Ocean Engineering 155 (2018) 201–210

Contents lists available at ScienceDirect

Ocean Engineering

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

An experimental comparison of velocities underneath focussed breaking waves

Alberto Alberello[a,*], Amin Chabchoub[b], Jason P. Monty[c], Filippo Nelli[d,a], Jung Hoon Lee[a], John Elsnab[c], Alessandro Toffoli[a]

[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC, 3010, Australia
[b] School of Civil Engineering, The University of Sydney, Sydney, NSW, 2006, Australia
[c] Department of Mechanical Engineering, The University of Melbourne, Parkville, VIC, 3010, Australia
[d] Centre for Ocean Engineering Science and Technology, Swinburne University of Technology, Hawthorn, VIC, 3122, Australia

ARTICLE INFO

Keywords:
Waves
Surface gravity waves
Wave focussing
Velocity
Kinematics
Wave breaking

ABSTRACT

Nonlinear wave interactions affect the evolution of steep wave groups, their breaking and the associated kinematic field. Laboratory experiments are performed to investigate the effect of the underlying focussing mechanism on the shape of the breaking wave and its velocity field. In this regard, it is found that the shape of the wave spectrum plays a substantial role. Broader underlying wave spectra leads to energetic plungers at a relatively low amplitude. For narrower spectra waves break at higher amplitudes but with a less energetic spiller. Comparison with standard engineering methods commonly used to predict the velocity underneath extreme waves shows that, under certain conditions, the measured velocity profile strongly deviates from engineering predictions.

1. Introduction

Rogue waves threaten safety and survivability of marine structures. The mechanisms leading to the formation of such extreme waves have been investigated and probabilistic descriptions derived to provide improved design criteria (e.g. Perlin et al., 2013; Bitner-Gregersen and Toffoli, 2014; Toffoli et al., 2012; Alberello et al., 2016a). Breaking of large waves is the most hazardous condition in terms of wave forces on marine structures (Faltinsen, 1993; Grue, 2002; Kim, 2008; Alberello et al., 2017). However, it remains elusive how the mechanism leading the formation of a rogue wave affects the wave shape at the breaking and the associated kinematic field.

Measurements under deep water breaking waves have shown that wave velocities, and associated forces, exceed those predicted by the potential flow theory in the crest region. Using Laser Doppler Anemometry (LDA) under plungers, Easson & Greated (Easson and Greated, 1984) report velocities two times larger than those predicted by linear theory and forces fives times larger than those of an equivalent 5th order Stokes wave. Analogous results are reported in Kim et al. (1992) for a spiller in random sea. Measured particle velocities in the crest region exceed those predicted using equivalent Stokes wave and linear superposition of the spectral components. Kim et al. (1992) argue that the asymmetric shape (crest higher than the troughs with forward leaning wave front) associated to large transient waves as a result of energy focussing might affect the accuracy of the estimation of the velocity field.

Breaking waves have also been experimentally investigated by means of Particle Image Velocimetry (PIV). This technique, compared to LDA, offers the advantage of obtaining fluid velocities over a plane (unlike pointwise LDA measurements). Under plungers, Skyner (1996) recorded particle velocities higher than the phase speed of the waves. Observations of velocities exceeding the phase speed were also made by Perlin et al. (1996), even though the fluid flow presents a different topology compared to Skyner (1996). Difference in the flow structure are most certainly related to a different underlying wave spectrum. PIV was systematically employed by Grue et al. (Grue et al., 2003; Grue and Jensen, 2006, 2012) to investigate breaking waves in deep water conditions. Monochromatic wave trains, unidirectional focussed wave groups and unidirectional random seas were all considered. However, the role played by different focussing mechanism on the velocity profile has not been assessed.

Grue et al. (2003) observed that all velocity profiles could be described by an universal profile if opportune dimensionless parameters were chosen. The velocity profile beneath a wave can be approximated by a third order monochromatic Stokes wave with the same period and

* Corresponding author.
E-mail address: alberto.alberello@outlook.com (A. Alberello).

https://doi.org/10.1016/j.oceaneng.2018.02.049
Received 3 March 2017; Received in revised form 6 February 2018; Accepted 21 February 2018

amplitude using the so-called Grue method (Grue et al., 2003). The wavenumber k and the steepness ε (product of the wavenumber and the linear wave amplitude a) are obtained numerically solving the system of equations:

$$\begin{cases} \dfrac{\omega^2}{gk} = 1 + \varepsilon^2 \\ k\eta_M = \varepsilon + \dfrac{1}{2}\varepsilon^2 + \dfrac{1}{2}\varepsilon^3 \end{cases} \tag{1}$$

The angular frequency is computed linearly from the trough-to-trough wave period (i.e. $\omega = 2\pi/T_{TT}$ being T_{TT} the distance between the troughs around the crest) and η_M is the maximum wave elevation. Once the solution is obtained the velocity profile has the exponential profile:

$$u_G = \varepsilon\sqrt{\frac{g}{k}}\exp(k\eta). \tag{2}$$

The Grue velocity profile matches previous breaking measurements reported in e.g. (Kim et al., 1992; Skyner, 1996; Baldock et al., 1996). Furthermore, the Grue method compares well with second order potential flow predictions (Stansberg et al., 2006; Johannessen, 2010). The good performance of the Grue method and its relative simplicity established it as one of the methods commonly accepted by industry standards to define the velocity profile under large waves (Stansberg et al., 2006).

Another method to estimate the velocity profile underneath a random wave field has been proposed by Donelan et al. (1992). The method is based on a superposition of wave components. Unlike traditional linear superposition, that has been found to overestimate crest velocities, in the Donelan method spectral wave components (surface and velocity corrections) are iteratively added to the perturbed solution. To compute the velocity profile the required steps are as follows. First a Fourier Transform algorithm is used to compute amplitudes, a_n, and phases, ε_n, of the surface elevation. A vertical grid is defined, i.e. z. The successive velocity and amplitude increments (δu_n and $\delta\eta_n$ respectively) are computed iteratively as

$$\delta u_n = a_n\omega_n\cos(\omega_n t + \varepsilon_n)\cdot\exp(k_n(z - \eta_{n-1})), \tag{3}$$

$$u_n = u_{n-1} + \delta u_n, \tag{4}$$

$$\delta\eta_n = a_n\cos(\omega_n t + \varepsilon_n), \tag{5}$$

$$\eta_n = \eta_{n-1} + \delta\eta_n. \tag{6}$$

Finally, the velocities for grid points outside the water domain have to be set to zero. From the iterative procedure it can be deduced that for the n^{th} component the mean water level is the pre-existing wavy surface and the velocities are computed over a varying z. The Donelan method has been found to compare well with field data (Donelan et al., 1992), but it has not been applied to focussed breaking waves yet.

In this paper the predictive performances of the Grue and Donelan methods are tested against laboratory measurements of the velocity profile underneath breaking rogue waves. The formation of the breaking waves in the wave flume is controlled by wave focussing techniques, e.g. (Longuet-Higgins, 1974; Tromans et al., 1991). Two techniques commonly used in model tests are compared: the dispersive focussing (Longuet-Higgins, 1974; Tromans et al., 1991), using different underlying JONSWAP spectra, and the nonlinear Schrödinger equation (NLS) framework (Zakharov, 1968). Whereas the velocity field under breaking waves generated by dispersive focussing has been examined in the past, it is yet uncertain how it compares to the kinematic field of breaking events generated using breathers solutions of the NLS that more realistically replicate wave evolution at sea. Other physical mechanisms can trigger the formation of breaking rogue waves in the ocean (e.g. directional focussing, wave-current interaction and bathymetry, see Onorato et al., 2013a), but only unidirectional deep water waves are considered in the present study.

The paper is structured as follows. In the next Section we describe the experimental set-up. The wave generation mechanisms are presented in Section 3. The evolution in space of the wave group and its spectral properties are shown in the following Section. Description of the wave shape, velocity profiles and comparison with engineering methods are discussed in Section 5. Final remarks are reported in the Conclusions.

2. Experimental set-up

The purpose of the experiments is to monitor the spatial evolution of a steep wave group and measure water particle velocity at breaking. Experiments have been conducted in the Extreme Air-Sea Interaction facility (EASI) in the Michell Hydrodynamics Laboratory at The University of Melbourne (Australia). The wave flume is 60 × 2 m (length × width). The water depth was imposed to be 0.9 m. At one end of the tank a computer-controlled cylindrical wave-maker produces user-defined wave forms. At the opposite end a sloping beach is installed to absorb the incoming wave energy. Optical access, to perform PIV measurements, is provided through a glass window on the side of the flume, located 34 m from the wave-maker. A schematic of the facility and the experimental set-up is shown in Fig. 1.

At the window, the shape of the breaking wave is recorded by a camera and PIV measurements can be undertaken. This technique has been used to explore coastal and ocean processes at laboratory scale since the 90s, e.g. (Greated et al., 1993; Chang and Liu, 1997). PIV allows the calculation of the spatio-temporal properties of the kinematic field by cross-correlating pairs of images of a properly seeded fluid. The analysis of two images, taken at time Δt apart, provides the displacement of the particles and consequently their velocity (Adrian and Westerweel, 2011). Experiments are performed with a two-dimensional PIV set-up, i.e. only the planar velocities components along the flow and in the vertical direction are extracted. The set-up is sketched in Fig. 2.

The laser beam is generated by Photonics DM20-527 dual head Nd:YLF laser that delivers 100 mJ/pulse at 15 Hz. The beam is converted in a light sheet at the centre of the tank via a series of optics. Images are recorded by Andor CMOS camera equipped with a Nikkor f/3.5 60 mm macro lens. The camera resolution is 2120 × 2560 pixel and the corresponding field of view is approximately 170 × 200 mm (horizontal × vertical). Silver coated glass spheres with mean particle diameter of 10 μm are used to seed the water. The laser and the particles used in the experiments provide a better image quality compared to a similar set-up used for preliminary tests (Alberello et al., 2016b; Lee et al., 2017). The separation time between images pairs is $\Delta t = 2.5$ ms. During the pre-processing step water surface is manually detected to mask the air side to improve the quality of the subsequent cross-correlation algorithm. The PIVlab tool for MATLAB (Thielicke and Stamhuis; Thielicke and Stamhuis, 2014) is applied to extract the velocity field in the horizontal and vertical direction.

The surface elevation is recorded by resistive wave gauges at various position along the tank. The probe positions, relative to the wave-maker, are $x \in$ 14.05, 25.15, 30.10, 32.60, 33.95, 34.90, 41.40, 45.15 m and the

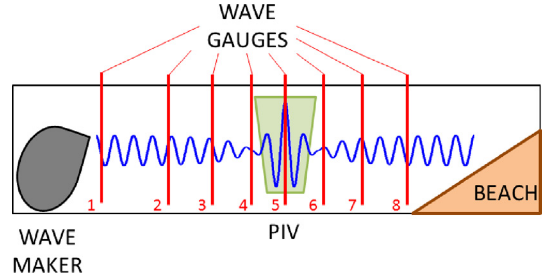

Fig. 1. Sketch of the EASI facility (not to scale).