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Three-dimensional reversed horseshoe vortex structures under broken solitary waves

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ABSTRACT

Turbulent vortical structures under broken solitary waves are studied using three-dimensional smoothed particle hydrodynamics (SPH) method. The numerical model predicts water surface evolution and horizontal velocity very well in comparison with the experimental results. The numerical results detect organized coherent structures characterized as reversed horseshoe (hairpin) vortices being generated at the back of the broken spilling wave and traveling downward. The counter rotating legs of the reversed horseshoe structures appear to be a continuous form of the previously found obliquely descending eddies. The reversed horseshoe structures are associated with the turbulence motion of sweep events (downwelling motion) and transport momentum and turbulent kinetic energy downward into the water column. Vortex turning play an important role on the generation and evolution of three dimensional reversed horseshoe structures from the spanwise breaking wave rollers.

1. Introduction

The turbulence associated with water wave breaking can play a crucial role in mixing processes beneath the free surface, wave damping, and sediment transport. The transfer of heat and mass due to the mixing processes can be vital for water quality and aquatic life. In addition, the vortex structures associated to the water wave breaking can have a dominant effect on the safety of vessels and structures located in the surf zone particularly in the extreme cases of tsunami waves (Banner and Peregrine, 1993; Battjes, 1988; Svendsen, 1987).

In the field, Voulgaris and Collins (2000) studied the vortices induced by the breaking waves and the relative contribution of bottom and surface generated turbulence by analyzing sand resuspension in the surf zone of three different UK beaches. It was reported that inside the surf zone, the vortices induced by breaking waves are the main mechanisms for sand resuspension and the surface-generated turbulence dominates over bed-generated turbulence. Ruessink (2010) studied turbulence dynamics beneath natural breaking surf zone by collecting data at Truc Vert Beach, France, during a 12-day period and under high-energy wave conditions. He illustrated that the Reynolds stresses increase with the ratio of wave height to water depth and decreases in magnitude towards the bed. He found out that in occasional positions, surface-generated turbulence is overwhelmed by bed-generated turbulence.

In the laboratory, Nadaoka et al. (1989) performed an experimental study of the periodic spilling waves breaking on a plane laboratory beach. In addition to the two-dimensional large-scale spanwise vortex structures under breaking waves with axis of rotation parallel to the wave crest, they found three-dimensional obliquely descending eddies (ODEs) behind the wave crest. The experiments revealed that the vortex structures possess large amounts of vorticity (with non-zero average) in otherwise almost irrotational velocity fields. Flow visualization was conducted using air bubbles entrained through the wave breaking process and strong three-dimensionality of the flow structure was observed behind the wave crest. Banner and Peregrine (1993), in their annual review paper, described the turbulence behind the breaker as a turbulent wake. They indicated that in a wave-moving frame of reference, the turbulence is primarily generated in the toe region, from where it spreads back as a wake that contains the momentum lost from the breaking process. In a fixed frame of reference of surf zone, a shear flow can be observed associated with the shoreward flow above the trough level and an undertow returning water towards the seaward direction.

Ting and Kirby (1994, 1995, 1996) conducted a series of experiments on the dynamics of surf-zone turbulence under plunging and spilling breakers revealing that the turbulent kinetic energy is transported landward under a plunging breaker and is dissipated within one wave cycle, whereas the turbulent kinetic energy is transported seaward under a spilling breaker and the dissipation rate is much slower. Chang and Liu (1998, 1999) measured fluid particle velocities for breaking waves in a laboratory. The results indicated that the maximum instantaneous vorticity was much larger than the ensemble-averaged vorticity. Under the broken waves, turbulence advection, production, and dissipation were equally important, while the turbulence diffusion was almost negligible. Downstream from the breaking point, the turbulence

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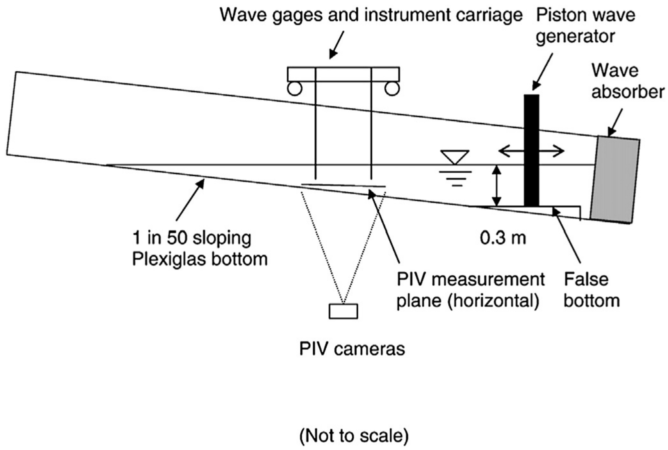

Fig. 1. Schematic plot of experimental set-up of the wave tank (Ting, 2006).

production and dissipation were of the same order of magnitude, but not identical. Cox and Kobayashi (2000) measured the instantaneous horizontal and vertical turbulent velocities induced by spilling waves and concluded that the turbulence generated by wave breaking was an order of magnitude larger than the turbulence generated in the boundary layer. Cox and Anderson (2001) performed particle image velocimetry (PIV) measurements to capture size and vorticity of the coherent structures produced by regular waves breaking on a plane slope in a wave flume. They observed vortices with axis of rotation in the vertical direction at the toe of the broken wave as well as obliquely descending eddies at the back of the broken waves. Ting (2006) performed an experimental study of large-scale turbulence under a solitary wave. In this study, vortices with axis of rotation in the vertical direction, called downbursts, were detected as well as the obliquely descending eddies.

In terms of numerical studies, Watanabe and Saeki (1999) used a three-dimensional large-eddy simulation (LES) method to study the large-scale vortex structures under spilling and plunging breakers. They concluded that the vorticity occurring around the air tube at the plunging phase characterized spanwise rollers. Vertical and obliquely descending eddies are then generated and stretched in the wave direction as the front progresses. Watanabe et al. (2005) described obliquely descending eddies as rib structures, which are essentially counter-rotating streamwise vortices induced by convective instability. These counter-rotating streamwise vortices arise between the spanwise rollers. The re-orientation of perturbations in the primary vorticity results into the streamwise vortex structures in the saddle region between the rebounding jet and the primary spanwise roller. Christensen and Deigaard (2001) and Christensen (2006) performed a LES method to model spilling and plunging breakers. The order of magnitude of the turbulent energy was found to be in agreement with the

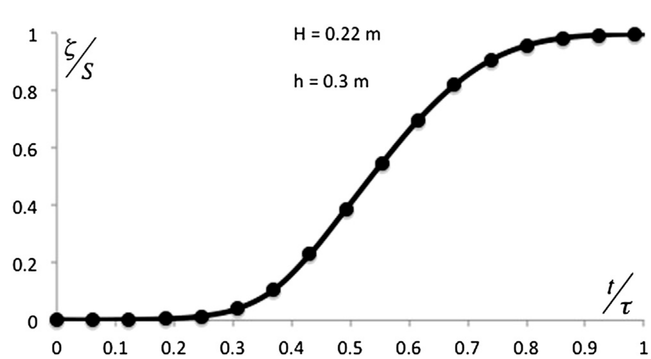

Fig. 2. Solitary wave generator trajectory.

experimental results. It was indicated that at the initial breaking point, vorticity is generated around the vertical as well as around the spanwise axis. Later, vorticity is turned into the streamwise direction.

In this paper, the coherent vortex structures generated under broken solitary wave in both cases of spilling and plunging breakers are investigated. The reason behind studying a single breaking wave is that the wave breaking process and the generation and evolution of the associated three-dimensional vortex structures can be investigated separately from the effect of returning undertow flow and the residual turbulence induced from previously broken waves in the case of periodic waves. Further, a solitary wave is a first approximation to a tsunami wave.

The three-dimensional smoothed particle hydrodynamics (SPH) method is used to numerically model the broken solitary waves and generated turbulent fields. The objectives of this study are to quantify the generation mechanisms and geometric configurations of coherent structures under broken solitary waves specifically the obliquely descending eddies and to show their role in turbulent momentum and kinetic energy transportation to the deeper portions of the water column. For this purpose the instantaneous flow field in both spilling and plunging breakers is investigated and the three dimensional coherent vortex structures are detected. The vortex structure tracking illustrates the physical mechanism of vortex generation under solitary broken waves. Reynolds shear stresses and turbulent momentum flux associated to the coherent vortex structures are studied and their variations over time are investigated. In addition, the vorticity equations and the role of vortex turning and vortex stretching terms at different stages of the vortex development are investigated.

2. Smoothed particle hydrodynamics numerical method and GPUSPH model

Smoothed particle hydrodynamics (SPH) method is a Lagrangian, mesh-free, particle method, in which the governing equations are discretized using an interpolation kernel function that approximates a delta function (Monaghan, 1994). This method was first introduced by Lucy (1977) and Gingold and Monaghan (1977) to solve gas dynamical problems of astronomical interest and later was used to model a wide range of problems including wave-related problems such as solitary waves on beaches (Monaghan and Kos, 1999), Scott Russell's wave generator (Monaghan and Kos, 2000), breaking waves (Colagrossi and Landrini, 2003; Monaghan et al., 2003), impact of wave on structures (Dalrymple et al., 2002; Gómez-Gesteira and Dalrymple, 2004), wave overtopping on the offshore platforms (Gómez-Gesteira et al., 2005), waves in the surf zone (Dalrymple and Rogers, 2006), and rip current system due to bed bathymetry variations (Farahani et al., 2014). Various other applications are mentioned in Monaghan (2005) and Monaghan (2012) review papers. SPH method has a Lagrangian nature, therefore it performs better in modeling free-surface problems that include large deformations. The main advantage of SPH method is that it does not require a computational grid as it is needed in finite difference, finite volume and finite element methods. Hence we avoid wasting computational power to deal with the mesh tangling and distortion problems since no computational mesh is used in the SPH method.

In the SPH method, a continuous medium is represented as a set of particles that carry kinematic and thermodynamic quantities of that medium. In our problem the governing equations are Navier–Stokes equations that are presented as:

$$\frac{\partial \rho}{\partial t} + \rho\left(\nabla \cdot \vec{u}\right) = 0 \quad (1)$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \vec{g} + \vec{\Theta} \quad (2)$$