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Measurements of surface thermal structure, kinematics, and turbulence of a large-scale solitary breaking wave using infrared imaging techniques

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ABSTRACT

The surface temperature fields of large-scale solitary breaking waves are measured using infrared imaging techniques in a laboratory surf and swash zone. The surface velocity fields obtained by cross-correlating the images are decomposed into wave and turbulent motions using two filtering methods in the spatial and temporal domains. The techniques presented here provide new quantitative descriptions for the evolution of the surface thermal structures, kinematics, and turbulence that are induced by unsteady and highly foamy turbulent coastal flows. Novel organized streaks of thermal structures, which exhibit a finger-like shape, are found on the water surface of the crest roller behind the head of the rebounding jet. These thermal streaks evolve with time and become isotropic when returning to the surrounding bulk water temperature. The Froude-scaled maximum flow speed, accelerations, and vorticity are $O(1)$, and the scaled turbulent kinetic energy (TKE) is $O(-1)$; these results are similar to previous findings from numerical results and periodic surf-zone breakers. Significant and concentrated structures of these quantities occur in the moving wave crest during the uprush phase; however, these structures only develop during the late stages of the backwash phase. The TKE increases shoreward from the surf to the swash zones. The ratio of the averaged variance of the turbulent velocity in the wave breaking zone does not agree with the canonical prediction for plane-wake turbulence; however, the ratio is similar to that of boundary-layer turbulence and decreases in the bore region and the swash zone, indicating an increase in the turbulence anisotropy shoreward from the surf to the shallower swash flow.

1. Introduction

Wave breaking in surf zones plays an important role in wave energy dissipation, sediment transport, and structure stability in coastal areas. The turbulence generated by breaking waves dissipates wave energy and has been considered an important source of sediment suspension (Yoon et al., 2013), which is closely associated with sediment transport and topographical changes in nearshore regions. Many coastal engineers have been interested in the wave loading that is generated by breaking waves and associated overtopping greenwater (e.g., McCabe et al., 2013; Jianhong et al., 2014). Reviews on surf-zone breaking waves, dynamics, and turbulence can be found in Peregrine (1983), Battjes (1988), Christensen et al. (2002), and Longo et al. (2002). Although there are numerous studies on surf-zone breaking waves, our knowledge remains limited regarding the roller and splashing regions of highly foamy surf-zone breaking waves where high-intensity air bubbles are entrained by plunging jets. The absence of novel measurements in this complex two-phase flow has impended our understanding of the behavior of breaking waves.

Laser Doppler velocimetry (LDV) has been used to measure the internal flow structure, undertow, turbulence intensity, turbulent transport terms, and Reynolds stresses in small laboratory surf zones under spilling and plunging breakers (e.g., Ting and Kirby, 1995; Stansby and Feng, 2005; De Serio and Mossa, 2006; Shin and Cox, 2006). However, measurements using LDV are usually restricted below the wave trough level because this technique fails (because of signal drop-out) in the aerated region of the breaking waves. Over the last decade, particle image velocimetry (PIV) has also been widely used in small laboratories to observe various types of breaking waves outside the aerated region or for small-scale breakers (e.g., Chang and Liu, 1999; Govender et al., 2002; Melville et al., 2002; Kimmoun and Branger, 2007; Huang et al., 2009b, 2010a, 2010b). When performing measurements using a typical PIV configuration, air bubbles can result in the loss of control of the laser sheet in the aerated region (Ryu et al., 2005). Moreover, the high-power laser light may be reflected by bubbles and damage the charge-couple device. In addition, recent progress on turbulence and current measurements in natural surf zones has been made using acoustic Doppler velocimetry (ADV) (e.g., Ruessink, 2010; Feddersen, 2012). These measurements are also performed far from the crest regions because air

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bubbles corrupt the acoustic signals; thus, data despiking and quality controls are required to perform ADV measurements in coastal regions (Elgar et al., 2005; Feddersen, 2010; Huang et al., 2012).

Flows on the water surface in surf and swash zones have been measured using video and cross-correlation-based techniques that are similar to the PIV algorithm (e.g., Holland et al., 2001). Most of these methods rely on the advection of optically visible surface features, i.e., typically the movement of bubbles and foam generated by breaking waves and bores, and patches of light reflected from the water surface. Indeed, the recorded patches are visible light energy that is reflected from ambient light sources; the reflection depends on the curvature of water surface. Because the patches are not directly radiated from the surface, it is difficult to obtain high traceability as surface “particle tracers” that follow the surface flow. Therefore, a novel measurement technique is needed to obtain high-quality surface flow measurements in challenging coastal zones.

Infrared imagery techniques have been used to observe the surface temperature fields of breaking waves. The turbulence generated by breaking waves disrupts the skin layer at the water surface and transports warmer water from below (i.e., bulk or subskin water) to the free surface, which results in cool and warm temperature structure patches (Jessup et al., 1997b). Infrared techniques can be used to record these thermal structures and thus detect normal or microscale breaking waves and quantify the heat and gas transfer during the breaking process (Jessup et al., 1997a, 1997b; Zappa et al., 2001; Loewen and Siddiqui, 2006; Veron et al., 2008; Sutherland and Melville, 2013). Jessup and Phadnis (2005) used infrared imagery techniques to measure the geometry and the kinematic properties of microscale breaking waves. Watanabe and Mori (2008) investigated the renewal of the surface temperature for nearshore breaking waves using an infrared technique. The authors performed a large-eddy simulation and inferred that the observed surface renewal could be related to subsurface longitudinal counter-rotating vortices. They used a PIV algorithm to obtain the celerity of the wave breaking crest. Furthermore, Veron et al. (2008) used infrared techniques with a PIV algorithm and laser-heated thermal marker tracking to measure the ocean surface temperature and velocity fields.

The shoaling process, breaking criterion, and runup heights of a solitary wave propagating on a plane slope for non-breaking or breaking solitary waves have been successfully determined from surface elevation measurements using wave gauges and runup wires or video cameras (Synolakis, 1987; Grilli et al., 1997; Li and Raichlen, 2001, 2002 Hwang et al., 2007; Hsiao et al., 2008). Measurements of the internal flow velocities have furthered our understanding of the flow dynamics and turbulence of solitary breaking waves. Li and Raichlen (2002) used LDV to measure the flow velocities before the breaking of a solitary wave on a slope. Moreover, Jensen et al. (2003) and Jensen et al. (2005) used PIV to study the early stages in the runup of small-scale collapsing-type solitary breaking waves over a sloping glass beach. The authors found large vertical accelerations and an on-shore jet in the runup front. Ting (2006) and Ting (2008) investigated the turbulent structures under a solitary breaking wave; Ting (2013) extended these measurements to study progressive plunging breaking waves. The authors argued that the near-bottom turbulence descending from the upper region evolved continuously from the free surface to the bottom and transitioned from a two-dimensional (2-D) to a three-dimensional (3-D) turbulent structure. Baldock et al. (2009) conducted a series of large-scale experiments to measure the kinematics of breaking solitary wavefronts using ADV. Examples were presented to illustrate the data quality and some features of the kinematics in the breaker zone. Furthermore, Sumer et al. (2011) conducted a bed stress measurement on a rigid bed and a pore pressure measurement on a sediment bed under plunging solitary waves. The authors found a substantial increase in the mean bed shear stress (by as much as a factor of 8) in the runup and rundown stages. The bed experienced upward pressure gradient forces during the downrush phase. Saelevik et al. (2013) used PIV to study the runup of solitary waves on two different beaches with a straight slope and a composite slope. A stagnation point at the beach boundary was observed for both beaches. The stagnation point for the straight beach moved upward faster than for the composite beaches.

In this study, we used infrared imaging techniques with a PIV algorithm, which is known as infrared image velocimetry (IRV), to experimentally study a large-scale solitary wave breaking and swash processes. The solitary breaking wave was studied to isolate the wave breaking process. Moreover, the extremely high and vertically uniform flow speed of the solitary wave enabled us to test the capability of the IRV. The recorded infrared images were used to study the evolution of surface temperature structures and to compute the surface flow velocity and its spatial derivatives during solitary wave breaking. New experimental results are presented for the surface thermal structures, kinematics, and turbulence of large-scale solitary wave breaking from the surf to the swash zone.

2. Experiments

The experiments were conducted in the Super Tank of the Tainan Hydraulics Laboratory (THL). The tank was 300 m long, 5.0 m wide, and 5.2 m deep. Waves were generated using a programmable PC-controlled hydraulically driven, dry back, piston-type wave maker at one end of the flume. A 1:20 concrete slope was constructed in the tail of the flume at a distance of 197.0 m from the wave board. The side wall and the bottom of the flume were made of smooth concrete with an estimated roughness of approximately 0.1–0.2 mm, which is equivalent to Manning coefficient of approximately 0.01. A movable carriage was installed on rails on the sidewalls of the flume. Fig. 1 is a schematic diagram of the experimental facilities and configuration and defines the Cartesian coordinate system used (x: streamwise/along flume direction, y: spanwise/cross flume direction, and z: vertical direction). The shoreline where the still water surface intersected the sloping bottom was located at approximately $x = 236.3$ m.

The surface temperatures were recorded using an integrated infrared imaging system developed by Veron et al. (2008) (Fig. 1). This system included an infrared digital camera (Indigo Merlin MWIR camera), a 60-W air-cooled CO2 laser (Synrad Firestar T60), which was equipped with an industrial marking head (Synrad FH index), and two computer-controlled scanning mirrors. These instruments were mounted inside a weatherproof, air-conditioned aluminum housing. More details about the infrared imaging system can be found in Veron et al. (2008). The infrared camera (320×256 pixels), which was manufactured with a thermal resolution noise equivalent temperature difference of 18 mK, was set at 60Hz to measure the temperature fields for four field of views (FOVs) by moving the carriage to four positions, which were denoted as p1 to p4. The first to the third FOVs were overlapped to observe the surface temperature field of the solitary breaking wave during overturning and impinging. The fourth FOV was located near the shoreline to observe the swash processes of the turbulent bore (Fig. 1). The positions of the four FOVs are summarized in Table 1.

The water surface elevations were measured using twenty-two capacitance-type wave gauges that were mounted 40 cm from the sidewall (Nos. 1–16 and Nos. 20–25), and three ultrasonic wave gauges that were mounted on the carriage (Nos. 17–19). Gauge 18 was set along the negative y direction outside the center of the FOV of the infrared image, while gauges 17 and 19 were set three meters from gauge 18 in the x direction. The ultrasonic wave gauges were moved with the carriage. The wave profiles were recorded simultaneously at a sampling rate of 50 Hz using the Microsoft NT-based Multi Nodes Data Acquisition System, which was developed by THL (Hwung and Chiang, 2005). The streamwise and vertical flow velocities were measured using an electromagnetic current meter (ECM) with a sampling rate of 50 Hz, which was set near the FOV of the infrared camera. The vertical positions of the ECMs were set at half the local still water depth. The positions of the wave gauges are summarized in Table 1. The streamwise, lateral,