CHAPTER 136

IMPACT BREAKING WAVE PRESSURES ON VERTICAL WALLS

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ABSTRACT

Impact wave pressures acting on a vertical wall were discussed by simultaneous measurements of the pressure and wave shapes at impact.

Experiments confirmed the principal role of adiabatic processes of trapped air bubbles to the generation of impact pressures. The most severe impulsive pressure was observed when breaking waves hit the wall with trapping small air bubbles or a very thin lens-shaped air pocket. The larger the amount of the entrapped air, the lower the magnitude of the impact pressures. Due to the pulsation of the air pocket, damped pressure oscillations were observed immediately after the impact pressure.

A predictive model, taking account of the adiabatic compression processes of the trapped air pocket, predicts fairly well the maximum impact pressure and the frequency of the damped pressure oscillation, in the case when plunging breakers collide against the wall.

1. INTRODUCTION

Impact pressures have been considered unlikely to be effective for sliding and overturning massive structures seawalls. Nevertheless, some studies (Weggel and Maxwell, 1970; Mogridge and Jamieson, 1980; Arami and Hattori, 1988) and recent field observations pointed out a clear evidence that such pressures can cause severe local damages to vertical wall type structures, and that the resulting damages would develop owing to successive attacks of breaking waves and cause sudden failures of the structures.

Since Bagnold (1939) proposed an air pocket model for the physics of the high impulsive wave pressure, many experimental studies have been performed to explicate the physics of etc.-

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impact processes. However, published data from the various studies provide very wide and different views on the wave-impact physics. Therefore, more detailed and reliable examinations on this process are absolutely necessary to the development of physical models predicting for the impact pressure. The principal aims of this study are as follows;
1. To explicate the difference of the wave-impact processes under various colliding conditions of breaking waves onto the wall,
2. To examine aerodynamic contributions of the entrapped air to the generation of the impact pressure, and
3. To propose a predictive model, taking account of adiabatic compression processes of the air pocket entrapped between the structure and wave.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURES

2.1 EXPERIMENTAL EQUIPMENT

General arrangement of the experimental equipment is shown in Fig. 1. Experiments were carried out in a glass-walled wave flume, 0.30 m wide, 0.55 m high, and 20 m long, in which a steel beach of 1/20 slope was installed. Regular waves were produced by a reflection-absorbing wave maker of flat type.

Fig. 1 General arrangement of the experimental equipment. (Units:m)

Vertical plane wall of a 35 mm thick plastic plate (0.30 m wide and 0.50 m high) was shored up with steel frames. The wall complex, having a natural frequency of 1.2 KHz in water, was mounted rigidly on a plastic mound with a foreshore slope of 1/10. Incident wave properties were detected by a capacitance-type wave gauge installed at the uniform water depth.

2.2 PRESSURE MEASUREMENTS

Impact pressures were measured by semi-conductor type transducers of 10mm in diameter. The pressure transducers have operational capacity of 100 gf/cm² and 200 gf/cm², with 100% overload capability. Their natural frequency in water is 9.6 KHz and the frequency response range DC to 4.8 KHz.

Four pressure transducers were located vertically along the centerline of the wall at an interval of 2.0 cm. The maximum impact pressure is occurred most likely in the vicinity of the still
vertical water level. Hence, two additional pressure transducers were set at 1.0 cm below and above the still water level and 5.0 cm apart from the centerline.

2.3 RECORDING THE IMPINGING BREAKING WAVE PROFILE

High-speed videos were simultaneously taken at 200 frames/s with the measurements of impact pressures. Photo. 1 is an example of the picture of wave shape at impact. Number of the last three digits on the top of the picture indicates the elapsed time in millisecond after the start of a test run. White arrows on the left hand side show the locations of the pressure transducers. Real-time pressure record from the pressure transducer \( P_4 \) at the still water level is monitored on the left hand side of the still. The synchronization between the pressure records and sequential stills was made by using the pressure monitor within an accuracy of 0.1ms.

Length measurements were made using a 1.0 cm square grid system, attached on the sidewall glass. The breaking wave height, the size and shape of trapped air pocket, the forward and upward velocities of wave surface at and in front of the wall were read from the pictures projected on a 29-inch video-screen.

2.4 EXPERIMENTAL PROCEDURES

In the repeated tests, impact pressures vary significantly owing to the instability of the wave breaking and the high reflection of the wall. We employed the two following procedures to ensure the repeatability of the experiments: (1) Every test run was made after the free surface disturbance due to the preceding test run was well subsided, and (2) The wave generator was controlled by a programmed analogue signal yielding a regular wave train. Outputs of the impact pressures were recorded on digital recorders over six wave periods at a sampling frequency of 5 KHz for extensive processing by computer. Data analyses were made for four subsequent breaking waves preceded by some non-breaking waves.

3. EXPERIMENTAL RESULTS OF THE IMPACT PRESSURE CHARACTERISTICS

Since wave-impact processes depend closely on the wall location relative to the wave breaking position (Chen and Melville, 1988), it is reasonable to characterize them by the development of wave breaking at the wall, or the colliding conditions. In this study, we will examine into the essential characteristics of
Photo. 2 Sequence of the still pictures of the wave surface. (Flip-through condition)
VERTICAL WALL BREAKING WAVES

WAVE PRESSURE RECORDS (No. 013-3) FOR THE FLIP-THROUGH IMPACT.

\( H_i = 4.7 \text{ cm}, \quad T = 1.7 \text{ s} \)
\( H_b = 5.7 \text{ cm}, \quad l = 0 \)
\( h_d = 2.5 \text{ cm} \)
\( \frac{P_{\text{max}}}{\rho g h_b} = 11.2 \)

Fig. 2 Wave pressure records (Flip-through condition) 
\((H_b=5.7\text{cm}, \quad T=1.7s)\)
impact pressures for the four following conditions, somewhat similar to Oumeraci, Klammer, and Partenscky (1991):

1. "Flip-Through" condition with no air bubbles.
2. Collision of the vertically flat wave front with entrapping small air bubbles — single peak pressure —.
3. Collision of plunging breakers with a thin air pocket — damped pressure oscillations with high frequencies —, and
4. Collision of fully developed plunging breakers with a thick air pocket — damped pressure oscillation with low frequencies —.

3.1 FLIP-THROUGH COLLISION WITH NO AIR BUBBLES.

Impact process due to the "flip-through" action (Cooker and Peregrine, 1991) is observed when incident waves break as upward deflected breaker near the wall. Photo 2, consisting of 8 still pictures, gives the wave shape changes during the collision on the wall. We notice from the sequential pictures that the wave shapes change a very similar process to the computation by Cooker and Peregrine (1991). The corresponding pressure records at various elevations are given in Fig. 2, in which 20 ms on the time axis refers to the time of the maximum peak pressure recorded at $P_1$ on the still water level. Thick arrows on the top of the pressure record at $P_1$ represent the shooting instant of the pictures.

Although the resultant peak pressures are not so high in the magnitude ($p_{\text{max},4}/\rho g H_b=11.2$), the pressure record at $P_4$ shows that an impact is occurred without a clear hit of the wave front.

3.2 COLLISION OF VERTICALLY FLAT WAVE FRONT WITH SMALL AIR BUBBLES

— SINGLE PEAK IMPACT PRESSURE —

Collision of breaking waves with vertical or slightly curled front brings about extremely high impact pressures ($p_{\text{max},4}/\rho g H_b=109.6$), as seen in Photo. 3 and Fig. 3. However, even the highest impact at $P_4$ is much lower than that due to a water hammer process.

The pictures about the instant of collision (Photo. 3 (e) and (f)) do not show apparently the air entrainment. But we can find out dark image indicating a group of small air bubbles trapped over the hitting region of wave crest (Photo. 3 (g) and (f)). The pressure records in this region (Fig. 3 $P_1$ - $P_3$) exhibit clear pressure fluctuations with very high frequencies of about 1,000 Hz during the impact. The peak pressures occur simultaneously at various elevations, but their magnitudes decrease remarkably with the distance from the hitting point of the wave crest.

If a small air pocket in a form of very thin lens is trapped in the vicinity of the impinging region of the wave crest, the pocket is collapsed into small air bubbles at impact. This also results in a single peak impact pressure. Occasionally we observed a fact that a fraction of the air bubbles was released upwards with wave splash. This results in noticeable reduction of the peak pressure and causes variability in the pressure magnitude. The experiments, however, confirm an important role of the trapped air bubbles to generation of the impact pressures.
Photo 3. Sequence of the still pictures of the wave surface. (Collision of the vertically flat wave front)
Fig. 3 Wave pressure records.
(Collision of the vertically flat wave front)
(Single peak impact pressure)
($H_b$ = 4.8 cm, $T$ = 1.7 s)

WAVE PRESSURE RECORDS (No. 129-6)
WITH AIR BUBLES.

- $H_1$ = 4.0 cm, $T$ = 1.7 s
- $H_b$ = 4.8 cm, $l$ = ?
- $h_d$ = 1.9 cm, $f_{ap}$ = 1100 Hz
- $P_{max} / \rho g H_b = 109.6$
3.3 COLLISION OF PLUNGING BREAKERS — DAMPED PRESSURE OSCILLATIONS OF HIGH FREQUENCIES —

Photo. 4 gives the trapping process of a two dimensional air pocket between the wall and wave. The pressure records at various elevations in Fig. 4 show that the adiabatic action of the air pocket gives rise not only to relatively high impact pressures on the wall $p_{\text{max}, 4}/gH_b = 51.9$, but also to damped oscillations with a high frequencies of 250 Hz, immediately after a rapid pressure drop. The pressure records in the air pocket zone $(P_1-P_3)$ exhibit almost the same variations both in magnitude and in phase. This indicates repeated compression and expansion of the air pocket. Immediately after the collision, the air pocket transforms into a group of air bubbles, in which the bubbles rotate violently (Photo. 4 (f)), and this will likely play some role in the reduction of pressure oscillations (Cooker and Peregrine, 1991). We can not yet specify any dominant process of the energy dissipation due to the violent motion of the air bubbles.

From the simultaneous records of the pressure and wave, we found an evidence that damped pressure oscillations continue until the air bubbles start to escape through the wave surface.

3.4 COLLISION OF FULLY DEVELOPED PLUNGING BREAKERS — DAMPED PRESSURE OSCILLATIONS OF LOW FREQUENCIES —

As plunging and curling of the breaking wave are developed, a large cylindrical air pocket will be trapped and confined between the wall and wave. As shown in Figs. 5 and 6, an increase of the air pocket thickness $l$, or the trapped air amount results in a decrease both in the peak pressure $p_{\text{max}}$ and in the frequency of damped pressure oscillation, $f_{\text{ap}}$. Both $p_{\text{max}}$ and $f_{\text{cap}}$ are inversely proportional to $l$. However, the other principal characteristics of the impact pressure are almost the same as those for the plunging breaker collision.
Photo. 4 Sequence of the still pictures of the wave surface. (Collision with entrapping a small air pocket)
Fig. 4 Wave pressure records. (Collision with a small air pocket)

$H_b = 5.9 \text{ cm, } T = 2.0 \text{ s}$
Predictive model for the impact pressure is developed under the following assumptions:
(1) The two dimensional air pocket can be substituted by a square pillar of width \(B\), height \(d\), and thickness \(l\).
(2) The adiabatic process of the air pocket is represented by an equivalent spring system, as shown in Fig. 7, having apparent spring constant \(k\), and
(3) Radial oscillation and energy dissipation of the air pocket are ignored.

The spring constant of the replaced air pocket can be written as
\[ k = \frac{(Ed/l)E_v}{\rho_w} \]
where \(E_v = 1.4\rho_{atm}\) is the bulk modulus of air and \(\rho_{atm}\) the atmospheric pressure. By introducing the virtual mass length \(K\) contributing the wave impact pressure (Bagnold, 1939), the maximum impact pressure \(p_{max}\) and the resonant frequency of the air pocket \(f_{ap}\) are obtained as
\[ p_{max} = \left(\rho_w K E_v / l\right)^{1/2} u_b \]  
and \[ f_{ap} = \left(\rho_w K l\right)^{1/2} \]
where \(\rho_w\) is the density of the water, and \(u_b\) forward velocity of the breaking wave front. The virtual mass length can be evaluated by measurements of impact pressure \(p\), the rising time \(T\), and the forward velocity of wave front \(u_b\) (Bagnold, 1939):
\[ K = \int_0^T \frac{p}{\rho_w u_b} dt \]

Figs. 8 and 9 show the agreements between the model and measurement, \(p_{max}\), \(M_{max}\), and \(f_{ap}\), \(M_{ap}\), with respect to the air pocket thickness \(l\), or the trapped air amount. Subscript \(M\) denotes the prediction. As seen in Fig. 8, due to the high variability in
measurement is not so good, especially when the air pocket is thin, \( l < 1 \) cm. The agreement, however, becomes better with increasing the pocket thickness. From investigations of the measured data, we can specify the following main factors causing the high variability: (1) The peak pressure region is much smaller than the diaphragm of pressure transducer, (2) The irregularity of the wave front changes the trapped air amount, and (3) The hitting location of wave crest tip is always shifted by high reflection of the wall. On the other hand, the model predicts reasonably well the frequency of the pressure oscillation, taking account of that the frequency should be lowered by boundary effects of the free surface, the bottom, and the wall (Topliss, Cooker, and Peregrine, 1992; Oumeraci and Partenscky, 1991).

\[ \text{Fig. 8 Comparison between the predicted and measured} \]
\[ \text{maximum pressures.} \]

\[ \text{Fig. 9 Comparison between the predicted and measured} \]
\[ \text{frequencies of the damped pressure oscillation.} \]

5. CONCLUDING REMARKS

Simultaneous measurements of the impact pressure and the wave shape change clarify that air bubbles and air pocket entrapped between the wall and the wave plays a predominant role to the occurrence of the high impact pressure. The wave-impact process is
occurrence of the high impact pressure. The wave-impact process is characterized by the development of the wave breaking at impact, because of that the entrapped air amount depends critically on the impinging front shape of breaking waves onto the wall. The larger air amount trapped gives the lower impact peak pressure and the longer period of damped pressure oscillations immediately after the impact. The damped oscillation continues until the compressed air in the pocket starts to escape through the free surface.

The model proposed describes the wave-impact process and predicts the maximum pressure and the frequency of damped pressure oscillations, when the air pocket of two dimensional form is trapped between the wall and the wave. High variability in the wave-impact process deteriorates validity of the model.

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