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Investigation of breaking and non-breaking solitary waves and measurements of swash zone dynamics on a 5° beach

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ABSTRACT

This study presents an experimental investigation of plunging breakers on a sloping beach with an inclination of 5.1°. The incident waves are solitary waves with various amplitudes from non-breaking waves to plunging breakers, and the area investigated is the swash zone. PIV (Particle Image Velocimetry) is performed on images captured at four different field of views (FOV). Shoreline position and maximum runup are measured, and are repeatable in both time and height, although cross-sectional variations of the shoreline shape are observed at maximum runup. For non-breaking waves the runup and fluid flow is computed by a boundary integral technique combined with a boundary layer model. Then, there is excellent agreement between the experimental and the computed velocity profiles at the lower region of the beach, while the boundary integral technique overpredicts the maximum runup height severely. For breaking waves the experiments indicate that the motion becomes more irregular as we move further up the beach. In addition, there are more irregularities present for waves with larger amplitude. Length and velocity of air bubbles entrapped by the plunging breakers are extracted from an image series captured with a large FOV. The images showed that a large air bubble remains intact for a time period during runup for the breaking waves.

1. Introduction

In shallow water with constant depth, the nonlinear effect and dispersion will be balanced for solitary waves [11]. During shoaling the wave will steepen, and at some critical point breaking may occur. Wave breaking is one of the most important physical features in the swash zone [4]. Breaking waves have a large impact on sediment transport onshore, which can result in beach erosion and affect construction located near the shore. Although breaking waves is a well-known phenomenon of our daily life, many physical aspects regarding wave breaking are still poorly understood.

Several experimental studies of breaking waves have been performed in the recent years. A broad range of different experimental methods have been utilized to measure quantities such as surface elevation, runup, shear stress, and velocities. Techniques such as Laser Doppler Velocimetry [12], PIV [2] and application of shear sensors [1] have been utilized. The swash zone is the region where the beach is partly wetted during runup and draw-down. Aeration and the small flow depth makes the swash zone a challenging region to study experimentally with the techniques mentioned above. A further development of the PIV method is Bubble image Velocimetry (BIV), which Rivillas-Ospina et al. [15] use to investigate velocity fields in plunging breakers. They compared the measurements with numerical simulations conducted with Reynolds Average Navier Stokes Equations Model. The model gave fairly good agreement with the measurements in the surf zone, but the model overpredicted the velocities in the swash zone as compared to the BIV measurements.

Surf zone dynamics for non-breaking solitary waves on a steep beach were investigated experimentally and theoretically by Pedersen et al. [10]. Boundary layer profiles were measured by PIV and good agreement with theory was obtained for regular flows. However, for larger amplitudes and far from the equilibrium shoreline undulations and rollers were observed. Velocity fields underneath shoaling solitary waves in the surf zone has recently been studied by Lin et al. [7,8]. The first study shows PIV measurements from a wide area of the surf zone for waves with various normalized amplitude. The latter study presents detailed high resolution PIV boundary layer measurements of one shoaling solitary wave.

One of the latest work on solitary waves on a plane beach has been conducted by Pujara et al. [13]. They investigated the flow evolution of the runup and draw-down of solitary waves in the range from non-breaking to plunging breakers. A shear plate was located at different positions along the beach and measurements revealed that the maximum positive bed shear stress was obtained in the tip of the swash tongue during runup, and was due to the evolution of a boundary layer and bore driven turbulence. The maximum negative bed shear stress

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was obtained at the end of the withdrawal. The flow is accelerated during downrush by gravity and the bed shear stress increases during draw-down until a maximum was reached right before the water ran out of the measuring area.

Until now, PIV measurements with high temporal resolution close to the beach have not been reported for plunging breaking waves in the swash zone. This article presents PIV measurements for solitary waves, of different amplitudes, that range from non-breaking to plunging cases on a beach with an inclination 5°. Some of the techniques are adopted from the study of non-breaking waves in [10], but the present investigation is more demanding due to longer swash zones and the presence of irregular flow and air bubbles due to the breaking. The article starts with a description of the experimental set-up and the computational Boundary Integral Model used in this study (Section 2). Further on, measured and computed results will be presented; the surface elevation of the incident waves in Section 3.1, surface development and maximum runup in Section 3.2, velocity profiles from the swash zone in Section 3.3, and air bubble investigation in Section 3.4. Finally, a discussion of the findings will be presented in Section 4.

2. Experimental set-up and formulation

2.1. The wave tank

The experiments were conducted in a 25 m long and 0.51 m wide wave tank located at the Hydrodynamics Laboratory at the University of Oslo. Incident waves were generated in an equilibrium depth of $H = 20.5$ cm by a piston type wave maker using the method described in Jensen et al. [5]. A PETG (Polyethylene Terephthalate Glycol-modified) beach with an inclination of 5.1° was placed in the wave tank with its toe 529.81 cm from the start position of the wave paddle. Two coordinate systems are introduced, one parallel to the still water level (x', z'), and one parallel to the beach (x,z) (see Fig. 1). The origin of both is at the equilibrium shoreline.

The amplitude to depth ratios should equal ($\alpha = 0.10, 0.12, 0.20, 0.30, 0.40, 0.50$), however, imperfection in the generation and frictional effects along the wave tank reduced the heights slightly such that the amplitude in front of the beach, A, became slightly less than αH. An acoustic wave gauge (ultra Banner U-Gage S18U, sample frequency of 200 Hz) measured the wave height at the toe of the beach and the Boundary Integral Method (BIM) was used to correct for the influence of the reflected wave. The resulting amplitudes are given in Table 2.

2.2. Instrumentation, measurements

To obtain velocity fields in the swash zone, high speed video was recorded at four different field of views (FOV), located upward along the beach (Table 1). The water in the tank was seeded with polymid particles with diameters of approximately 50 μm. A Quantronix Darwin Duo pulsed laser generated a light sheet parallel to the centreline of the wave tank, and a Photron SA5 high speed camera (1024× 1024) synchronized with the laser, captured images of the illuminated particles. A Carl Zeiss Makro- Planer 2/50 zf (50 mm) lens was used. Images were collected at 3000 frames per seconds (*fps*). The image processing were performed in DigiFlow [3]. PIV was performed using interrogation windows of 32× 8 pixels with a 75% overlap. Oblong interrogation windows are beneficial in boundary layer flow and have been employed previously by Liu et al. [9] and Pedersen et al. [10]. A temporal averaging of 10 images was applied to reduce noise from the data. No differences in the measurements were obtained when velocities from an averaging of 10 and 15 images were compared to each other. This implies that a temporal averaging of 1/300 s (10 images) is acceptable. The errors related to the PIV algorithm are described in detail in Raffel et al. [14]. The average particle image diameter for a randomly chosen image from this experiment was found to be approximately 3.16 pixels. This is close to the optimal particle size that minimizes the PIV error related to peaklocking. The high capturing rate allows us to investigate large velocity without large pixel displacements preventing aliasing, and also the high temporal resolution minimize the error concerning out of plane motion. If there is no loss of particles, and the particle distribution is uniform, the PIV error can be limited to 0.05 pixels [6]. This corresponds to an error of approximately 0.5 cm/s for instantaneous measurements. The averaging in time applied to the measurements will reduce this error.

To investigate air bubbles encapsulated by the plunging breakers, the camera was moved further away from the wave tank, resulting in much larger FOV than the FOVs installed to obtain velocity fields. This FOV will be referred to as FOV A and covers $0\,\text{cm} < x < 60\,\text{cm}$. The frame rate was reduced to 500 *fps* and a continuous dedolight 400D was used as illumination, replacing the laser. A white background sheet was attached to the side wall of the wave tank and the water was dyed dark blue to increase the contrast of the images.

The maximum runup was measured by capturing images of the

Table 1
Location of the different FOVs in cm. The dimensions of the FOVs are approximately 4 cm × 4 cm.

FOV	I	II	III	IV
Location, *x*	[8.49–13.04]	[36.35–40.26]	[77.55–81.53]	[117.76–121.80]
Location, *z*	[−0.05–3.78]	[−0.16–3.54]	[−0.04–3.79]	[−0.85–3.09]

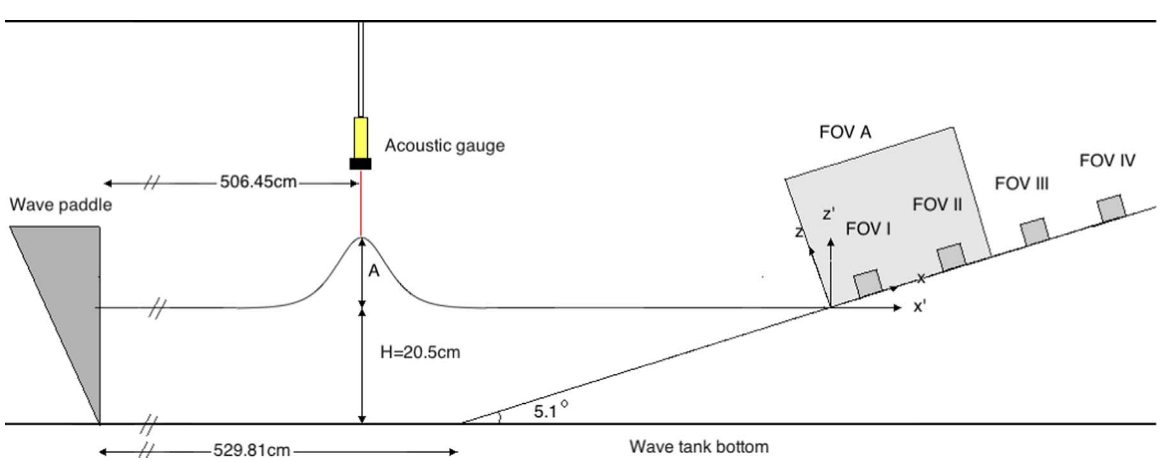

Fig. 1. Sketch of the experimental set-up.