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Large-scale turbulence under a solitary wave

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Abstract

The structure of large-scale turbulence under a broken solitary wave on a 1 in 50 plane slope was studied. Three-component velocity measurements were taken at different heights above a smooth bed in the middle surf zone using an acoustic Doppler velocimeter. The measured data showed that turbulent velocity components were well correlated in the middle part of the water column. The velocity correlations could be produced by an oblique vortex similar to the obliquely descending eddy observed previously by other investigators. The vertical distributions of the relative values of the components of the Reynolds stress tensor showed that the structure of turbulence evolved continuously between the free surface and the bottom. The evolution was related to transition from two-dimensional to three-dimensional flow structures and the effect of the solid bottom on flow structures. Time histories of measured turbulent kinetic energy and turbulence stresses showed episodic turbulent events near the free surface but more sporadic turbulence in the lower layer. Large or intense turbulent events were found to have short duration and time lag relative to the wave crest point. These events also maintained good correlations between the turbulence velocity components close to the bottom.

Instantaneous turbulent velocity fields were measured near the bottom at the same cross-shore location by using a stereoscopic particle image velocimetry system. These measurements showed that the near-bed flow field was characterized by large-scale, coherent flow structures that were the sources of most of the turbulent kinetic energy and turbulence stresses. The types of organized flow structures observed included vortices and downbursts of turbulence descending directly from above, lateral spreading of turbulent fluid along the bed, and formation of vortices in shear layers between fluid streams. A common feature of the organized flow structures near the bed was the large turbulence velocities in the longitudinal and transverse directions, which reflected the influence of a solid bottom on the breaking-wave-generated turbulence arriving at the bed.

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1. Introduction

In a laboratory study of regular breaking waves on a plane beach, Nadaoka et al. (1989) observed that the wave breaking process produces horizontal vortices with axis of rotation parallel to the wave crest. Behind the wave crest, these span-wise vortices turn quickly into three-dimensional vortices that extend obliquely downward. The obliquely descending eddies (ODEs) are identifiable for only a short time, and rapidly break up into chaotic, three-dimensional turbulence. Although similar vortices occur repeatedly in successive breakers, their size and location may vary from structure to structure. Using a conditional sampling technique, Nadaoka et al. (1988) showed that intense, intermittent turbulence in breaking waves transports more turbulent kinetic energy and fluid momentum than incoherent turbulence. They also observed large eddies hitting a sand bed and lifting up sediment into suspension. The formation of sediment clouds was coincided with measurements of large suspended sediment concentration.

Using laser-induced fluorescence (LIF) technique, Yeh and Mok (1990) studied the formation of turbulence in propagating bores generated by a dam break. They observed sporadic, three-dimensional turbulence patches in the turbulent flow region behind the bore front. They conjectured that these turbulence patches were created by intermittent advection of re-circulating flow in the surface roller. Yeh and Mok (1990) measured the shedding frequencies of the turbulence patches. They found that the Strouhal number is not constant, but increases with the Froude number. This is different from flow around

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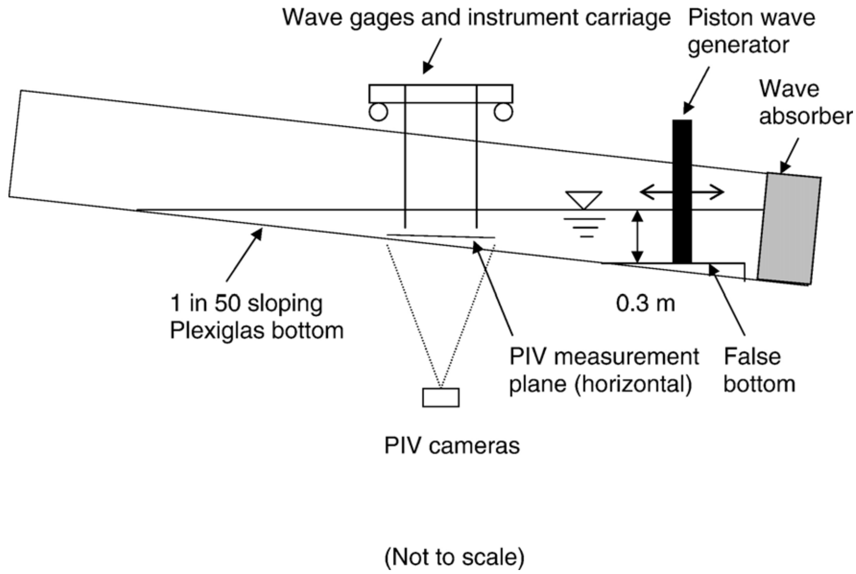

Fig. 1. Experimental arrangement.

submerged bodies, where the Strouhal number is around 0.2 over a wide range of Reynolds number. The Shrouhal number and Froude number were defined as fd_1/C and $C/\sqrt{gd_1}$, respectively, where f is the shedding frequency, d_1 is the still water depth ahead of the bore front, and C is the bore propagation speed.

Using single-point measurements, Cox and Kobayashi (2000) showed that intense, intermittent turbulence exists in the surf zone for spilling regular waves. They found that intermittent turbulent events extend into the bottom boundary layer, and produce instantaneous turbulent kinetic energy and shear stress that are an order of magnitude larger than the corresponding phase-averaged values. They also found that intermittent turbulent motions account for a significant fraction of the total turbulent kinetic energy and shear stress in the entire time series.

Cox and Anderson (2001) measured the instantaneous velocity field in a horizontal plane under plunging regular waves using particle image velocimetry (PIV). Vortices with axis of rotation in the vertical direction were found after the waves had broken. Their measurements provided support for the existence of obliquely descending eddies observed by Nadaoka et al. (1989) and other investigators. Melville et al. (2002) measured the velocity field under deep-water breaking waves using digital particle image velocimetry (DPIV). They found that the wave breaking process generates at least one coherent vortex which propagates slowly downstream. They also found that the ensemble-averaged Reynolds stress $<u'w'>$ is everywhere negative, and that the turbulent kinetic energy, vorticity and Reynolds stress decay as t^{-1}. Here, u' and w' are the longitudinal and vertical components of turbulent velocity fluctuation, respectively, and t is time.

Okayasu et al. (2002) used a high-speed digital video camera to image the movement of sand by large eddies in a laboratory surf zone. They measured the near bottom velocity

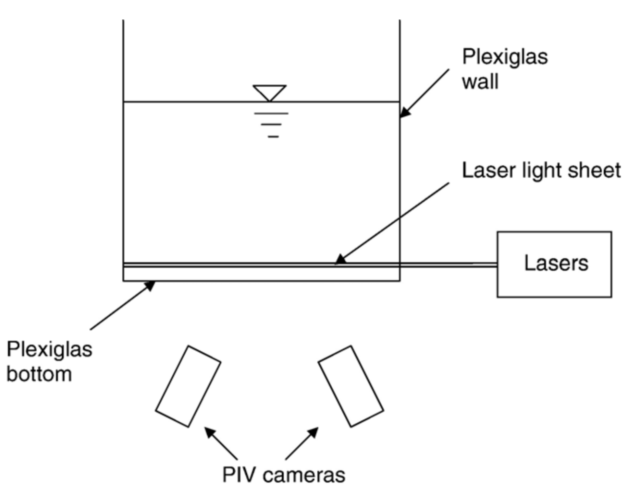

Fig. 2. Configuration of stereoscopic particle image velocimetry system.

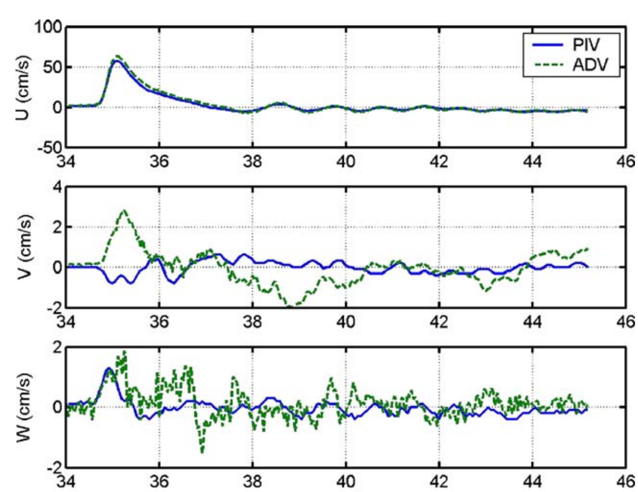

Fig. 3. Comparison of PIV and ADV measurements.

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