Coastal Engineering 138 (2018) 66–79

Contents lists available at ScienceDirect

Coastal Engineering

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

Large-scale laboratory observation of flow properties in plunging breaking waves

Byoungjoon Na[a,b], Kuang-An Chang[a,b,*], Zhi-Cheng Huang[c], Wen-Yang Hsu[d], Wei-Liang Chuang[a], Yang-Yih Chen[e]

[a] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA
[b] Department of Ocean Engineering, Texas A&M University, College Station, TX 77843, USA
[c] Institute of Hydrological and Oceanic Sciences, National Central University, Jhongli, Taoyuan 320, Taiwan, ROC
[d] International Wave Dynamic Research Center, Tainan Hydraulics Laboratory, National Cheng Kung University, Tainan 709, Taiwan, ROC
[e] Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung 804, Taiwan, ROC

ARTICLE INFO

Keywords:
Wave breaking
Air entrainment
Void fraction
Turbulence
Scale effect

ABSTRACT

A plunging breaking wave of 1-m height was generated in a very large wave tank of 5 m in width, 5 m in depth, and 300 m in length filled with freshwater. The surface velocities in the highly aerated region of the breaking wave were measured using bubble image velocimetry (BIV), while the void fraction profiles were measured using fiber optic reflectometers (FOR). The internal velocities below the aerated region were also measured using an array of acoustic Doppler velocimeters (ADV). A wavelet-based technique was used to detect vortical structures at the free surface and estimate their length scales. The measured surface velocity fields were decomposed into wave induced and turbulence induced components to investigate the temporal and spatial evolution of mean kinetic energy and turbulent kinetic energy. It was found that turbulence is advected and diffused mainly following the phase speed of the breaking wave, rather than from the wave group velocity during the first splash-up process. The internal velocity measurements below the aerated regions show that turbulent kinetic energy decreases exponentially as the depth increases. Since scale effects under breaking waves with turbulence and air entrainment are less understood, results in flow kinematics, turbulence, and void fraction in the present study were compared with that in Lim et al. (2015) which investigated small scale plunging breaking waves with a 0.2-m wave height. It was found that flow kinematics and some dynamic properties such as void fraction and turbulent kinetic energy can be well represented between different physical scales if the traditional Froude scaling law is applied. Other dynamic properties, including bubble number and size distributions, seem to be significantly affected by the physical scales.

1. Introduction

Surface wave breaking is one of the naturally occurring multiphase flows at the air-sea interface which entrains air during the process. Many excellent laboratory studies on the air entrainment mechanism, focusing on void fraction and breaking-induced bubbles, have been reported (Lamarre and Melville, 1991; Hwung et al., 1992; Deane and Stokes, 2002; Cox and Shin, 2003; Hoque and Aoki, 2005; Blenkinsopp and Chaplin, 2007; Kimmoun and Branger, 2007; Rojas and Loewen, 2007, 2010; Mori et al., 2007b). Earlier studies (Miller, 1976; Basco, 1985; Bonmarin, 1989) contributed to the qualitative description of the breaking process and air entrainment, and the geometric properties of bubble plumes. The breaking process, such as wave overturning and subsequent impinging and splash-ups, was examined using video recordings, including the size, shape, and position of the resulting bubble plume. Multiple splash-ups were observed from a single breaker that is responsible for the generation of co-rotating and counter-rotating vortices under the breaker.

Using intrusive resistance-type or optical-fiber based probes, advances were made on void fraction measurements in mostly small scale, controlled laboratory setting. Hwung et al. (1992) reported a deeper penetration of air bubbles and a higher maximum void fraction of 18% in plunging breakers, compared to the 12% void fraction in spilling breakers. Cox and Shin (2003) showed void fraction ranging from 15% to

* Corresponding author. Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA.
E-mail address: kchang@tamu.edu (K.-A. Chang).

https://doi.org/10.1016/j.coastaleng.2018.04.002
Received 6 March 2017; Received in revised form 13 February 2018; Accepted 3 April 2018

20% at a measurement point in the aerated region while Hoque and Aoki (2005) reported void fractions of 20% under plunging breakers and 16% under spilling breakers. More recently, Mori et al. (2007b) measured void fraction of 24% under plunging breakers and 19% under spilling breakers. In most studies, despite small variations, plunging breakers exhibit a higher void fraction compared to spilling breakers. Overall the measured void fractions utilizing resistance-type probes are within 25% in the studies.

Optical-fiber based void fraction probes have been employed in breaking wave studies in more recent laboratory works (Blenkinsopp and Chaplin, 2007; Rojas and Loewen, 2010; Lim et al., 2015; Na et al., 2016). Interestingly, a much higher void fraction of around 90% in plunging breakers was reported. The optical-fiber based probes are relatively newer, and in general are of higher sensitivity and frequency response with a lower dimension over the traditional resistance-type probes. It is not clear whether the discrepancies in the measured void fractions are caused by the technology differences, or simply by the measurement point locations. It is also not clear if different physical scales contribute to the discrepancies. It is worth pointing out that Lim et al. (2015) demonstrated [see their Fig. 15a] that a very different void fraction magnitude may be obtained if the measurement locations are 2–3 cm off from the roller.

Air entrainment in breaking waves has been found, both experimentally and numerically, to affect the wave energy distribution and dissipation. Lamarre and Melville (1991), (1992) concluded that 30–50% or more of the total pre-breaking wave energy was lost in entraining the bubble plume, and air entrainment has a significant effect on wave energy dissipation. Lim et al. (2015) (hereafter referred as *L15*) concluded that the total energy is significantly overestimated if void fraction is not considered in laboratory generated plunging breaking waves. Moreover, recent numerical modeling considering air entrainment and its effect to the turbulent dissipation rate (Shi et al., 2010; Ma et al., 2011; Derakhti and Kirby, 2014) showed that the energy dissipation rate increases with the presence of air bubbles during breaking.

Scale effects due to air entrainment in breaking wave studies have been a concern in the applicability of mostly small scale laboratory measurements. Führboter (1970) discussed the energy dissipation process due to air entrainment during wave breaking. The amount of entrained air depends not only on the Froude and Reynolds numbers, but also on the Weber number. Deane and Stokes (2002) showed that bubble size distributions measured in breaking waves in the open ocean exhibited two distinct power-law scales with a slope change occurring at the bubble radius of about 1 mm. This particular scale, termed the Hinze scale, occurs when the shearing force of turbulence (to break up bubbles) is balanced by the restoring force of surface tension. The reported Hinze scale is, as expected, smaller but still close to that found in small-scale freshwater laboratory experiments (2–4 mm in general, see Na et al., 2016). These results provide evidence that the bubble fragmentation process and its resulting bubble size distribution may remain similar between large scale oceanic breakers (predominantly the spilling type) and small scale laboratory breakers, implying that the bubble fragmentation process is similar (bubbles continue to break up until they reach the Hinze scale). Furthermore, Mori et al. (2007b) investigated void fractions, bubble distributions, and turbulent properties of surf zone breaking waves in midscale experiments using ADV and a dual-tip resistivity void fraction probe. They found a similar bubble size distribution, consistent with the finding that the bubble fragmentation process may be independent of the breaker scale. However, they observed that the void fraction of the larger scale breakers is 2–4 times greater than that of smaller scale breakers.

A large-scale (or near-prototype scale) laboratory experiment, with a breaking wave height of O (1 m), is essential for providing an intermediate step to fill in the gap between the small-scale laboratory measurements and field observations for turbulence under breaking waves (Thornton et al., 2000). Scott et al. (2005) observed turbulence on a fixed barred beach (i.e., without sediments) under large scale laboratory breaking waves. They found that the turbulence level was the greatest at the bar crest, and showed that the associated turbulent kinetic energy (TKE) was transported to the bed. Subsequently, Yoon and Cox (2010) performed observations of turbulence over an evolving beach at a large scale laboratory. They found that both the time-averaged TKE and the turbulence dissipation rate showed a large increase near the bottom. Oh et al. (2008) studied the evolution of turbulent coherent structures under large scale wind-generated breaking waves. They showed that the overall evolving characteristics of coherent structures in large scale and microscale breakers are qualitatively the same. Huang and Hwang (2015) investigated the evolution of surface turbulence on large-scale solitary breaking waves using an infrared imaging technique. They observed that concentrated thermal structures occurred in the moving wave crest during the uprush phase and during the late stages of the backwash phase. They also found that the TKE increased shoreward from the surf to the swash zones.

Scale comparisons featuring the mean and turbulent properties of breaking waves are often studied using the Froude similarity law (e.g., Stive, 1985; Watanabe and Mori, 2008; Huang and Hwang, 2015). Stive (1985) compared wave heights, wave set-up, and profiles of maximum and mean horizontal velocities of surf-zone breaking waves between two flumes with different physical dimensions. He showed that these quantities do not deviate significantly for wave heights ranging from 0.1 m to 1.5 m when using the Froude similarity. Watanabe and Mori (2008) investigated surface temperature distributions from infrared sensing in small- and large-scale wave flumes to study surface renewal created by subsurface vortices beneath breaking waves. They showed that the initial formation of longitudinal counter-rotating vortices can be characterized by the Froude number, while the frequency of surface renewal in a bore region correlates exponentially with the Reynolds number. Heller et al. (2008) studied the scale effects in subaerial landslide generated impulse waves based on the Froude similarity law. They showed that the scale effects reduced the relative wave amplitude, but had a relatively minor effect on the wave celerity.

Kiger and Duncan (2012) reported that the effects of scale in breaking intensity is an extremely important issue. Indeed it is still inconclusive whether the scale effects are significant when applying the Froude similarity. Stive (1985) measured free surface elevations and velocity fields, using laser Doppler velocimetry (LDV) outside the aerated region, under both small and large scale surf-zone breaking waves and provided systematic comparisons of wave heights, set-ups, and vertical profiles of horizontal velocities. Based on the comparisons of the kinematic property, *Stive* concluded that scale effects in these quantities were virtually nonexistent. However, it is unclear whether the same conclusion would be made if the velocity measurements were taken inside the aerated region with a very high concentration of air bubbles (LDV does not work in that region). Moreover, the void fraction and turbulent property inside the aerated region were not measured in *Stive's* study while these quantities are more likely to be affected by scale since they may not follow the Froude scaling. These have been proven to be a difficult task in the past due to the limited capabilities of instrument and measurement techniques. As far as the authors know, the present study is the first attempt at such a challenge in a systematical way after Stive (1985). Indeed, few studies that included the measurements of void fraction, internal velocities, and turbulence in highly aerated breaking waves were reported before *L15*. Hence, *L15* was used as the primary reference to the present study because both studies share the same measurement techniques, analysis methods, and types of breaking waves.

The objective of this study is to investigate experimentally large scale plunging breaking waves by measuring velocity fields and void fractions using bubble image velocimetry (BIV), ADV, and fiber optic reflectometers (FOR), and then compare the findings with the results of *L15* (and other studies) to examine the scale effects. The present study focuses on whether flow kinematics, turbulence, and void fraction can be appropriately scaled when the Froude scaling law is applied. Froude scaling has been commonly used to scale up physical quantities of