DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

LABORATORY STUDY OF SHOCK PRESSURES OF BREAKING WAVES

TECHNICAL MEMORANDUM NO. 59

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FOREWORD

The design of structures to withstand wave action calls for a knowledge of the forces which may be expected on the structures. The wave forces may generally be considered as of two kinds: that due to hydrostatic pressure and that due to shock pressure. Unfortunately very little is known about the latter, either as to magnitude or duration. This report deals with a study of shock pressures caused by laboratory waves based on research done in the laboratory of the Beach Erosion Board.

Culbertson W. Ross, author of the report, is a Hydraulic Engineer in the Research Division of the Beach Erosion Board and under the supervision of Joseph M. Caldwell, Chief of the Division. At the time this report was prepared, the technical staff of the Board was under the general supervision of Colonel W. P. Trower, President of the Board; Colonel E. A. Hansen, Resident Member; and R. O. Eaton, Chief Technical Assistant. The report was edited by A. C. Rayner, Chief, Project Development Division. Views and conclusions stated in this report are not necessarily those of the Beach Erosion Board.

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LABORATORY STUDY OF SHOCK PRESSURES OF BREAKING WAVES

by
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INTRODUCTION

In attempting a rational design of marine structures, it is important to know the forces which the structures will be called upon to resist. Waves breaking against structures or rocks frequently throw water high in the air. A pressure of about one-half pound per square inch is indicated for each foot of height to which the water is projected.

Pressures as great as 100 psi (pounds per square inch) caused by waves breaking on a structure at Dieppe, France, were observed by Rouville, Besson and Petry(1)*. Bagnold(2) has observed pressures as high as 80 psi caused by 10-inch waves in a wave tank.

The Beach Erosion Board, being especially interested in the subject of wave pressures on shore structures, has continued studies of the pressures caused by breaking waves. The Board's study was designed to investigate the high-intensity shock pressures on the structures as contrasted to the much smaller hydrostatic pressures developed by the rise of the wave against the face of the structure.

APPARATUS

Tests were made in a wave tank 96 feet long, 2 feet deep, and 1.5 feet wide. A 24-foot section at the end farthest from the wave generator has glass walls which make it possible to observe and photograph the breaking waves.

Waves were generated by a wave machine of the moving bulkhead type (Figure 1). The bulkhead was caused to move by a crank wheel and connecting rod. The speed of rotation of the wheel could be varied to produce waves with periods from 1 to 5 seconds. The length of the crank arm was variable in 1/2-inch steps from 2 to 11 inches to generate waves of various heights.

* Numbers in parentheses refer to references on page 22.

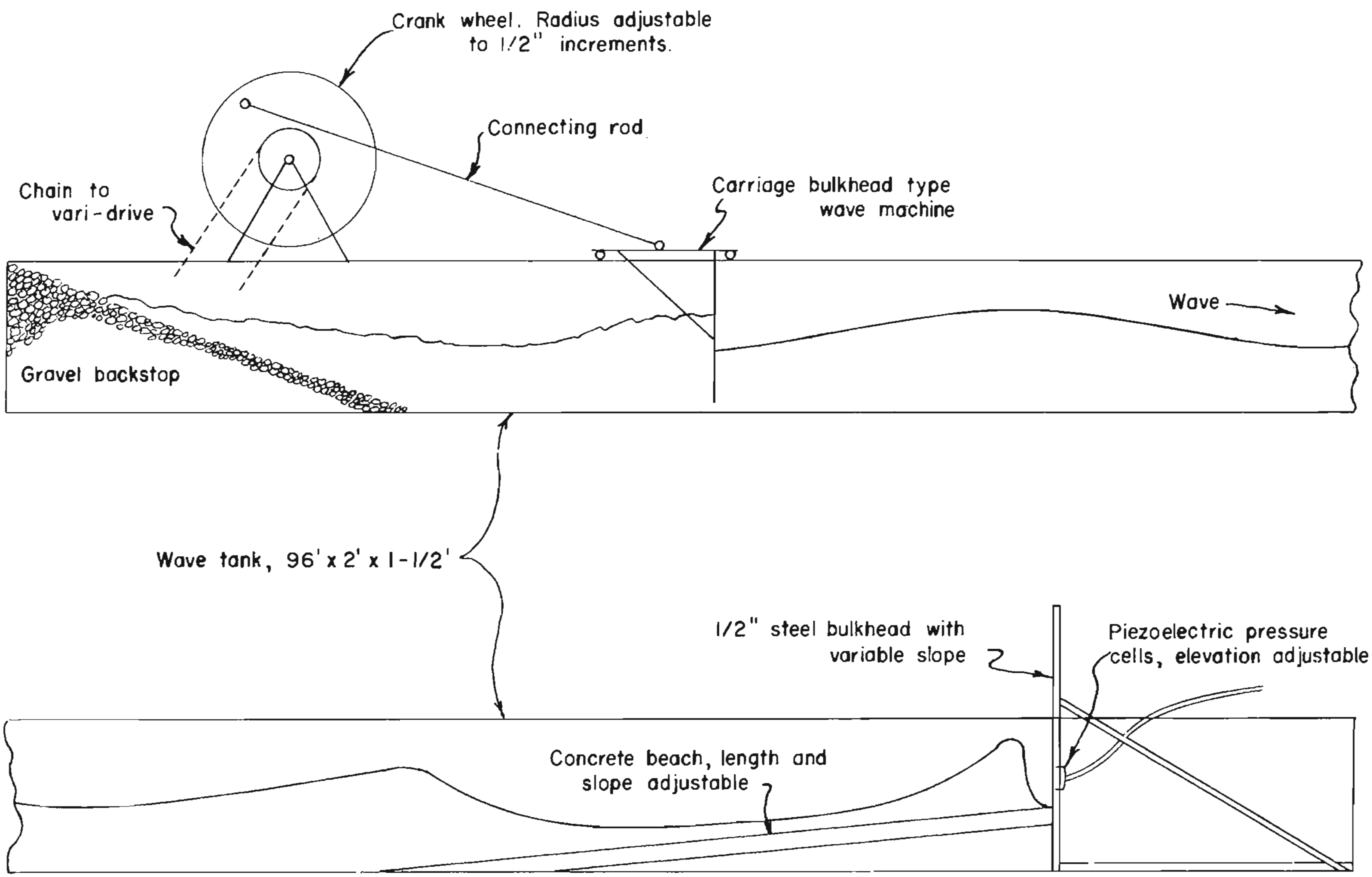

FIGURE 1 DIAGRAM OF WAVE TANK

The bulkhead representing the vertical structure against which the waves were to break consisted of two 1/2-inch steel plates. A pressure cell was mounted in each plate. The plates were mounted on a steel frame and could be raised or lowered to change the vertical position of the cells. The sensitive surface of the cells was flush with the surface of the plates. The cells were 9 inches apart horizontally. Only one pressure cell was used for part of the tests, as difficulties were encountered at first in keeping the cells in operating condition.

Waves were caused to break by placing concrete slabs to form a beach in front of the bulkhead. The height of the beach at the bulkhead was 10 inches above the bottom of the wave tank. Various beach slopes from 0.078 (1 on 13) to 0.176 (1 on 5.5) were used. A diagram of the wave tank, wave machine and bulkhead with pressure cells is shown in Figure 1.

A recording wave gage, usually located about 30 feet in front of the bulkhead, was used to give a time profile of the waves when desired.

The pressure sensitive element of the pressure cells consists of a stack of four thin discs of tourmaline crystal (Figure 2)(3). This material is sensitive to hydrostatic pressure changes, whereas quartz requires that the pressure be on two surfaces only. A small charge of electricity is produced between the two sides of the plate when the plate is subjected to a change of hydrostatic pressure (piezoelectric effect). The flat surfaces of the plates are covered with a conducting material to collect the charge of electricity produced at the surface of the plates. Sides with similar polarity are connected together and to the leads of the cell; the sides of opposite polarity are insulated from each other. The pile of plates is set in and backed by a strong metal case, one surface of the pile being separated from the water and wave action by only thin layers of wax, rubber and shellac. The possibility of spurious signals caused by resonance or by loss of sensitivity in connecting parts is greatly reduced by the simple and strong construction of the cells.

The pressure cells produce approximately 34 micro-micro-coulombs of electricity for a change of pressure of one pound per square inch. The voltage produced depends on the capacity of the cell, leads and output circuit and was about 0.05 volt per pound per square inch change in pressure for the arrangement used. The time that the voltage will be maintained depends on the resistance of the insulation of the cell, leads, and output circuit. The leakage resistance should be on the order of 1,000 megohms to prevent the charge leaking away too quickly. The drop in voltage is computed from the formula

$$E = E_o \ e^{-\frac{t}{CR}}$$

in which

- t is time in seconds,
- E is potential in volts at time t,
- E_o is potential in volts at time zero,
- R is leakage resistance in ohms,
- C is capacity in farads, and
- e is the base of natural logarithms.

The value of C for the arrangement used was about 7×10^{-10} farads. Thus for 1,000 megohms resistance, the voltage would drop to 14 percent of its original value in 1/10 second.

The voltage generated by the pile is carried by coaxial cable to the grid of an electronic tube which is biased to draw no current (cathode follower circuit). The output of the electronic tube goes to an oscilloscope. The oscilloscope used in these tests had an input resistance of 2 megohms. The arrangement of the apparatus is shown schematically in Figure 2.

The two pressure cells were used with a dual channel oscilloscope, enabling simultaneous recording of the two pile signals on the same photographic plate. One of the vertical amplifiers was of the AC type and the other of the DC type. The sweep of the oscilloscope was triggered by the signal from the piles, thereby preventing exposure of the film until the pressure signal entered the oscillograph.

In practice, the circuit was improved by adding a separate and more positive-acting trigger circuit giving single sweeps of the beam and manual reset. Also added were two delay lines which delayed the signal about 4 micro-seconds, insuring a delay of the start of the rise of the pressure signal until the beam sweep of the oscillograph had been activated.

The traces of the oscilloscope were recorded frame by frame on 35-millimeter film. The film was loaded in the camera in 100-foot rolls and the film was advanced manually by a lever for each exposure. The camera used has a f 1.5 lens which allows very rapid trace sweeps to be photographed. The traces could be viewed through an auxiliary eyepiece while being photographed.

In addition to the film records of the oscillograph traces, three films of waves breaking against a vertical wall were taken with a high speed motion picture camera on 16-millimeter film. Film speeds from 400 to 600 frames per second were used.

CALIBRATION OF PRESSURE-RECORDING APPARATUS

The cells and recording apparatus were calibrated by placing the cells in a small chamber and releasing air pressure by the breaking of a diaphragm or the expulsion of a cork (Figure 2). The first method released the pressure in about 1/10,000 second and the other in about 1/1,000 second. The electric charge produced by tourmaline is linear

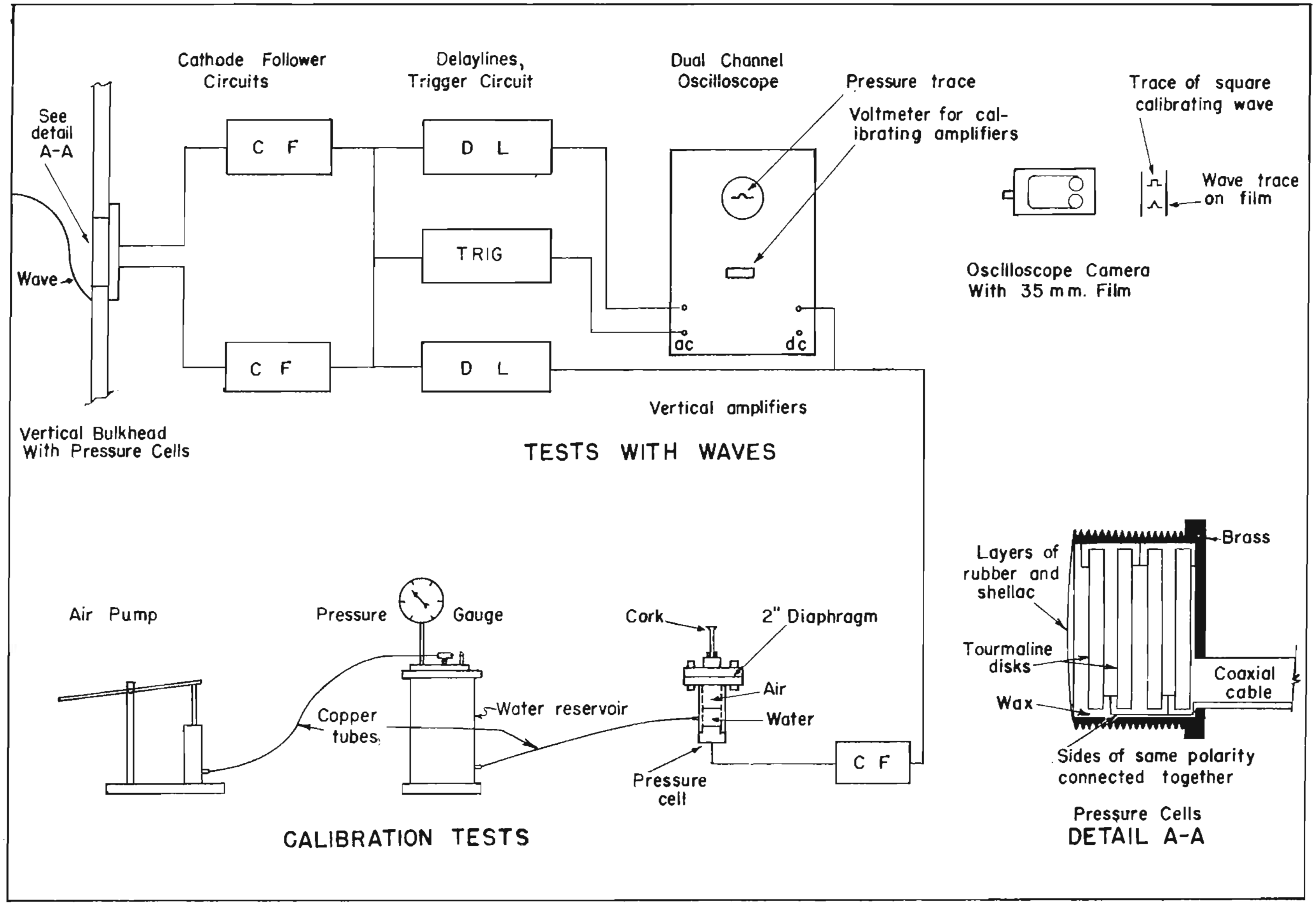

FIGURE 2 · PATH OF SIGNAL FOR WAVE AND CALIBRATION TESTS with changing pressure so the calibration obtained through release of pressure may be used to measure the increase of pressure produced by the breaking waves.

The portion of the calibration diaphragms exposed to the pressure was 2 inches in diameter. Diaphragms of steel and bronze with thicknesses of 0.001 or 0.002 inch ruptured at from 20 to 70 pounds per square inch. Diaphragms of cellophane gave sharp breaks at pressures of from 5 to 15 pounds per square inch.

The data from the calibration tests of one of the pressure cells are shown on Figure 3. The oscilloscope traces from two calibration tests are shown in Figure 4 (A and B).

The response of the amplifiers of the oscilloscope was checked by applying voltages at various frequencies and measuring the height of the traces. The sensitivity of the DC vertical amplifier is about 33 inches per volt (RMS) at 20 cycles per second and drops linearly to 60 percent of this value at 200,000 cycles per second. The sensitivity of the AC amplifier is about 40 inches per volt (RMS) at 20 cycles per second and drops linearly to about 90 percent of this value at 1,000,000 cycles per second.

TYPES OF BREAKING WAVES

Three types of wave conditions were used in the tests.

First Waves. The size of the first wave formed by the wave generator varies with the starting position of the crank wheel. The second wave was caused to break at a point to give impact pressure on the bulkhead containing the pressure cells by selecting the starting point of the crank wheel so that the back wash of the first wave caused the second wave to break in the desired position. Following waves usually do not produce impact pressure.

Early Waves. Waves starting with the second full-sized wave and ending with roughly the tenth are called early waves. These waves were caused to break in proper position by adjustment of the water depth. At the correct water depth, the backwash of the preceding wave is such as to cause each wave to break in a position to give impact pressure.

Late Waves. The size of the wave generated by the wave machine depends on the water depth. After the waves reflected from the bulkhead reach the wave machine, the size of the waves generated varies with the phase of the reflected wave at the wave machine; occasionally one of these later waves will break in a position to give impact pressure.

The first two conditions are reproducible and are reliable pressure producers. However, slight variations of the wave height or period or water depth cause the waves to break too early or too late to produce

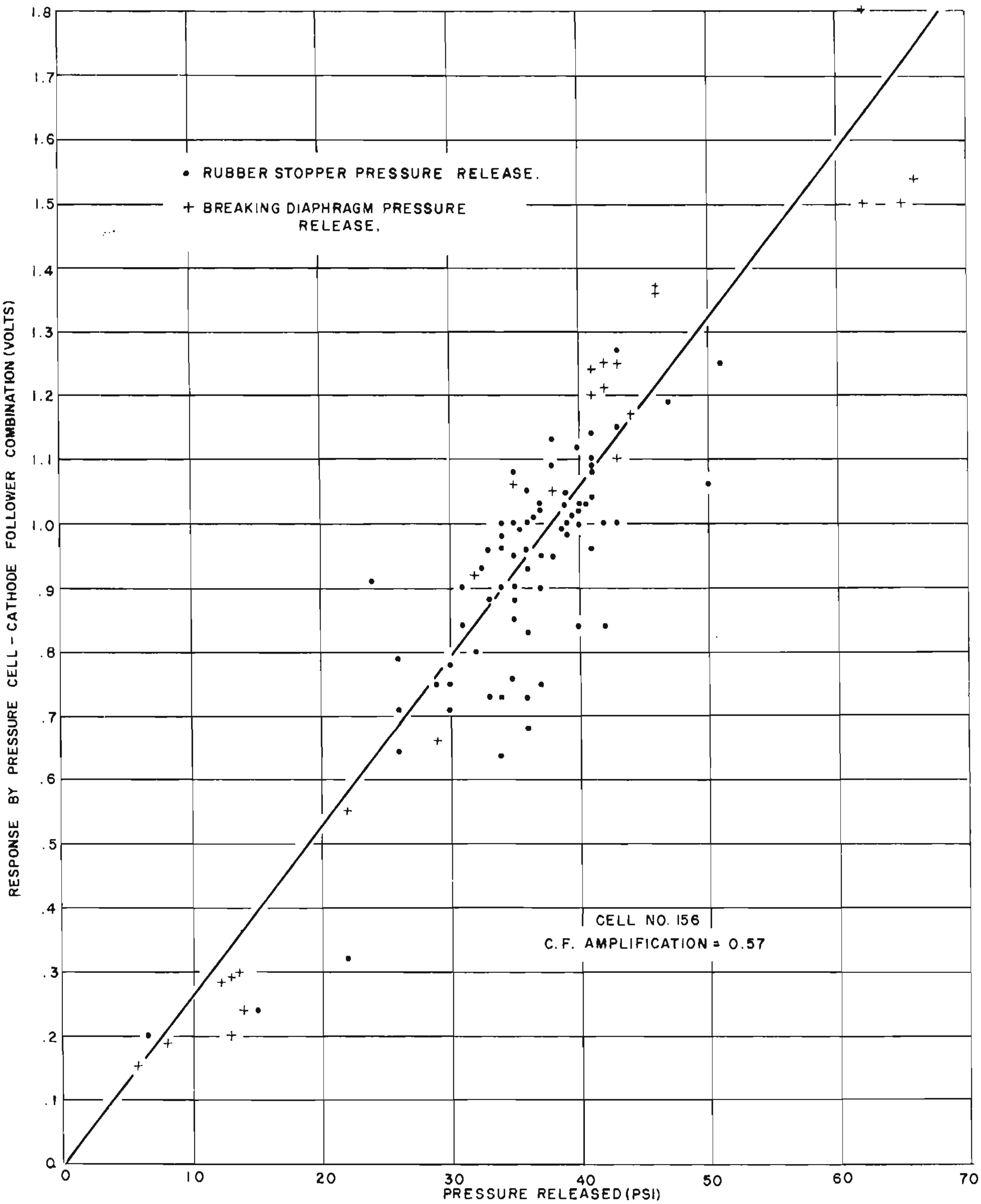

FIGURE 3 CALIBRATION OF PRESSURE CELL WITH CATHODE FOLLOWER

FIGURE 4 - OSCILLOSCOPE TRACES

A. Photographs of the oscilloscope traces representing release of 43-psi pressure by the rupture of a 2-inch diaphragm of 0.001-inch steel.

There are two traces from one pressure cell, one being through the D.C. amplifier and the other through a delay line and the A.C. amplifier. The delay line inverts one trace with respect to the other. The sweep time was 1/720 second. It is difficult to release pressure quickly without oscillations. These may be noted in the traces.

B. Oscilloscope traces representing release of 36-psi pressure by the expulsion of a cork.

The sweep time is 1/14 second. The pressure release occurred in slightly more than 0.001 second. The traces indicate the error caused by the loss of the signal with time. The D. C. amplifier trace falls only about 6 percent in 1/14 second. This drop is caused by the loss of charge through the insulation of the cell and leads. The A.C. amplifier holds the signal for only about 1/60 second with a similar loss of signal.

C. Oscilloscope trace representing a pressure of 13.2 psi, observation No. 25 in Table 1. The sweep time is 1/60 second.

The trace of the square wave used to calibrate the amplifiers is also present. The voltage represented by the wave can be found by comparison with the scale of the calibrating wave. A comparison with the results of the calibration tests then indicates the pressure caused by the wave in psi.

D. Oscilloscope traces of pressures of breaking waves.

The higher trace is from observation No. 8 in Table 1. The larger trace represents a pressure of 13.5 psi and the smaller a pressure of 2.4 psi. The pressure-time integrals are the same however, 0.011 psi-second. The sweep time is 1/120 second.

E. Trace representing a pressure of 18.9 psi, observation No. 39 in Table 1. The sweep time is 1/60 second.

F. Two pressure traces representing pressures of 8.5 and 4.9 psi, observation No. 47 in Table 1. The pressure cells were at different elevations. The sweep time was 1/60 second.

G. Pressure traces representing pressures of 6.3 and 6.5 psi, observation No. 51 in Table 1. The sweep time is 1/60 second.

H. Pressure traces representing pressures of 6.3 and 5.5 psi, observation No. 55 in Table 1. The sweep time is 1/60 second.

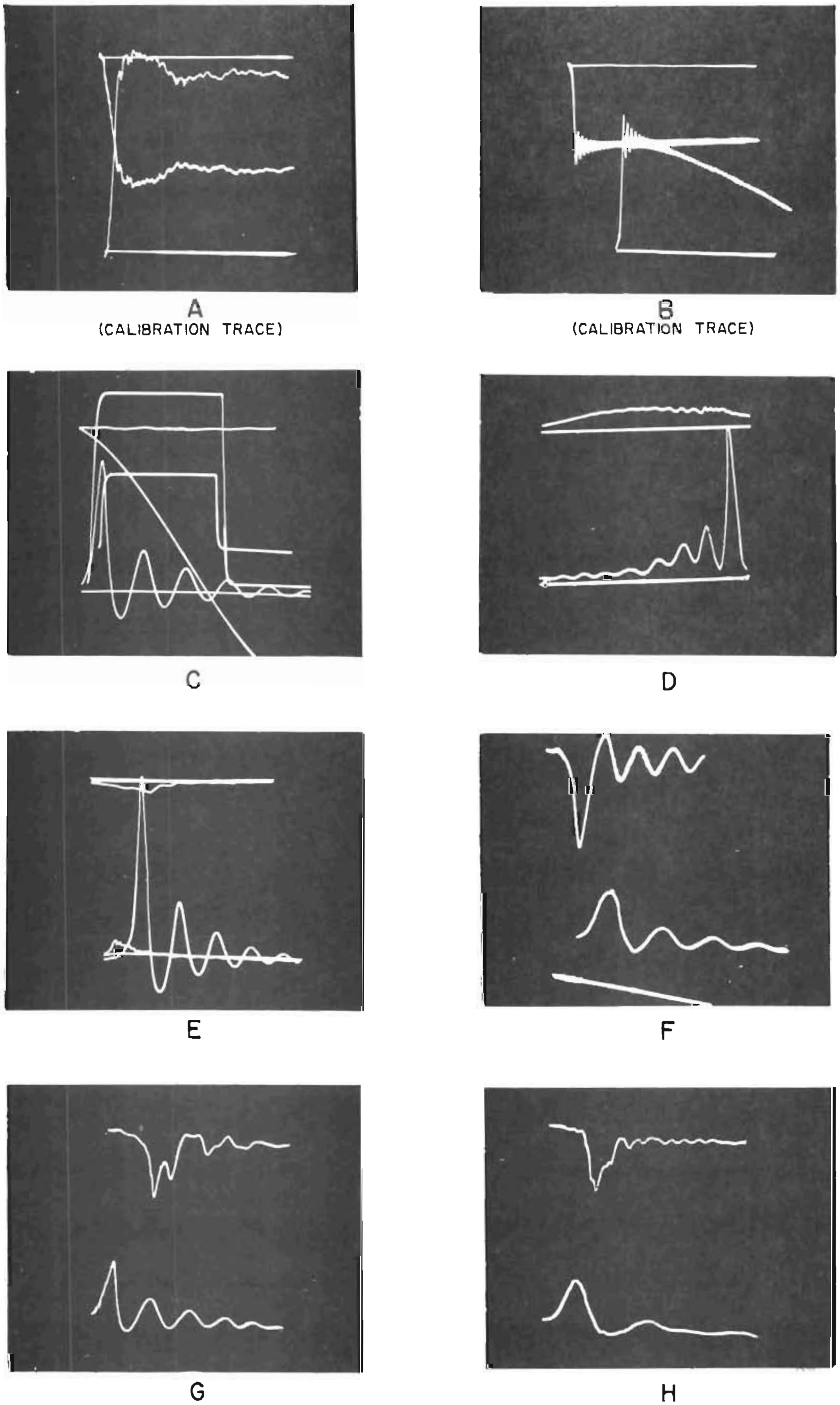

FIGURE 4 OSCILLOSCOPE TRACES

TABLE 1
SELECTED SHOCK PRESSURE OBSERVATIONS

Obs. No.	Wave Period sec.	Stroke Of crank in.	Still Water Depth in.	Pres. cell Height in.	Approx. Wave Height in.	Type of Wave	Beach Slope	Max. Pres. psi	Pres. Time Integral psi-sec
1	3.5	4	12.4	14.5	4.0	E	0.094	5.9	0.0078
2	4.0	4	13.0	12.9	4.0	L	0.094	4.2	0.0064
				14.5				9.1	0.0142
3	4.0	4.5	13.2	13.4	4.0	L	0.176	9.0	0.0132
4	4.0	5	13.4	12.9	4.0	E	0.094	10.6	0.0098
5	4.0	5	14.0	14.5	4.5	L	0.094	10.1	0.0130
6	4.0	5	12.7	15.0	4.0	L	0.078	7.0	0.0057
7	5.0	5	12.6	14.5	4.0	E	0.094	7.5	0.0083
8	4.0	5.5	12.2	13.4	4.5	L	0.176	13.5	0.0110
9	4.0	5.5	13.8	14.5	4.5	L	0.094	8.3	0.0150
10	3.0	6	13.4	12.9	5.0	L	0.094	10.4	0.0100
11	4.0	6	14.0	14.5	5.0	E	0.094	10.0	0.0114
12	4.0	6	13.0	14.5	5.0	E	0.094	12.2	0.0099
13	4.0	6	13.4	12.9	5.0	L	0.094	21.4	0.0114
14	5.0	6	13.0	14.5	3.5	L	0.094	10.4	0.0190
15	5.0	6	13.1	14.5	3.5	L	0.094	7.2	0.0182
16	4.0	7	14.0	12.9	5.5	L	0.094	15.7	0.0165
17	4.0	7	14.0	12.9	5.5	L	0.094	6.1	0.0129
18	4.0	7	14.2	13.3	5.5	E	0.144	14.6	0.0147
19	4.0	7	14.2	13.3	5.5	E	0.144	10.8	0.0094
20	5.0	7	13.4	14.5	5.0	L	0.094	11.1	0.0036
21	5.0	7	12.7	14.5	5.0	F	0.094	9.1	0.0114
22	3.0	7.5	12.7	12.6	6.0	E	0.176	6.0	0.0134
23	4.0	7.5	14.0	13.3	5.5	E	0.144	7.6	0.0150
24	4.0	7.5	14.0	13.3	5.5	E	0.144	8.8	0.0215
25	4.0	8	13.8	14.5	6.0	F	0.094	13.2	0.0120
26	4.0	8	13.2	14.5	6.0	E	0.094	5.4	0.0199
27	5.0	8	13.1	15.2	5.0	F	0.094	7.5	0.0164
28	5.0	8	13.7	15.2	5.0	F	0.094	5.9	0.0130
29	5.0	8	13.1	15.2	5.0	F	0.094	9.4	0.0147
30	5.0	8	12.0	13.3	4.5	F	0.078	6.5	0.0123
31	5.0	8	12.4	14.5	4.5	F	0.094	7.1	0.0133
32	5.0	8	11.9	12.9	4.5	F	0.078	2.6	0.0096
33	4.0	9	13.7	14.4	6.5	F	0.094	4.4	0.0048
				15.2				5.6	0.0189
34	5.0	9	13.2	14.5	6.5	L	0.094	6.8	0.0022
35	5.0	9	13.2	14.5	6.5	E	0.094	5.3	0.0024
36	5.0	9	13.6	14.5	6.5	L	0.094	11.5	0.0206
37	5.0	9	12.0	13.6	6.0	F	0.078	4.8	0.0056
				15.0				5.9	0.0226
38	5.0	9	12.0	13.6	6.0	F	0.078	5.6	0.0086
				15.0				3.0	0.0153
39	5.0	9	14.6	14.5	7.0	L	0.094	18.9	0.0182
40	3.7	9.5	10.7	14.5	7.0	E	0.094	16.7	0.0088
41	3.7	9.5	10.7	14.5	7.0	F	0.094	8.0	0.0087
42	4.0	9.5	14.0	14.1	7.0	L	0.144	7.6	0.0096

TABLE 1 (Continued)

Obs. No.	Wave Period	Stroke of crank	Still Water Depth	Pres. cell Height	Approx. Wave Height	Type of Wave	Beach Slope	Max. Pres.	Pres. Time Integral
43	5.0	10	12.2	14.2	7.5	F	0.078	3.3	0.0117
				15.0				4.7	0.0088
44	5	10	12.2	14.2	7.0	F	0.078	4.3	0.0127
				15.0				6.1	0.0132
45	5	10	12.2	14.2	7.0	F	0.078	7.5	0.0116
				15.0				2.3	0.0105
46	5	10	12.2	14.2	7.0	F	0.078	6.1	0.0136
				15.0				6.0	0.0125
47	5	10	12.2	14.2	7.0	F	0.078	8.5	0.0137
				15.0				4.9	0.0093
48	5	10	12.2	14.2	7.0	F	0.078	4.5	0.0116
				15.0				5.8	0.0090
49	5	10	12.2	14.2	7.0	F	0.078	8.3	0.0172
				16.0				5.9	0.0091
50	5	10	12.2	14.2	7.0	F	0.078	4.8	0.0142
				16.0				4.3	0.0090
51	5	10	12.2	14.2	7.0	F	0.078	6.5	0.0129
				16.0				6.3	0.0061
52	5	10	12.2	13.5	7.0	F	0.078	6.1	0.0112
				15.3				5.0	0.0150
53	5	10	12.2	13.5	7.0	F	0.078	3.3	0.0097
				14.4				5.9	0.0135
54	5	10	12.3	14.4	7.0	F	0.078	6.4	0.0139
				13.5				3.5	0.0103
55	5	10	12.3	14.4	7.0	F	0.078	6.3	0.0152
				13.5				5.5	0.0099
56	5	10	12.3	14.4	7.0	F	0.078	5.9	0.0168
				13.5				4.4	0.0106
57	5	10	12.3	13.3	7.0	F	0.078	4.3	0.0135
				13.0				3.1	0.0071
58	5	10	12.2	14.2	7.0	F	0.078	10.2	0.0119
59	5	10	12.2	14.2	7.0	F	0.078	10.9	0.0075
60	5	10	13.0	14.5	7.5	L	0.078	6.5	0.0021
61	5	10	13.0	14.5	7.5	F	0.078	2.6	0.0181

The data in Table 1 are selected to show conditions which gave high pressures. Many tests were made in which low pressures, or no pressures were produced. For many conditions (wave periods, wave size, beach slope, etc.) the waves could be caused to break and give pressures by adjusting the water depth in the wave tank. The depth which caused high pressures to be developed depended on the type of waves.

The maximum motion of the bulkhead producing the waves is about twice the stroke of the crank arm. Wave height is measured before reaching beach slope. "F" indicates that the wave causing the pressure was the first full wave; "E" indicates a wave after the first but before the influence of any reflection of the first wave travels from the bulkhead to the wave machine and back again; and "L" indicates a wave after the heights of the waves becomes somewhat variable because of variation of depths caused by reflected waves at the wave machine.

FIGURE 5 - HIGH SPEED MOTION PICTURE OF A BREAKING WAVE

The periods of time between the frames in 1/120-second units were 6,3, 1, 1, 1, 3 and 6.

The velocity of the front of the wave before striking the bulkhead was 6.6 feet per second. The vertical velocity of the spray was about 25 feet per second (equivalent to a pressure of 4 psi).

The wave was the second wave of a train of 4-second waves. The still water depth was 12.4 inches, the wave height before reaching the beach slope was 6 inches, the beach slope was 0.176 and the pressure cell height was 14.2 inches.

The pressure measured by the cell was 1.6 psi and the time-integral of the pressure was 0.0121 psi-second. This low pressure was due to the wave starting to break too far in front of the bulkhead. The bulkhead should have been just in front of the wave in frame A.

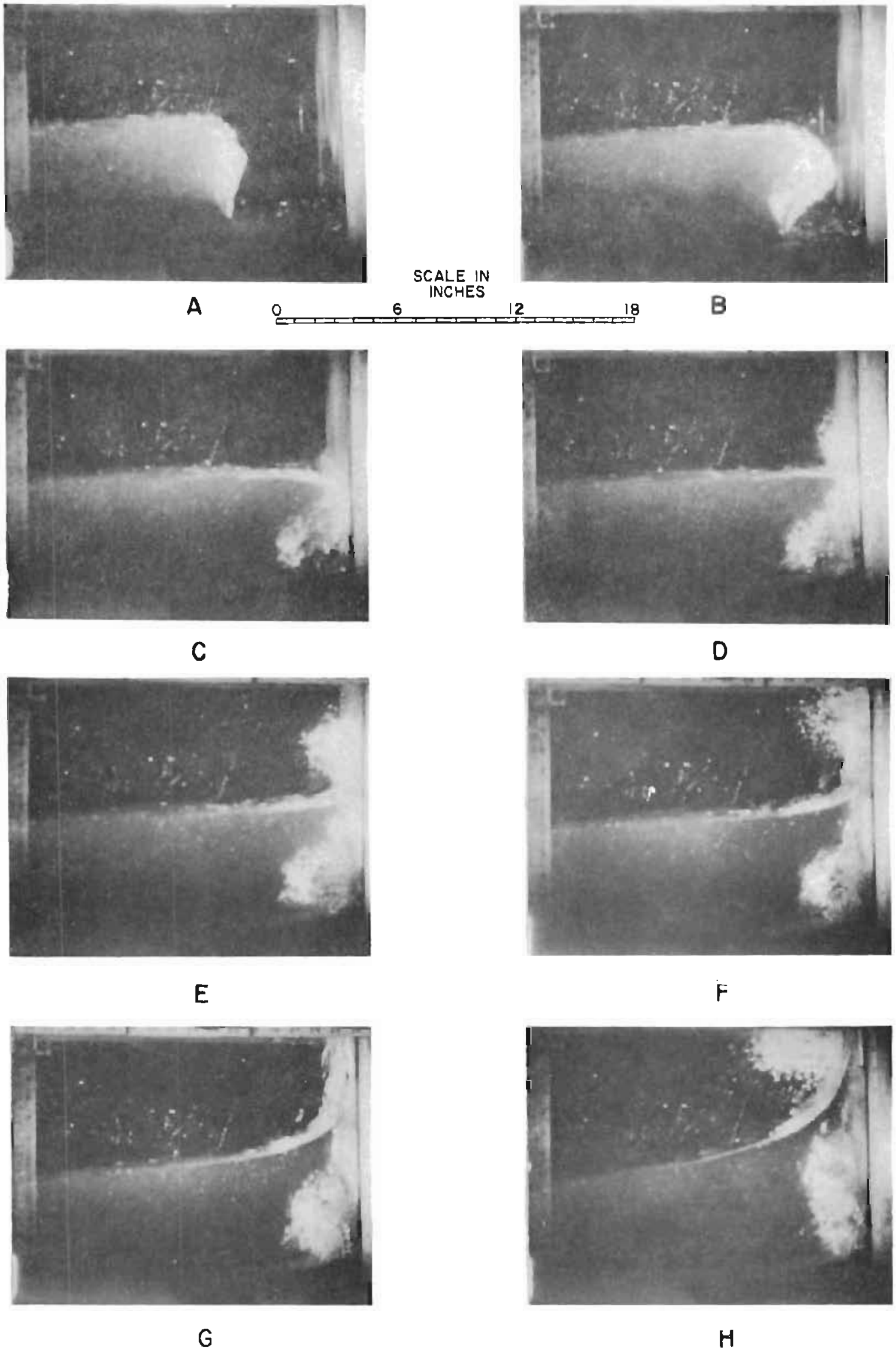

FIGURE 5 HIGH SPEED MOTION PICTURE OF A BREAKING WAVE

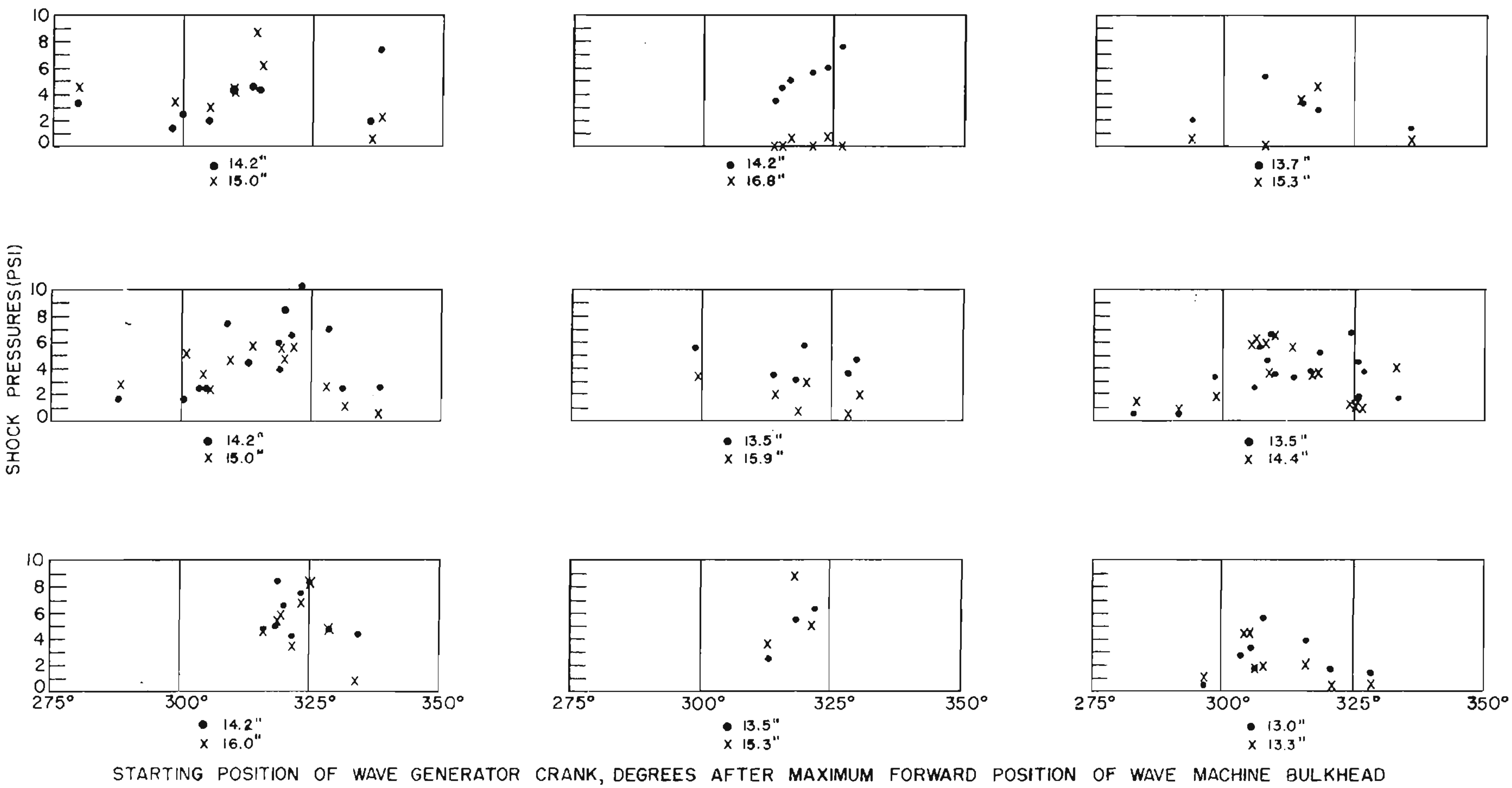

FIGURE 6 SIMULTANEOUS SHOCK PRESSURES

Note: Figures with legends (●, X) indicate height of pressure cell above bottom of tank. Stillwater level 12.24" above bottom of tank.

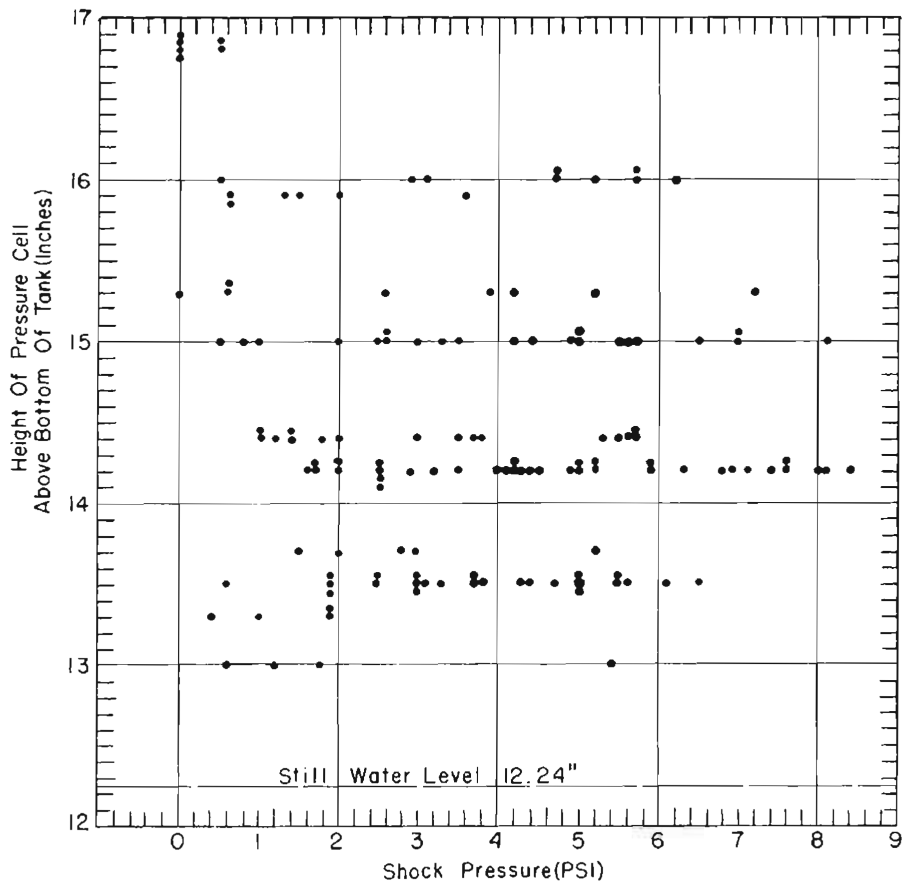

FIGURE 7 COMPARISON OF VERTICAL POSITION OF PRESSURE CELLS WITH SHOCK PRESSURES

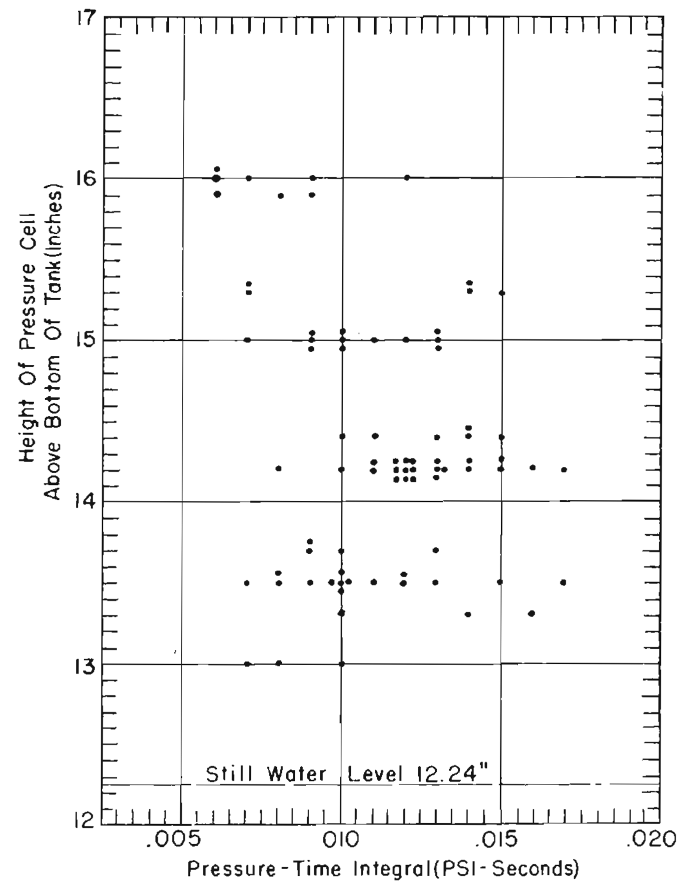

FIGURE 8 COMPARISON OF VERTICAL POSITION OF PRESSURE CELLS WITH PRESSURE TIME INTEGRALS

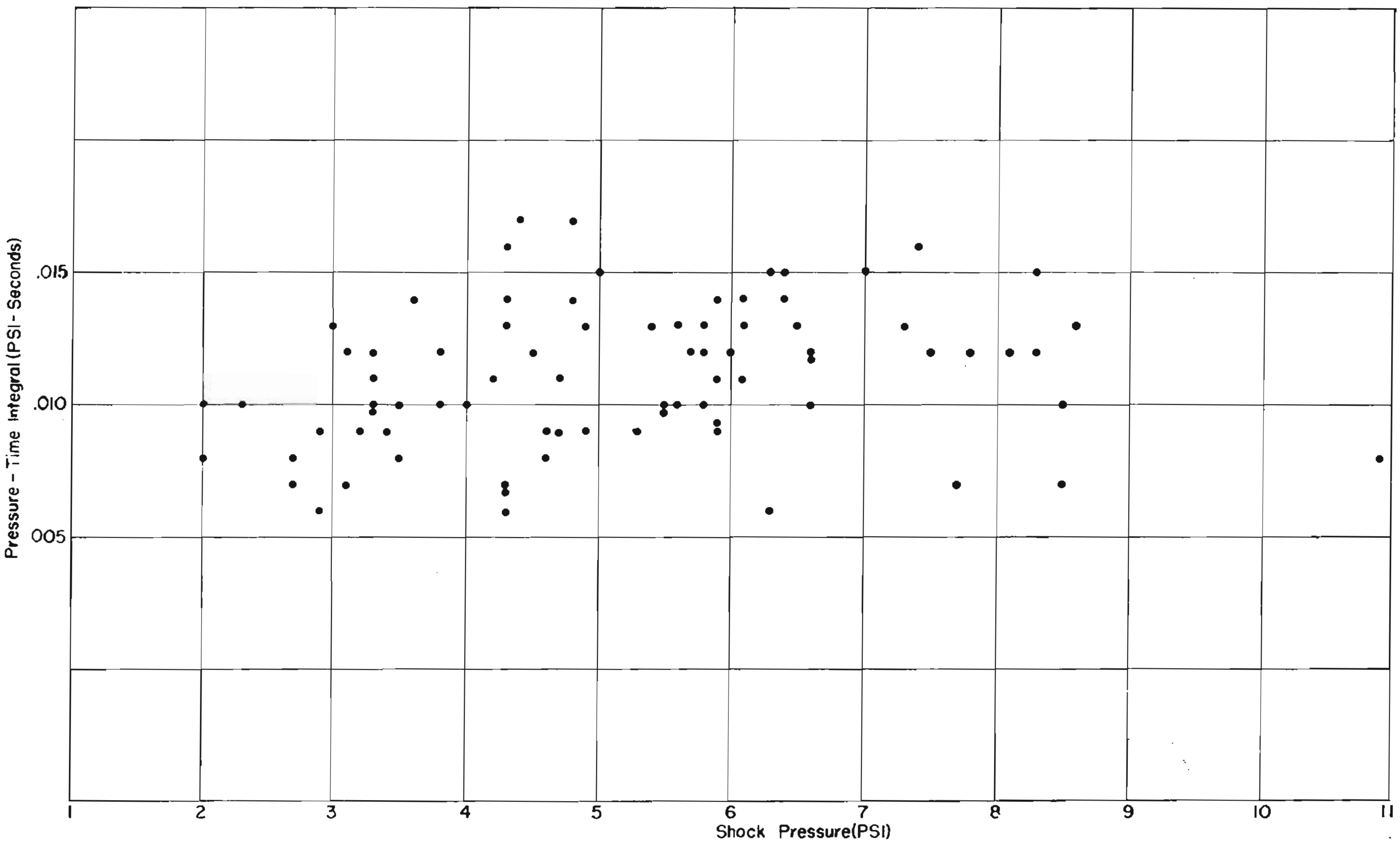

FIGURE 9 RELATION OF SHOCK PRESSURE TO THE TIME-INTEGRAL OF THE PRESSURE

impact pressure. For the third wave condition, the production of impact pressure was infrequent, though sometimes very high pressures were produced.

OBSERVED PRESSURES

Of the several thousand waves which developed sufficient pressure to trigger the oscilloscope, four wave pressures were recorded greater than 18 psi, twenty-one greater than 10 psi, and more than three hundred greater than 5 psi. The maximum hydrostatic pressure which would be produced with wave reflection (clapotis) is only about 0.5 psi for the waves used in these tests.

On the whole, greater pressures occurred more frequently and over a larger area of the bulkhead with larger waves. However, sometimes a small wave would produce a high pressure of very short duration.

Twenty-two consecutive tests of the first wave type with two pressure cells gave 44 values of the pressure with an average pressure of 5 psi. Simultaneous pressures of from 3 to 5 psi occurred with the cells separated vertically by 2 inches and horizontally by 9 inches. This indicates that high pressures occurred over a relatively large area of the bulkhead at the same time.

Most of the shock pressures were observed when the pressure cells were from 1 inch below to 3 inches above the still water level.

A sample of the wave data with experimental conditions is given in Table 1. Sample oscilloscope traces indicating the shock pressures are shown in Figure 4 (C to H).

Some frames from a high speed motion picture film of a breaking wave are shown in Figure 5.

Data from a series of tests of the first wave type are shown in Figures 6 to 9. These tests were made with the water level constant and the plots show the relation between the shock pressure, starting position of the wave machine, vertical position of the pressure cells, and the pressure-time integral.

Figure 6 indicates pressures simultaneously recorded from two pressure cells over a substantial vertical range with a 9-inch horizontal separation of the cells.

Figure 7 shows the variation of the observed pressures with elevation of the pressure cell (and the distance of pressure cell above still water level). The maximum pressure was observed about 2 inches above the still water level. Almost no pressures were observed at 4.6 inches above still water level. The test waves were about 7 inches high before reaching the beach.

Figure 8 shows similar data for the time-integral of the pressure for the same series of tests.

Figure 9 shows the relation of the shock pressure to the time-integral of the pressure. The plot indicates that there is little relationship between the pressure and the time-integral of the pressure. The time-integral of the pressure seems to approach a limit of about 0.017 psi-second for this series of tests.

Bagnold(2), using waves 10 inches high, photographed numerous oscilloscope traces indicating pressures as high as 18 psi and observed very infrequent traces indicating pressures as high as 80 psi. In his work the time-integral of the pressure caused by the waves seemed to approach a limit of 0.018 psi-second.

Rouville, Besson, and Petry(1) photographed traces indicating pressures as high as 88 psi caused by waves from 8 to 15 feet high. Bagnold measured the time integral of the pressures for these waves and found values from 0.38 to 0.73 psi-second. When these values are converted to the corresponding values for 7-inch waves on the three-halves power basis, the values are 0.003 to 0.010 psi-second.

MECHANICS OF BREAKING WAVES

As a wave advances onto the upward sloping beach in front of the vertical bulkhead the lower part of the wave is retarded by the friction and pressure of the beach while the top part continues with almost its original velocity. As the top of the wave overtakes the bottom, the front of the wave may become almost a vertical plane just before the wave breaks. If the wave comes in contact with the vertical bulkhead at that instant, high pressure may be expected. If no air were present, the condition would be such as to produce water hammer with the corresponding pressures. However, some air is always trapped by the irregularities of the wave front and as bubbles in the water. The trapped air is compressed and its cushioning effect lowers the top pressure and causes the pressure to continue over a longer time.

The water and air under pressure at the surface of the bulkhead can escape neither backward, because of the pressure of the remainder of the wave, nor downward, because of the beach. Upward there is no restraint other than the atmosphere and gravity. The pressure is relieved by the projection of a sheet of water and air as spray upward along the face of the bulkhead.

The motion of the water in the wave may be measured in terms of momentum, the product of the moving mass, M, and its velocity, v. The momentum is changed by the action of a force, F, acting through a period of time. The force that stops the wave and reflects part of it in the reverse direction is due to the pressure, P, on the bulkhead (plus part of the horizontal component of the pressure on the beach). Change of momentum = change in Mv = $g\int F\,dt = g\iint P\,dt\,da$ where A is the area of the bulkhead subject to pressure and g is the acceleration of gravity.

Individual periodic waves in very shallow water become approximately translation waves of the solitary wave type(5). The momentum of a solitary wave with a height of 6 inches and a water depth of 10 inches is about 500 pounds-feet per second per foot length of crest. If this acts on a strip of the bulkhead 6 inches high a pressure time-integral of 0.220 psi-second is obtained. (The wave velocity is 6.5 feet per second and the wave volume above still water per foot of crest is 1.24 cubic feet.)

The highest values of $\int P\,dt$ obtained from the shock pressures was about 0.02 psi-second. This would indicate that only a small part of the momentum of the wave produces shock pressure, usually much less than 10 percent.

In Figure 5 the front of the top part of the wave is advancing at 6.6 feet per second and the pressure-time integral was 0.0121 psi-second(4). A sheet of water 1.6 inches thick moving at 6.6 feet per second should cause a pressure-time integral of 0.0121 psi-second or if the velocity is reversed, the change in momentum being doubled, a thickness of 0.8 inch will give this value for the pressure-time integral. It may be noted in Figure 5 that the horizontal extension of the fast moving part of the wave was much longer than 1.6 inches. It seems to indicate that only the front part of the wave is stopped by shock pressure. This part forms a wedge and the remainder of the water is deflected upward along the bulkhead in streamline flow with a pressure not much greater than the hydrostatic pressure corresponding to the height of the jet. The high impact pressure lasted slightly less than 1/60 second or the interval between frames C and E in Figure 5.

The shape of the shock pressure trace and its height depend a great deal on the locations of the masses of trapped air relative to the pressure cell. In about half of the traces, negative pressures were observed showing that a mass of air had been compressed so much that, in re-expanding, it threw the water back with enough velocity to cause the pressure of the trapped air to drop below atmospheric pressure. In many cases there was a regular vibration of the pressure with decreasing amplitude, indicating repeated contractions and expansions of a bubble.

Bagnold considers the shock pressure to be caused by a column of water extending from the top of the breaking wave a distance of four-tenths of the wave height and with a thickness of two-tenths of the wave height. In Figure 5 it may be noted that the vertical width of the part of the wave moving forward with greater velocity is about 2.4 inches which is four-tenths of the height of this wave as measured before reaching the toe of the beach.

The thickness of two-tenths of the wave height is 1.2 inches. This value is half way between the value of 0.8 inch for complete reversal of the momentum and 1.6 inches without the reversal of the momentum, as computed from the measured value of 0.0121 psi-second for the pressure-time integral. Perhaps just half of the momentum was reversed; the other half going into the upward spray. In this case, the pressure-time integral would have been 0.0160 psi-second if the momentum were completely reversed.

In many of the wave pressure traces the shock pressure graded into the after pressure so that it was difficult to determine the stopping point for the pressure-time integral of the shock pressure. The after-pressure is frequently two or three times the pressure to be expected with the clapotis type of wave reversal. The after-pressure is more noticeable with lower positions of the pressure cell.

SCALE RATIO

On an average both the pressures and the pressure-time integrals were larger with larger waves. The variability of the data and the small range in size of the waves preclude reaching any definite conclusion as to the scale ratio to use to predict pressures and duration of pressures which may be caused by larger waves. The ratio for the pressure-time integral seems to be in the neighborhood of the first power of the scale ratio or somewhat larger. Tests on a much larger scale are proposed in the large outdoor wave tank capable of producing 6-foot waves now nearing completion.

When waves of larger size are considered, the shape may be expected to be similar and the corresponding horizontal sections of the breaking wave will be increased by the scale ratio, s. The velocity, C, of waves in shallow water is proportional to the square root of the depth, d, ($C = \sqrt{gd}$, g being the acceleration of gravity). Larger waves may be expected to break in proportionally deeper water. The velocity is thus proportional to the scale ratio, s, to the one-half power. The momentum is the product of the mass, M, and the velocity, v, (C is usually used for wave form velocity and v is used for water velocity). The scale ratio for the momentum causing the shock pressures should then be the product of the scale ratio for the mass and the velocity of the mass or s to the three-halves power. Then if 7-inch waves produce a shock pressure impulse of 0.02, a 14-foot wave (24 times as high as the 7-inch wave) might be expected to produce an impulse of $0.02 \times 24^{3/2}$ or 2.35 psi-seconds.

The extent of the area of the structure subject to pressure may be expected to vary in the vertical direction with the size of the wave and the scale ratio, and must be considered if the total impulse acting on the structure is desired.

EFFECTS ON STRUCTURES

Storm waves are far less regular in shape than experimental waves and the chance of an individual wave breaking at just the right position to cause high pressure is much less than in wave tank tests designed and operated to obtain high pressures. In spite of the rarity of extreme pressures, over the life of a structure they will occur, therefore the effect of shock pressures on structures must be considered.

If a 14-foot wave breaks against a vertical structure causing a pressure of 100 psi with a pressure-time integral of 2.35 psi-seconds, the duration of the pressure will be 0.0235 second. Although the duration of the pressure is short, the pressure wave travels at the speed of sound (12,000 feet or more per second in masonry structures) and the effect of the pressure spreads completely through a masonry structure of any reasonable thickness.

Let us consider a 6-foot cube of masonry weighing 160 pounds per cubic foot, thus having a total weight of 34,600 pounds. This cube might form the top of a sea wall. If a pressure of 100 psi is applied to the front face for 0.0235 second (impulse 2.35 psi-seconds) and the block is restrained by a friction force equal to 65 percent of its own weight, it will move 1.5 inches while the force is applied and will then have a velocity of 10.9 feet per second. It will be stopped by friction after moving 2.85 feet farther. The block could be held in place by a strength of 100 psi in shear in the bottom joint or with friction if 22 similar cubes are piled on top and in back of it. If the block is held at its lower back edge the impulse would start it rolling. If the joint under the block is partly open and filled with water, the pressure would be transmitted to the underside and exert a formidable uplift force. After the shock pressure is over a great deal of forward momentum remains in the wave and any block which has been loosened by the shock may be carried farther by the impinging water or dragged seaward as the water recedes.

As the elasticity of trapped air is an important factor in minimizing maximum shock pressures, structures with rough but impermeable surfaces capable of trapping substantial quantities of air are probably to be preferred to smooth-face structures.

SUMMARY

The waves used in the present investigations were from approximately 3.5 to 7.5 inches in height. Maximum observed shock pressures were 21 psi. Data are insufficient to establish definitely the relation between pressure and wave height, but an approximate linear relationship is indicated. The maximum pressure of 21 psi compares with 80 psi for 10-inch waves observed by Bagnold and 100 psi for 15-foot waves observed by Rouville, Besson and Petry. The elasticity of trapped air prevents occurrence of maximum possible pressures. Pressures of from 4 to

6 psi were observed simultaneously with two pressure cells separated 9 inches horizontally and 2 inches vertically with 7-inch waves, indicating that at least the lower shock pressures may occur over a large area of the structure at one time. Shock pressure may occur from near the top of the breaking wave to a substantial distance below the still water line.

The shock pressure impulse is only a small part of the momentum of the wavc, usually less than 10 percent. The remainder of the momentum is expended over a much longer time and at much lower pressure. The time-integral of the shock pressure approaches a value of 0.02 psi-second for 7-inch waves. This limit probably depends on the three-halves power of the scale ratio for waves of other sizes.

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