CHAPTER 103

FIELD MEASUREMENTS OF IMPACT PRESSURES IN SURF

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ABSTRACT

Field measurements were made of the vertical distribution of impact pressures exerted by breaking waves. Four distinct types are recognized and compared. These are near-breaking wave, plunging breaker, spilling breaker and post-breaking bore. The measurements were obtained by placing a 6 foot aluminum flat plate, backed by a cylinder in the surf zone, so that the flat faced the approaching breakers. Five sensors were placed at one foot intervals on the flat. The sensors consisted of strain gage mounted aluminum diaphragms.

Results indicated that impact pressure is significantly influenced by breaker type. The bore generated the largest impact pressures, followed in decreasing order by plunging breaker, spilling breaker and near breaking wave. In the vertical array, the largest impact pressures were recorded at or near the top, except for the bore where the reverse occurred. A qualitative explanation is given of various phenomena associated with impact pressures, by considering breaker mechanics.

INTRODUCTION

As waves travel toward the shore and eventually break, they either dissipate on a sloping beach or strike a fixed object sometimes with forces which significantly exceed those of non-breaking waves. The resisting solid may be a cliff or a man-made structure. Thus interest in the phenomenon of breaking wave impact forces may range from coastal erosion to the design and protection of coastal structures.

The pressure-time pattern recorded when a breaking wave strikes a rigid object typically consists of two parts, a long period pressure of relatively low intensity, and superimposed on the initial pressure rise, a relatively high very short period pressure, of the order of milliseconds associated with the impact of the free surface. See figure 1.

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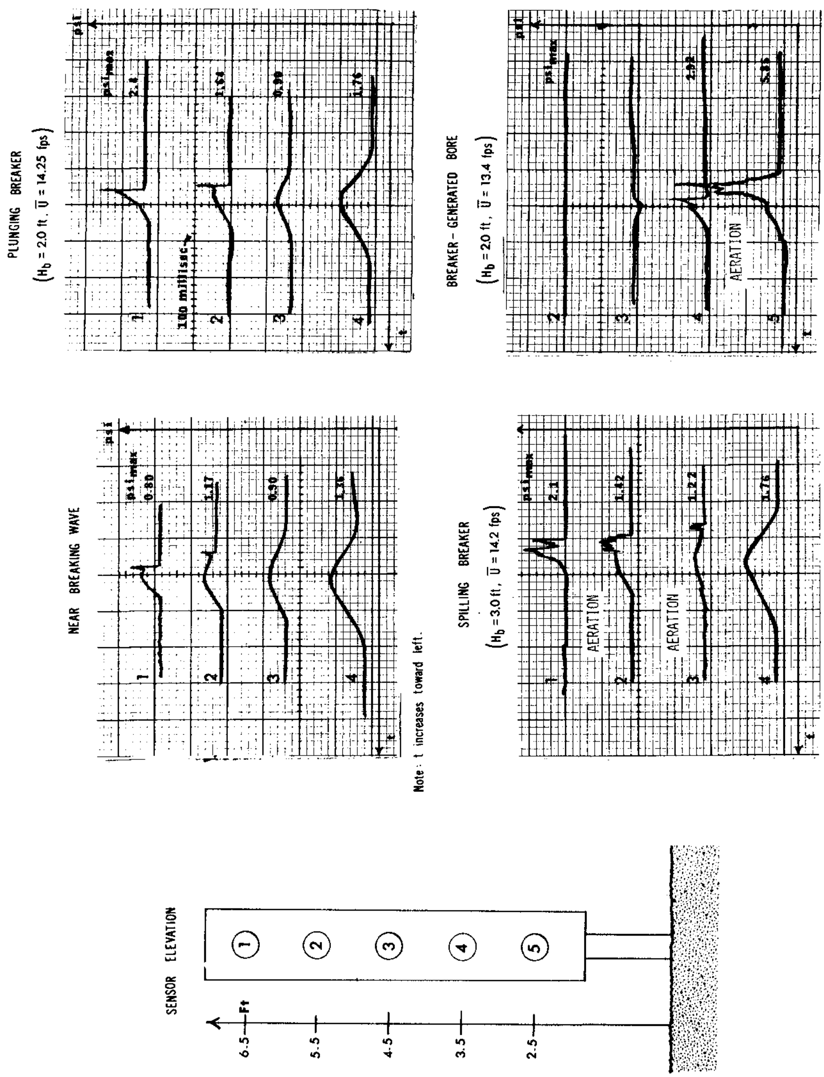

Fig. 1
OSCILLOSCOPE PRESSURE PATTERNS

In this paper, attention is focused on the "impact pressure" portion of the total force. "Impact pressure" Wiegel (1964), Weggel, (1968), refers to the impact of the free surface of a translatory mass of water against a rigid surface. These pressures are distinguished by relatively large magnitude and short duration. The phenomenon is also referred to as "shock pressure" but in this paper the less ambiguous term, "impact pressure" will be used.

Impact pressures have been investigated extensively in the laboratory. These include Bagnold (1939), Denny (1951), Ross (1955), Hayashi and Hattori (1958), Nagai (1960) and Weggel (1968) among others.

Full scale studies in the field are notably lacking. The well-known work of Gaillard (1904) and Molitor (1934) did not include sensing devices capable of recording the transient, high magnitude signals associated with impact pressures. As far as we know, the only published data on full scale impact pressures at several points along a vertical gradient, is that of Rouville, Besson, and Petry (1938) at Dieppe. A field study reported by Morison, Johnson, and O'Brien (1954) recorded the total force exerted by breaking waves on a pile. Although outside the scope of the present study, their paper contains relevant results and is referred to later.

An examination of the above literature indicated wide disagreement in the interpretation of results and a serious lack of field data. Accordingly a field program was planned with the following aims: 1. To measure impact pressures generated by full-scale breakers under field conditions. 2. To obtain a vertical gradient by using an array of simultaneously recording sensors, whose exposed faces are small relative to wave height. 3. To identify and record the breaker types generating the impact as the data is taken. 4. To compare the results with published laboratory and field data. 5. To eliminate any effect due to the Bagnold air cushion which has been observed only in laboratory channels with confining sidewalls.

THE EXPERIMENTAL DESIGN

A. Choice of field site. The outer shore of Cape Cod proved to be an ideal location. The summer topography consists of a rather steep foreshore with an extensive tide-flat of approximately 1° - 3° slope exposed at low tide by the 10-12 feet tide range. The typical sea-state in August consists of regular swell with periods of the order of 8 seconds. High frequency secondary waves due to local wind are usually absent.

B. Strategy. The sensor system was emplaced at low tide on the exposed flat. Figure 2 illustrates structural details of the system. A 10 ft. vertical pipe fastened to the top of the cylinder served to keep the conducting cables high above the surf and splash. The conducting cables, which were used for power in and signal back, were then carried horizontally through the air to the beach area.

As the tide began to rise, the first impact pressures were generated by bores created by waves breaking seaward of the sensor system. As the tide continued to rise, the sensing system received the impact of plunging or spilling breakers. Finally at high tide, forces due to a series of near breaking waves were recorded by the sensor system. On the falling tide the reverse sequence occurred. In this way it was possible to get two complete sets of data per tide cycle.

C. The sensing and recording system. The basic support structure consisted of a 6 ft. aluminum cylinder. A portion of the curvature of the cylinder was removed down the full length and an aluminum flat face clamped on as shown in figure 2. At 1 ft. intervals along the vertical length of the flat, two inch diameter openings were cut. A thin aluminum disc was then clamped over each opening, to serve as an impact sensor in the form of a strain-gage mounted diaphragm. Calibration of the strain-gage mounted diaphragm-amplifier unit was accomplished by static loading. Dynamic calibration was also carried out. Details are given in Tech. Rept. no. 14, 1974, Miller et al.

The water-tight cylinder contained the required wiring, strain gage amplification and associated electronics. The structure was supported by three turnbuckle-tightened cables leading from anchors buried in the sand flat. The base was supported by a steel rod driven 3 feet into the sand. The resulting structure offered a rigid, stable, support for the vertical array of sensors.

Signals passed through the conducting cable to the shore to be recorded by a 4-channel oscilloscope with polaroid camera attachment. A switching box enabled us to monitor 4 of the 5 sensors simultaneously. Power was supplied by a 5 KW portable generator.

For each recorded breaker, an observer noted 1) the elapsed time for the wave to travel from a staff 50 ft. seaward, to the sensor system; 2) the breaker height using a scale painted on the cylinder and 3) the breaker type.

RESULTS

The oscilloscope records are illustrated in figure 1. Simultaneous traces from four sensors are shown for a single wave. Each trace is identified by a number corresponding to a particular sensor

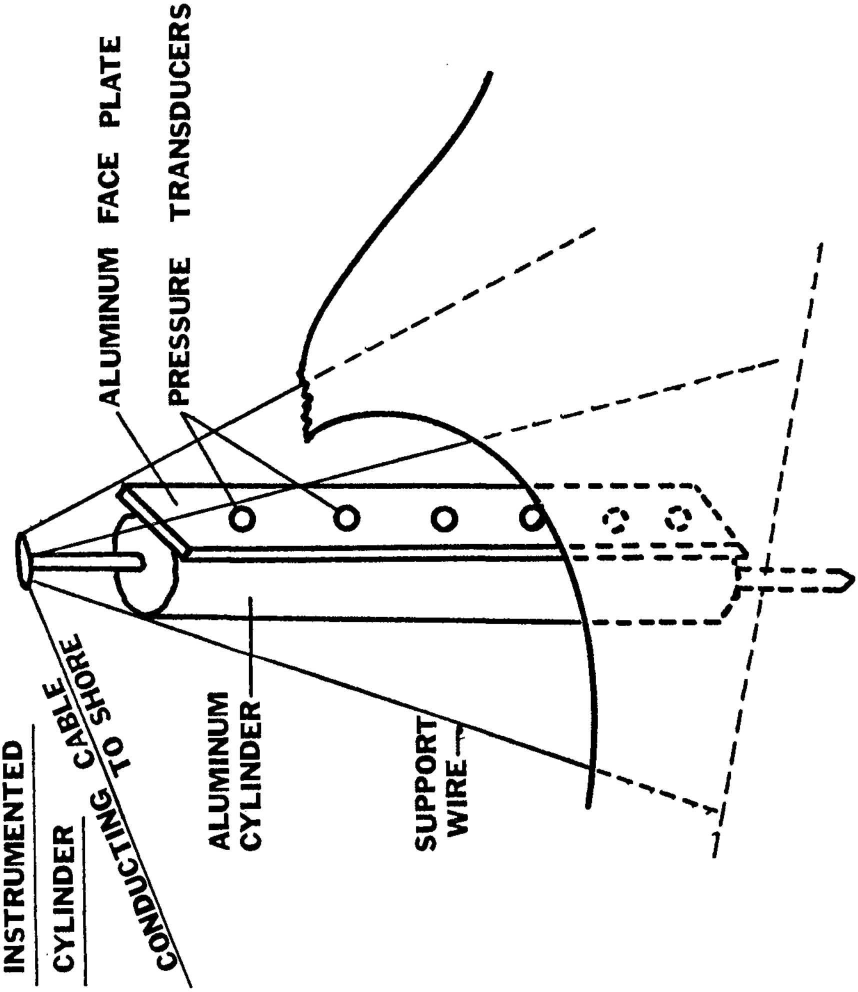
INSTRUMENTED CYLINDER
CABLE CONDUCTING TO SHORE
ALUMINUM FACE PLATE
PRESSURE TRANSDUCERS
ALUMINUM CYLINDER
SUPPORT WIRE

Fig. 2

whose position above the bottom is indicated at the left. Time is read from right to left. Typical records were selected, one for each of the breaker types. Although the magnitudes vary, the shape of the traces are repeated with little variation for other waves within each breaker type category. It thus appears that the pressure-time trace is a diagnostic property.

1. Near breaking wave. Impact pressure consists of a small but distinct single "spike" confined to the upper portion of the vertical gradient, as the wave strikes the sensor structure. A relatively large phase lag between the first arrival of the wave at sensor 2 and the later arrival at sensor 1, reflects the wave slope at the time of impact. The local inclination of the free surface in the vicinity of the sensor face also affects the magnitude of the impact pressure. With respect to this factor, the maximum impact will occur when the free surface of the wave strikes all parts of the sensor face simultaneously. The impact pressure magnitude is less, depending upon the degree of departure from this criterion.

2. Plunging breaker. Impact pressure is relatively large and distinct, consisting of a single spike which dominates the total pattern in the upper part of the gradient. Air entrainment is not yet present in the near breaking and plunging breaker, as shown by the single distinct trace in the impact region. In contrast to the near breaking wave, the phase lag for "impact spikes" between sensor 2 and sensor 1 is much smaller, indicating a near-vertical forward face. In several of the plunging breaker records the first arrival is recorded at the upper sensor. This indicates that the traces were recorded at the early overturning stage of the front face of the plunging breaker.

3. Spilling breaker. The upper two sensors show compound partly blurred, impact pressure spikes due to the presence of significant amounts of entrained air, as is characteristic of the spilling breaker. The maximum impact pressure is recorded at the upper part of the vertical gradient, as is also the case for plunging breakers and near-breaking waves.

4. Post-breaking bore. Records at fewer sensors in the vertical array reflects the drop in height as the bore is formed from the breaking wave. Compound impact pressure spikes due to aeration are noted, as in the case of the spilling breaker. The impact pressure gradient is reversed however.

The maximum impact pressure for each breaker type is given in frequency distribution form in figure 3. Although there is insufficient data for statistical estimates of the mean and standard deviation, the available data shows a progression in average maximum impact pressure from near breaking, through spilling and plunging breakers to post-breaking bores.

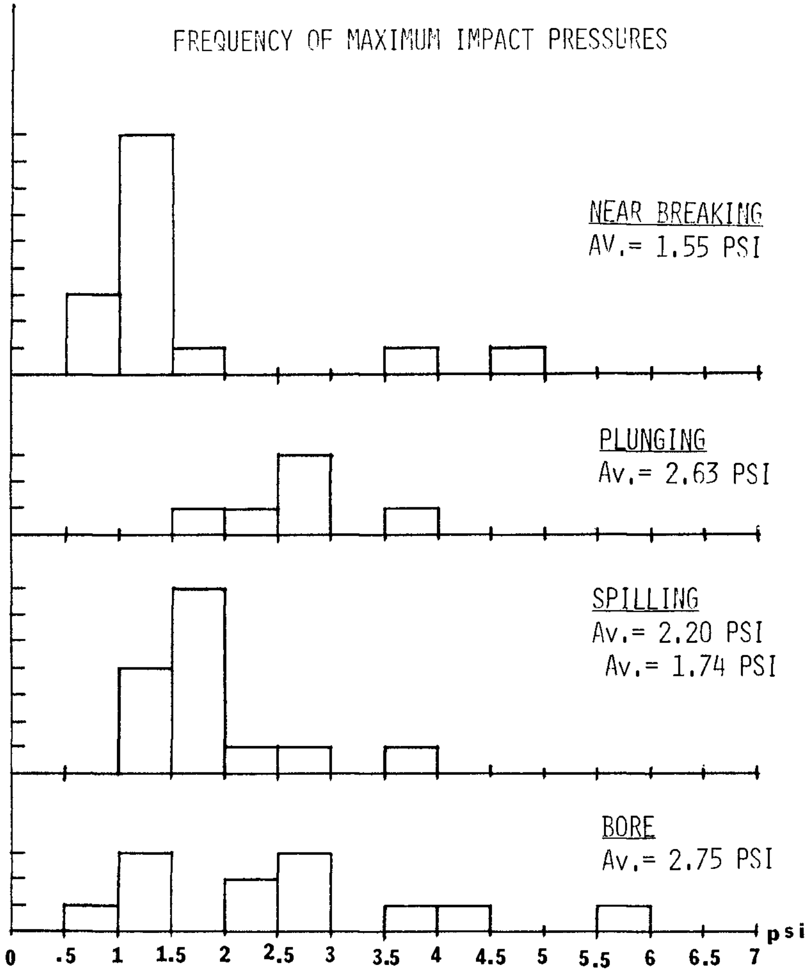
FREQUENCY OF MAXIMUM IMPACT PRESSURES
NEAR BREAKING
AV.= 1.55 PSI
PLUNGING
Av.= 2.63 PSI
SPILLING
Av.= 2.20 PSI
Av.= 1.74 PSI
BORE
Av.= 2.75 PSI
psi
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7

Fig. 3

Dynamic pressure vs. wave velocity

The dynamic pressure of waves in general may be expressed as $p/w = (f)\ U^2/2g$ where p/w is the pressure head, $U^2/2g$ is the head of the fluid at impact and f is a coefficient, w is unit weight of water and U is wave velocity. A large number of equations for both waves and breakers can be expressed in this manner by adjusting (f) to fit the particular equation. This relationship is shown by Hayashi and Hattori (1958) who list more than 10 equations published by various authors. Hayashi and Hattori present these equations rearranged in the form given above, with the appropriate value of (f). They plot p/w vs. $U^2/2g$ comparing their experimental data with a line at (f) = 4 as well as several other lines, including (f) = 2, Hiroi (1920) and others.

We have expanded their figure to include other model data and full scale field data, (figure 4) and added a line representing Bagnold's 1939 equation, $p_{max} = 0.54\ \rho U^2 H/D$, where D is the thickness of the Bagnold air cushion, and H is the crest to trough wave height. Converting to the general form, one obtains $p_{max}/w = (1.08\ H/D)\ U^2/2g$. According to Bagnold the air cushion thickness D is of the order of 0.4 (H) at maximum. It is thus possible to evaluate the coefficient (f) = (1.08 H/D), as 2.70. For comparison, a line at (f) = 10 is plotted which passes through Hayashi and Hattori's recorded laboratory data at small values of $U^2/2g$ and also through the much larger values of $U^2/2g$ calculated from the full scale Dieppe data.

The Cape Cod data for full scale breakers appear to follow the trend of $p/w = (f)\ U^2/2g$, with spilling breakers plotting roughly along the (f) = 1.6 line and plunging breakers along the (f) = 2 line. The Cape Cod bore and the Dieppe data points however do not follow the trend of $p/w = (f)U^2/2g$ at all.

Impact pressure vs. wave height

Intuitively it would appear that a simple functional relationship should exist between wave force and wave height. In this regard all available published laboratory and field data has been plotted in figure 5. The ordinate is impact pressure in units of pounds per square inch and the abscissa is breaker height (H_b) in inches. It is not clear in the solitary wave studies of Bagnold and subsequently Denny, whether the wave height is taken at near-breaking or just breaking stage.

The data points consist of laboratory or full scale magnitudes either for individual observations or averages, as indicated. Several points are derived from Bagnold (1939, fig. 21), who gives curves based on experiments which predict the time-history of pressure impulses assuming adiabatic compression of the enclosed air cushion. The maxima are plotted for three values of D, thickness of the air cushion.

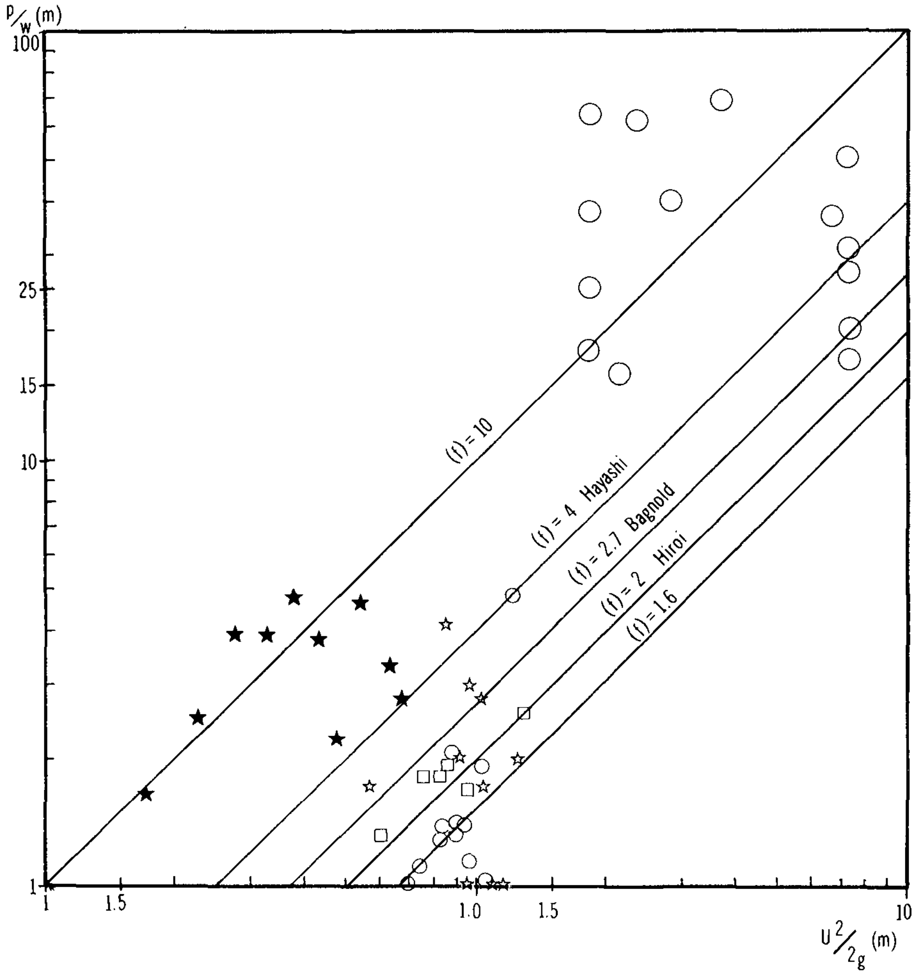

Figure 4. Dynamic pressure vs. wave velocity.

◯ Dieppe. Rouville et al.

☆ Bore
□ Plunging Breaker
○ Spilling Breaker
} Cape Cod data.

★ Lab (Solitary) Hayashi et al.

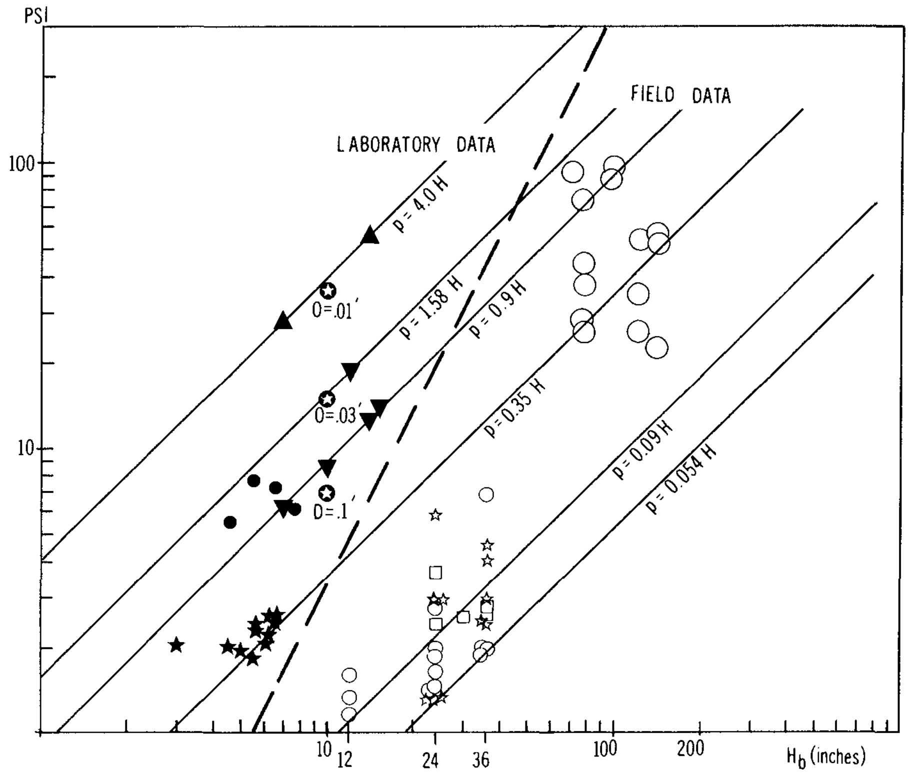

Figure 5. PSI vs. Breaker height.

Laboratory
- ● Ross (av. "First Wave")
- ▲ Denny max.
- ▼ Denny most freq. calm water
- ▼ Denny most freq. disturbed water
- ★ Nagai
- ✪ Bagnold

Field
- ◯ Dieppe
- ☆ Bore
- □ Plunging Breaker
- ○ Spilling Breaker

} Cape Cod data.

In addition to the various data points, several lines of the form $p = (K\gamma)H$ are shown, where K is a numerical coefficient and γ is the unit weight of water. Hiroi (1920) was the first to propose this simple linear equation in the form $p = 1.5\gamma H$ or PSI = 0.054 H (inches). The upper three lines are due to Denny and are based on empirical fit to very large numbers of experimented results. The line PSI = $0.09H_b$ is an empirical fit to the Dieppe data.

It can be seen that the full scale field data gives much lower values for impact pressure than would be expected from the model studies. The suitability of a single linear equation for H vs. p seems also open to question. These points will be covered in the discussion section.

DISCUSSION

Morison, Johnson and O'Brien (1954) conducted a field study in which breakers are distinguished from near breaking waves and from the breaker generated bore. They measured wave forces on a 3½ inch pile hinged at the base. A plot of wave height vs. wave force indicates that for given height the magnitude of the force is correlated with the wave or breaker type. These are arranged in decreasing order with respect to wave force.

Designation by Morison, et al.	Probable Breaker Type according to Miller et al.	Comment
"Foam line"	Bore	greatest forces recorded
"Breaker with some foam"	Bore?	
"Breaker"	Plunging Breaker	magnitudes overlap with bores
"Sharp peak swell starting to break"	Spilling Breaker	magnitudes overlap with plunging breakers
"Sharp peak swell"	near breaking wave	lowest forces recorded

Wiegel (1964) commenting on the field data of Morison et al and also on laboratory observations notes that "the forces exerted on a pile by a 'foam line' of a certain height were considerably higher than the forces for a breaking wave of the same height."

Although our field data is recorded at individual points in a vertical gradient rather than for an entire piling, the results are strikingly similar to those of Morison et al, in one respect. The same progression in magnitude vs. wave or breaker type was found in our field experiments, as shown in figures 2 and 3. We have attempted a qualitative interpretation of breaker mechanics.

I. Post-breaker bores

On the average the bore appears to generate the highest impact pressure but the data shows a wide scatter. The vertical distribution of impact pressures is consistently maximum at the lowest sensor, decreasing upward.

A. Bore generated by plunging breaker

The abrupt collapse of the plunging breaker is accompanied by a sharp decrease in height and significant increase in celerity. The new wave-form is that of a bore. The large scale vortices and associated air entrainment results in a rapid dissipation of the initial energy of the bore. However, the impact pressure is recorded just after generation. It is reasonable to expect a higher impact pressure than in the parent plunging breaker. The form of the bore typically consists of a steep face and flat top . The horizontal velocity of water particles in the vicinity of the entire front face is at or near that of the bore velocity. The upper portion of the face consists of a turbulent mixture of air and water containing as high as 20-30% air bubbles per unit volume. Miller 1972, Fuhrboter (1970). The base of the bore-face contains little or no air bubbles. The difference in local density leads to significantly higher momentum at the lower portion of the bore face. The net result is maximum impact pressures at the base of the bore.

B. Bore generated by Spilling breaker

The spilling breaker also transforms into a bore during the gradual decrease in wave height after breaking. Since the spilling breaker is characterized by initial small scale breaking just at the crest, it is some time before the fully developed bore is generated. The slow loss in wave height is accompanied by energy dissipation at such a rate that the celerity does not show abrupt or significant increase over that of the initial spilling breaker. The maximum impact pressure is at the base of the front face, as in all bores.

The preceding discussion leads to an expectation of:

1. Maximum impact pressure at the lowest recording sensor.

2. A wide variation in impact pressure magnitudes but with maximum values higher than those due to plunging or spilling breakers.

II. Plunging breaker

The plunging breaker may result in relatively high impact pressures due to the following:

1. The free surface has not yet begun the process of air entrainment, thus the mass per unit volume of the moving fluid is that of water.

2. During the early stages of breaking a large portion of the face is essentially vertical, and may impact simultaneously over the area of the sensor. The water particle velocity in the upper portion of the face is close to that of the wave velocity. This leads to high values in the middle or top of the instrument array.

3. The jet-like overturning crest may impact the uppermost sensor leading to large values at the top of the instrumented section.

Spilling breaker

The initial celerity of the spilling breaker is not significantly different than that of the plunging breaker. The breaking process begins in a small region at the crest, and expands gradually as the wave subsides, thus the steep to vertical front face so characteristic of the plunging wave does not develop on a large scale. Consistent with this, the fluid particle velocity is equal to that of the wave velocity, only in the vicinity of the crest. Since the free surface does not impact the full sensor face simultaneously, the expectation is that the impact pressures will be less than those of the plunging breaker, and will be similar in magnitude to those due to the near-breaking wave.

The vertical distribution of impact forces is presented in summary in figure 6. Two graphs are given for each of three categories: Bore, Plunging breaker and Spilling breaker. The ordinate indicates the sensor position. One graph presents results for three simultaneously recording sensors, and one graph presents results for two simultaneously recording sensors. The abscissa gives the ratio of the observed impact pressure to the maximum observed for a given wave. The patterns show consistent maximum at the lowest sensor for bores, and the reverse for spilling and plunging breakers. One additional pattern found in both plunging and spilling breaker data shows the maximum at the middle of the gradient. To facilitate comparisons a straight line connects average values, by sensor level.

The Dieppe data (Rouville et al) represents the only available field data recorded in a manner similar to ours, although it is for much larger breakers. Although Rouville et al did not indicate breaker shape, it is striking to note that with the exception of two runs, all of their data fit the bore pattern, with maximum value at the lowest sensor. This leads to the inference that most of the Dieppe data for exceptionally large impact pressures, was generated by bores from waves breaking just seaward of the sea wall.

Nagai (1960) carried out model studies and developed empirical predictions for maximum impact pressure based on consideration of breakwater shape, changes in wave height, and incident wave steepness. He

Fig. 6

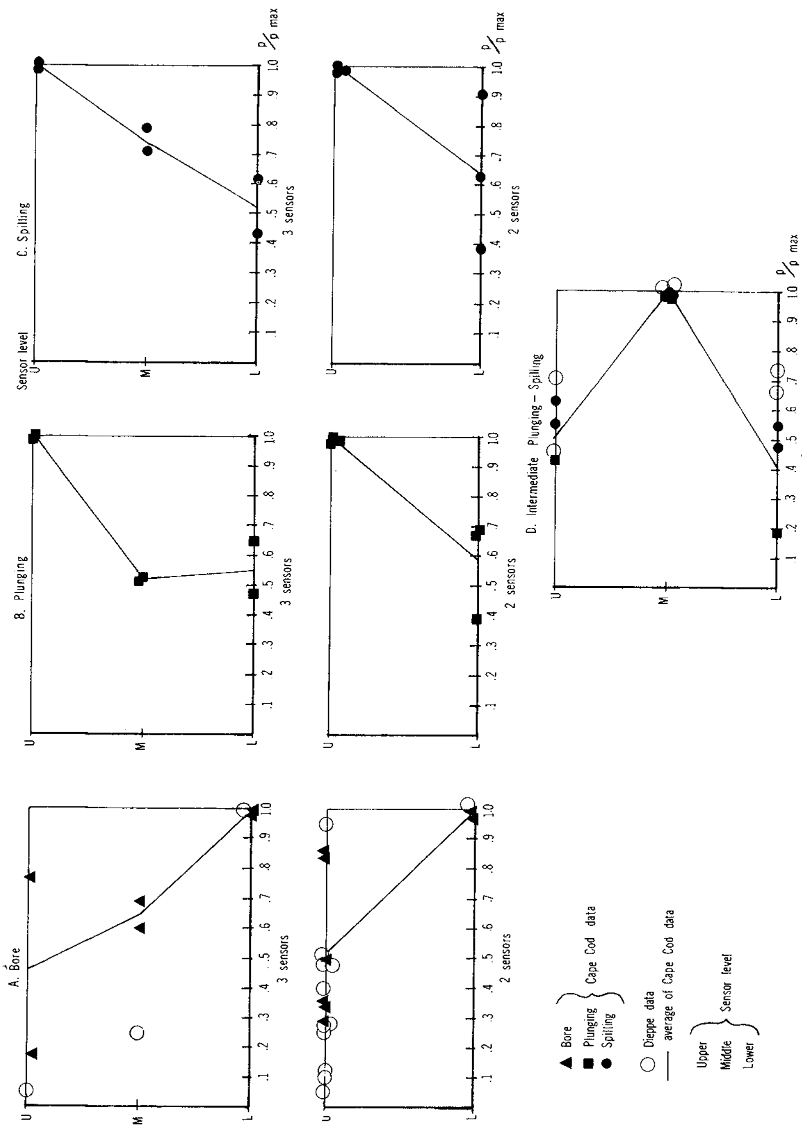

Figure 6. Vertical distribution of impact pressure.

fits predicted impact pressures to the Dieppe data with some success. Although he does not consider breaker shape explicitly, his "Type C" is suggestive of the post-breaker bore.

The evidence accumulated in figure 5 indicates that a single linear equation for impact pressure as a function of wave or breaker height is insufficient to yield reliable predictions. Bagnold (1939) observed that linear scaling of his model study results gave full-scale values more than ten times too high when compared with the Dieppe field data. Our Cape Cod data also plotted in figure 5 shows the same effect. He attributed the discrepancy to rarity of occurrence of the air pocket, irregularity of the surface of waves in nature, and most importantly to the presence of air in the water -- "the ultimate limit to the intensity of shock pressures .... is set by the quantity of air locked in and on the surface of the wave before impact." Denny (1951) draws similar conclusions but his experiments stress that a disturbed free surface will result in lower impact pressures, as shown in figure 5. Weggel (1968) also stresses the importance of air in the mechanics of wave impact.

We feel that the explanations given above are all valid, but the key lies in recognizing that different breaker types give different impact pressures. Air entrainment is insignificant in the near breaking and early plunging wave, but the degree to which the free surface is irregular, is important. On the other hand air entrainment is of great significance in the spilling breaker and post-breaker bore. Furthermore, the vertical distribution of impact loading for these two breaker types is significantly dependent on the vertical distribution of air in the water.

Figure 4 gives some evidence that recognition of breaker types may lead to a family of prediction equations of the general form $p/w = (f)U^2/2g$ as discussed earlier. Collection of large numbers of field observations of impact pressures for the various breaker types is needed before reliable prediction equations can be devised.

CONCLUSIONS

I. Full scale data taken at Cape Cod support the initial premise that the nature and magnitude of impact pressure is directly related to breaker shape. Analysis of published studies support this conclusion.

a. The strong bore formed just after the collapse of the plunging breaker generates the largest impact pressures. Weak bores generated by spilling breakers on the other hand, do not generate large impact pressures. This results in a wide scatter of data for this breaker type.

b. The maximum impact pressure in the vertical gradient is at the base of the bore.

c. The next largest impact pressures are due to plunging breakers, but the gradient is reversed, with maximum at the top.

d. The spilling breaker is similar in vertical gradient, but smaller in magnitude.

e. Although the near-breaking wave generates the smallest impact pressures, impact "spikes" are noted when the wave surface strikes the sensor face.

II. The role of entrained air and of the angle of impact of the free surface, are reasonably explained when breaker shapes are taken into account.

III. Typical time-pressure patterns were found to characterize the various breaker types. Thus the time-pressure pattern is a diagnostic property.

IV. Extreme shock pressure due to entrapped air did not occur. In view of the geometry of our sensor structure, these pressures were not expected. We feel that confining sidewalls as in the laboratory studies of Bagnold and of Denny or in full scale waves striking an I beam, Wiegel, Beebe and Moon (1957) are required before the Bagnold air pocket phenomenon can occur.

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