurs closer to the shoreline and where the gradients in both wave height and water depth are large. Large dynamic setup is therefore likely on steep beaches, resulting in very different long wave generation from that on mildly sloping beaches. This is consistent with the previous work of Baldock and Huntley [2] and Battjes et al. [4].



a) t=32.88s



b) t=34.76s



c) t=36.24s

Figure 7. Spatial variation of surface elevation envelope and low frequency surface elevation at the times indicated.
—□—, low frequency wave; —∇—, envelope (rhs).

Conclusions

New experimental data have been presented on the dynamics of a transient wave group during shoaling and breaking. The transient wave group propagates faster than predicted by linear theory, a result of non-linear effects in shallow water. During wave breaking a dominant plunging breaker dissipates the short wave energy over a narrow surf zone, leading to large radiation stress gradients. These lead to a large dynamic setup in front of the group in addition to the commonly observed setdown beneath the group. The dynamic setup forces free long waves which radiate offshore. The data show that the radiated wave is generated in the final stages of shoaling and in the surf zone, as opposed to being a reflection of the incident bound wave originating further offshore. Novel data show the spatial structure of the short wave envelope and long wave, and these are consistent with radiation stress theory and explain the observed dynamic setup. The magnitude of the dynamic setup and associated radiated long wave is expected to be a function of beach slope, and greater on steeper beaches.

Acknowledgements

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References

[1 Baldock, T. E., Swan, C. and Taylor, P. H. A laboratory study of non-linear surface waves on water. *Philos. Trans. R. Soc. Lond. A*, **354**, 1996, 649-676.

[2] Baldock, T.E and Huntley, D.A.. Long wave forcing by the breaking of random gravity waves on a beach. *Proc. R. Soc. Lond. A,* **458**, 2002, 2177-2201.

[3] Barthel, V., Mansard, E. P. D., Sand, S. E. and Vis, F. C. Group-bounded long waves in physical models. *Ocean Engineering*, **10**, 1983, 261-294.

[4] Battjes, J. A., Bakkenes, H. J., Janssen, T.T., and van Dongeren, A. R., Shoaling of subharmonic gravity waves. *J. Geophys. Res*, **109**, 2004, doi:10.1029/2003JC001863.

[5] Guza, R. T. and Thornton, E. B.. Observations of surf beat. *J. Geophys. Res.*, **90**, 1985, 3162-3172.

[6] Hunt, A., Extreme waves, overtopping and flooding at sea defences. DPhil thesis, University of Oxford, 2003, 255pp.

[7] Janssen, T. T., Battjes, J. A. and Van Dongeren, A. R. Observations of long waves induced by short wave groups. *J. Geophys. Res.*, **108**, 2003, 3252-3264.

[8] Johannessen, T.B and Swan, C., On the non-linear dynamics of wave groups produced by the focusing of surface water waves. *Proc. R. Soc. Lond. A*, **459**, 2003, 1021-1052

[9] Longuet-Higgins, M. S. and Stewart, R. W. Radiation stress and mass transport in gravity waves, with application to “surf beats”. *J. Fluid Mech.*, **13**, 1962, 481-504.

[10] Munk, W. H. Surf beats. *Trans. Am. Geophys. Union*, **30**, 1949, 849-854.

[11] Sobey, R. J. and Liang, H-B. Complex envelope identification of wave groups. *Proc. 20th Int. Conf. Coastal Engng.*, 1986, 752-766, ASCE, New York.

[12] Symonds, G., Huntley, D. A., and Bowen, A. J. Two-dimensional surf beat: long wave generation by a time-varying breakpoint. *J. Geophys. Res.*, **87**, 1982, 492-498.

[13] Tucker, M. J. Surf beats: sea waves of 1 to 5 min. period. *Proc. R. Soc. London Ser. A*, **202**, 1950, 565-573.

[14] Watson, G., Barnes, T. C. D. and Peregrine, D. H. The generation of low frequency waves by a single wave group incident on a beach. *Proc. 24th Int. Conf. Coastal Eng.*, ASCE, 1994, 776-790.