CHAPTER 104

IMPACT PRESSURES PRODUCED BY BREAKING WAVES

by

Norbert L. Ackermann
Professor of Water Resources Engineering
Asian Institute of Technology

and

Ping-Ho Chen
Graduate Student
Asian Institute of Technology

ABSTRACT

Experiments were conducted in a vacuum tank in order to investigate the effect which entrained air has on impact loads which are produced when waves break upon a structure. In these experiments a flat plate was dropped onto a still water surface in an environment where the ambient pressure of the surrounding air could be controlled. Rings of varying height were fixed to the surface of the falling plate in order to trap different volumes of air between the falling plate and the water, Experimentally determined values were obtained of the maximum pressure p_{max} when the plate struck the water surface for various ring heights δ and ambient pressures p_o in the vacuum tank.

Experimental results indicate that the pressure rise or shock pressure $p_s = (p_{max}-p_o)$ decreased with reductions in the ambient pressure and volume of entrapped air. Even when air was removed such that the absolute pressure in the tank was equal to the vapor pressure of the water, water hammer conditions, where the peak pressures depend upon the celerity of sound waves in the media, were never found to occur.

INTRODUCTION

The spatial distribution of the magnitude and duration of impact loads produced by waves breaking against a structure are little understood at the present time. Design procedures for such conditions are based on empirical relationships(1)(2) that have little basis on a rational analysis of the hydrodynamic features that produce these impact loads. Most experimental investigations on the problem of shock pressures produced by waves breaking upon a structure have been conducted in wave channels(3)(4)(5)(6)(7). The advantage of such an experimental arrangement is that the relationship between the wave characteristics and the impact loads can be studied directly. In a wave channel considerable experimental difficulties have been experienced however in arranging for the wave to impinge upon the structure at the moment of breaking. It is difficult,if not impossible, to control in a systematic manner the impact conditions; such as the velocity of impact, the volume of entrained air, the ambient pressure and area of impact.

In order to identify the dynamic features of the impact loads other than by specifying the wave conditions in the channel that produced these loads, experimental tests were conducted in which a plate was used to strike a water surface. As described by Wang[8], this could be made equivalent, in a dynamic sense, to a column of water striking a flat surface. Predetermined volumes of air could be trapped between the water and the plate through the use of small cups or rings fixed to the face of the falling plate. Prior to impact,the ambient pressure of the air in these rings could be controlled by reducing the pressure within the test chamber using a vacuum pump.

Kamal[9] had conducted experiments using an apparatus which was somewhat similar but which differed most significantly from that used in the present study in that the apparatus used by Kamal could not control the ambient pressure or density of the air trapped between the plate and the water surface. Bagnold[3] suggested that the impact pressures produced by a wave breaking against a vertical wall depended upon the amount of air trapped between the wave and the structure. If no air were present water hammer pressures were believed to occur, water hammer pressures have therefore often been suggested in the literature as a reasonable upper limit for the peak pressures which could exist when a wave would break against a structure. Such pressures were never recorded experimentally however. Explanations have been given that the situation where water hammer pressures would occur were statistically extremely small and that even small amounts of entrained would air greatly reduce the celerity of the pressure wave and consequently the magnitude of the peak pressure.

THEORETICAL CONSIDERATIONS

Fig.1 is a schematic diagram showing entrapped air within a cylindrical chamber. The air is compressed by a column or piston of water having an initial velocity V_o. This compression of the entrapped mass of air was suggested by Bagnold[3] to be representative of the mechanism that created impact pressures when a breaking wave struck a vertical wall. If it is assumed that the air is compressed adiabatically the equation of motion of the water column can be expressed as

$$\rho_w K \frac{d^2x}{dt^2} - p_o\left(\frac{\delta}{x}\right)^{\gamma} + p_o = 0 \qquad (1)$$

In Eq.(1), ρ_w is the density of water, δ is the height of the air chamber, γ is the adiabatic gas constant, x and t are the distance and time coordinates, respectively, and K is the length of the impinging mass of the water column whose motion is described by the x,t coordinates. Eq.(1) originally proposed by Bagnold also can be used to describe the compression of a volume of air trapped in a cylindrical chamber which is attached to a flat plate which strikes the still water surface. The mass of the falling plate should be large so that the velocity of the moving plate is not influenced by the pressure forces in the chamber. For this condition, the value of K represents the length of an effective water column whose motion can be described by the x,t coordinates. The mass of this water column can be considered for purposes of convenience as a virtual mass equal to

$$\text{virtual mass} = \rho_w K \frac{\pi D^2}{4} \qquad (2)$$

where D is the diameter of the cylindrical chamber attached to the falling plate.

Using Eq.(1) Mitsuyasu[10] determined the relationship describing the maximum pressure p_{max} as

$$\frac{\rho_w V_o^2}{5p_o}\left(\frac{K}{\delta}\right) + 1.4 - \left(\frac{p_{max}}{p_o}\right)^{0.4/1.4} - 0.4\left(\frac{p_{max}}{p_o}\right)^{-1.0/1.4} = 0 \qquad (3)$$

The ratio K/δ can be considered as a geometrical property of the cylinder-piston mechanism used in the modeling concept. Fig.2 shows the theoretical relationship as predicted by Eq.(3), between the maximum pressure rise or shock pressure $p_s = (p_m - p_o)$ and the ambient pressure p_o for various values of K/δ. This figure is constructed for a constant value of $\rho_w V_o^2$. As the initial volume of the entrapped air reduces, the shock pressure p_s increases. As δ approaches zero, the maximum pressure p_s becomes infinite as can be seen from an inspection of Eq.(3). Such an analysis assumes however that the water is incompressible. If the compressibility of the water is considered, the upper limit of the impact pressure against a rigid structure will be governed by the water hammer equation.

$$p_{max} = \rho_w V_o C \qquad (4)$$

In Eq.(4) C is the celerity of a pressure wave in the media. The air leakage models proposed by Mitsuyasu[10] and Verhagen[11] show that an air pocket will always exist at the condition of maximum shock pressure. Only by completely removing the air from the water-structure environment could impact pressures conceivably be produced of the magnitude indicated by Eq.(4). In the present study, it was attempted to produce such a condition by conducting the experiments in a vacuum tank from which the air could be removed. Impact pressures were experimentally determined under conditions in which the ambient air pressure varied from atmospheric pressure to the vapor pressure of water. By substituting data from the experimental results into Eq.(1) or Eq.(3), the value of K could be calculated. This value was then computed for the theoretical value of K which would exist if the effective mass of the water was equal to the virtual mass of a disk in a semi-infinite fluid having a diameter equal to that of the cup shaped cylinder attached to the face of the falling plate. The value of K corresponding to such a hypothesis would yield $K = 2D/3\pi$.

EXPERIMENTAL INVESTIGATION

Two mechanical systems were constructed which permitted a falling plate to strike a water surface in a tank where the ambient pressure could be controlled.

System 1: Hinged Plate

The plate shown in Fig.3 was hinged about one of its edges. A pressure transducer having a frequency response of 5,500 Hz was mounted flush with the surface of a protruding part of the plate that had a diameter of 10 cm as shown in the figure. Small rings used to trap air between the plate and the water could be mounted on the plate. The transducer was spatially prepared to operate in a range of pressure of ± 15 psi gage. The maximum overload pressure was 75 psi. A recording oscillograph manufactured by Consolidated Electrodynamics Corporation Type 5-124 having a galvanometer with a frequency response of 2000 Hz was used to record the pressure response.

The maximum velocity of the plate,at the location of the pressure transducer, prior to impact was approximately 10.0 ft/sec. Fig.4 shows the relationship between the measured shock pressure, the height of the cylindrical disks or rings attached to the face of the falling plate and the ambient pressure in the vacuum tank. Both alcohol and water were used as the liquids in the vacuum tank.

System 2: Vertically Falling Plate

The plate used in system 2 was circular having a diameter of 30 cm as shown in Fig.5. The pressure transducer and recording oscillograph was the same as that described in system 1. The plate had a vertical motion with a maximum fall velocity prior to impact of 4.87 ft/sec. Fig.6 shows the relationship between the experimentally determined values of the shock pressure, ambient pressure in the vacuum tank and the height of the rings mounted on the face of the falling plate. The rings had a diameter of 5/8 inch.

DISCUSSION OF RESULTS

System 1

As shown in Fig.4, the maximum pressures produced at impact, for each combination of ambient pressure and ring size, exhibited an increasing degree of scatter about the average value for each series of 25 tests, as the ambient pressure in the vacuum tank and the height of the "air-rings" were reduced. However, as the pressure in the tank approached the vapor pressure of the water, the impact pressures produced by the plate striking the water surface never approached the magnitudes which would have occurred if water hammer conditions existed. It appeared that the entrapped air always governed the impact producing forces even though the ambient pressure in the tank was reduced as low as the vapor pressure of the water.

When water was replaced by alcohol, the measured pressures increased in proportion to the density change of the liquids. Such a variation would be predicted however by both water hammer theory as well as the equations which described the air pocket as the predominate mechanism dictating the magnitude of the impact pressures. Table 1 presents the average shock pressure measured for tests with both alcohol and water. In these tests the depth of the liquid in the tank was 7 inches and the ambient pressure was atmospheric. Twenty five tests were conducted for each ring height.

Table 1 - Average Value of Impact Pressures in Tank Using Both Alcohol and Water

Ring Height δ	Ave.Value of 25 Measurements of Shock Pressure in water p_{water}	in alcohol $p_{alcohol}$	$\frac{p_{water}}{p_{alcohol}}$	$\frac{\rho_{water}}{\rho_{alcohol}}$
0 in	10.12	7.67	1.32	1.27
0.125 in	8.69	6.89	1.26	1.27
0.250 in	7.53	5.97	1.26	1.27
0.375 in	6.23	5.18	1.20	1.27
(Ambient Air Pressure Atmospheric)		Average	1.26	1.27

The average pressure increased by a factor of 1.26 when using water instead of alcohol. This ratio was approximately equal to the respective increase in density of the two liquids which was 1.27.

System 2

The experimentally determined data for the plate which fell vertically onto the water surface is shown in Fig.6. In this figure the shock pressure is presented as a function of the ambient air pressure in the tank for differing heights of air rings which were attached to the plate. The data showed increasing scatter as the air ring height was reduced. The greatest variation in experimental data resulted when $\delta = 0$. Such a behavior is understandable since, as δ decreases, the volume of air trapped between the water and the plate for each test would become more variable. When $\delta = 0$ however the maximum impact pressure was still an order of magnitude less than that which would have existed if water hammer pressures occurred. The pressure $p = \rho_W V_o C$ was 322 psi; more than four times the allowable overload pressure of the pressure transducer. After each series of tests the transducer was recalibrated. There was no indication that any time the pressure transducer had been loaded beyond its overload capacity.

In order to insure that the results were not in error as a result of a possible non coplanar alignment of the water-plate interface at the moment of impact, the face of the plate was later machined to a wedge or conical shape form shown in Fig.5. This change in the geometry of the plate did not produce a significant change in the experimentally determined values.

The values of K computed from Eq.(3) using the experimentally determined data is shown in Fig.7. When the ambient pressure was atmospheric and the ring heights were 1/8 inch or larger, the value of K could be approximated reasonably well by considering that the water mass used in Eq.(1) was equal to 1/2 of the virtual mass of a circular disk in an infinite fluid having a diameter equal to that of the rings which were attached to the falling plate. The factor of 1/2 was used since the virtual mass of a disk (virtual mass = $\rho D^3/3$) in an infinite fluid is computed assuming that fluid completely surrounds the disk. In the present experiments the fluid is only exposed to one face of the disk shaped opening of the air pockets at the moment of impact. The value of K is seen to increase with decreasing ambient pressure. This result seems reasonable since with a decrease in the ambient pressure the mass of decelerating water increases as more of the liquid enters the cylindrical shaped air pockets or rings.

CONCLUSIONS

Bagnold's[3] model describing shock pressures caused by the adiabatic compression of air pockets formed between a breaking wave and vertical wall was investigated:

(i) For cylindrical shaped air pockets originally at atmospheric conditions having a diameter of 5/8 inch and a length of 1/8" or greater, the effective mass of fluid which could be considered to behave as a piston compressing the air trapped in the cylindrical shaped pocket could be approximated by using one half of the theoretically determined value of the virtual mass of a disk

in an infinite fluid. The diameter of this disk should be equal to that of the cylindrical shaped air ring or pocket attached to the falling plate.

(ii) The maximum recorded shock pressures, for conditions where the ambient air pressures in the tank varied between atmospheric and the vapor pressure of the water, were always an order of magnitude less than water hammer pressures.

It therefore appears that shock pressures produced by a wave breaking against a structure in field conditions could never produce pressures that would approach those predicted by water hammer theory.

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LIST OF SYMBOLS

C	velocity of sound in water
D	diameter
K	length
p	pressure
p_{max}	maximum pressure
p_o	ambient pressure
p_s	shock pressure or pressure rise
V_o	velocity
t	time
x	length coordinate
γ	adiabatic gas constant
δ	height of ring
ρ_w	density of water

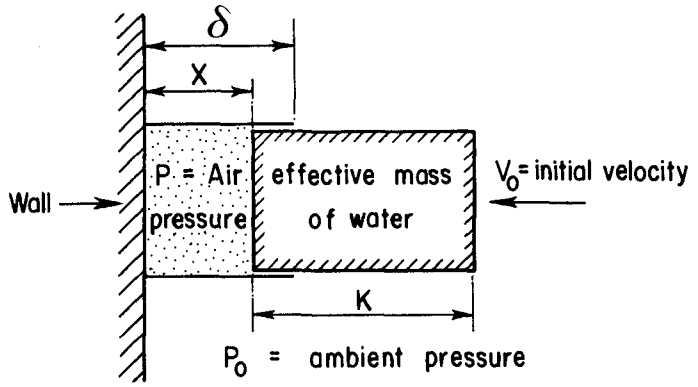

Fig. 1 Schematic diagram of column of compressed air and piston of water

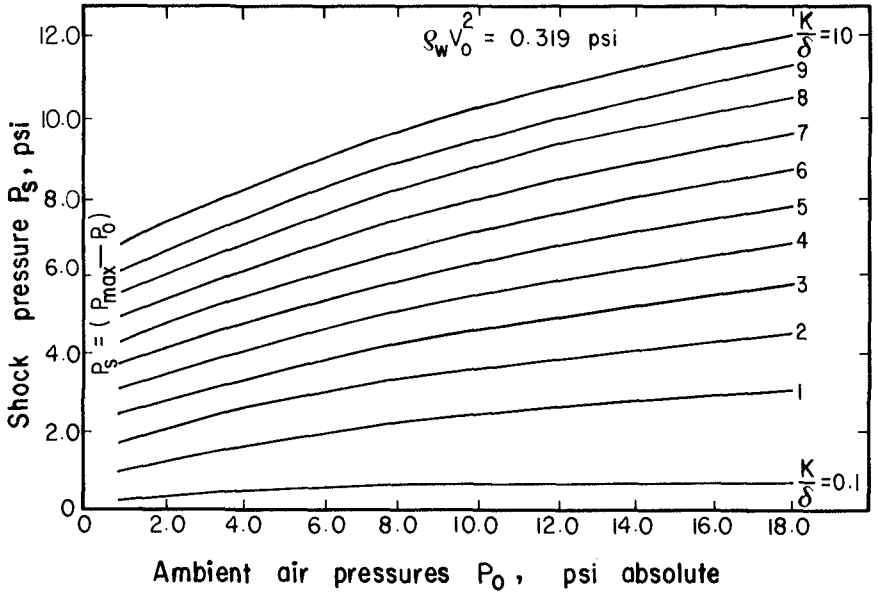

Fig. 2 Theoretical relationship between shock pressures and ambient air pressure derived from Bagnold's model

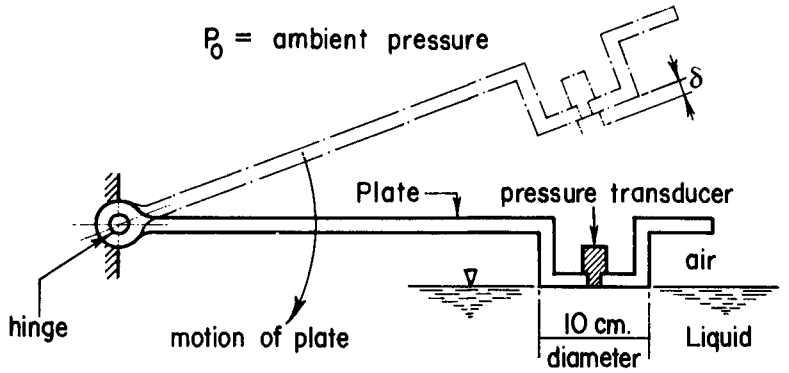

Fig.3 Schematic diagram of hinged plate with pressure transducer which struck water surface

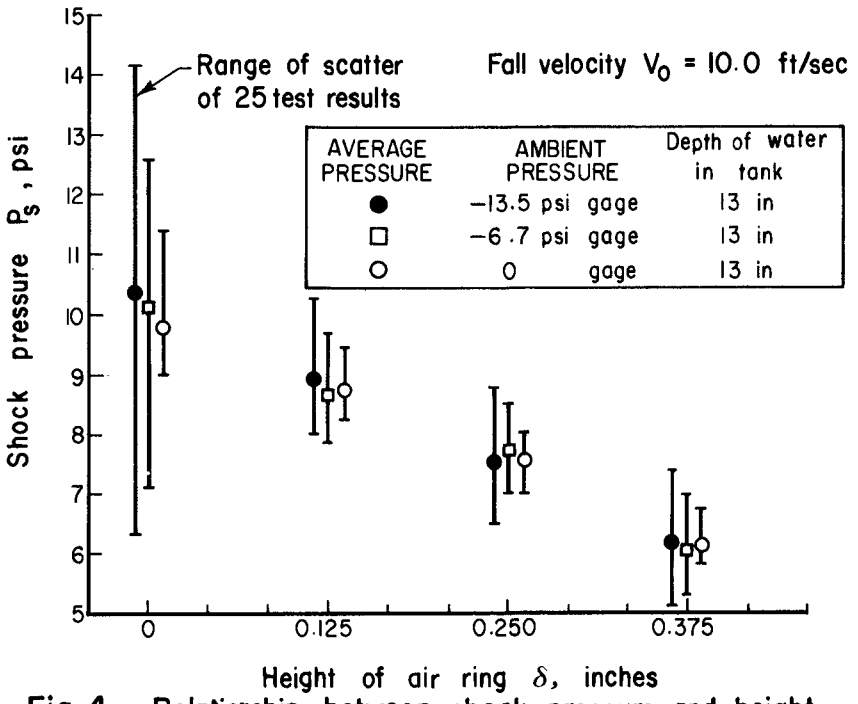

Fig. 4 Relationship between shock pressure and height of air ring for different ambient air pressures

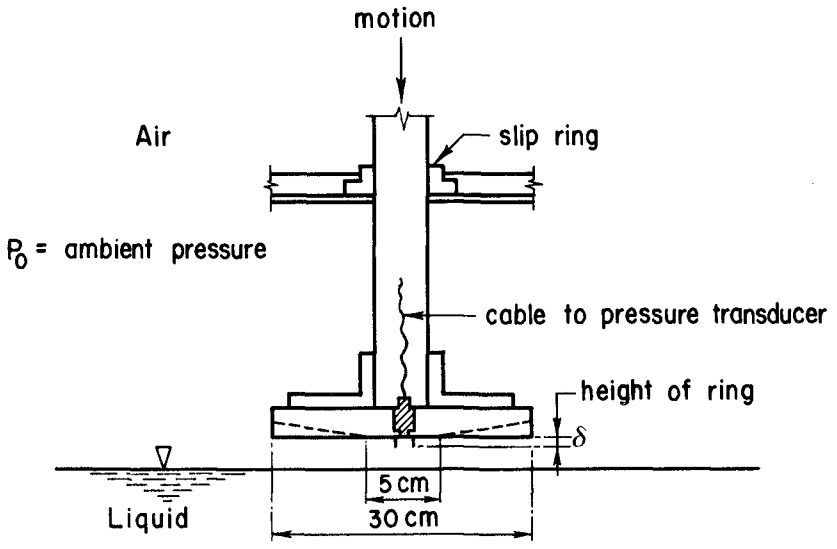

Fig.5 Schematic diagram of circular plate and pressure transducer which struck water surface

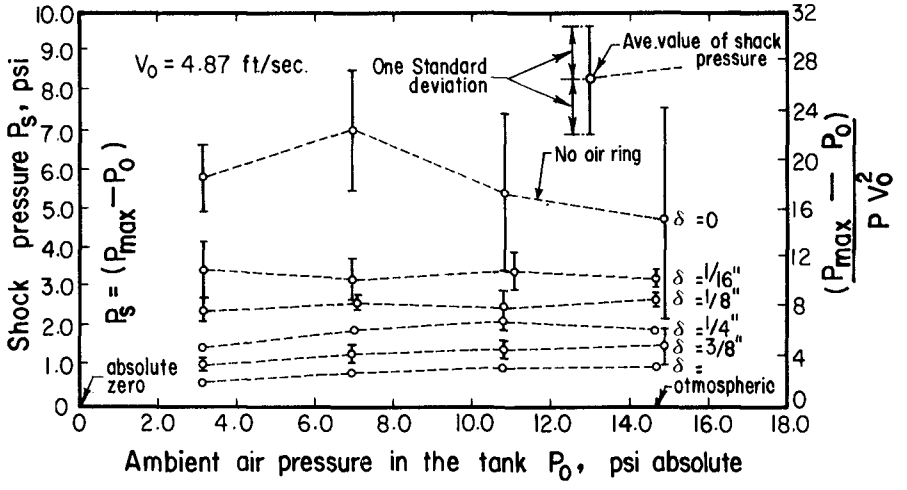

Fig.6 Experimentally determined relationship between shock pressure and ambient air pressure for constant value of impact velocity V_0

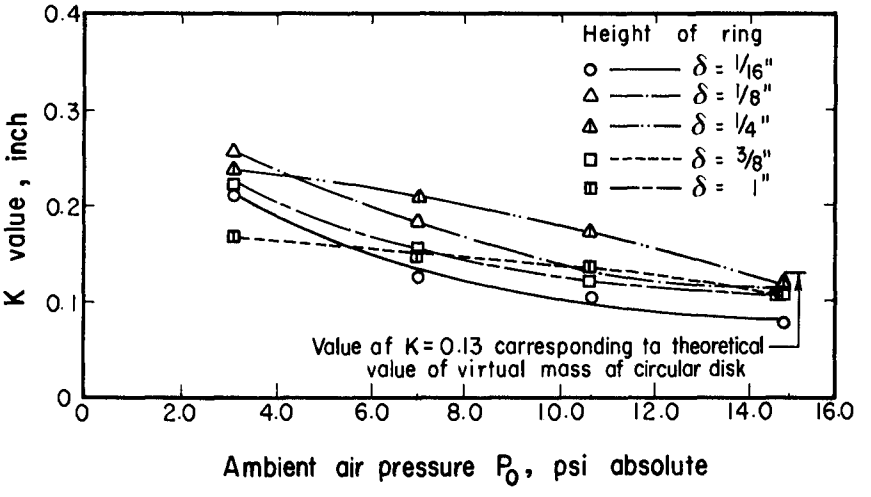

Fig.7 Relationship between K values and ambient air pressures