Experimental investigation of solitary breaking waves in the swash zone,*

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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). The PIV measurements are compared with computed velocity fields from a Boundary Integral Model (BIM). There is excellent agreement between the experimental and the computed result for the non-breaking waves. The experimental results from the breaking waves indicate that the motion becomes more irregular as we move further up the beach. In addition, there seem to be more irregularities present for waves with larger amplitude. 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. Length and velocity of air bubbles entrapped by the plunger breakers are extracted from a image series captured with large a FOV. The images showed that a large air bubble seems to be stable 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 (Peregrine, 1983). If the depth decreases as the wave travels towards the shore, the wave will steepen, and at some critical point breaking may occur. Breaking waves are one of the most important physical features in the swash zone (Elfrink and Baldock, 2002). Breaking waves have a large impact on sediment transport onshore, which can result in erosion on cliffs and affect construction located near the shore. Although breaking waves is a well-known phenomenon from 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 (Petti and Longo, 2001), PIV (Cowen et al., 2003) and shear sensors (Barnes et al., 2009) has been utilized. The swash zone is defined as the region where the beach is partly wetted during runup and rundown. Air bubbles and the thin liquid film 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. (2012) use to investigate velocity fields in plunging breakers.

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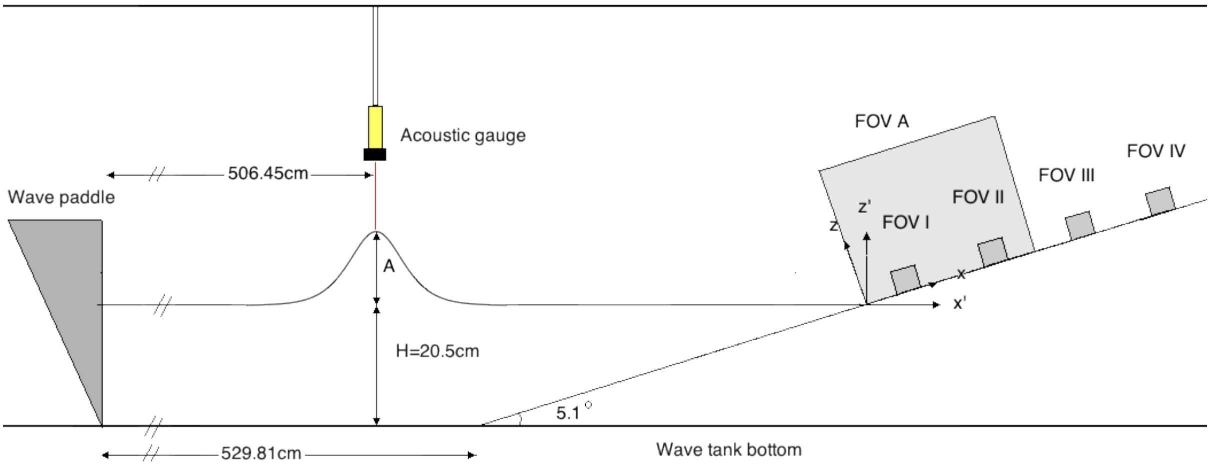


Figure 1: *Sketch of the experimental set-up.*

Until now, PIV measurements with high resolution close to the beach have not been conducted for breaking waves in the swash zone. This paper presents PIV measurements where the amplitude of the solitary breaking waves varies. The paper starts with a description of the experimental set-up in chapter 2. Further on, results from different parts of the experiment will be presented, herein the surface elevation of the incident waves in chapter 3.1, surface development and maximum runup in chapter3.2, velocity profiles from the swash zone in chapter 3.3, and air bubble investigation in chapter 3.4. Finally, a discussion of the findings will be present in the last chapter 4.

2 Experimental set-up

Laboratory experiments of non-breaking to plunging breaking waves in the swash zone were conducted in the Hydrodynamics lab at the University of Oslo. Solitary waves with normalized amplitude $A/H = (0.0989, 0.1191, 0.1981, 0.2958, 0.3939, 0.4874)$ were generated in a 25m long and 0.51m wide wave tank with a piston type wave paddle as described in Jensen et al. (2003). An acoustic wave gauge (ultra Banner U-Gage S18U) measured the height of the incident waves with a sample frequency of 200Hz. The deviation from the mean δ_i for some measured quantity σ_i is calculated in following manner,

$$\delta_i = \frac{\sigma_i - \overline{\sigma}}{\overline{\sigma}} \tag{1}$$

where $\overline{\sigma}$ is the mean of the three repeatitions.

A PETG (Polyethylene Terephthalate Glycol-modified) beach was mounted into the wave tank with an inclination of 5.1°. The toe of the beach was 529.81cm from the start position of the wave paddle. The effect of the roughness of PETG plates is documented in Pedersen et al. (2013). The water depth was kept constant at 0.205m. Origo was defined as the point where the still water level intersected the beach. Two coordinate systems were introduced, one parallel to the still water level (x', z'), and one parallel to the beach (x, z) (See Figure 1). To obtain velocity fields in the swash zone, images were captured at four different field of views (FOV), located upward along the beach (Table 1). The different FOV's are denoted with roman numbers. 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 x 1024) synchronized with the laser, captured images of the illuminated particles. A Carl Zeiss Makro- Planer 2/50 zf lens was used. Images were collected at 3000 frames per seconds (fps). The image processing were performed in DigiFlow (Dalziel, 2006). PIV was performed using interrogation windows of 32 x 8 pixels

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]

Table 1: *Location of the different FOVs in cm. The dimensions of the FOVs are approximately 4cm x 4cm.*

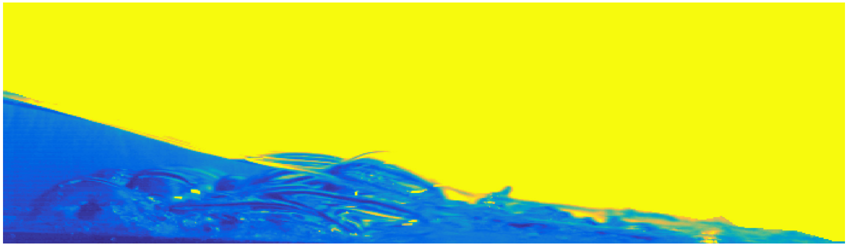


Figure 2: *Image of the swash tongue for* $A/H = 0.4874$.

with a 75% overlap. The rectangular sized interrogation windows can be an advantage when studying velocity close to boundaries. This is further discussed in Pedersen et al. (2013). An averaging in time was applied where 10 images was used.

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 is located at $x = [0 - 60]$cm. 500 fps were used in this investigation, 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 in the images.

The maximum runup was measured by capturing images of the shoreline at its maximum position. A high speed Photron APX camera was mounted on rails above the beach in the wave tank with same inclination as the beach. A high pulsed white light was used as illumination. The field of views were based on estimates of the runup height for each case. The camera captured 125 frames per second. The maximum shoreline profiles were tracked manually for each wave.

3 Results

Visual inspection of the experiments revealed that the cases with normalized amplitude $A/H = 0.0989$ and $A/H = 0.1191$ did not break while entering the beach, while all the other cases developed into plunging breakers. This seems to be in compliance with numerical studies by Grilli et al. (1997). The plunger breakers encapsulated large amounts of air, which resulted in air bubbles in the swash tongue of the breaking waves (Figure 2).

3.1 Surface elevation of the incident waves

The surface elevation measured with the acoustic wave gauge for $A/H = 0.0989$ is shown in Figure 3. Cubic interpolation is used to remove noise from the signal, and linear interpolation is used to filter dropouts. The surface elevation measurements are in agreement with computed surface elevation from the BIM simulatitions.

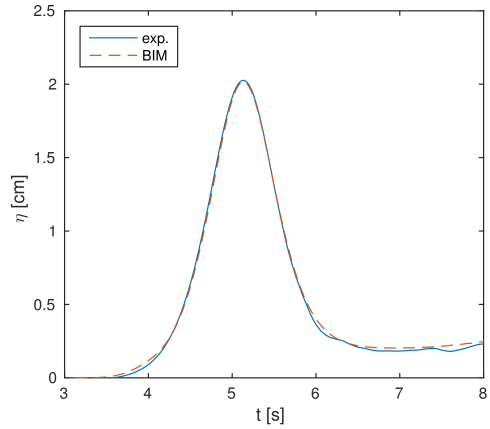


Figure 3: *Measured and computed surface elevation for* $A/H = 0.0898$.

A/H	S_o	$r[cm]$	R/A	$e_r[\%]$	t	$e_t[\%]$
0.0989	0.43	87.25	3.82	1.68	8.86 s	0.15
0.1191	0.39	105. 67	3.85	0.27	8.67 s	0.15
0.1981	0.30	147.37	3.22	0.93	8.53 s	0.31
0.2958	0.25	191.67	2.80	1.08	8.03 s	0.78
0.3938	0.22	227.42	2.50	0.11	7.82 s	0
0.4874	0.19	267.46	2.37	2.27	7.30 s	1.64

Table 2: *Maximum runup measurements where A/H is normalized amplitude, S_o is (Grilli et al., 1997) solitary wave breaking parameter, r is the runup in the direction along the beach, R is the vertical projection of the maximum runup, t is the time corresponding to max runup and e is the estimated error in the measurement*

3.2 Surface development and maximum runup

To investigate how the waves propagate towards the shore and onshore both simulation and measurements have been conducted. A BIM model was used to visualize the development of the waves as they were propagating towards the shore (See Figure 4).BIM only managed to estimate the full runup for the waves with normalized amplitude $A/H = 0.989$, and the third plot in Figure 4 corresponds to the point of maximum runup height for that wave. The time of maximum runup was estimated to $t = 9.08s$ and the corresponding runup was $r = 114.82cm$ in the direction along the beach. The BIM model had some difficulties with the waves with amplitude $A/H = 0.1191$. The contact angle between the wave front and the beach was too steep, and the BIM model was not able to predict the runup for this case. The $A/H = 0.1191$ wave is therefore omitted in the figure. The BIM succeeded in calculating the surface of the breaking waves until the point were the plunger hits the beach.

The measured maximum runup heights and deviations for each waves are available in Table 2. Both the time of maximum runup and the location seem to be over-predicted by the BIM simulation for the waves $A/H = 0.989$. The BIM model does not account for viscous effect in the simulations, and this may be the reason for the deviation between simulation and measurements. The Table shows that the maximum runup seemed to be repeatable for all waves including the breaking waves.

The contour of the shoreline at maximum runup are shown in Figure 5. The shoreline seemed to be repeatable for case 10 (Figure 5a), but has a parabolic shape. The maximum runup is clearly dependent on cross sectional direction of the tank (the width of the wave tank). This is probably due to bending of the beach which has been measured using a straightedge and a

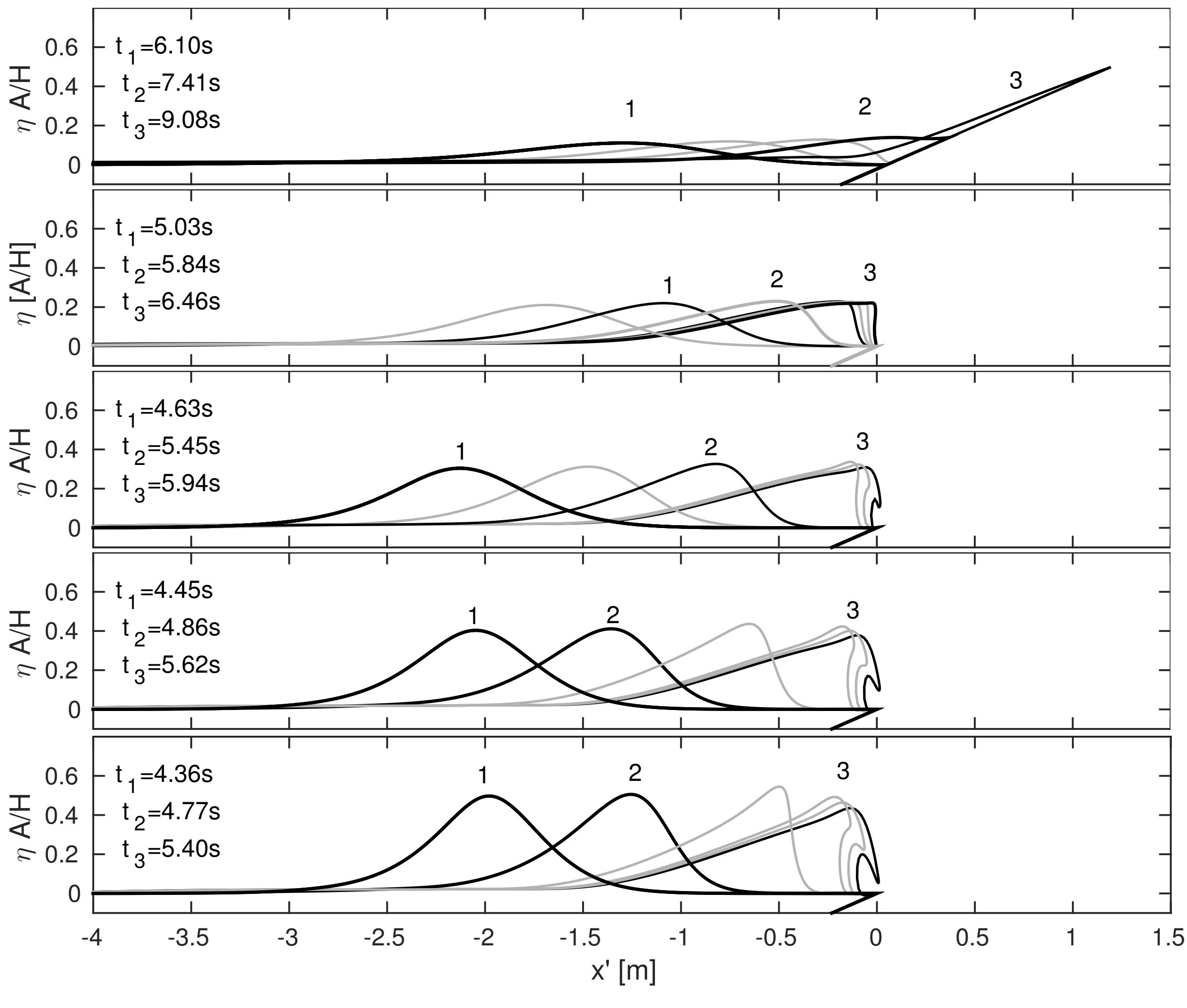
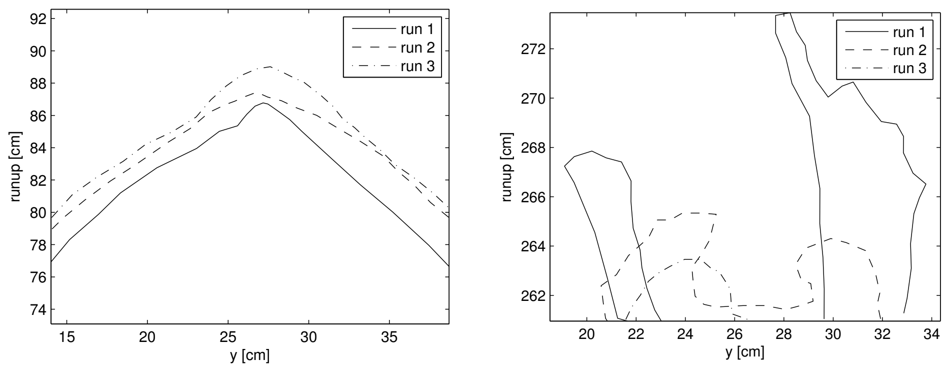


Figure 4: *BIM simulation of the waves the upper to lower figures correspond to* $A/H = (0.0989, 0.1981, 0.2958, 0.3939, 0.4874)$, *respectively.*



(a) $A/H = 0.0989$ (b) $A/H = 0.4874$

Figure 5: *Shoreline contours at max runup.*

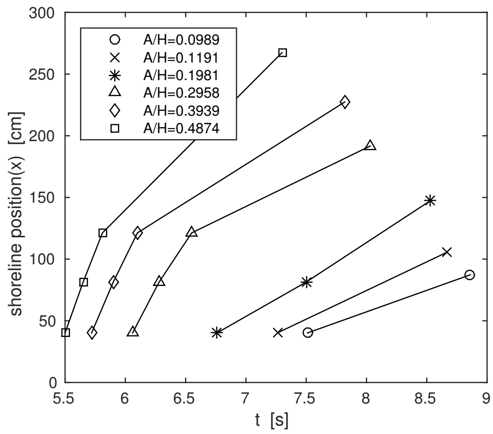


Figure 6: *Shoreline position as a function of time for all cases. The first measurements correspond to the swash tongue arrival time for FOV I, II, III. The last measuring point for all cases correspond to measurement of maximum runup*

feeling gauge. The maximum bend of the beach was 3.4mm and located at 2.0m from origo in the middle of the cross section of the beach. The variation of 3.4 mm in the z direction should correspond to 3.4cm in the x direction since the beach slope is 1:10. It is clear from Figure 5 that the cross sectional variation is much larger than 3.4 cm. The contour of the maximum shoreline seemed to vary a lot for the three repititions of the breaking wave $A/H = 0.4874$ (Figure 5b).

An estimate of the arrival time of the wave for FOV II, III and IV, were measured based on the intensity changes in images captured at each FOV. Each image in each time series was compared to the initial image taken before the wave paddle starts. The image where the sum of light intensity differs more than a given threshold (1000) from the initial image, correspond to the time when the wave enters that FOV. The measured shoreline positions as a function time are presented in Figure 6. The maximum error obtained for three different runs was 0.18%. This indicate that the shoreline motion was repeatable for each of the FOV.

3.3 Velocity profiles from the swash zone

Velocity profiles are extracted from the PIV data that are obtained from the four different FOV, approximately from 10cm to 120cm from the equilibrium shoreline. First, a comparison between computed BIM and measured PIV velocities for $A/H = 0.989$ will be given for FOV I and II, (See Figure 7). There seems to be excellent agreement between measured and computed

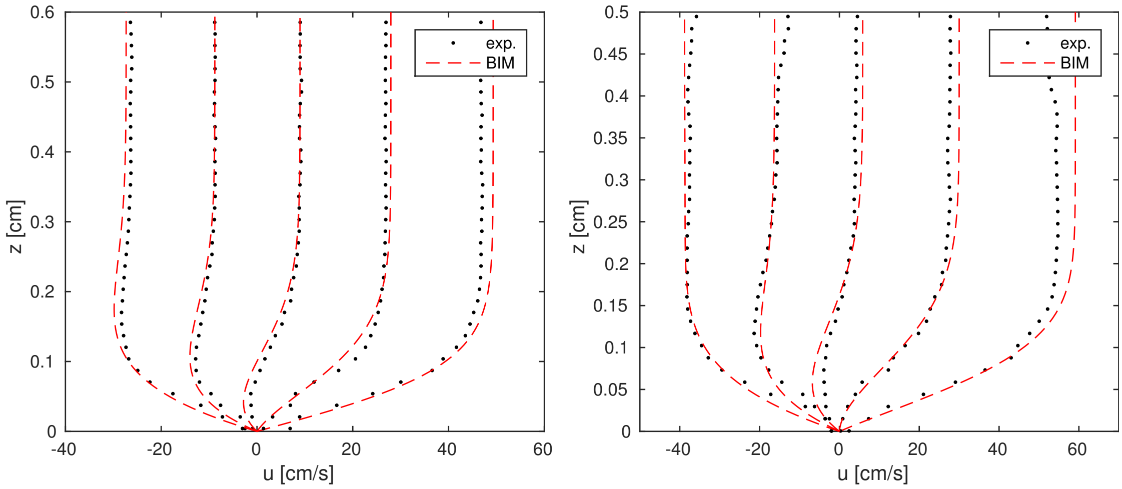


Figure 7:
Left: Velocity profiles from FOV I x=8.7cm t=[7.48, 7.82, 8.15, 8.48, 8.81]s
Right: Velocity profiles from FOV II x=40.1cm t=[7.76, 8.10, 8.76, 9.10]s

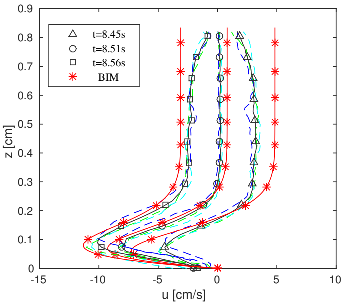
velocity profiles. The computed velocities are over-predicted by the BIM model, in the front of the wave, for both the FOVs, and this may explain why the BIM computation over predicts the maximum runup given in the previous section.

In order to investigate the development of the boundary layer upwards the sloping beach, velocity profiles in the period close to outer flow reversal have been emphasized, and velocity profiles from FOV II, III and IV will be presented. FOV II is located about 40cm from origo, and velocity profiles obtained from this FOV is shown in Figure 8. For $A/H = 0.1981$ sparse seeding was obtained close to the surface, which led to artefacts in the velocity profiles near $z \approx 1$. The PIV method fails to calculate the velocity in this area due to the low particle density. An outer flow seems to be constant for both non-breaking and breaking waves. The event of a swash tongue moving with a constant velocity U upward a beach, can be compared to the problem of accelerating an infinite long plate from rest to a constant velocity U with a viscous fluid on top, Stokes first problem (White and Corfield, 2006). Dimensional analysis will then give us a relationship between the boundary layer thickness δ and the viscosity ν and the time t, $\delta \approx \sqrt{\nu t}$. This implies that the boundary layer will grow with time, and this seems to be the case for the small non-breaking waves with amplitude $A/H = 0.0989$ (Figure 7). However, for the strong plunging breakers the boundary layer decreases with time. This implies that the motion is more irregular than for the non-breaking waves.

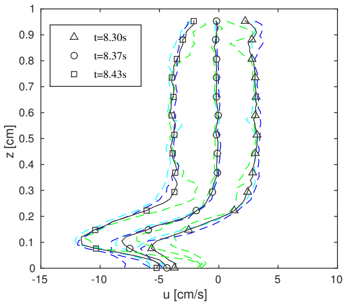
FOV III is located about 80cm from origo along the beach. For $A/H = 0.0989$ and $A/H = 0.1191$, the swash tongues were too thin, and particles within the tongue were impossible to detect. Consequently, only $A/H = 0.1981 - 0.4874$ will be presented for this FOV. None of the cases had an outer flow with constant velocity at times close to outer flow reversal (Figure 9). This indicates that the motion was more irregular for this FOV than for FOV II.

FOV IV is located about 120cm from where the still water reaches the beach. At this FOV, only $A/H = 0.2958 - 0.4874$ will be presented due to the thin swash tongue for the other waves. Velocity profiles are given in Figure 10. The velocity was less repeatable at this location than for the other FOVs. The velocity profiles seemed to be more irregular, especially for $A/H = 0.4874$, where the average velocity profile obtained before flow reversal resembles the parbolic velocity profiles from fully developed turbulent channel flow, as described in White and Corfield (2006).

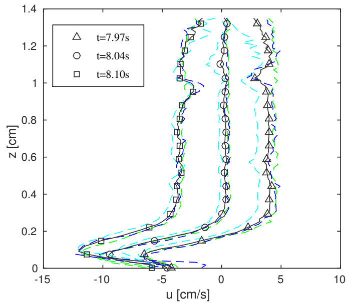
Inspection of movies of the front of the swash tongue from FOV IV (furthest up the beach) shows that a systematic swirling effect were present in the front of the swash tongue. Particle Tracking Velocimetry (PTV) have been utilized to investigate this phenomenon. Figure 11 shows how the velocities vary at one spot in fluid as a function of time. The velocities seem to



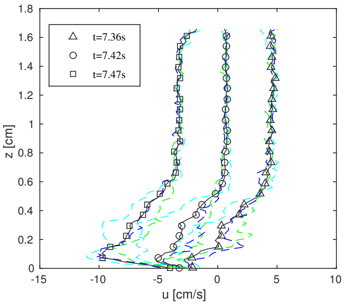
(a) $A/H = 0.0989$



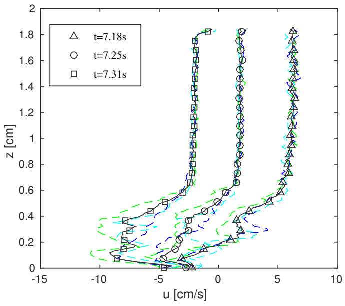
(b) $A/H = 0.1191$



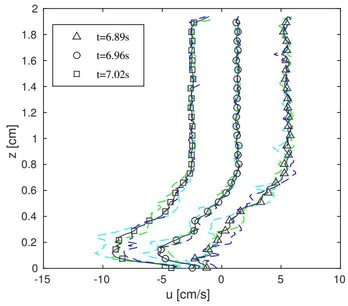
(c) $A/H = 0.1981$



(d) $A/H = 0.2958$

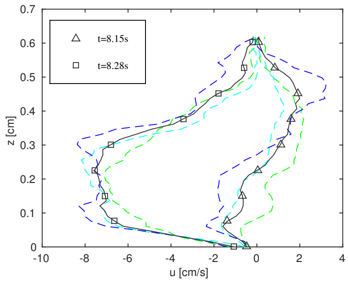


(e) $A/H = 0.3939$

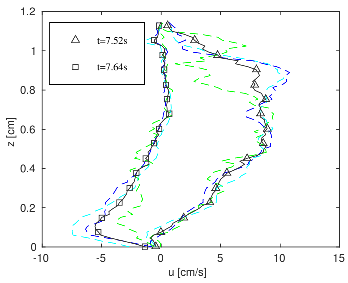


(f) $A/H = 0.4874$

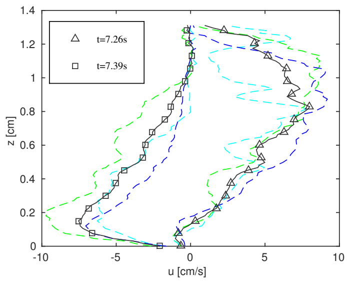
Figure 8: *FOV II, mean velocity profiles before and after the outer flow reverses* ($\triangle$,$\square$). *Colors: blue, cyan, green and red correspond to run 1,2,3 and BIM respectively.* $x = 40.11cm$.



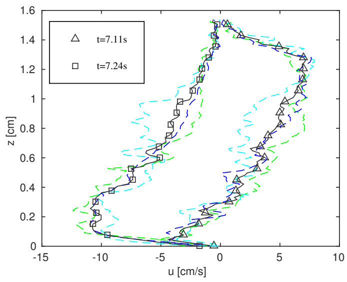
(a) $A/H = 0.1981$



(b) $A/H = 0.2958$

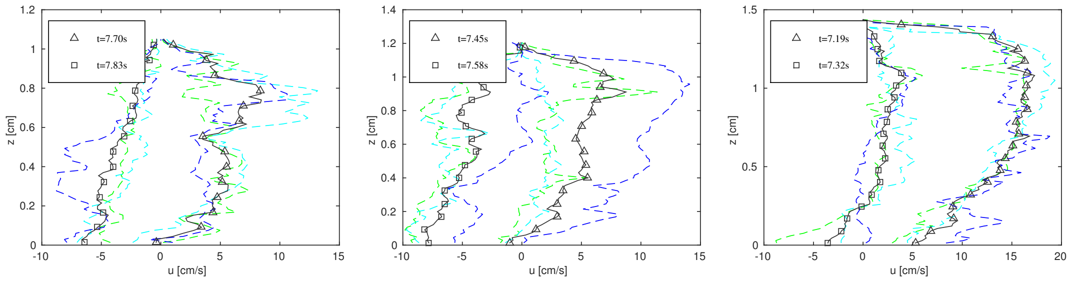


(c) $A/H = 0.3939$



(d) $A/H = 0.4874$

Figure 9: *FOV III, mean velocity profiles before and after the outer flow reverses* ($\triangle$,$\square$). *Colors: blue, cyan and green correspond to run 1,2 and 3.* $x = 81.40cm$



(a) $A/H = 0.2958$ (b) $A/H = 0.3939$ (c) $A/H = 0.4874$

Figure 10: *FOV IV, mean velocity profiles before and after the outer flow reverses (△,□). Colors: blue, cyan and green correspond to run 1,2 and 3.* $x = 121.25cm$

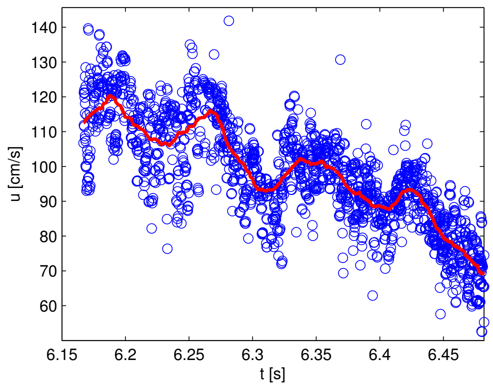


Figure 11: *FOV III Collection of velocities of particles within a distance of 0.05cm from the point(x,z)=(120,0.3)cm. The data is collected from* $A/H = 0.4874$*, run 2. Blue circles: Raw data points. Red line: 2 order interpolation with 40 evaluation points*

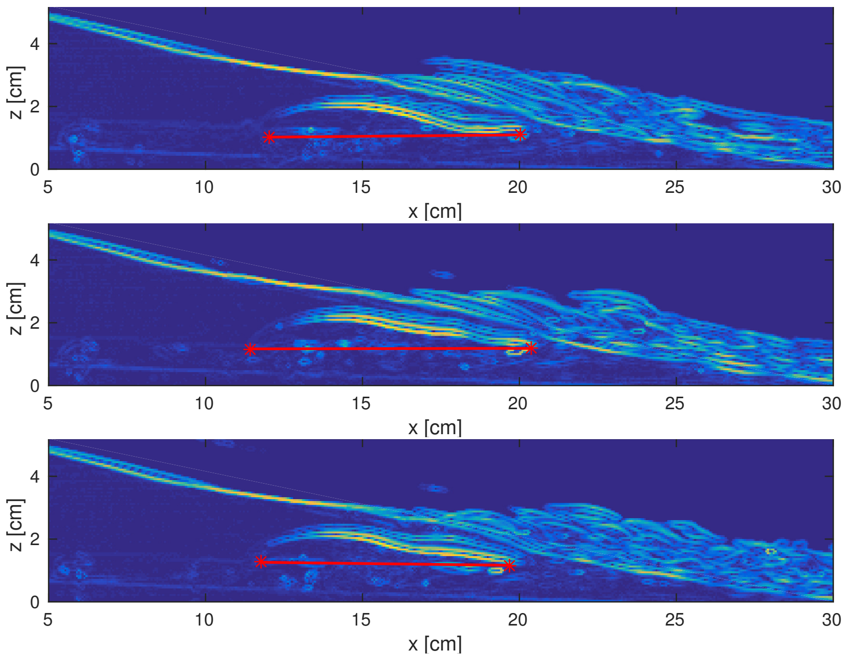


Figure 12: $A/H = 0.2958$, *run 1,2 and 3. t=6.06s*

Main bubble size	Run 1 [cm]	Run 2 [cm]	Run 3 [cm]
$A/H = 0.2958$:	8.00	8.94	7.90
$A/H = 0.4874$:	9.24		8.17

Table 3: *Size of the main bubble measured at t=6.06s for case 30, and t=5.54s for case 50*

oscillate, in addition to a linear decaying trend. The red line represents an interpolation of all the data, where 40 points are considered at each evaluation point. This indicates that there is a systematic velocity field in the front of the swash tongue.

3.4 Bubble investigation

For all the plunger breakers, the plunge encapsulated air, resulting in one large air bubble. As the waves propagated upward the beach, this large air bubble divided into smaller air bubbles, which again divided into even smaller air bubbles. Before reaching maximum runup, all the air bubbles had risen to the surface, for all waves. The images captured with the large FOV A provides some information about this air bubble formation, (see Figure 12 and 13). To enhance the shape of the bubbles the gradient magnitude image is represented. The shape of main bubble seems to be oval with a thin tongue in the front, for $A/H = 0.2958$. The shape of the main air bubble seems to vary more for $A/H = 0.4874$, especially for run2, where the large air bubble can't be found in the image. The length of the main bubble for three different runs is given in Table 3. It is clear that images from the three different runs for $A/H = 0.2958$ is more similar than for $A/H = 0.4874$. This supports the hypothesis that irregularity increases as normalized amplitude of the waves increases.

The air bubble velocity in the direction along the beach is given in Table 4. The largest velocities were obtained in the front of the bubbles, and may explain the shape of the thin tongue in the front of the air bubble observed for $A/H = 0.2958$. The bubble findings indicates that the motion becomes more irregular as the amplitude of the waves increases.

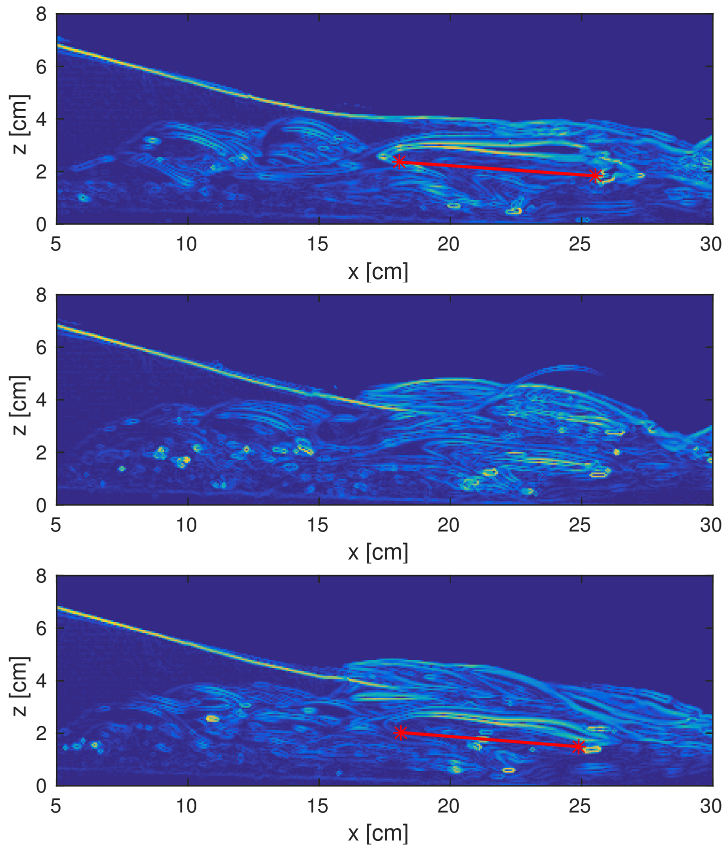


Figure 13: $A/H = 0.4874$, *run 1,2 and 3. t=5.54s*

$A/H = 0.2958$	Run 1	Run 2	Run 3
Front velocity [m/s]	2.05	2.20	2.48
Tail velocity [m/s]	2.10	2.05	2.23
$A/H = 0.4874$			
Front velocity [m/s]	3.26		2.01
Tail velocity [m/s]	1.58		2.23

Table 4: *Velocities along the beach for the main air bubble. t=6.06s for case 30, and t=5.54s for case 50*

4 Discussion

The experimental result from the non-breaking waves generated in this study coincide with the numerical result from BIM model. Both, the surface elevation and velocities seems to agree with numerical result. However, deviations between the computed and the measured maximum runup was observed for the smallest waves. Also the BIM model over predict the velocity in front of the wave. Discrepancies between computation and measurement may be due to viscosity effect in the thin swash tongue, but may also be caused by bending effects of the beach. The beach bended due to its own weight and an additional bending was also observed due to wave load.

The measurement of the breaking waves showed that the fluid motion becomes more irregular and less repeatable as we move further up the beach. In addition, the motion seemed to be more irregular for the waves with the stronger plunger breakers than for those with smaller amplitude. The maximum runup was repeatable in both time and height, but large variation of the cross shore profiles was obtained for the breaking waves. The results from the bubble investigation showed that the air bubble seemed to be repeatable in shape for the waves with amplitude $A/H = 0.2958$ but not for waves with amplitude $A/H = 48.74$. Overall, irregular motion seems to increase with larger breaking waves and as the waves propagate upwards the beach.

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