CHAPTER 23

SHOCK PRESSURE OF BREAKING WAVES

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INTRODUCTION

Most of you have observed waves breaking against rocks or structures, and have noted that water is frequently thrown high in the air. The pressure required to project water in a vertical direction is about one half pound per square inch for each foot of height. We may therefore expect to find substantial pressure involved in the mechanics of a wave breaking against a structure.

Pressures as great as 100 psi caused by waves breaking on a structure at Dieppe, France, have been observed by Besson and Petry (1938).

Bagnold (1939) 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 the study of the pressures of breaking waves. This 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 on the wave against the face of the structure.

EQUIPMENT USED IN THE TESTS

The pressure sensitive elements of the pressure gauges consist of plates of tourmaline crystal. This material is sensitive to hydrostatic pressure changes. The plates are separated from the water by only thin layers of wax, rubber, and shellac. The element, consisting of four one-inch disks or wafers, is set in and backed by a strong metal case. The possibility of spurious signals caused by resonance or of loss of sensitivity in connecting parts is greatly reduced by the simple and strong construction of the gauges.

The application of pressure to the gauges produces a small charge of electricity: 34 micro-micro coulombs for one pound per square inch change in pressure. The surfaces of the tourmaline disks are covered by thin conducting coatings which collect the charge. A voltage is produced which is inversely proportional to the capacitance of the gauge and leads. It is necessary that the resistance or the insulation be in the order of 1000 megohms to prevent the charge from leaking away too quickly. The voltage is carried to the grid of a radio tube by coaxial cable. The tube is biased so that the grid draws no current. The output of the radio tube can then be connected to the oscilloscope which has an input resistance of only 2 megohms.

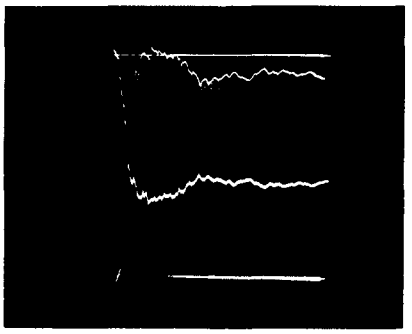
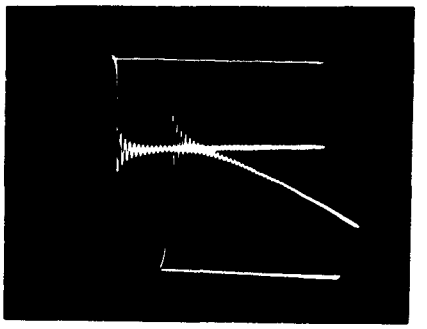


Figure 1



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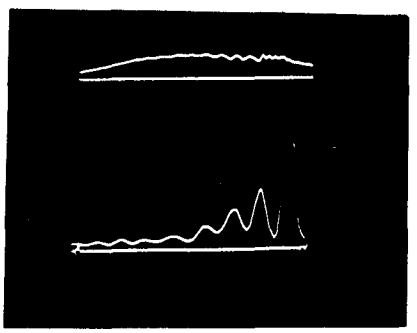

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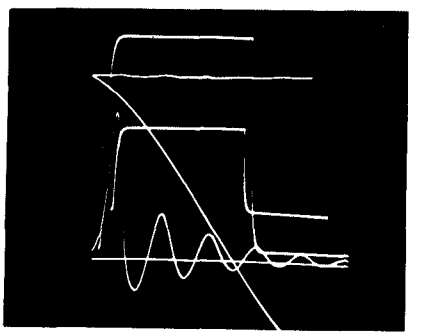

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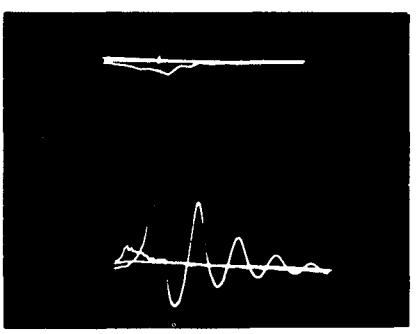

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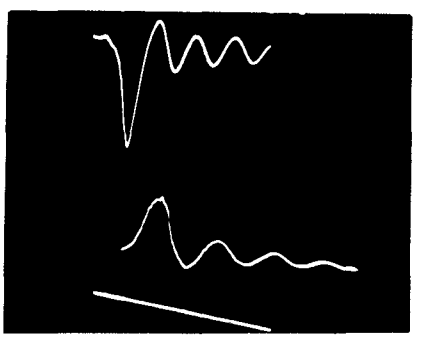

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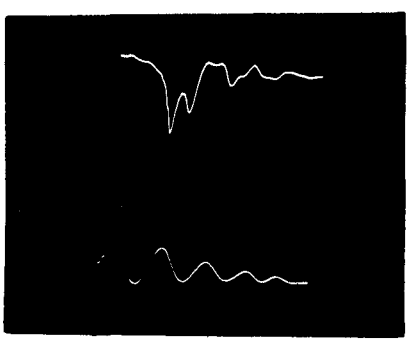

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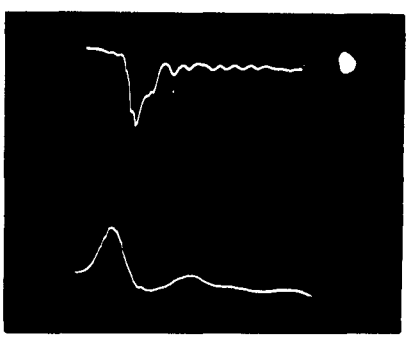

Figure 9

DESCRIPTION OF FIGURES

Figure 1

The traces represent the release of a pressure of 43 psi 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 is 1/720 second. The pressure was released in slightly more than 1/10,000 second. It is difficult to release pressure quickly without oscillations. These may be noted in the traces.

Figure 2

These traces represent the 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 1/1,000 second. The traces indicate the error caused by the loss of signal with time. The D.C. amplifier trace falls only about 6 per cent 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 will hold the signal for only about 1/60 second with a similar loss of signal.

Figure 3

Figure 3 is a diagram of the wave tank in which the tests were made.

Figure 4

These traces represent the pressures of two breaking waves. The larger one represents a pressure of 13.5 psi and is number 8 in Table 1. The smaller one represents a pressure of 2.4 psi. The time-pressure integrals are the same, however, 0.011 pound-seconds per square inch. The sweep time is 1/120 second.

Figure 5

This trace represents a pressure of 13.2 psi and is number 25 in Table 1. The sweep time is 1/60 second. The trace of the square wave which is used to calibrate the amplifiers is also present. By comparison with the square wave the voltage represented by the wave trace can be found. A comparison with the results of the calibration tests with release of pressure then indicates the pressure in psi.

Figure 6

The larger trace represents a pressure of 18.9 psi. This is number 39 in Table 1.

Figure 7

These traces represent pressures of 8.5 and 4.9 psi. The pressure cells were at different elevations. The sweep time was 1/60 second. This wave is number 47 in Table 1.

Figure 8

These traces represent pressures of 6.3 and 6.5 psi caused by a breaking wave. The sweep time was 1/60 second. They are number 51 in Table 1.

Figure 9

These traces represent pressures of 6.3 and 5.5 psi. The sweep time was 1/60 second. They are number 55 in Table 1.

Two pressure cells were used with a dual channel oscilloscope. One of the amplifiers of the oscilloscope was an AC type and the other a DC type. The sweep of the oscilloscope was triggered by the signal.

A 4 micro-second delay line and special triggering device were used in many of the tests to insure that we were not losing the initial rise of the signal.

The traces on the oscilloscope screen were recorded by an oscilloscope camera.

The cells and 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. 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 with changing pressure so that the calibration with the release of pressure may be used with the increase of pressure produced by the breaking wave. The oscilloscope traces from two calibration tests are shown in Figures 1 and 2.

The tests were made in an indoor tank with a length of 96 feet, a depth of 2 feet, and a width of 1 1/2 feet. A diagram of the wave tank is shown in Figure 3.

The waves were generated by a wave machine of the moving bulkhead type. The bulkhead was caused to move by a crank wheel and connecting rod. The speed of rotation of the wheel could be varied to give 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 give waves of various heights.

The pressure cells were mounted in two 1/2-inch steel plates. Each plate formed one half of the bulkhead representing the vertical structure against which the waves were to break. The sensitive faces of the cells were flush with the surface of the plates. The plates were mounted on a steel frame and could be raised or lowered to change the vertical position of the gauges.

The waves were caused to break by a beach formed of concrete slabs. The height at the bulkhead was 10 inches. Various beach slopes were used from 0.078 to 0.176.

A recording wave gauge was used to give a time profile of many of the waves. It was located about 30 feet in front of the bulkhead.

TYPES OF BREAKING WAVES

Three types of wave conditions were used in the tests.

First, a small wave is formed by starting the wave machine at a certain point in its cycle. If the size of the small wave is regulated correctly by the starting position of the machine, the backwash of this small wave will cause the next or first full-sized wave to break against the bulkhead.

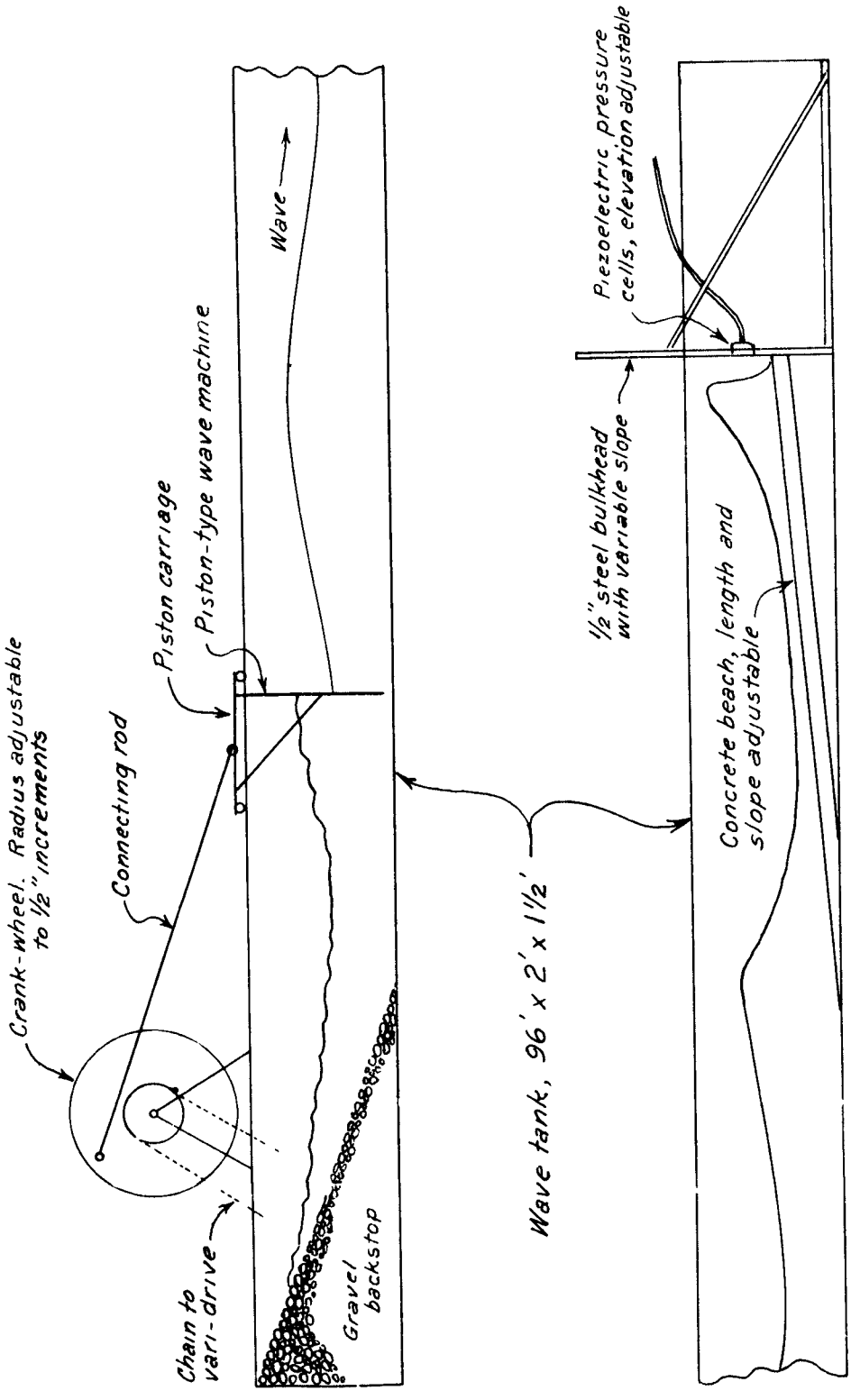

Figure 3. Diagram of wave tank

Waves starting with the second and ending with roughly the tenth are called early waves. These early waves were caused to break in proper position by adjustment of the water depth. At this depth the backwash of the preceding wave is such as to cause each wave to break in proper position.

After 8 to 12 waves have broken on the bulkhead, the influence of the reflected waves traveling from the bulkhead to the wave machine and then back to the bulkhead causes variation in height of the incident waves. The total distance is about 160 feet. These are called late waves.

The first two conditions are reproducible and reliable pressure producers. A slight variation of the period, depth, etc. would cause the waves to break too early or too late to produce much pressure. For the third wave condition, the production of pressure was infrequent. Sometimes very high pressures were produced, however.

The height of the waves varied from 3 to 7.5 inches as measured 30 feet from the bulkhead. The height of the third wave was measured because in subsequent waves the record was complicated by the reflected wave.

PRESSURES PRODUCED BY BREAKING WAVES

Four wave pressures were recorded greater than 18 psi, twenty-one greater than 10 psi, and more than 300 greater than 5 psi. The maximum pressure which would be produced by hydrostatic pressure (clapotis) is only about 0.5 psi.

High pressures occured more frequently and over a larger area of the bulkhead with larger waves. However, sometimes a large wave would break with a big bang and produce a pressure of one or two psi and then a small parasitic wave between the larger waves would slap the bulkhead lightly and produce a pressure of seven or eight psi.

Twenty-two consecutive tests of the first wave type gave 44 values of the pressure with an average of 5 psi. Simultaneous pressures of from 3 to 5 psi occured with the gauges separated vertically by 2 inches. The gauges are separated 9 inches horizontally. 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 gauges were between one inch below and three inches above the still water line.

A sample of the wave data with experimental conditions is given in Table 1.

Some oscilloscope traces indicating the shock pressures are shown in Figures 4 to 9.

The durations of the shock pressures are short. Bagnold has noted that the time integral of the pressures seems to approach an upper limit. Numerous measurements were made of the time integral of the pressures produced by the waves in these tests. The maximum values found were slightly greater than 0.02 psi-seconds.

SHOCK PRESSURE OF BREAKING WAVES

EFFECT ON STRUCTURES

If we consider the pressure of 18 psi developed by 7-inch laboratory waves, we may well be interested in what full-scale ocean waves may do to a structure.

In these tests, the larger pressures are of too short duration for a structure of much weight to be moved appreciably. At model scale, most types of pressure gauges have too much inertia and resiliency for them to even detect these pressures.

Measurements have shown that the velocity of the peak of a breaking wave approaches the wave velocity. The velocity of the face of the wave decreases rapidly with lower elevation. If we assume a horizontal thickness of the breaking wave as 3 inches and its velocity at the same elevation as 3 feet per second, we find a momentum of 0.32 lbs-ft/sec-in.^{2}, equivalent to an impulse or a pressure-time integral of 0.01 psi-second. If the velocity is reversed, this amount is doubled. This is the approximate magnitude for the higher values of the impulse measured. It may be remembered that a variable amount of the momentum will be overcome by hydrostatic pressure which may account for the lower values. Some of the momentum is not reversed but is converted to turbulence and into the vertical motion of the spray.

If air were not present, we might well expect the pressure to approach the pressure of water hammer. However, some air is always trapped by the breaking wave. The more air trapped, the lower the shock pressure and the longer its duration.

When we consider waves of larger size, we may expect the shape to be similar. The corresponding horizontal section of the breaking wave will be increased in length by the scale ratio.

The velocity of waves in shallow water is proportional to the square root of the depth of the water. Since the larger waves may be expected to break in proportionally greater depth, the velocity will then be greater by the square root of the scale ratio.

The scale ratio for the impulse should be the product of these or the scale ratio raised to the three-halves power. If 7-inch waves produce an impulse of 0.02, a 14-foot wave should then produce an impulse of $0.02 \times 24^{3/2}$ or 2.35 psi-seconds.

The range of wave sizes in these tests was not large enough to check this scale ratio. We hope to make some tests on a much larger scale when our wave machine is completed for our 635-foot tank.

Pressure measurements have been made with full-scale waves at Dieppe, France. The pressure records of 7 waves give values of from 0.38 to 0.73 psi-seconds for the impulse. When corrected for the scale of the wave, these values become 0.003 to 0.010 psi-seconds as 7-inch waves.

Bagnold found the time-integral of the pressure for his 10-inch waves to approach 0.018 psi-seconds. This becomes 0.010 when reduced to the scale of these tests.

TABLE I

DATA FOR SOME OF THE WAVES PRODUCING SHOCK PRESSURES

No.	Wave period	Stroke of crank	Still Water depth	Pres. cell height	Max. pres.	Pressure time integral	Type of wave	Approx. wave height	Beach slope
	sec.	in.	in.	in.	psi	psi-sec.		in.	
1	3.5	4	12.4	14.5	5.9	0.0078	E	4.0	0.094
2	4.0	4	13.0	12.9	4.2	0.0064	L	4.0	0.094
				14.5	9.1	0.0142			
3	4.0	4 1/2	13.2	13.4	9.0	0.0132	L	4.0	0.176
4	4.0	5	13.4	12.9	10.6	0.0098	E	4.0	0.094
5	4.0	5	14.0	14.5	10.1	0.0130	L	4.5	0.094
6	4.0	5	12.7	15.0	7.0	0.0057	L	4.0	0.078
7	5.0	5	12.6	14.5	7.5	0.0083	E	4.0	0.094
8	4.0	5 1/2	12.2	13.4	13.5	0.0110	L	4.5	0.176
9	4.0	5 1/2	13.8	14.5	8.3	0.0150	L	4.5	0.094
10	3.0	6	13.4	12.9	10.4	0.0100	L	5.0	0.094
11	4.0	6	14.0	14.5	10.0	0.0114	E	5.0	0.094
12	4.0	6	13.0	14.5	12.2	0.0099	E	5.0	0.094
13	4.0	6	13.4	12.9	21.4	0.0114	L	5.0	0.094
14	5.0	6	13.0	14.5	10.4	0.0190	L	3.5	0.094
15	5.0	6	13.1	14.5	7.2	0.0182	L	3.5	0.094
16	4.0	7	14.0	12.9	15.7	0.0165	L	5.5	0.094
17	4.0	7	14.0	12.9	6.1	0.0129	L	5.5	0.094
18	4.0	7	14.2	13.3	14.6	0.0147	E	5.5	0.144
19	4.0	7	14.2	13.3	10.8	0.0094	E	5.5	0.144
20	5.0	7	13.4	14.5	11.1	0.0036	L	5.0	0.094
21	5.0	7	12.7	14.5	9.1	0.0114	F	5.0	0.094
22	3.0	7 1/2	12.7	12.6	6.0	0.0134	E	6.0	0.176
23	4.0	7 1/2	14.0	13.3	7.6	0.0150	E	5.5	0.144
24	4.0	7 1/2	14.0	13.3	8.8	0.0215	E	5.5	0.144
25	4.0	8	13.8	14.5	13.2	0.0120	F	6.0	0.094
26	4.0	8	13.2	14.5	5.4	0.0199	E	6.0	0.094
27	5.0	8	13.1	15.2	7.5	0.0164	F	5.0	0.094
28	5.0	8	13.7	15.2	5.9	0.0130	F	5.0	0.094
29	5.0	8	13.1	15.2	9.4	0.0147	F	5.0	0.094
30	5.0	8	12.0	13.3	6.5	0.0128	F	4.5	0.078
31	5.0	8	12.4	14.5	7.1	0.0133	F	4.5	0.094
32	5.0	8	11.9	12.9	2.6	0.0096	F	4.5	0.078
33	4.0	9	13.7	14.4	4.4	0.0048	F	6.5	0.094
				15.2	5.6	0.0189			
34	5.0	9	13.2	14.5	6.8	0.0022	L	6.5	0.094
35	5.0	9	13.2	14.5	5.3	0.0024	E	6.5	0.094
36	5.0	9	13.6	14.5	11.5	0.0206	L	6.5	0.094
37	5.0	9	12.0	13.6	4.8	0.0056	F	6.0	0.078
				15.0	5.9	0.0226			
38	5.0	9	12.0	13.6	5.6	0.0086	F	6.0	0.078
				15.0	3.0	0.0153			
39	5.0	9	14.6	14.5	18.9	0.0182	L	7.0	0.094
40	3.7	9 1/2	10.7	14.5	16.7	0.0088	E	7.0	0.094
41	3.7	9 1/2	10.7	14.5	8.0	0.0087	F	7.0	0.094
42	4.0	9 1/2	14.0	14.1	7.6	0.0096	L	7.0	0.144
43	5.0	10	12.2	14.2	3.3	0.0117	F	7.5	0.078
				15.0	4.7	0.0088			

TABLE 1 (Continued)

No.	Wave period	Stroke of crank	Still water depth	Pres. cell height	Max. pres.	Pressure time integral	Type of wave	Approx. wave height	Beach slope
	sec.	in.	in.	in.	psi	psi-sec.		in.	
44	5	10	12.2	14.2	4.3	0.0127	F	7.0	0.078
				15.0	6.1	0.0132			
45	5	10	12.2	14.2	7.5	0.0116	F	7.0	0.078
				15.0	2.3	0.0105			
46	5	10	12.2	14.2	6.1	0.0136	F	7.0	0.078
				15.0	6.0	0.0125			
47	5	10	12.2	14.2	8.5	0.0137	F	7.0	0.078
				15.0	4.9	0.0093			
48	5	10	12.2	14.2	4.6	0.0116	F	7.0	0.078
				15.0	5.8	0.0090			
49	5	10	12.2	14.2	8.3	0.0172	F	7.0	0.078
				16.0	5.9	0.0091			
50	5	10	12.2	14.2	4.8	0.0142	F	7.0	0.078
				16.0	4.3	0.0090			
51	5	10	12.2	14.2	6.5	0.0129	F	7.0	0.078
				16.0	6.3	0.0081			
52	5	10	12.2	13.5	6.1	0.0112	F	7.0	0.078
				15.3	5.0	0.0150			
53	5	10	12.2	13.5	3.3	0.0097	F	7.0	0.078
				14.4	5.9	0.0135			
54	5	10	12.3	14.4	6.4	0.0139	F	7.0	0.078
				13.5	3.5	0.0103			
55	5	10	12.3	14.4	6.3	0.0152	F	7.0	0.078
				13.5	5.5	0.0099			
56	5	10	12.3	14.4	5.9	0.0168	F	7.0	0.078
				13.5	4.4	0.0106			
57	5	10	12.3	13.3	4.3	0.0135	F	7.0	0.078
				13.0	3.1	0.0071			
58	5	10	12.2	14.2	10.2	0.0119	F	7.0	0.078
59	5	10	12.2	14.2	10.9	0.0075	F	7.0	0.078
60	5	10	13.0	14.5	6.5	0.0021	L	7.5	0.078
61	5	10	13.0	14.5	2.6	0.0181	F	7.5	0.078

TABLE 1 - NOTES

The data in Table 1 is selected to show conditions which gave high wave 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 for pressure depended on the type of wave.

The motion of the bulkhead producing the waves is about twice the length of the crank arm.

"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.

Because of the inertia of the water, pressure is not quickly released downward or backward as a wave breaks against a vertical structure. However, a substantial amount of water is usually thrown upward because nothing but air interferes with its upward escape. Therefore, the tops of vertical structures must be designed to withstand the force of falling water.

CONCLUSIONS

The time integral of the pressure approaches a value of 0.02 psi-seconds for 7-inch waves. This limit depends on the three halves power of the scale ratio for waves of other sizes.

No limit on the magnitude of the pressure developed can be given except that which would develop with water hammer. However, the elasticity of the trapped air should always preclude pressures of such high values.

Design of structures should normally be based on the total momentum to be reversed. Usually the high pressures will not be important.

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