Coastal Engineering 77 (2013) 120–139

Contents lists available at SciVerse ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Laboratory measurements of large-scale near-bed turbulent flow structures under plunging regular waves

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ARTICLE INFO

Article history:
Received 14 February 2012
Received in revised form 15 February 2013
Accepted 19 February 2013
Available online 28 March 2013

Keywords:
Plunging regular waves
Breaking wave vortices
Downbursts
Wave bottom boundary layer
Turbulent kinetic energy
Turbulent shear stresses
Sediment transport

ABSTRACT

The turbulent velocity field associated with the breaking of plunging regular waves on a 3% plane slope was measured in a plane running parallel to the slope using a particle image velocimetry (PIV) system. The measurement plane was located within the wave bottom boundary layer. The horizontal distance from the point of incipient breaking to the center of the measurement area was approximately 12 times of the breaking depth. The same wave train was generated 36 times and in each trial three consecutive wave cycles were recorded at a sampling rate of 15 Hz. The measured velocity fields were separated into a mean flow and a turbulence component using the ensemble averaging technique. The impingement process of breaking-wave-generated vortices on the bottom was investigated. The results showed that the impact of a plunging wave vortex on the bottom was a highly transient and three-dimensional phenomenon. The vortex arrived at the bottom around the instant of maximum positive wave-induced velocity. The surge of turbulence continued for a time of about $\sqrt{2H_b/g}$, where H_b is breaker height and g is acceleration due to gravity. The impingement region was not stationary, but continued to travel onshore with an initial speed close to the wave celerity. The distributions of turbulent velocity fluctuations and related momentum fluxes depended on the types of vortices produced. Plunger vortices generated at incipient breaking in deeper water had the characteristics of a three-dimensional vortex loop with counter-rotating vorticity. Large apparent shear stresses were measured in the flow attachment and detachment zones in front and behind the vortex loop. Transverse vortices generated in the subsequent splash in shallower water produced an asymmetrical impingement pattern similar to that of an inclined jet; the downburst of turbulent fluid was deflected outward and shoreward resulting in large onshore fluxes of turbulence energy near the bottom. Large apparent shear stresses were measured in the impingement zone and wall jet region. The motions of glass spheres sliding along the bottom were investigated. It was found that the velocities of glass spheres impacted by downbursts could significantly exceed the wave-induced velocities. It was also found that glass spheres could be trapped by counter-rotating vortices and carried for considerable distances onshore. The measured data suggested that compared to spilling waves, downbursts in plunging waves would enhance onshore sediment transport.

1. Introduction

The instantaneous turbulent velocity fields associated with breaking-wave-generated vortices impinging on a plane slope are investigated in this paper. The large eddies were produced by a train of plunging regular waves as they overturned and plunged into the water ahead at breaking. This process produced a sequence of jet-splash cycles during which several large transverse vortices were produced. Particle image velocimetry (PIV) measurements were taken below the first and second plunge point to capture the near-bed velocity fields associated with the plunger vortex generated at incipient breaking and a second, larger vortex produced by the first splash-up. The latter descended the water column and impinged on the bottom at a horizontal distance equal to approximately 12 times of the breaking depth from the wave breaking point.

The motivation behind this study is the relationship between breaking waves and beach profiles. It is well known that high, steep waves generated during storms tend to result in seaward sediment transport and beach erosion, whereas milder and longer period waves such as swells move sediment onshore and produce an accreting beach (see Silvester and Hsu, 1993). Dean (1973) postulated that the reasons why some wave conditions erode a beach while others accrete are related to how breaking waves transport suspended sediment. In the surf zone, sediment transport can be produced by wave-induced shear stresses initiating sediment particle motion and moving the particles along the bed (bed load transport), and by breaking waves putting sediment particles into suspension for transport by organized wave-induced flows and currents (suspended load transport). Because suspended load transport is conspicuous in the turbulence-dominated region of the outer surf zone, studying the coupled fluid and sediment motion in this region should provide insight into how breaking waves transport suspended sediment. In

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http://dx.doi.org/10.1016/j.coastaleng.2013.02.014

this paper, the outer surf zone is the outer breaking region where rapid wave transformation takes place. It is distinguished from the inner surf zone where the wave shape of the broken waves is self-similar and has a saw-tooth shaped profile (Svendsen et al., 1978).

Breaking waves on beaches can be broadly classified into spilling, plunging, collapsing, and surging (Galvin, 1968). This study is concerned with plunging regular waves. On a given slope, plunging breakers are formed by less steep, longer period incident waves. The characteristics of a plunging breaker have been described extensively in the literature (e.g. Basco, 1985; Jansen, 1986; Peregrine, 1983). The classic form consists of a steepening wave crest that curls over to form an overturning jet. The jet plunges into the water ahead to form a plunger vortex, and also creates a splash-up which projects forward to impact the free surface at a second plunge point, thus initiating a sequence of jet-splash cycles. A strongly plunging breaker may produce several distinct jet-splash cycles and transverse vortices before the broken wave is transformed into a turbulent bore (Zhang and Sunamura, 1990). The transverse vortices initially have their axis of rotation parallel to the wave crest, but oblique vortices will appear spontaneously behind the wave crest (Nadaoka, 1986). In a strongly plunging breaker, the transverse vortices may reach the bottom quickly and maintain their two-dimensionality.

The formation and evolution of vortices are related to the wave characteristics of the breaking waves. Laboratory studies have shown that the beach slope S_0 and deep-water wave-height-to-wavelength ratio or offshore wave steepness H_0/L_0 are the two important parameters for determining the wave characteristics at breaking, including the breaker height, breaking depth, free-fall height of the plunging jet, plunging jet impact velocity and angle, plunge distance, and splash distance. The beach slope and offshore wave steepness may be combined into the surf similarity parameter, $\xi_0 = S_0/(H_0/L_0)^{1/2}$, which is the parameter commonly used to distinguish between different breaker types. The range of ξ_0 values is between 0.5 and 3.3 for plunging breakers and below 0.5 for spilling breakers (Battjes, 1974). Battjes (1974) showed that the wave-height-to-water-depth ratio at breaking, H_b/h_b, is an increasing function of ξ_0. On a 1 in 35 slope, for example, the value of H_b/h_b may be equal to 1.2 for a strongly plunging breaker with $\xi_0 = 0.6$, compared with 0.8 for a spilling breaker with $\xi_0 = 0.2$ (Ting and Kirby, 1994). Galvin (1969) found that the dimensionless plunge distance, ℓ_p/H_b, decreases as beach slope increases and the dimensionless splash distance, ℓ_s/H_b, is approximately equal to the dimensionless plunge distance. Okayasu (1989) found that the dimensionless distance from the breaking point to the inner surf zone, ℓ_t/H_b, decreases as the beach slope increases and is nearly independent of the offshore wave steepness. Chanson and Lee (1997) found that the dimensionless free-fall height of the plunging jet, $(A_b - A_i)/A_b$, where A_b is wave crest amplitude at breaking and A_i is height of the plunging jet impact measured above still water level, increases as the offshore wave steepness decreases. Using the PIV technique, Chang and Liu (1998) measured a fluid particle velocity equal to 1.68 times of the wave celerity and an acceleration equal to 1.1 times of gravity at the tip of the overturning jet in a plunging breaker.

Due to high concentrations of entrained air bubbles, it has always been a challenge to measure the fluid kinematics near the surface of a breaking wave. Jansen (1986) used fluorescent particles and ultraviolet light to study the fluid motions in the aerated region of spilling and plunging breakers. He found that particle trajectories inside the jet-splash motions are smooth and repeatable from wave to wave, which indicates that the fluid motions are highly organized during the initial stages of breaking. Using a laser light sheet and fluorescent particles, Lin and Huang (1992) observed vertical vortex motions behind the wave crest in plunging waves and concluded that the fluid motion in the jet-splash sequence is three-dimensional. Raichlen and Papanicolaou (1988) estimated the area of bubble mass on the front face of breaking waves from high-speed motion pictures. For a wide range of incident wave conditions including both spilling and plunging waves, they found that the dimensionless cross sectional area of bubbles mass, A/H_b^2, increases monotonically from zero at breaking to a maximum around unity in a horizontal distance equal to about 10 times of the breaking depth, then decreases. Thus, breaking-wave-generated vortices take a relatively long time or horizontal travel distance to descend to the bottom. During this time, major changes in wave height and shape are taking place. Therefore, surface wave characteristics and properties of breaking-wave-generated turbulence are not necessarily correlated when they are measured at the same cross-shore location. When analyzing irregular breaking waves, which have varying breaking points, it becomes a challenge to associate turbulent or high concentration sediment events with breaking wave events (see Scott et al., 2009).

There have been numerous laboratory investigations of the breaking-wave flow field below trough level. The earlier studies were conducted using single-point measurement devices such as hot-film or laser-Doppler anemometers (LDA). The instruments were normally employed to measure two components of water particle velocity in the longitudinal vertical plane; the transverse component was not measured. From these two-component velocity measurements, the distributions of time- and ensemble-averaged wave and turbulence quantities such as undertow, turbulent kinetic energy, Reynolds stress, vorticity and strain rates were determined. For a general survey of surf zone turbulence the interested reader is referred to Christensen et al. (2002) and Longo et al. (2002). Because this study is concerned with the instantaneous flow fields under plunging waves only the pertinent articles will be discussed here.

Nadaoka (1986), and Nadaoka et al. (1988, 1989) gave attention to the large-scale structure of turbulence in a laboratory surf zone. They observed that the transverse vortices produced by breaking waves will evolve quickly into vortices extending obliquely downward (obliquely descending eddies). They showed that breaking-wave turbulence is highly intermittent, and suggested that the intermittency is related to the arrival of obliquely descending eddies. Using conditional sampling, Nadaoka et al. (1988) separated measured turbulence velocities into a coherent and an incoherent component; the coherent turbulence is associated with the large eddies, whereas the incoherent turbulence is the residual turbulence. Their analysis showed that coherent turbulence transports more turbulent kinetic energy and fluid momentum than incoherent turbulence. Using entrained air bubbles as tracers, they further observed that the impingement of large eddies on a sand bed coincided with measurements of large suspended sediment concentration, thus demonstrating the role of large eddies in sediment suspension under breaking waves.

Cox and Anderson (2001) analyzed LDA measurements of instantaneous longitudinal and vertical turbulence velocities under plunging regular waves. They found that intermittent turbulence accounts for a significant fraction of the total turbulent kinetic energy in the time series. They also determined the diameter and maximum vorticity of a breaking-wave-generated vortex from PIV measurements. Ting (2006) analyzed the instantaneous turbulence velocities under a breaking solitary wave. An acoustic Doppler velocimeter (ADV) was used to measure all three components of water particle velocity. He found that the fluctuating shear stresses $u'v'$, $u'w'$ and $v'w'$ are correlated during turbulent events, which suggests the presence of organized flow structures. Using a stereoscopic PIV system, Ting (2008) captured counter-rotating vortices reminiscent of the obliquely descending eddies described in Nadaoka (1986).

It is extremely difficult if not impossible to obtain conclusive information about the structure of large eddies from single-point measurements; data interpretation is complicated by many factors including the relative positions of eddies and sensors, age of eddies, and the temporal resolution and spatial distribution of sensors. Using the PIV technique, Kimmoun and Branger (2007) measured the instantaneous velocity fields under plunging regular waves from the breaking point to the shoreline. They produced detailed space-time evolution of the ensemble-averaged flow field in the longitudinal vertical plane. Their