CHAPTER 189

CAUSE AND CHARACTERISTICS OF IMPACT PRESSURE EXERTED BY SPILLING AND PLUNGING BREAKERS ON A VERTICAL WALL

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Abstract

Detailed measurements of spilling and plunging wave pressures on a vertical wall are carried out to identify and compare their characteristics. Kinematical differences between the spilling and plunging breakers enable us to investigate better the generation mechanism and characteristics of the impact pressure. Further, the reliability of numerically computed breaking wave pressure is investigated through the comparisons with the experimental results. It is made clear that the impact pressure can be well expressed in terms of internal kinematics of breaking waves.

Introduction

Impact pressure of breaking waves has been studied by many investigators, but for only plunging breakers (e.g. Bagnold, 1939; Kirkgoz, 1982; Chan and Melville, 1988; Cooker and Peregrine, 1990; Oumeraci et al., 1992; Hattori et al., 1994). Since the impact pressure exerted by a plunging breaker on a vertical wall usually takes place near the elevations where air is entrapped, some of the investigators related the cause of occurence of the impact pressure to entrapped air dynamics, to reduced velocity of sound in a water-air mixture etc. and thus much less attention is paid on the role and contribution of the kinematics of water particles to the impact pressure.

Discussing different ideas about the generation mechanism of the impact pressure, Azarmsa et al., (1996a) made clear that generation of the impact pressure is independent of breaker type and showed that even spilling breakers exert the impact pressure on a vertical wall. Besides, they made clear that entrapped air

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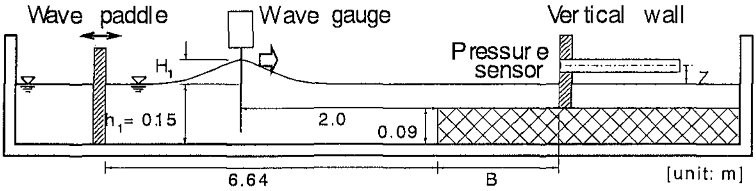


Figure 1: Experimental set-up.

does not play any role in generation of the impact pressure, although pressure oscillations are linked to entrapped air dynamics. Such conclusions turned our attention round from the entrapped air dynamics to the kinematics of the breaking waves as the key factor in generation of the impact pressure and related problems. To understand how the kinematics of breaking waves and the impact pressure are related, the internal kinematics of incipient breaking waves were computed numerically and applied to the calculation of the impact pressure in two different ways (Azarmsa et al., 1996a). The results indicated that both the horizontal and vertical components of velocity and acceleration of water particles should be considered in computations of the impact pressure.

In this study, spilling and plunging wave pressures exerted on a vertical wall are investigated to make clear the common and individual characteristics of the impact pressure exerted by these breakers. Moreover, the experimental and numerical results are compared to investigate the reliability of the vertical distribution of the maximum pressure computed on the base of the internal kinematics of breaking waves, as suggested by Azarmsa et al., (1996a). Further, since the internal kinematics of overturned waves is more critical than that of waves just at breaking, our attention is also focused on the pressure exerted by overturned waves. The results will be compared with the pressure exerted by waves which just break on the wall and the role of entrapped air will be discussed.

Experiments

Experiments were conducted in a $54m$ long, $1m$ wide, and $1m$ deep wave channel. A computer-controlled piston-type wave maker was used to generate the desired solitary waves.

Figure 1 shows a view of the wave channel and apparatus used for the experiments. A reef with the crown height of 9.0 cm was made of stainless steel plates and installed in the wave channel to make the generated solitary waves break. The dimensionless incident wave heights of generated spilling and plunging breakers are respectively $(H_1/h_1 = 0.24)$ and $(H_1/h_1 = 0.55)$, where $h_1 = 15cm$ is water depth in the wave channel. A vertical wall with 60.0 cm height and 2.0 cm thickness made of acrylic material was installed on the reef. In order to prevent probable vibrations of the vertical wall from transferring to the pressure transducers, the transducers were set not to the acrylic wall but to a rigid steel frame which was directly fixed to side walls of the wave channel. An acrylic frame was used to hold the transducers in a vertical slit which was already prepared in the wall so that the transducers were not in contact with the vertical wall. The small space less than 0.1 cm between the acrylic frame and the vertical wall was coated by gum tape.

Pin point pressure transducers with operational capacity of 500 gf/cm^2 and overload capacity of 120 % were used for pressure measurements. Natural frequency of the pressure transducers are 10 KHz. Adaptors filled with silicon grease were used with the pressure transducers. Each adaptor had a pin hole of only 0.5 mm in diameter which enabled us to measure pressure very locally. Pressure data were recorded and digitized with 20 KHz sampling frequency which was adequate for being able to record the peak pressure during the impact and to collect sufficient numbers of data around the peak, as the shortest pressure rise time was 0.4 ms.

The spilling and plunging wave pressures were measured in detail at various elevations (spaced 5 mm apart, above the wave through level, here S.W.L.) and for different wall locations in their breaking zones. Since the breaking point varies with the breaker type, we were obliged to locate the wall in two different areas on the reef to measure pressure in the breaking zones of the spilling and plunging breakers. Hence, for the purpose of comparison, dimensionless relative distance of the wall from the breaking point, $\delta x/h_1$, is adopted to show the wall location in the breaking zone.

Numerical Simulations

Fully nonlinear BIM is used to compute the spilling and plunging wave profiles, the associated water particle velocities and accelerations, and the exerted pressure on a vertical wall installed in their breaking zones. Computations are made for the same incident waves and bottom topography used in the experiments. Details of the computational approaches, the concepts used for pressure computations and the computed free surface profiles of the spilling and plunging breakers (in the absence of the wall) at different stages of overturning process are presented in previous work of Azarmsa et al. (1996a).

Figure 2 indicates how the spilling and plunging wave profiles vary during the collision with a vertical wall modeled at different locations on the reef. When these breakers collide with a vertical wall at a location before the breaking point (**Fig. 2** (a)), their horizontal momentum smoothly converts into the vertical momentum and as a result, water rises up the wall. For the wall at the breaking point (**Fig. 2** (b)), the front face of both the breakers converges toward a point on the wall. The elevation of the focus of the front face of the plunging breaker on the wall is only a little higher than the elevation of the incident wave crest. But since the slope of the front face of the spilling breaker is milder than that of the plunging breaker, the water line at the wall càn considerably rises up the wall

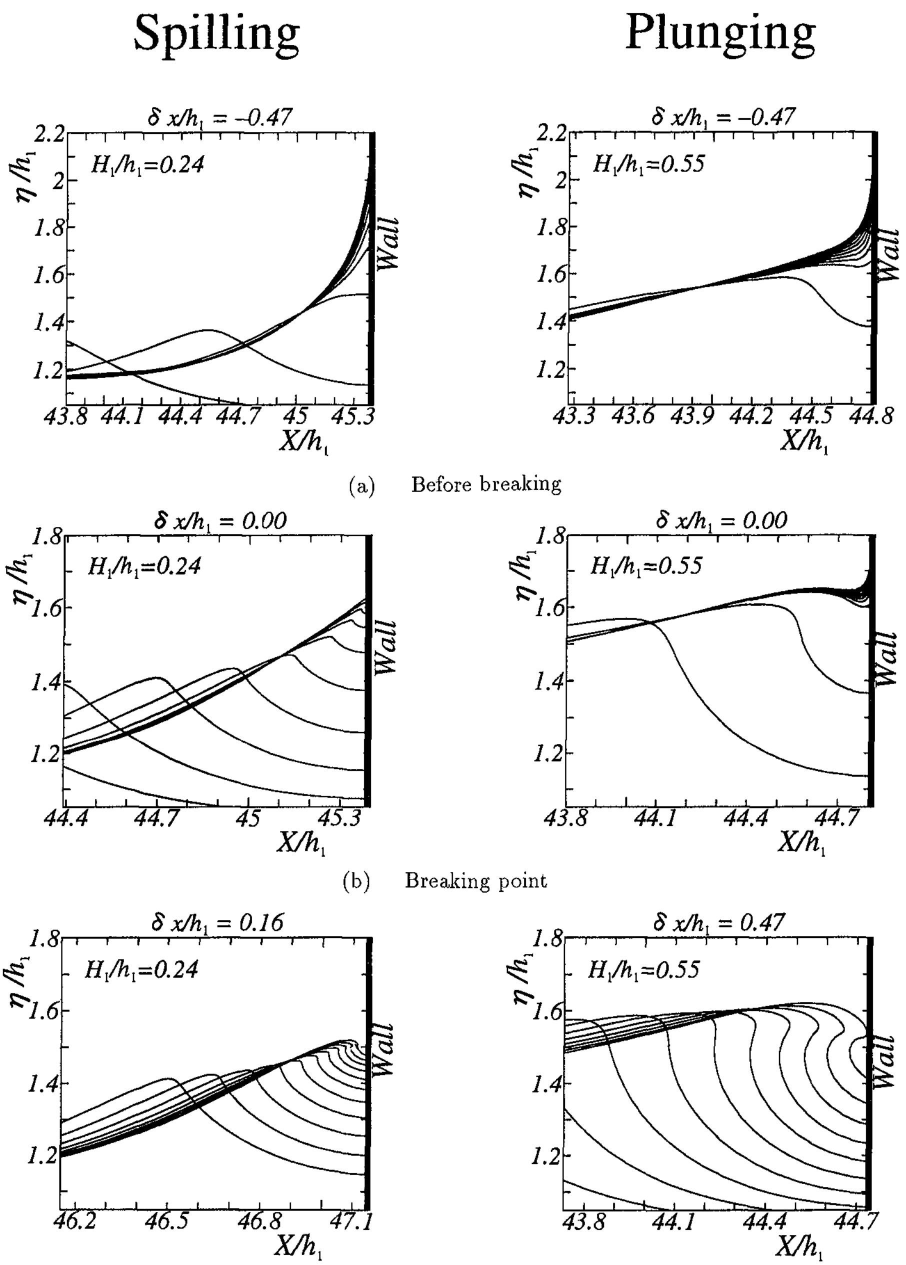


Figure 2: Computed profiles for the spilling and plunging breakers during the collision with a vertical wall.

before that the wave crest could make a contact with the wall. As a result, the elevation of the focus of the front face of the spilling breaker on the wall is much higher than the elevation of the incident wave crest. **Figure 2** (c) indicates that collision of the plunging breaker with the wall at a location after the breaking point results in entrapping air. However, air is not entrapped between the front face of the spilling breaker and the wall, as expected.

Pressure Time Histories

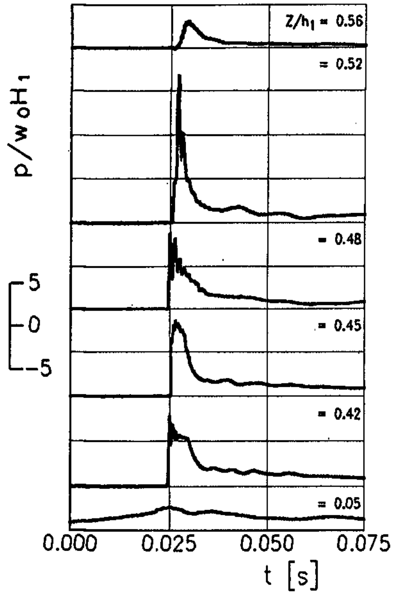
In order to investigate the characteristics of the plunging and spilling wave pressures, detailed measurements of pressure in both horizontal and vertical directions were carried out and variation of pressure time history with wall locations in the breaking zone and elevations along the wall are investigated.

a) Plunging Breaker

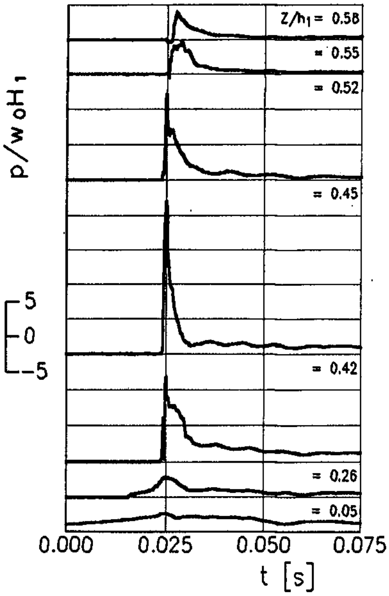
Pressure records on the wall installed in a location very near to the breaking point ($\delta\ x/h_1 = -0.13$) are shown in **Fig. 3** (a). The pressure measured near the still water level is very similar to the standing wave pressure and characterized by long pressure rise time and low maximum pressure value. However, as the elevation increases, the dimensionless value of maximum pressure exerted on the wall becomes larger so that $p_{max}/\omega_0 H_1 > 15$ is observed at the elevation of $z/h_1 = 0.52$ just below the wave crest. Comparisons among the pressure time histories measured between the elevations $z/h_1 = 0.42$ and 0.52 reveal that although the pressure rise times in these records are very short and more or less the same, the maximum pressure values and the pressure fall times differ from case to case.

Figure 3 (b) illustrates the pressure time histories recorded on the wall installed at the breaking point ($\delta\ x/h_1 = 0.00$). Comparisons between **Fig. 3** (a) and (b) reveal that for only a small ($2.0cm$) change in the wall location, the pressure time histories measured at the elevations of $z/h_1 = 0.42$, 0.45 and 0.52 have considerably changed. The maximum pressure value has increased more than twice at the elevations of $z/h_1 = 0.42$ and 0.45, but it has decreased at the elevation of $z/h_1 = 0.52$.

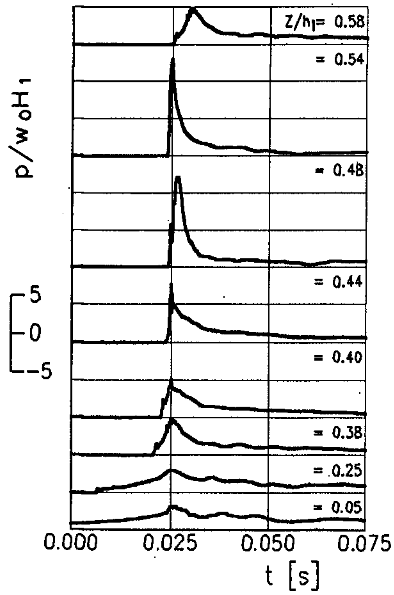
In fact, when the wall is located at the location of $\delta\ x/h_1 = -0.13$ violent vertical motion of the water on the wall prevents the wave crest from making a direct impact on the wall and causes the water particles near the wave crest to move upward. However, change of the wall location from $\delta\ x/h_1 = -0.13$ to the breaking point ($\delta\ x/h_1 = 0.00$) allows the wave to deform more before colliding with the wall. As a result, the wave front face becomes nearly vertical and the wave crest makes a direct impact on the wall just before that the water rising on the wall reaches the wave crest elevation. Therefore, change in the wall location allows a change in direction of movement of the water particles near the wave crest from an upward direction to a nearly horizontal one. Moreover, the water jet observed by video camera just starts forming at the breaking point. In other



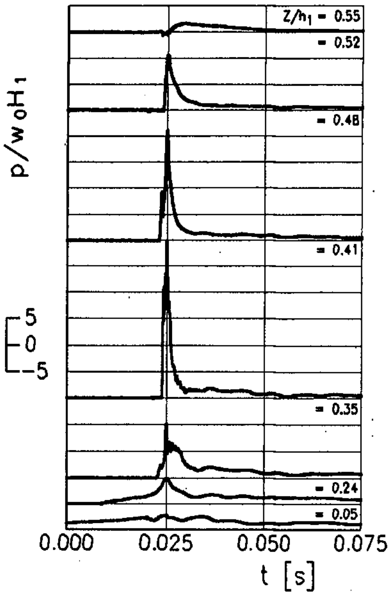
a) Near breaking ($\delta\ x/h_1 = -0.13$)



b) Breaking point ($\delta\ x/h_1 = 0.00$)



c) After breaking ($\delta\ x/h_1 = 0.07$)



d) After breaking ($\delta\ x/h_1 = 0.47$)

Figure 3: Time histories of the plunging wave pressure recorded on the wall at different locations.

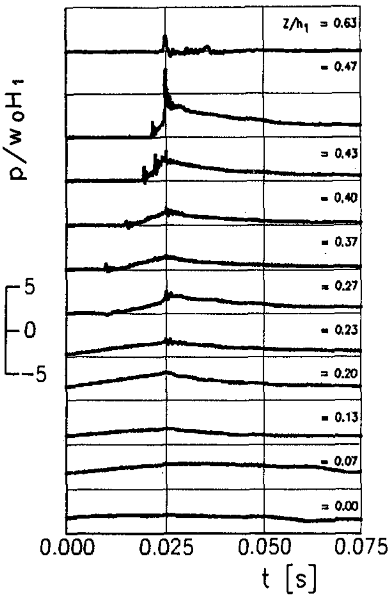
words, the velocity and acceleration of water particles which are near the wave crest and form the jet have also increased. Therefore, it can be concluded that the reason why both of the pressure intensity and the elevations at which high pressures take place change sensitively with the wall locations should be closely related to the rapid change in the wave kinematics.

Time histories of the pressure exerted on the wall installed at two different locations after the breaking point are shown in **Fig. 3** (c) and (d). Pressure time histories measured on the wall at different elevations, especially those near the still water level are characterized by low frequency oscillations which are supposed to be excited due to the dynamics of air entrapped between the curved front face of a plunging breaker and a vertical wall. Entrapped air also makes the pressure rise time become longer. Comparisons between **Fig. 3** (b) and (d) reveal that although the pressure rise time becomes longer due to the entrapped air influence, the maximum pressure value remains in the same order or becomes even larger (e.g. at the elevation of $z/h_1 = 0.41$, **Fig. 3** (d)) than those measured at the breaking point ($\delta\ x/h_1 = 0.00$). This confirms that the maximum pressure value does not necessarily change inversely with the pressure rise time, as mentioned before. Moreover, the impact pressure occurs in a wider area on the wall at the location of $\delta\ x/h_1 = 0.47$. Comparisons between the pressure time history recorded at the elevation of $z/h_1 = 0.41$ (**Fig. 3** (d)) and the pressure records on the wall at the breaking point (**Fig. 3** (b)) reveal that the overturned waves may exert even stronger impacts on the wall than the waves which just break on the wall with an almost vertically fronted face (see also **Fig. 6** (c) and (e)). As long pressure rise time, multiple peaks and low frequency oscillations following the peaks reveal and also as seen in **Fig. 2**, a big amount of air is entrapped between the front face of the overturned wave which collides with the wall at the location of $\delta\ x/h_1 = 0.47$. Therefore, occurence of such a high impact pressure may be related to the velocity and acceleration of water particles which their values have also become larger, in comparison with their values at the breaking point. As a result, it can be concluded that although the entrapped air is generally supposed to reduce the intensity of the impact pressure, it does not necessarily control the occurence of high impact pressures.

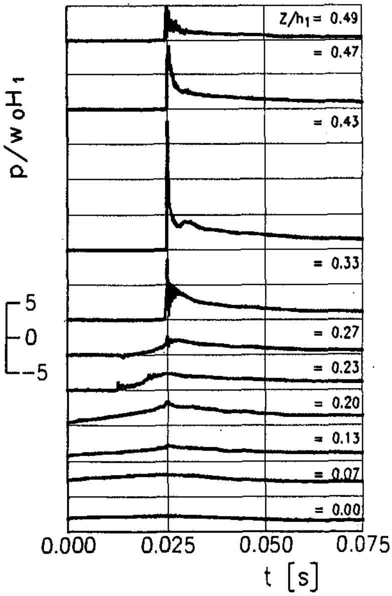
b) Spilling Breaker

Figure 4 (a) indicates that for a wall location close to the breaking point ($\delta\ x/h_1 = -0.27$), the pressure recorded at and near the still water level is similar to the standing wave pressure. However, as the elevation increases, the pressure rise time becomes shorter and the maximum value of pressure increases so that it exceeds the value of $7\omega_0 H_1$ at the elevation of $z/h_1 = 0.47$.

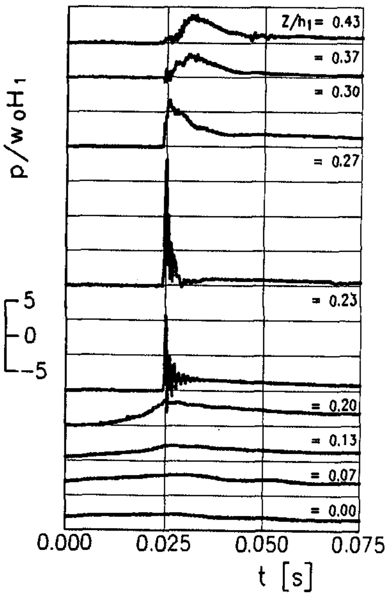
The pressure time histories recorded at the breaking point (**Figure 4** (b), $0.33 < z/h_1 < 0.47$) are characterized by short rise time and high peak value. The pressure time history recorded at the elevation of $z/h_1 = 0.43$ reveals that even the spilling breaker exerts the impact pressure on the wall. This indicates



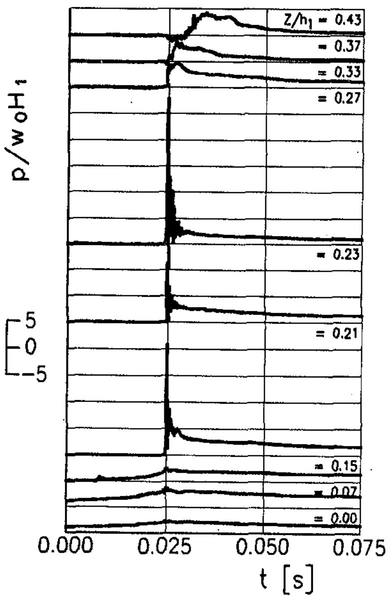
a) Near breaking ($\delta\ x/h_1 = -0.27$)



b) Breaking point ($\delta\ x/h_1 = 0.00$)



c) After breaking ($\delta\ x/h_1 = 0.67$)



d) After breaking ($\delta\ x/h_1 = 1.47$)

Figure 4: Time histories of the spilling wave pressure recorded on the wall at different locations.

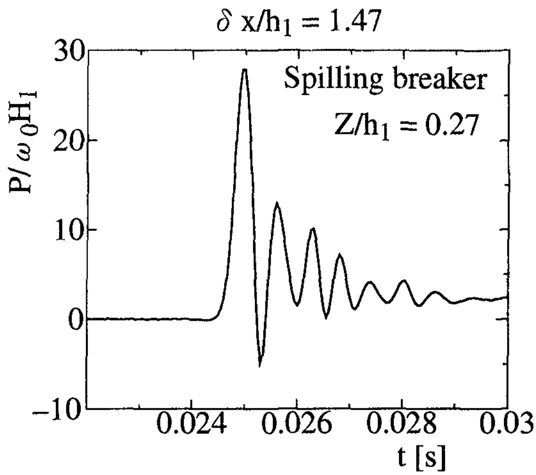


Figure 5: Oscillations in the time history of the spilling wave pressure.

that occurence of the impact pressure is independent of breaker type, as concluded by Azarmsa et al., (1996a). Since a spilling breaker does not entrap an air pocket (as previously seen in **Fig. 2**), this result also indicates that the impact pressure may be generated even in the absence of entrapped air. As the elevation increases (above the elevation of $z/h_1 = 0.43$), the maximum value of pressure decreases, although the pressure rise time remains short.

The results shown in **Fig. 4** (c) and (d) make clear that as well as a plunging breaker, a spilling breaker also exerts the impact pressure on a vertical wall at a location after the breaking point. As seen previously (**Fig. 3**(c)), low frequency oscillations which demonstrates presence of an entrapped air pocket are observed in the time histories of the plunging wave pressure. In contrast, very high frequency oscillations are detected in the time histories of the spilling wave pressure. To see better these oscillations, one of these records is shown in **Fig. 5** in a smaller time scale. Frequency of these oscillations is more than 1.6 KHz which is much higher than the frequency of oscillations observed in the time histories of the plunging wave pressure (reported here or those reported in the literature). Besides, these oscillations are damped in less than $4ms$. Therefore, it seems that these oscillations are excited by some small air bubbles temporarily entrapped between the unstable wave front and the vertical wall or resulted from partial compression and expansion of the air between the wall and upper side of the wave front when it is forced to go out rapidly (see wave profiles of the spilling breaker while colliding with a wall at a location after the breaking point, **Fig. 2** (c)).

Comparisons between the spilling (**Fig. 4**) and plunging (**Fig. 3**) wave pressures exerted on the wall in the after breaking area ($\delta\, x/h_1 > 0.00$) reveal that air pocket entrapped by the plunging breaker causes the pressure rise time to increase. From the comparisons, it is also understood that for the records with almost the same maximum pressure values, the pressure rise times are different and vice versa, as also mentioned before. Therefore, it can be concluded that the maximum pressure value does not necessarily obey an inverse relation with the pressure rise time, although some empirical formulas for the peak value of pressure have been based on such an assumption (e.g. Weggel and Maxwell; 1970, Kirkgoz; 1990, Hattori et al.; 1994).

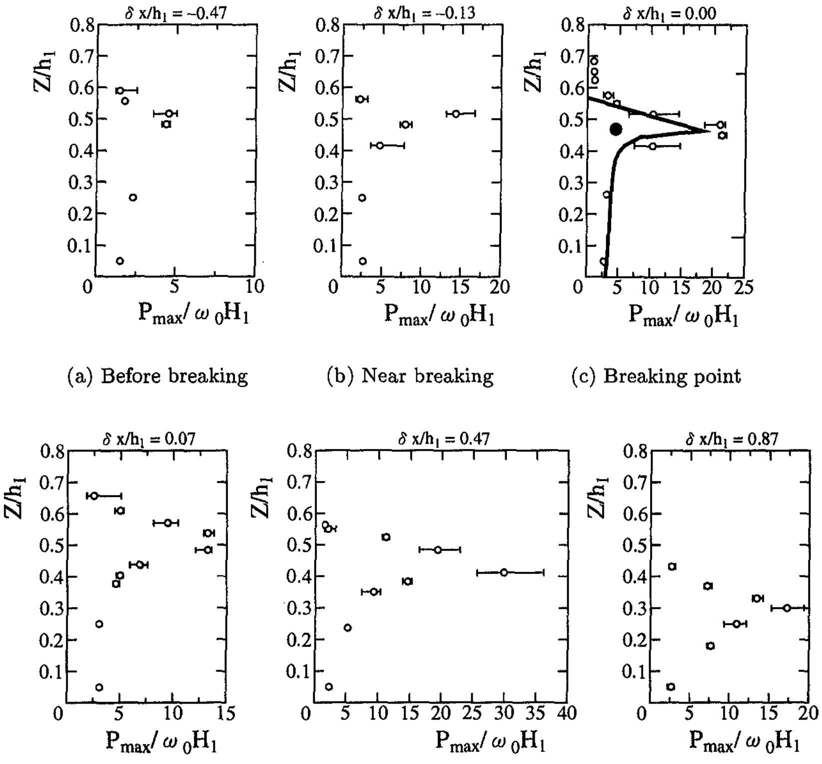
Vertical Distribution of the Maximum Pressure

The study of vertical distribution of the maximum pressure is important not only for evaluating the critical force and momentum working on the structure during the wave impact but also for investigating the localized characteristics of the impact pressure which may be the cause of the local damages in a vertical structure.

To derive the vertical distribution of the maximum pressure, the maximum pressure values of repeated tests carried out under the identical initial experimental conditions are averaged and normalized by $\omega_0 H_1$ at each measuring point. **Figures 6** and **7** respectively show the obtained results for the plunging and spilling breakers at different wall locations in their breaking zones. At each measuring point, the range of pressure variation and the mean value for repeated experiments are illustrated by the interval between two bars and open circle, respectively. From the comparisons, it is found that for both the breakers the peak value of pressure exerted on the wall increases as the wall is shifted more from the before breaking area ($\delta x/h_1 < 0.00$) toward the breaking point ($\delta x/h_1 = 0.00$).

At the breaking point ($\delta x/h_1 = 0.00$), both the experimental and numerical results are illustrated. The solid circle indicates the calculated peak value of the pressure resulted from the direct impact of the free jet on the wall. This value is calculated on the base of horizontal momentum and inertia of the jet (Azarmsa et al., 1996 (a)). The solid line represents vertical distribution of maximum pressure computed directly from the BIM by considering both of the horizontal and vertical components of water particle kinematics. Agreement between the experimental result and the numerical one using the BIM (the open circles and the solid line) reveals that vertical distribution of both the plunging and spilling wave pressures can be computed under the assumption of irrotational flow in the incompressible and inviscid fluid. Moreover, the difference between the peak values of the pressure resulted from each of the computational concepts (the solid circle and line) indicates the significant contribution of vertical velocity and acceleration of water particles in generation of the impact pressure.

As seen, both the breakers exert the impact pressure on the wall not only at the breaking point but also in the after breaking area ($\delta x/h_1 > 0.00$). From the comparisons, it is also found that as the wall is moved from the breaking point toward the after breaking area, size of the area on the wall subjected to



(a) Before breaking (b) Near breaking (c) Breaking point

(d) Just after breaking (e) After breaking (f) After breaking

Figure 6: Vertical distribution of the maximum pressure exerted by the plunging breaker on the wall at different locations.

high pressures becomes larger and reach to its largest value at the location of $\delta\ x/h_l = 0.47$ for the plunging breaker and $\delta\ x/h_l = 1.47$ for the spilling breaker. Therefore, it can be concluded that the total force exerted on the wall in the after breaking area should be the largest. On the other hand, comparisons between **Fig. 6** and **Fig. 7** reveal that size of the impact zone for the spilling breaker is smaller than that for the plunging breaker. This is because size of the jet (which contains water particles of the most critical kinematics) excited by a spilling breaker is much smaller than that by a plunging breaker. From the comparisons, it is also found that the ranges of pressure variation for the repeated experiments are larger for the spilling breaker. The reason why in the impact zone the spilling wave pressure varies more sensitively with the repeats of the experiments is also related to the fact that size of the jet excited by a spilling breaker is small. In fact because of the smallness of the jet size, the elevation at which the impact pressure is exerted on the wall may change owing to a small

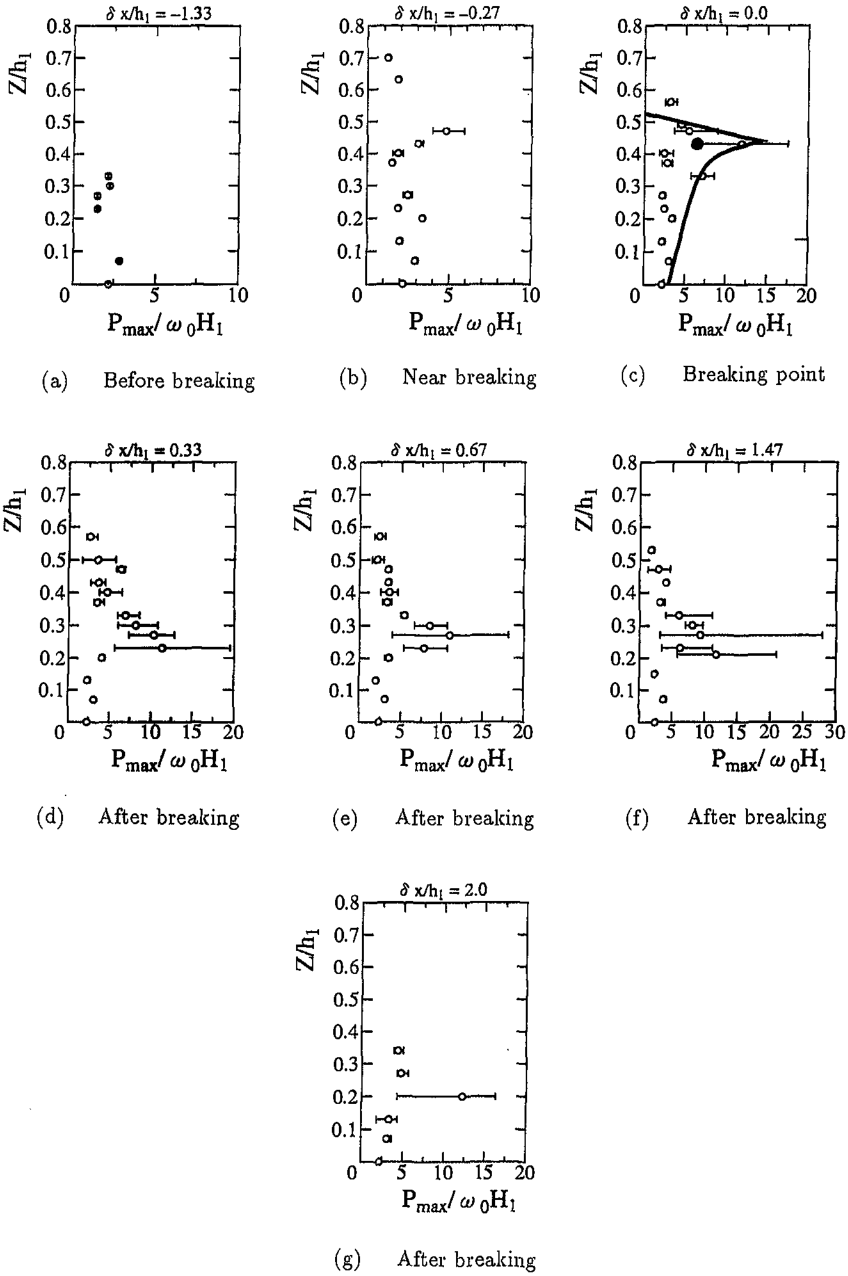


Figure 7: Vertical distribution of the maximum pressure exerted by the spilling breaker on the wall at different locations.

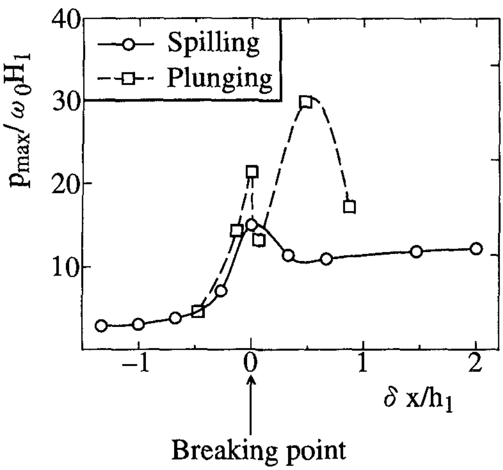


Figure 8: Variation of the peak value in the vertical distribution of maximum pressure with wall locations.

change in the collision condition of a spilling breaker with a vertical wall and as a result, a fixed pressure transducer may or may not be affected by strong impact pressure, from one to another repeat of the experiments. Therefore, it can be concluded that the variability of the maximum pressure in repeated tests is not only due to the randomness and dynamics of entrapped air, but also may be because of the size and elevation of the jet at the instant of collision.

For both of the breakers, variation of the peak value in the vertical distribution of the maximum pressure with wall locations is shown in **Fig. 8** . The results for the plunging breaker reveal that pressure exerted by an overturned wave may be even higher than that by a wave just breaking on the wall with an almost vertically fronted face. The reason may be related to the fact that kinematics of an overturned wave is more critical than the kinematics of the same wave just at the breaking point. In contrast, the pressure peaks recorded for the spilling breaker at different wall locations near the breaking point and in the after breaking area are almost the same. This is not unexpected because the kinematics of the spilling breaker does not change so much during the overturning process. **Figure 8** also reveals that the obtained values for the spilling breaker are smaller than those for the plunging breaker. Since there is a big difference between the spilling and plunging breakers with regard to the volume of entrapped air, if the impact pressure is related to the reduced velocity of sound in a water-air mixture (Schmidt et al., 1992; Hattori, 1994; Peregrine and Topliss, 1994), the pressure exerted by the spilling breaker is expected to be higher (see discussion made by Azarmsa et al., 1996a). However, the results of this study make clear that occurrence of the impact pressure can not be related to the water hammer effect even if the reduced velocity of sound in a water-air mixture is used.

Conclusions

The results of this study clearly show that different types of breaking waves at different steps of their overturning process exert the impact pressure on a vertical structure. It is made clear that occurence of the impact pressure can not be related to the water hammer effect, even if the reduced velocity of sound in a water-air mixture is used. Besides, it is shown that although the entrapped air reduces the intensity of the impact pressure, it does not necessarily control the occurence of high impact pressures. Further, it is made clear that occurence of the impact pressure is closely related to the internal kinematics of breaking waves. Therefore, the condition under which the impact pressure may occur is not critically dependent on wave geometry, entrapped air dynamics and so on. In other words, the structures subjected to the breaking waves quite frequently experience the impact pressure. As a result, even if the impact pressure is supposed to cause local damage in the structure, after sufficient number of repeats of the event at different elevations the stability of the structure may be threaten in whole.

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