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Flow kinematics of focused wave groups on a plane beach in the U.K. Coastal Research Facility

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Abstract

Measurements are presented of the water particle kinematics of focused wave groups generated in the U.K. Coastal Research Facility. Single and repeated wave groups are considered at normal and 20° incidence to a 1:20 plane beach. The single focused wave groups model extreme transient events without the complication of reflections during the data acquisition process. A symmetry-based separation of harmonics method is used to interpret the water particle kinematics at the point of focus. Although the largest component is linear, there are also considerable second order kinematics terms (both low frequency and high frequency). Away from the free surface, the 2nd order difference contribution to the kinematics is a return current opposed to the direction of wave advance. For repeated wave groups, the measured kinematics confirms the presence of a low frequency free wave, followed by higher frequency waves of the main group and trailing higher order harmonic waves. In the breaker and surf zones, there is also evidence of the saw-tooth behaviour of broken waves, followed by scatter due to breaker-induced turbulence. Pulsatile wave breaking of repeated wave groups at oblique incidence is found to drive a longshore current.

Keywords: Water particle kinematics; Laser Doppler anemometry; Acoustic Doppler anemometry; Extreme waves; Coastal hydrodynamics

1. Introduction

Coastal inundation by wave overtopping of sea defences is a worsening hazard due to rising sea levels and an increasingly severe storm environment. Physical modelling of the transformation of storm-induced waves as they travel up a beach and interact with a coastal structure has primarily been based on regular and random wave tests, both of which are severely affected because of wave reflections. Regular waves are unrepresentative of actual extreme events. Random wave simulations require very long runs in order to capture near-extreme events and are contaminated by physically irrelevant reflections due to the basin geometry. By using a focused wave group to model the average shape for an extreme wave profile consistent with a random process with a specified wave spectrum, these disadvantages are overcome.

Single focused wave group tests are transient and of very short duration, a matter of a few wave periods, as the transient extreme event is modelled deterministically. As a result, the test is completed before reflected waves from the beach and coastal structure have travelled back to the wave generator, re-reflected and begun to contaminate the wave field in the tank or basin. Given that in both offshore and coastal engineering, much of the important wave-driven physics is dominated by the response to

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the largest waves in a random sea, careful experiments with isolated groups of large waves can provide high quality data for assessment of engineering performance.

Previous investigations using focused wave groups to model large transient events in wave flumes and basins have been carried out by Longuet-Higgins (1974), Rapp and Melville (1990), Baldock et al. (1996), Barnes (1996), and Johannessen and Swan (2001). Various techniques have been used to generate the focused wave groups. Longuet-Higgins modulated the paddle driving frequency. Barnes superimposed solitary waves on a long sinusoidal wave trough. Rapp and Melville, Baldock et al., and Johannessen and Swan created wave focusing events using many superimposed regular wave trains, based on linear wave theory. Baldock et al. examined the effect of nonlinear wave–wave interactions on the structure of unidirectional wave groups and introduced the concept of group inversion in an experimental context to investigate the free surface structure of the focused wave groups. Johannessen and Swan extended this work to spread-sea wave groups and formally presented a separation of harmonics method linked to group inversion by which to examine the odd and even components of the water surface motions.

Although there has been much work on the kinematics of extreme waves in deep water (see e.g. Baldock et al. (1996) and Johannessen and Swan (2001)), there has been little research to date into the kinematics of focused waves in the coastal environment. The present paper considers focused wave groups generated in the U.K. Coastal Research Facility (UKCRF). The shape of the focused wave groups is determined from an input (sea) spectrum using the NewWave approach of Tromans et al. (1991) that reproduces the expected shape of a local extreme wave event. A laser Doppler anemometer (LDA) and an acoustic Doppler velocimeter (ADV) are used to measure water particle kinematics under single and repeated focused wave groups at normal and 20° incidence to a 1:20 plane beach. The focus point of the groups is at the toe of the beach. Velocity measurements are obtained at the beach toe offshore of the breaker zone, in the breaker zone and in the surf zone.

One important issue is the location of the focus point for a wave group. Since waves are dispersive, there are strong and rapid changes in the physical appearance of a wave group as it propagates. From an energy viewpoint, focusing occurs when the wave group becomes most compact in space and the local energy density highest. For individual waves within the group, wave focusing can be defined as the point in both space and time where the tallest crest ever occurs. If a wave group is perfectly focused with respect to both energy and phase, both of the conditions arise simultaneously. In our experimental work, the focus point was chosen to be the toe of the plane 1:20 beach — the start of shoaling before breaking occurs further inshore.

The idea of group inversion to decompose the composite structure of focused wave groups is applied to the water particle kinematics. This approach was applied deterministically to the results of nonlinear free-surface simulations (Taylor and Haagsma, 1994) and then statistically to field data from the North Sea (Jonathan and Taylor, 1996). For carefully controlled wave groups in a flume, the first use of this idea was by Baldock et al. (1996), to demonstrate the phase alignment of free-surface crests for the crest-focused groups and troughs for trough-focused groups on deep water. In a series of very careful laboratory basin experiments, Johannessen and Swan (2001) used the technique to separate out the first few harmonics explicitly for directionally focused wave groups on deep water. It is worth just noting that, if the wave behaviour is linear, then both crest and trough focusing give rise to identically the same wave envelope behaviour, the surface fluctuations being simply 180° out of phase at all times and positions. Second order non-linear triad-type interactions would cause the phase alignment of crest and trough focused events to breakdown. In our experiments, this breakdown of phase alignment is not seen prior to breaking.

In this paper, analysis of the measured *kinematics* of a single crest-focused wave group and its associated inverted (trough-focused) form allows the separation of the flow components of a wave group on intermediate water depth into its fundamental components, and reveals its harmonic structure. Before breaking occurs, the wave kinematics well below the free-surface are dominated by two contributions — oscillatory linear wave components and the return current associated with second-order long waves and opposed to the direction of primary wave propagation. This return flow can be substantial near the bed, leading for example to sediment transport offshore. The harmonic separation method applied here has clear practical advantages, as the odd harmonics are mainly related to the linear wave structure, whereas the even harmonics dominate the local surface set-down of the wave group as well as second order low and high frequency wave contributions to the kinematics. The 2nd order sum contributions are only important near the free-surface.

2. Experimental arrangement and instrumentation

The U.K. Coastal Research Facility (UKCRF) is a 36-m longshore by 20 m cross-shore coastal wave basin. The wave-maker consists of 72 piston paddles that are independently controlled and operated in non-absorption mode. Fig. 1 shows the layout of the UKCRF. The still water depth at the wave-maker paddles is 0.5 m. The concrete basin floor is horizontal for a distance of 8.33 m from the wave-maker paddles to the toe of a 1 in 20 plane beach constructed of sand with a surface cement layer. The lateral boundaries comprise solid walls of marine plywood that are fully reflective.

During the paddle calibration phase, thirteen wave gauges were positioned along the toe of the beach. Two further gauges were located inshore of the central gauge, and used to monitor the wave reflection characteristics of the beach. Each paddle was first calibrated for regular waves as follows. Small-amplitude waves were generated at a prescribed frequency, and the gradient obtained of the linear relationship between the measured wave amplitude and the input signal amplitude to the