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Volumetric velocity measurements of turbulent coherent structures induced by plunging regular waves

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ABSTRACT

The instantaneous turbulent velocity fields induced by the breaking of plunging regular waves on a 1 in 40 plane slope were measured using a volumetric three-component velocimetry (V3V) system. The measurement volume was located in the outer surf zone to capture the plunger vortex generated at incipient breaking and the splash-up vortex generated at the second plunge point. The measurement volume extended from a few millimeters above the bottom to just below the wave trough level. The aerated water was seeded with fluorescent particles and long-pass filters were used to block scattered light from entrained air bubbles. The volumetric velocity measurements revealed the three-dimensional (3D) structure of breaking-wave-generated vortices previously captured in two-dimensional (2D) planes using a particle image velocimetry (PIV) system. The evolution of the vortices was also captured. The most common turbulent coherent structure observed was a vortex loop with counter-rotating vorticity; two longitudinal vortices oriented obliquely upward in the direction of wave propagation are connected at the base by a transverse vortex. The vortex loop was carried in a downburst of turbulent fluid, which impinged on the bottom around the instant of maximum positive (onshore) wave-induced velocity. Downbursts carried large amount of turbulent kinetic energy and induced large apparent shear stress over the bottom. The distributions of vorticity, turbulent kinetic energy, turbulent kinetic energy flux and turbulent shear stress in the transverse segment of a vortex loop were examined. In a separate experiment, water particle velocities associated with non-breaking waves were measured at different heights above a plane slope using an acoustic Doppler velocimeter (ADV) to verify the V3V measurements.

1. Introduction

This study is concerned with the large eddies produced by the breaking of plunging regular waves on a plane slope. These large-scale, turbulent coherent structures carry large amount of turbulent kinetic energy and momentum in the flow field and play an important role in sediment suspension and transport in the surf zone (Nadaoka et al., 1988). Because coherent structure maintains a distinct phase relationship between the flow variables of its constituent components as it evolves in space and time (Blackwelder, 1987), one must measure flow quantities simultaneously over the spatial extent of a coherent structure in order to fully resolve its characteristics. The earlier velocity measurements in breaking waves were commonly conducted using hot-film or laser-Doppler anemometer (LDA). From these single-point measurements, the distributions of time- and ensemble-averaged properties of mean flow and turbulence quantities were obtained. Although conditional sampling of turbulent velocity fluctuations can be used to detect coherent motions, the flow topology cannot be resolved by single-point measurements alone. Full-field velocity measurements in a two-dimensional (2D) plane become available in the 1990s with the advent of particle image velocimetry (PIV). Nevertheless, additional assumptions are required to reconstruct the 3D flow field from 2D measurements. Only in recent years are truly three-component, three-dimensional (3C3D) velocity measurement techniques available. To date, our understanding of the sporadic, three-dimensional (3D) coherent structures in breaking waves remains incomplete due to lack of detailed measurements of the instantaneous 3D flow field.

Using the PIV technique, Ting (2013) measured the instantaneous turbulent velocity fields associated with the large eddies produced by the breaking of plunging regular waves on a 3% plane slope. The 2D velocity measurements were taken in the longitudinal–transverse plane very close to the bottom. The out-of-plane (vertical) velocity component was calculated from the two measured in-plane (horizontal) velocity components using the continuity equation and a slip boundary condition. The measured velocity fields capture breaking-wave-generated vortices as they impinge on the bottom. These coherent structures induce large apparent shear stresses over the bed. He found different flow patterns produced by the impingement of the first and second vortices on the bottom, which may be related to the differences in the plunging jet impact angle and water depth. However, the 3D structure of the vortices and their generation mechanism remain unclear.

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In this paper, we present detailed velocity measurements obtained in a 3D measurement volume under a train of plunging regular waves. As in Ting (2013), the velocity measurements were conducted in the outer surf zone to capture the breaking wave vortices generated at incipient breaking and at the second plunge point. A detailed introduction on turbulence and coherent structures in breaking waves including many experimental and numerical contributions to the topic of plunging waves can be found in Ting (2013) and is not repeated here. Recent research articles on breaking waves not reviewed in Ting (2013) include several experimental and numerical studies (Derakhti and Kirby, 2014; Farahani and Dalrymple, 2014; Lubin and Glockner, 2015; Sumer et al., 2013; Ting et al., 2013; and Zhou et al., 2014). Ting et al. (2013) describe the technique of volumetric three-component velocimetry (V3V) for turbulence measurements under breaking waves; the same experimental technique is used in this present study. The study by Sumer et al. (2013) deals with plunging regular waves on a steep slope (1 in 14) with wave breaking occurring in very shallow water almost at the still water shoreline. A hot-film anemometer was used to measure bed shear stress in the surf and swash zones. They found that the ensemble-averaged bed shear stress onshore of incipient breaking is increased by nearly a factor of 2 compared to the pre-breaking wave bottom boundary layer, and the root-mean-square value of the fluctuating component of bed shear stress by a factor of 5 to 6. Furthermore, the first vortex produces an offshore-directed, sharp increase in bed shear stress as it moves onshore. To determine the bed shear stress from velocity measurements would require measuring the velocity profile within the bottom boundary layer. In our experiment, the measurement volume extends from a few millimeters above the bottom to just below the wave trough level. Therefore, the structure of the free surface layer and bottom boundary layer is not resolved. The flow characteristics of the plunging jet and splash-up and the interaction of breaking wave vortices with the bottom are left to a future study.

Farahani and Dalrymple (2014) and Zhou et al (2014) simulated the turbulent coherent structures observed in the solitary wave experiment of Ting (2006, 2008). The solitary wave formed a gently spilling breaker on a 1 in 50 slope. Two-dimensional velocity fields were measured using a stereoscopic PIV system in the middle of the water column and near the bottom. The measured data captured large coherent structures consisting of a pair of counter-rotating vortices in a downburst of turbulent fluid. The size of the vortices is about 1/2 the local water depth, and the transverse spacing between adjacent downbursts varies from 2 to 5 times the local still water depth. The downburst and vortices descend rapidly through the water to impinge on the bottom. It was suggested that the counter-rotating vortices are parts of a 3D vortex loop created by non-uniform wave overturning and carried downward with the falling water from the broken wave. Farahani and Dalrymple (2014) simulated the wave tank set-up using the 3D smoothed particle hydrodynamics (SPH) method. Their numerical results predict the formation of vortex loops with counter-rotating vorticity, which they characterized as reversed horseshoe vortices. They described these hairpin vortices as initiated from the portions of the spanwise vortex where there are relatively high curvatures. Under the influence of velocity gradient, portions of the vortex are turned and converted from spanwise to streamwise and vertical components. The vortex loops are subsequently left behind the wave crest. Farahani and Dalrymple (2014) also conducted numerical simulations for a plunging breaker but found no reversed horseshoe vortices in this case. They concluded that the plunging wave breaks in very shallow water and thus there is not sufficient water depth to develop the reversed horseshoe structures. Zhou et al. (2014) simulated the solitary wave experiment using 3D Large-Eddy Simulation (LES). Their simulation results show that 3D hairpin vortices are generated due to shear instability. The hairpin vortices exhibit the characteristics observed in the laboratory experiment. Furthermore, hairpin vortices become more densely populated when the wave propagates landward and more downbursts are able to reach the bottom in shallow water. The instantaneous bottom stress was also computed by using the nearest resolved instantaneous velocities and the wall function.

Using LES, Lubin and Glockner (2015) predicted the generation and evolution of aerated vortex filaments during the breaking of a single unstable periodic sinusoidal wave. Unlike the downbursts and counter-rotating vortices described above, these aerated vortex filaments are observed only under plunging breaking waves. The 3D vortical tubes are elongated in the direction of wave propagation and connect the splash-up with the spanwise tube of air entrapped by wave overturning. Their simulation results indicate that the generation mechanism and evolution of the vortex filaments is a localized process remaining very close to the impact zone, and that the vortices do not contribute to the total energy dissipation. Aerated vortex filaments were not observed when coarser grids were used in the computer simulation, which suggests that high grid resolution is essential to bringing out the formation of these coherent structures.

Most numerical models of breaking waves do not consider the effect of entrained air bubbles on the liquid turbulence. Lamarre and Melville (1991, 1994) observed that the potential energy of bubble plumes in deep-water wave breaking can be 30 to 50% of the total energy dissipated by breaking. Therefore, a robust model of breaking waves would need to account for bubble entrainment and the interaction between dispersed bubbles and the breaking-wave-induced coherent structures, in addition to the complex free surface features occurring in three-dimensional wave breaking. Recently, Derakhti and Kirby (2014) combined a polydisperse two-fluid model and a bubble entrainment model in a LES scheme to simulate the turbulent bubbly flow in the deep water wave breaking of a focused wave packet. They validated their numerical model using experimental measurements of mean flow, turbulence velocities, and bubble plume properties from the laboratory experiments of Rapp and Melville (1990) and Lamarre and Melville (1991). Their simulation results predicted that bubble induced dissipation accounts for about 50% of the total breaking induced dissipation regardless of breaker type and intensity.

The remainder of this paper is organized as follow: experimental methods including the principle of operation of V3V are described in Section 2. Wave measurements and pictures of the breaking waves are shown in Section 3.1. Comparison of V3V and ADV measurements is provided in Section 3.2. V3V measurements and the results of data analysis are presented in Section 3.3. The results of this study are related to the literature and the problems still to be addressed are discussed in Section 4. Conclusions are drawn in Section 5.

2. Experimental methods

The experiment was conducted in a 25-m-long, 0.90-m-wide and 0.75-m-deep tilting flume. A piston type wave generator was programmed to generate cnoidal waves with a wave height of 0.115 m and wave period of 4.0 s. The still water depth at the wave generator was 0.298 m. The corresponding values of deep-water wave-height-to-wave-length ratio H_0/L_0 and surf similarity parameter ξ_0 based on linear shoaling are 0.0033 and 0.43, respectively. The same experiment was repeated a total of 30 times. Each trial was started from still water condition. The generated wave train immediately propagates onto a 1 in 40 (2.5%) plane slope. After the initial start-up of a few wave cycles, subsequent waves break around a still water depth of 0.15 m. Each wave overturns to form a plunger vortex which is followed by the generation of several splash-up vortices before the broken wave is transformed into a turbulent bore.

Wave elevations were measured at 17 locations on the plane slope between the wave generator and still water shoreline using the procedure described in Ting (2013). A summary of the measurement locations and the measured wave height and wave setup and setdown is given in Table 1. The wave transformation and fluid velocity measurements were conducted separately, but they were synchronized with wave generation. Therefore, these measurements should represent the