

Observation of Coherent Turbulent Structure Under Breaking Wave

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Observation of the spatial evolution of turbulent structures in the surf zone is presented through quantitative measurements of the internal flow fields of spilling waves propagating on a 1:20 slope by Particle Image Velocimetry (PIV). The global ensemble-averaged flow method was employed for turbulence decomposition by repeating the same experiment 25 times in each field of view (FOV). Seven FOV were integrated to represent the global results, which covers the breaking wave from the outer to the inner surf zones. Results show that a relatively large turbulent motion is initially organized in the crest of the breaking wave in the bore-established region. As the wave crest passes, this turbulent structure will then stretch downward to the lower interior region of the water column. Turbulent convection and diffusion terms were estimated. It is found that the convection transport is very significant in spreading the turbulent structure from the wave crest to the trough region.

NOMENCLATURE

C :	local wave phase speed
C_f :	empirical diffusion coefficient
d :	local still water depth
h :	local mean water depth
h_b :	mean water depth at breaking point
H_b :	wave height at breaking point
k :	turbulent kinetic energy
l :	turbulence mixing length scale
L_0 :	deep-water wave length
N :	repeating number of test runs
$\tan \beta$:	bottom slope
T_c :	turbulent convection
T_d :	turbulent diffusion
u :	streamwise velocity
w :	vertical velocity
x :	horizontal (streamwise) coordinate
z :	vertical coordinate
η :	surface elevation
'	(superscript) fluctuating quantities
\sim :	(superscript) mean quantities
$\langle \rangle$:	ensemble averaging

INTRODUCTION

The hydrodynamics of breaking waves in the surf zone have been an important subject for coastal and environmental engineering. Detailed reviews on hydrodynamics in the surf zone can be found in Peregrine (1983), Battjes (1988) and Christensen et al. (2002). Flow visualization is a powerful technique with which to experimentally investigate qualitative flow structures of wave breaking. For instance, Nadaoka et al. (1989) found the generation of oblique descending eddies under breaking waves by this technique. Lin and Hwung (1992) employed a fluorescent dye illuminated by an ultraviolet lamp to exhibit the motion of the surface roller, the bubble-mixing process, and the vortex stretching

of plunging breakers. Additionally, experimental studies providing quantitative details have been carried out for decades. Svendsen et al. (1978) focused on the variation of surface profiles using a wave-gauge technique. Investigations of the internal flow of breaking waves using Laser Doppler Velocimetry (LDV) were reported by Stive (1980), Nadaoka and Kondoh (1982), Ting and Kirby (1996), and Stansby and Feng (2005). Although LDV provides the advantage of a high sampling rate on a fixed point, it is difficult to provide a complete evolution of flow structures in the surf zone.

In recent years, Particle Image Velocimetry (PIV) has been used frequently due to its full-field map of velocity. An exhaustive guide on the development of the PIV system and its applications to water waves can be found in Raffel et al. (1998) and Grue et al. (2003), respectively. Although PIV is a more effective flow measurement technique than LDV, the spatial resolution and frame rate are still limited so that it is not satisfactory for the research of breaking waves. For example, Chang and Liu (1999) measured the kinematics of breaking waves at an intermediate constant water depth. Their results focused on the range of one single frame at the breaking location. Oblique descending eddies were investigated in the spanwise plane by Cox and Anderson (2001), Son and Kihm (2001), and Watanabe et al. (2006). However, the flow induced by wave breaking evolves broadly on a sloping bottom from breaking point to the inner surf zone. It is difficult to display flow evolution from a local fixed measurement of PIV. In order to understand the evolution of internal flow in the surf zone, the PIV measurements should be integrated from several different positions, as given by Qiao and Duncan (2001), Melville et al. (2002), and Kimmoun and Branger (2007).

The main purpose of this study is to investigate the evolutionary flow structures of breaking waves in the surf zone using PIV. In the past, quantitative results by LDV provided only physical information at measuring points in the vertical direction. However, flow properties such as shear deformation, convection, etc. are difficult to explore from the single-point measurement. Based on the literature, what seems to be lacking in quantitative experimental evidence is the spatial distributions of wave breaking in the surf zone. In this paper, global ensemble-averaged flow is represented by a mosaic method. An external triggering system is added to resolve the limitation of PIV's temporal resolution. This system controls the trigger signals of the PIV precisely and

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