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A Model Study of Wave Run-up on Sloping Structures

by

Kenneth N. Granthem

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A Model Study of Wave Run-up on Sloping Structures

Abstract

Curves have been developed from laboratory experiments which indicate (1) the effect of different side slope angles of a sloping structure on wave run-up, (2) the effect of the parameter wave steepness (H/L) on wave run-up on sloping structures, (3) the effect of the parameter relative depth (d/L) on wave run-up on sloping structures, and (4) the effect of structure porosity on wave run-up. Maximum wave run-up occurs, for the range of angles examined, at approximately 30 degrees. As the wave steepness parameter (H/L) increases, the wave run-up increases and, as the relative depth parameter (d/L) decreases the wave run-up increases.

This report is concerned with a sloping structure model study, with a presentation of the data and with an analysis of the results. The limitations of this study should be noted. This study only involves the effect of the side slope on wave run-up on sloping structures, and the effects of the two parameters wave steepness (H/L) and relative depth (d/L) on wave run-up on sloping structures. Also, the wave approach was restricted to the direction perpendicular to the axis of the structure.

Introduction

This investigation was conducted for the primary purpose of determining experimentally the effect of side slope angle and structure porosity on wave run-up.

For the sake of this discussion sloping structures will be construed as:

1. Breakwaters
2. Earth dams
3. Embankments along lake fronts and ocean fronts

Wave run-up on sloping structures is important in the problem of slope protection in engineering structures exposed to wave action. A large amount of energy is released when a wave peaks up, breaks and runs-up on the sloping structure. This energy becomes apparent in the vertical rise of water and in the damage caused to sections of the sloping surface which are inadequately protected above the minimum wave run-up elevation.

A particular case of major importance is where a breakwater has been constructed for the purpose of quieting the surface of the water in the lee of the breakwater structure. As the model study will show, if proper angles of side slope are not used in the design, wave run-up can become great enough to overtop the breakwater and cause large disturbances in the quiet protected area. The problem of overtopping is not restricted to breakwaters and is also of major importance in earth dam consideration.

A model study was conducted in the wave channel (figure 1) in the Hydraulics Laboratory at the University of California, Berkeley, for the purpose of studying the effects of structure side slope angle and structure porosity on wave run-up. Parameters of wave steepness (H/L) and relative depth (d/L) and their effects on wave run-up also were investigated.

Laboratory Equipment

The experimental equipment consisted of the glass-walled wave channel shown in Figure 1. The bottom profile of the channel gave an effect of waves propagating from deep water into shallow water (where d/L 0.5). The channel was 1 foot wide, 3 feet high and 60 feet long, with a wave generator at one end and with a model structure at the other end. A two channel Brush recorder recorded the water surface time history by means of wire resistance elements (Morison, 1949).

The models which were used consisted of (1) a smooth flat surface with a porosity n = 0%, (2) a specially constructed box (Figures 3 and 5) 6 feet long by 0.83 feet wide by 0.30 feet deep filled with 1½ inch maximum angular stone (Figures 4 and 5) with a porosity n = 32.6% and (3) the same box filled with well rounded pea gravel (Figures 2 and 3) with a porosity n = 28.9%. Slope changes by erosion were prevented in structures 2 and 3 by means of wire netting across the exposed surface (Figures 3 and 5).

Experimental Procedure

The experimental procedure was to:

1. Generate waves for each run, of various periods, heights and lengths in the channel, and record the surface-time history of the waves on a Brush recorder. This was essentially a calibration of the wave channel without a structure in place.

2. Install the smooth surface type structure (Figure 10).

3. Keep depth constant, period constant, wave height constant, wave length constant and vary the side-slope angle of the structure for each run; the wave run-up on the structure was measured using waves which had the same amplitude, period and length as waves in the original calibration of the wave channel (step 1), (Figure 8).

4. Repeat step number 3 with a new period, new wave height, and new wave length (Tables 1, 2 and 3).

5. Measure wave run-up, with slope of structure constant, and varying the wave steepness (H/L). This investigation was repeated for angles of 15 degrees, 30 degrees and 45 degrees.

6. Measure wave run-up with slope angle of structure and wave steepness (H/L) constant and varying the relative depth (d/L). This investigation was only completed for the angle of 30 degrees.

7. Steps 3, 4, 5 and 6 were repeated for each type of stone structure. Data for all laboratory measurements are summarized in Tables 1, 2, 3.

In each run, a series of about ten waves was recorded before wave reflections from the structure confused the record. The wave run-up on the structure was measured for these initial waves. The wave machine was stopped and the water allowed to become quiet, then the run was repeated. Each run was repeated three or more times.

Consistency was maintained between runs and between measurements on different type structures by the visual surface time history of the waves recorded on the Brush recorder (Figure 8). By observation of the surface time history of the waves, it was found that the reflected energy of the waves did not appear in the record until approximately after the ninth or tenth wave had impinged upon the structure.

Wave run-up was defined, and measured, as the distance from the still water level to the point where the entire face of the structure was wetted. Spray, resulting from breaking waves, which progressed past the point of wave run-up was not included in the measurement.

Experimental Results

In order to determine the effect of the wave steepness (H/L) on wave run-up, experiments were performed on three model structures (porosity n = 0%, porosity = n 28.9%, and porosity n = 32.6%) over a relatively large range of values of H/L. The angle of slope of the structure was maintained constant for each range of H/L and for each type of structure (Figure 12). This condition was investigated for three different angles, 15 degrees, 30 degrees and 45 degrees (Figures 12, 13 and 14). For the angles of 30 and 45 degrees (Figures 13 and 14) there is an increase in wave run-up for increasing values of $H/L > 0.03$. It is apparent from examination of these curves that there is a greater advantage in having structures with high roughness coefficients and with relatively large porosity. Undoubtedly, the irregularity of these curves, especially with the lower values of H/L, is due to friction effects as the waves rush up the slope. Supplementary data on the effect of roughness have been studied recently in Denmark by Bruun[3]. There is a large percentage decreases in wave run-up, for the same energy dissipation on the structure, for structures with large porosity values. It is apparent from the curves that the free board needed to prevent overtopping of a structure is much greater for the condition of a smooth surface than for the condition of high porosity.

Figures 16, 17, 18, and 19 were obtained in order to determine the effect of the slope angle on wave run-up. Experiments were performed on three model structures (n = 0%, n = 28.9% and n = 32.6%) over a range of angles which embraced the interval from 15 degrees to 90 degrees. The relative depth (d/L) and the wave steepness (H/L) were maintained constant for each range of angles. The results are consistent in that the maximum value for wave run-up occurs in the vicinity of 30 degrees for each set of experiments covering this investigation (Figures 16, 17, 18 and 19). It is significant to note here that there is a decrease in wave run-up for angles smaller than 30 degrees and for angles larger than 30 degrees. This fact is important in breakwater design where wave run-up is a major problem. From current literature[8] it is the consensus of opinion that the slope angle should cover the range of 1 on 1½ to 1 on 1-1 3/4 which unfortunately very closely approximates 30 degrees for both end conditions. Few specific criteria exist for the determination of side-slope angles, the main consideration is in finding an equilibrium slope in the above mentioned range.

Also, it is very significant to note in Figure 16 that there was a relatively large wave run-up (in one case, n = 0%) for values of low d/L, H/L and low angle of slope, these waves simply "surged" up the breakwater surface without breaking. For the increasing values of H/L and d/L larger amounts of energy were dissipated on the structure. The waves were consistent in that they all broke on the structure slope up to the "critical" angle of 30 degrees, above 30 degrees the wave "surged" up the slope without breaking and there was an obvious decline in wave run-up. As the angle of slope increased there was an increase in reflected wave energy, consequently there was a decrease in wave run-up.

Figure 15 was obtained in order to determine the effect of the relative depth (d/L) on wave run-up. For this particular investigation the slope angle was maintained constant for a large range of values of d/L. The wave steepness (H/L) also was maintained constant. The range of values for d/L covered extremes from a very small to a value approaching the deep-water ratio of 0.5. In all cases, for an increasing value of d/L, there was an obvious decline in wave run-up for the same amount of energy dissipation on each type structure.

Figure 11 represents a model wave breaking on a permeable model structure. The energy of the model wave was dissipated rapidly in a short distance. The sudden loss in energy was caused by the water flowing between the particles. The work done was an absorption of energy by the breakwater; consequently, there was a minimum of wave run-up. For model waves breaking on a smooth surface and for the same energy as mentioned above, the energy of the wave was dissipated only as work done by the water in climbing to a peak elevation. Little energy was absorbed by the structure; consequently, there was a maximum of wave run-up.

Conclusions

The primary aim of the laboratory program was to investigate the effect of various slope angles and side slope porosity on wave run-up and to investigate the effect of the parameters H/L and d/L. These data cover reasonable prototype conditions. The permeable structure was assembled in such a manner as to prevent a natural equilibrium condition on the side slope for the full range of angles investigated (15°-90°). Prototype stone for both sizes of model stone probably would seek an equilibrium slope smaller than 45 degrees. Nevertheless, the following conclusions may be formed on the basis of this study as follows:

(a) Structure porosity has a major effect upon wave run-up,

(b) The primary variables affecting wave run-up appear to be H/L, d/L, angle of side slope and porosity of the structure,

(c) The critical point of slope angle appears to be approximately 30 degrees. Any variation from this point, decreasing or increasing, will probably decrease wave run-up, other things being equal,

(d) For values of increasing wave steepness (for $H/L > 0.03$) there is an increase in wave run-up,

(e) For decreasing values of d/L there is an increase in wave run-up.

Acknowledgment

The author appreciates the suggestions, supervision and assistance of Professor J. W. Johnson in carrying out the experiments and presenting the results.

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Symbols and Notation

1. **Backwash** - water or waves thrown back by an obstruction such as a breakwater.

2. **Breakwater** - anything which breaks the force of waves at a particular place, thus forming protection for vessels, etc. A solid structure - usually of masonry, protecting a harbor, anchorage, or basin from wind and waves. Breakwaters are free standing structures.

3. **Deep Water** - where depth is greater than one-half the wave length.

4. **Depth** (d) - vertical distance from still water level.

5. **Fetch** - In forecasting waves, the area of water over which the wind blows.

6. **Fetch Length** - In forecasting waves, the horizontal distance (in a fetch) over which the wind blows.

7. **Median Diameter** - the size of the sieve opening through which 50% of a sample by weight passes.

7'. **R** - Vertical rise of wave on structure.

8. **Reflected wave** - the wave which is returned seaward when a wave impinges upon a very steep beach or cliff.

9. **Rip Rap** - wall of stone thrown together irregularly.

10. **Rubble** - Loose, angular, and water-worn stones along a beach.

11. **Shallow water** - water in which the depth is less than one-half the wave length at the particular time.

12. **Still water level** (SWL) - the surface of the water if all wave action were to cease.

13. **Wave** - An oscillatory movement in the sea which results in an alternate rise and fall of the surface.

14. **Wave Height** (H) - vertical distance between crest and preceding trough.

15. **Wave Length** (L) - horizontal distance between successive wave crests measured perpendicular to the crest.

16. **Wave period** (T) - the time, in seconds, for a wave crest to traverse a distance equal to one wave length.

17. **Wave steepness** (H/L) - the ratio of the wave's height to its length.

18. **Relative depth** (d/L) - the ratio of the depth to the wave length.

19. **Wave rise parameter** (R/H) - the ratio of the vertical wave rise in structure to the wave height.

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Table One

Run No.	Breakwater deg.	Breakwater slope	Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	$\frac{d}{L}$	$\frac{H}{L}$	Max. Run-up -R- ft.	$\frac{R}{H}$
1	90		smooth surface	0.98	0.170	2.75	14.85	0.066	0.012	0.100	0.591
2	75		"	0.98	0.170	2.75	14.85	0.066	0.012	0.125	0.735
3	60		"	0.98	0.170	2.75	14.85	0.066	0.012	0.130	0.765
4	45		"	0.98	0.170	2.75	14.85	0.066	0.012	0.150	0.883
5	30		"	0.98	0.170	2.75	14.85	0.066	0.012	0.175	1.03
6	15		"	0.98	0.170	2.75	14.85	0.066	0.012	0.250	1.47
7	15		smooth board	0.98	0.254	0.667	2.26	0.434	0.112	0.275	1.08
8	30		"	0.98	0.254	0.667	2.26	0.434	0.112	0.375	1.48
9	45		"	0.98	0.254	0.667	2.26	0.434	0.112	0.230	0.905
10	60		"	0.98	0.254	0.667	2.26	0.434	0.112	0.200	0.788
11	90		"	0.98	0.254	0.667	2.26	0.434	0.112	0.165	0.650
12	20		"	0.98	0.254	0.667	2.26	0.434	0.112	0.300	1.18
13	25		"	0.98	0.254	0.667	2.26	0.434	0.112	0.350	1.38
14	35		"	0.98	0.254	0.667	2.26	0.434	0.112	0.360	1.43
15	15		"	0.98	0.307	1.00	4.30	0.218	0.071	0.350	1.14
16	20		"	0.98	0.307	1.00	4.30	0.218	0.071	0.550	1.79
17	25		"	0.98	0.307	1.00	4.30	0.218	0.071	0.650	2.12
18	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.790	2.57
19	35		"	0.98	0.307	1.00	4.30	0.218	0.071	0.600	1.95
20	45		"	0.98	0.307	1.00	4.30	0.218	0.071	0.475	1.55
21	60		"	0.98	0.307	1.00	4.30	0.218	0.071	0.400	1.30
22	90		"	0.98	0.307	1.00	4.30	0.218	0.071	0.350	1.14

Remarks: All runs are the average values of three trials or more.

Table One (Cont'd.)

Run No.	Breakwater deg.	Breakwater slope	Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	d/L	H/L	Max. Run-up -R- ft.	R/H
23	15		smooth surface	0.98	0.233	1.33	6.63	0.148	0.035	0.340	1.46
24	20		"	0.98	0.233	1.33	6.63	0.148	0.035	0.400	1.72
25	25		"	0.98	0.233	1.33	6.63	0.148	0.035	0.380	1.63
26	30		"	0.98	0.233	1.33	6.63	0.148	0.035	0.425	1.82
27	35		"	0.98	0.233	1.33	6.63	0.148	0.035	0.375	1.61
28	45		"	0.98	0.233	1.33	6.63	0.148	0.035	0.350	1.50
29	60		"	0.98	0.233	1.33	6.63	0.148	0.035	0.300	1.29
30	90		"	0.98	0.233	1.33	6.63	0.148	0.035	0.265	1.14
31	15		smooth board	0.98	0.075	1.00	4.30	0.218	0.017	0.150	2.00
32	15		"	0.98	0.132	1.00	4.30	0.218	0.031	0.200	1.52
33	15		"	0.98	0.186	1.00	4.30	0.218	0.043	0.250	1.34
34	15		"	0.98	0.225	1.00	4.30	0.218	0.052	0.287	1.28
35	15		"	0.98	0.247	1.00	4.30	0.218	0.056	0.337	1.36
36	15		"	0.98	0.263	1.00	4.30	0.218	0.061	0.312	1.19
37	15		"	0.98	0.285	1.00	4.30	0.218	0.066	0.367	1.29
38	15		"	0.98	0.318	1.00	4.30	0.218	0.074	0.387	1.22
39	15		"	0.98	0.329	1.00	4.30	0.218	0.076	0.425	1.29
40	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.775	2.52
41	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.675	2.20
42	30		"	0.98	0.270	1.00	4.30	0.218	0.063	0.587	2.17
43	30		"	0.98	0.260	1.00	4.30	0.218	0.060	0.475	1.83
44	30		"	0.98	0.210	1.00	4.30	0.218	0.049	0.412	1.96
45	30		"	0.98	0.200	1.00	4.30	0.218	0.047	0.300	1.50
46	30		"	0.98	0.180	1.00	4.30	0.218	0.042	0.250	1.39
47	30		"	0.98	0.110	1.00	4.30	0.218	0.026	0.150	1.36
48	30		"	0.98	0.080	1.00	4.30	0.218	0.019	0.100	1.25

Remarks: All runs are the average values of three trials.

Table One (Cont'd.)

Run No.	Breakwater		Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	$\frac{d}{L}$	$\frac{H}{L}$	Max. Run-up -R- ft.	$\frac{R}{H}$
	deg.	slope									
49	45		smooth [redacted]	0.98	0.342	1.00	4.30	0.218	0.079	0.675	1.97
50	45		"	0.98	0.332	1.00	4.30	0.218	0.077	0.612	1.84
51	45		"	0.98	0.293	1.00	4.30	0.218	0.068	0.550	1.88
52	45		"	0.98	0.267	1.00	4.30	0.218	0.062	0.400	1.50
53	45		"	0.98	0.245	1.00	4.30	0.218	0.057	0.325	1.33
54	45		"	0.98	0.224	1.00	4.30	0.218	0.052	0.250	1.12
55	45		"	0.98	0.184	1.00	4.30	0.218	0.043	0.200	1.09
56	45		"	0.98	0.140	1.00	4.30	0.218	0.033	0.150	1.07
57	45		"	0.98	0.075	1.00	4.30	0.218	0.017	0.075	1.00
58	30		smooth board	1.23	0.178	0.70	2.50	0.492	0.071	0.200	1.12
59	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.783	2.55
60	30		"	1.12	0.223	0.800	3.19	0.351	0.071	0.375	1.68

Remarks: All runs are the average values of three trials.

Table Two

Run No.	Breakwater deg. slope		Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	$\frac{d}{L}$	$\frac{H}{L}$	Max. Run-up -R- ft.	$\frac{R}{H}$
1	18		1½ in. max.	0.98	0.170	2.75	14.9	0.066	0.012	0.100	0.590
2	20		angular	0.98	0.170	2.75	14.9	0.066	0.012	0.137	0.806
3	25		stone	0.98	0.170	2.75	14.9	0.066	0.012	0.162	0.954
4	31		"	0.98	0.170	2.75	14.9	0.066	0.012	0.175	1.03
5	36		"	0.98	0.170	2.75	14.9	0.066	0.012	0.125	0.735
6	50		"	0.98	0.170	2.75	14.9	0.066	0.012	0.125	0.735
7	77		"	0.98	0.170	2.75	14.9	0.066	0.012	0.137	0.806
8	90		"	0.98	0.170	2.75	14.9	0.066	0.012	0.175	1.03
9	21		"	0.98	0.307	1.00	4.30	0.218	0.071	0.300	0.979
10	17		"	0.98	0.307	1.00	4.30	0.218	0.071	0.225	0.733
11	24		"	0.98	0.307	1.00	4.30	0.218	0.071	0.325	1.06
12	31		"	0.98	0.307	1.00	4.30	0.218	0.071	0.350	1.14
13	37		"	0.98	0.307	1.00	4.30	0.218	0.071	0.337	1.10
14	52		"	0.98	0.307	1.00	4.30	0.218	0.071	0.325	1.06
15	72		"	0.98	0.307	1.00	4.30	0.218	0.071	0.287	0.935
16	90		"	0.98	0.307	1.00	4.30	0.218	0.071	0.300	0.979
17	17		"	0.98	0.254	0.667	2.26	0.434	0.112	0.137	0.540
18	23		"	0.98	0.254	0.667	2.26	0.434	0.112	0.150	0.590
19	29		"	0.98	0.254	0.667	2.26	0.434	0.112	0.175	0.690
20	35		"	0.98	0.254	0.667	2.26	0.434	0.112	0.225	0.885
21	42		"	0.98	0.254	0.667	2.26	0.434	0.112	0.175	0.690
22	49		"	0.98	0.254	0.667	2.26	0.434	0.112	0.187	0.737
23	72		"	0.98	0.254	0.667	2.26	0.434	0.112	0.175	0.690
24	90		"	0.98	0.254	0.667	2.26	0.434	0.112	0.200	0.788
25	32		"	0.98	0.254	0.667	2.26	0.434	0.112	0.200	0.788
26	17		"	0.98	0.233	1.33	6.63	0.148	0.035	0.200	0.859
27	20		"	0.98	0.233	1.33	6.63	0.148	0.035	0.237	1.02
28	23		"	0.98	0.233	1.33	6.63	0.148	0.035	0.250	1.07
29	28		"	0.98	0.233	1.33	6.63	0.148	0.035	0.287	1.23
30	33		"	0.98	0.233	1.33	6.63	0.148	0.035	0.287	1.23
31	45		"	0.98	0.233	1.33	6.63	0.148	0.035	0.187	0.802
32	60		"	0.98	0.233	1.33	6.63	0.148	0.035	0.225	0.965
33	90		"	0.98	0.233	1.33	6.63	0.148	0.035	0.200	0.859
34	48		"	0.98	0.233	1.33	6.63	0.148	0.035	0.250	1.07
35	38		"	0.98	0.233	1.33	6.63	0.148	0.035	0.300	1.29
36	30		"	0.98	0.233	1.33	6.63	0.148	0.035	0.287	1.23

Remarks: All runs are the average values of three trials.

Table Two (Cont'd.)

Run No.	Breakwater deg.	Breakwater slope	Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	$\frac{d}{L}$	$\frac{H}{L}$	Max. Run-up -R- ft.	$\frac{R}{H}$
37	15		1½ in. max.	0.98	0.329	1.00	4.30	0.218	0.076	0.237	0.720
38	15		angular	0.98	0.318	1.00	4.30	0.218	0.074	0.225	0.708
39	15		stone	0.98	0.285	1.00	4.30	0.218	0.066	0.185	0.649
40	15		"	0.98	0.263	1.00	4.30	0.218	0.061	0.167	0.635
41	15		"	0.98	0.247	1.00	4.30	0.218	0.056	0.151	0.611
42	15		"	0.98	0.225	1.00	4.30	0.218	0.052	0.140	0.620
43	15		"	0.98	0.186	1.00	4.30	0.218	0.043	0.119	0.640
44	15		"	0.98	0.164	1.00	4.30	0.218	0.037	0.106	0.646
45	15		"	0.98	0.132	1.00	4.30	0.218	0.031	0.094	0.712
46	15		"	0.98	0.075	1.00	4.30	0.218	0.017	0.073	0.971
47	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.292	0.953
48	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.258	0.840
49	30		"	0.98	0.270	1.00	4.30	0.218	0.063	0.229	0.849
50	30		"	0.98	0.260	1.00	4.30	0.218	0.060	0.185	0.712
51	30		"	0.98	0.210	1.00	4.30	0.218	0.049	0.172	0.810
52	30		"	0.98	0.200	1.00	4.30	0.218	0.047	0.154	0.770
53	30		"	0.98	0.180	1.00	4.30	0.218	0.042	0.115	0.639
54	30		"	0.98	0.150	1.00	4.30	0.218	0.035	0.096	0.639
55	30		"	0.98	0.110	1.00	4.30	0.218	0.026	0.078	0.708
56	30		"	0.98	0.080	1.00	4.30	0.218	0.019	0.055	0.684
57	45		"	0.98	0.342	1.00	4.30	0.218	0.079	0.336	0.983
58	45		"	0.98	0.332	1.00	4.30	0.218	0.077	0.276	0.832
59	45		"	0.98	0.293	1.00	4.30	0.218	0.068	0.268	0.914
60	45		"	0.98	0.267	1.00	4.30	0.218	0.062	0.258	0.968
61	45		"	0.98	0.245	1.00	4.30	0.218	0.057	0.189	0.772
62	45		"	0.98	0.224	1.00	4.30	0.218	0.052	0.172	0.760
63	45		"	0.98	0.184	1.00	4.30	0.218	0.043	0.146	0.793
64	45		"	0.98	0.150	1.00	4.30	0.218	0.035	0.109	0.729
65	45		"	0.98	0.140	1.00	4.30	0.218	0.033	0.101	0.722
66	45		"	0.98	0.075	1.00	4.30	0.218	0.017	0.053	0.880
67	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.350	1.14
68	30		"	1.12	0.223	0.80	3.19	0.351	0.071	0.150	0.673
69	30		"	1.23	0.178	0.70	2.50	0.492	0.071	0.100	0.563

Remarks: All runs are the average values of three trials.

Table Three

Run No.	Breakwater deg.	Breakwater slope	Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	$\frac{d}{L}$	$\frac{H}{L}$	Max. Run-up -R- ft.	$\frac{R}{H}$
1	17		½ in. pea gravel	0.98	0.254	0.667	2.26	0.434	0.112	0.075	0.296
2	21		"	0.98	0.254	0.667	2.26	0.434	0.112	0.075	0.296
3	24		"	0.98	0.254	0.667	2.26	0.434	0.112	0.113	0.450
4	27		"	0.98	0.254	0.667	2.26	0.434	0.112	0.125	0.493
5	30		"	0.98	0.254	0.667	2.26	0.434	0.112	0.150	0.591
6	35		"	0.98	0.254	0.667	2.26	0.434	0.112	0.187	0.737
7	37		"	0.98	0.254	0.667	2.26	0.434	0.112	0.175	0.688
8	42		"	0.98	0.254	0.667	2.26	0.434	0.112	0.137	0.530
9	54		"	0.98	0.254	0.667	2.26	0.434	0.112	0.125	0.492
10	90		"	0.98	0.254	0.667	2.26	0.434	0.112	0.200	0.788
11	15		"	0.98	0.307	1.00	4.30	0.218	0.071	0.275	0.835
12	23		"	0.98	0.307	1.00	4.30	0.218	0.071	0.275	0.835
13	27		"	0.98	0.307	1.00	4.30	0.218	0.071	0.350	1.14
14	29		"	0.98	0.307	1.00	4.30	0.218	0.071	0.337	1.10
15	33		"	0.98	0.307	1.00	4.30	0.218	0.071	0.375	1.22
16	40		"	0.98	0.307	1.00	4.30	0.218	0.071	0.337	1.10
17	47		"	0.98	0.307	1.00	4.30	0.218	0.071	0.300	0.978
18	72		"	0.98	0.307	1.00	4.30	0.218	0.071	0.225	0.734
19	90		"	0.98	0.307	1.00	4.30	0.218	0.071	0.275	0.835
20	17		"	0.98	0.233	1.33	6.63	0.148	0.035	0.175	0.751
21	20		"	0.98	0.233	1.33	6.63	0.148	0.035	0.225	0.965
22	24		"	0.98	0.233	1.33	6.63	0.148	0.035	0.263	1.13
23	28		"	0.98	0.233	1.33	6.63	0.148	0.035	0.263	1.13
24	32		"	0.98	0.233	1.33	6.63	0.148	0.035	0.275	1.18
25	36		"	0.98	0.233	1.33	6.63	0.148	0.035	0.225	0.965
26	44		"	0.98	0.233	1.33	6.63	0.148	0.035	0.225	0.965
27	54		"	0.98	0.233	1.33	6.63	0.148	0.035	0.175	0.751
28	68		"	0.98	0.233	1.33	6.63	0.148	0.035	0.225	0.965
29	90		"	0.98	0.233	1.33	6.63	0.148	0.035	0.200	0.858
30	17		"	0.98	0.170	2.75	14.9	0.066	0.012	0.100	0.588
31	23		"	0.98	0.170	2.75	14.9	0.066	0.012	0.100	0.588
32	28		"	0.98	0.170	2.75	14.9	0.066	0.012	0.164	0.965
33	32		"	0.98	0.170	2.75	14.9	0.066	0.012	0.175	1.03
34	37		"	0.98	0.170	2.75	14.9	0.066	0.012	0.138	0.812
35	43		"	0.98	0.170	2.75	14.9	0.066	0.012	0.150	0.883
36	52		"	0.98	0.170	2.75	14.9	0.066	0.012	0.150	0.883
37	71		"	0.98	0.170	2.75	14.9	0.066	0.012	0.138	0.812
38	90		"	0.98	0.170	2.75	14.9	0.066	0.012	0.175	1.03

Remarks: All runs are the average values of three trials.

Table Three (Cont'd.)

Run No.	Breakwater deg.	Breakwater slope	Composition of Breakwater	Depth -d- ft.	Wave Height -H- ft.	Wave Period -T- sec.	L ft.	d/L	H/L	Max. Run-up -R- ft.	R/H
39	15		¼ in. pea gravel	0.98	0.329	1.00	4.30	0.218	0.076	0.275	0.835
40	15		"	0.98	0.318	1.00	4.30	0.218	0.074	0.250	0.786
41	15		"	0.98	0.285	1.00	4.30	0.218	0.066	0.225	0.790
42	15		"	0.98	0.263	1.00	4.30	0.218	0.061	0.175	0.665
43	15		"	0.98	0.247	1.00	4.30	0.218	0.056	0.150	0.608
44	15		"	0.98	0.225	1.00	4.30	0.218	0.052	0.137	0.609
45	15		"	0.98	0.186	1.00	4.30	0.218	0.043	0.113	0.609
46	15		"	0.98	0.164	1.00	4.30	0.218	0.037	0.075	0.457
47	15		"	0.98	0.132	1.00	4.30	0.218	0.031	0.050	0.379
48	15		"	0.98	0.075	1.00	4.30	0.218	0.017	0.025	0.334
49	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.300	0.977
50	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.300	0.977
51	30		"	0.98	0.270	1.00	4.30	0.218	0.063	0.250	0.926
52	30		"	0.98	0.260	1.00	4.30	0.218	0.060	0.200	0.770
53	30		"	0.98	0.210	1.00	4.30	0.218	0.049	0.175	0.834
54	30		"	0.98	0.200	1.00	4.30	0.218	0.047	0.150	0.750
55	30		"	0.98	0.180	1.00	4.30	0.218	0.042	0.125	0.696
56	30		"	0.98	0.150	1.00	4.30	0.218	0.035	0.100	0.667
57	30		"	0.98	0.110	1.00	4.30	0.218	0.026	0.063	0.574
58	30		"	0.98	0.080	1.00	4.30	0.218	0.019	0.030	0.375
59	45		"	0.98	0.342	1.00	4.30	0.218	0.079	0.263	0.769
60	45		"	0.98	0.332	1.00	4.30	0.218	0.077	0.230	0.693
61	45		"	0.98	0.293	1.00	4.30	0.218	0.068	0.200	0.683
62	45		"	0.98	0.267	1.00	4.30	0.218	0.062	0.175	0.655
63	45		"	0.98	0.245	1.00	4.30	0.218	0.057	0.160	0.653
64	45		"	0.98	0.224	1.00	4.30	0.218	0.052	0.130	0.580
65	45		"	0.98	0.184	1.00	4.30	0.218	0.043	0.100	0.544
66	45		"	0.98	0.150	1.00	4.30	0.218	0.035	0.075	0.500
67	45		"	0.98	0.140	1.00	4.30	0.218	0.033	0.063	0.450
68	45		"	0.98	0.075	1.00	4.30	0.218	0.017	0.037	0.508
69	30		"	1.12	0.223	0.80	3.19	0.351	0.071	0.267	1.20
70	30		"	0.98	0.307	1.00	4.30	0.218	0.071	0.400	1.30
71	30		"	1.23	0.178	0.700	2.50	0.492	0.071	0.167	0.939

Remarks: All runs are the averages of three trials.

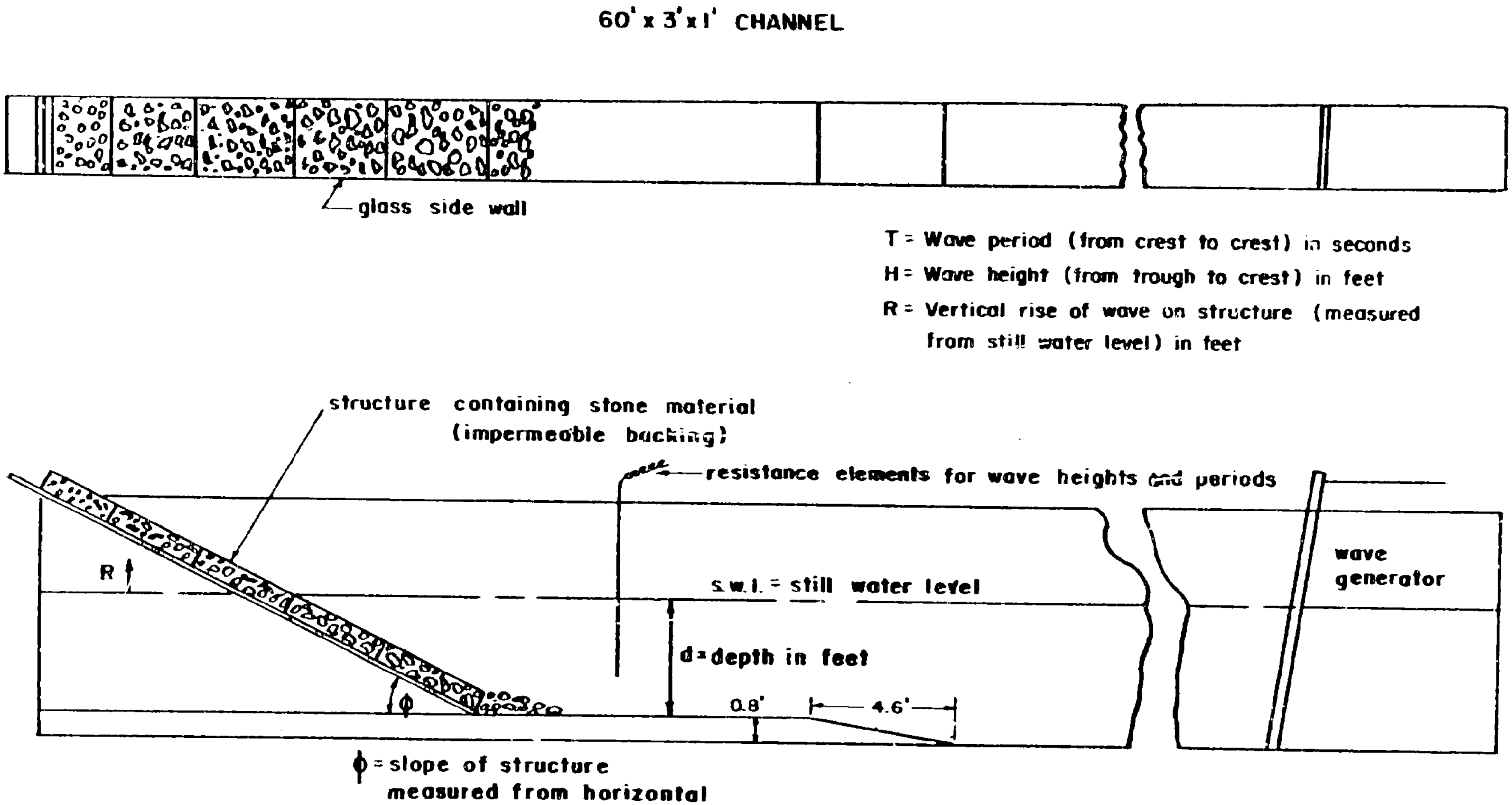

FIGURE 1 – Channel arrangement for model study with test terminology

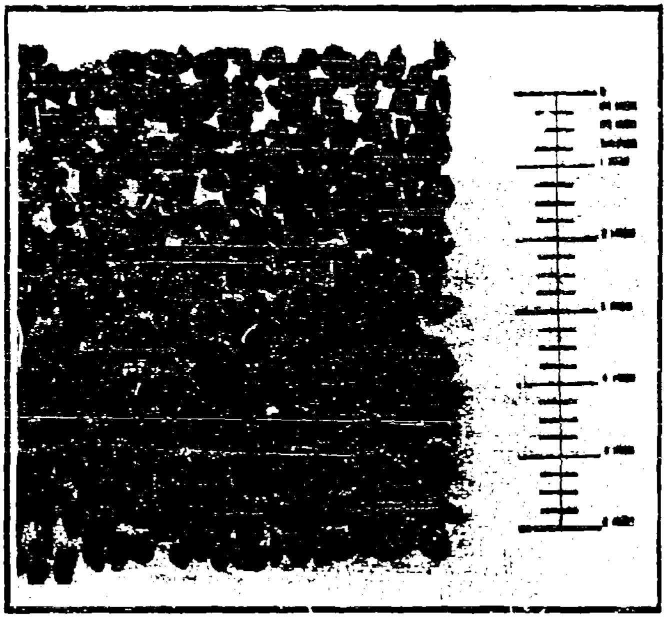

FIGURE 2 - Sample of well rounded pea gravel used in model.

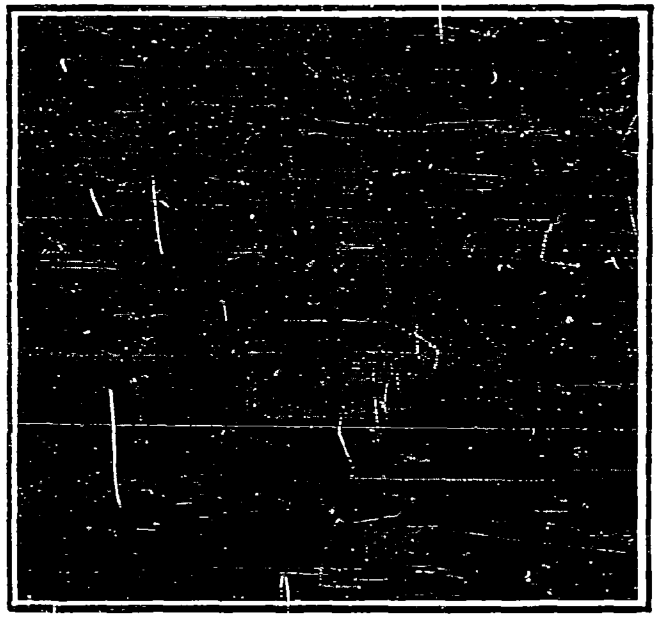

FIGURE 3 - Assembled model with pea gravel in place.

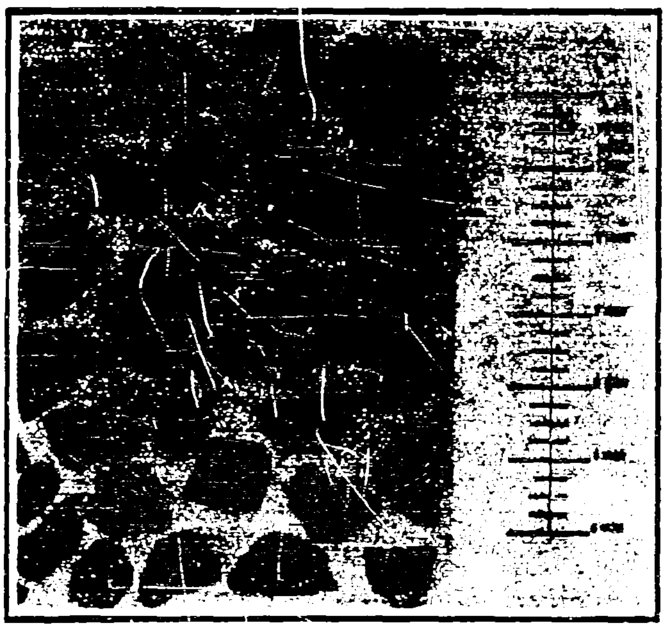

FIGURE 4 - Sample of angular stone used in model.

FIGURE 5 - Assembled modal with angular stone in place.

Keuffel & Esser Co., N. Y. No. 359-81
Semi-Logarithmic, 1 Cycle × 10 to the inch, 5th lines accented.
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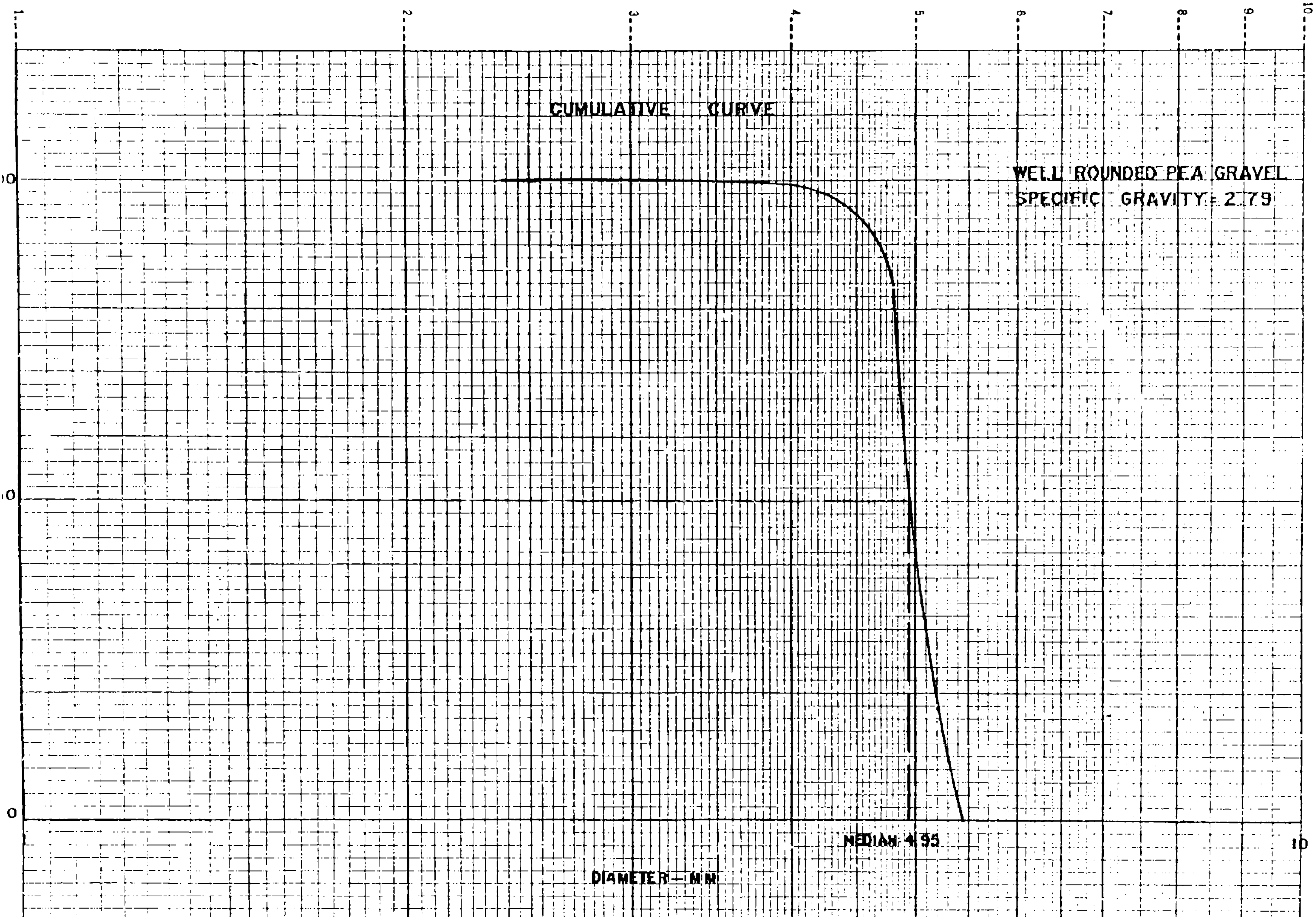


FIGURE 6

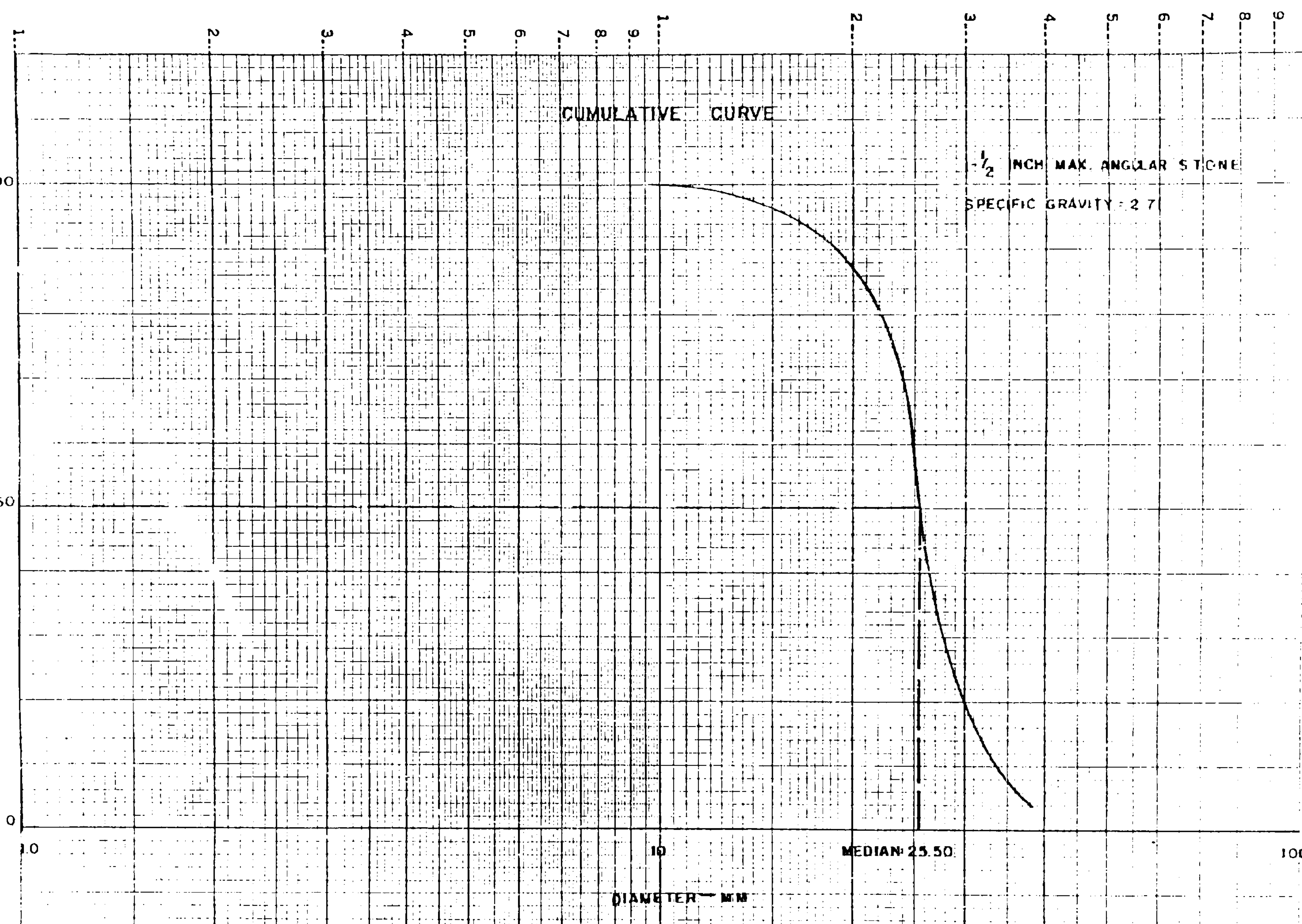

CUMULATIVE CURVE
1-1/2 INCH MAX. ANGULAR STONE
SPECIFIC GRAVITY: 2.7
MEDIAN: 25.50
1.0
10
100
0
50
100
DIAMETER — MM

FIGURE 7

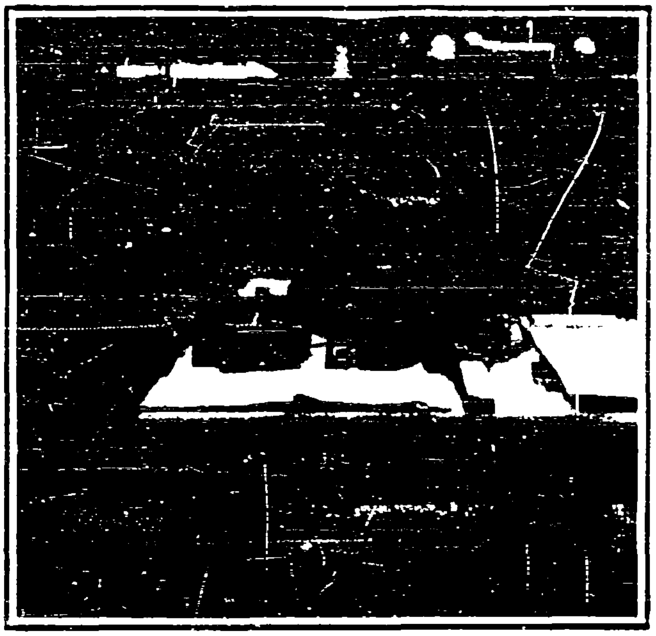


FIGURE 8 - Recording Station.

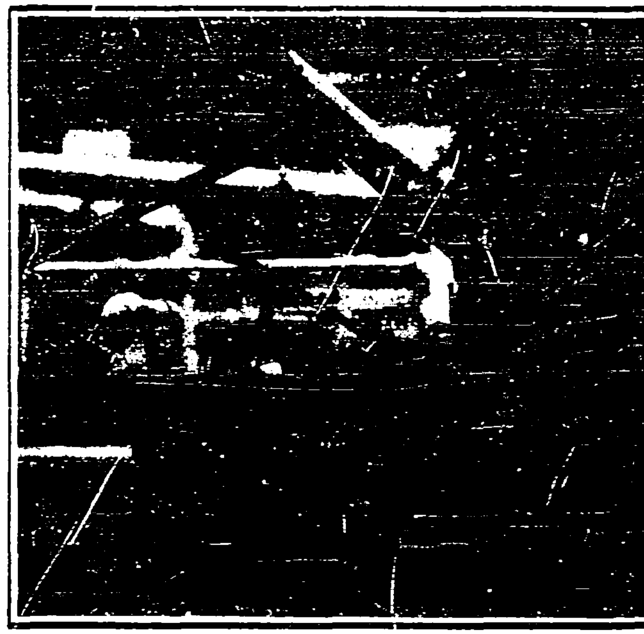


FIGURE 9 - Determining angle of sloping structures.

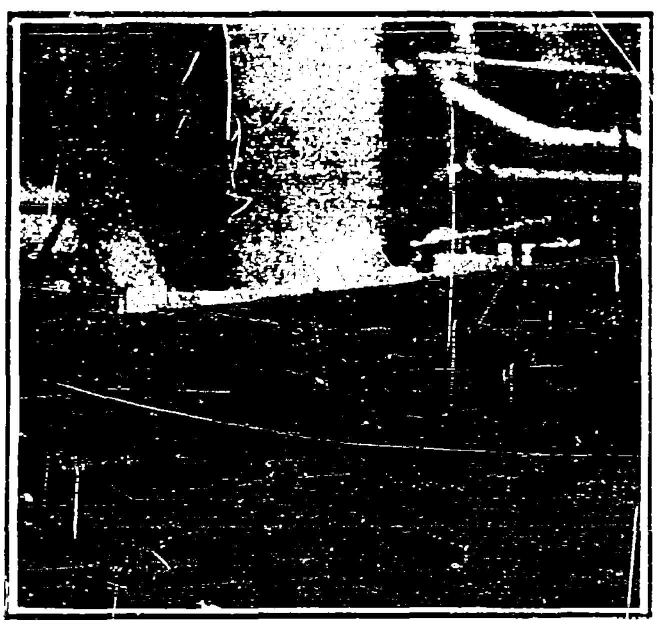


FIGURE 10 - Smooth surface structure and wave measuring elements.

FIGURE 11 - Model wave breaking on permeable structure.

$\phi = 15°$

$\frac{d}{L} = 0.218$

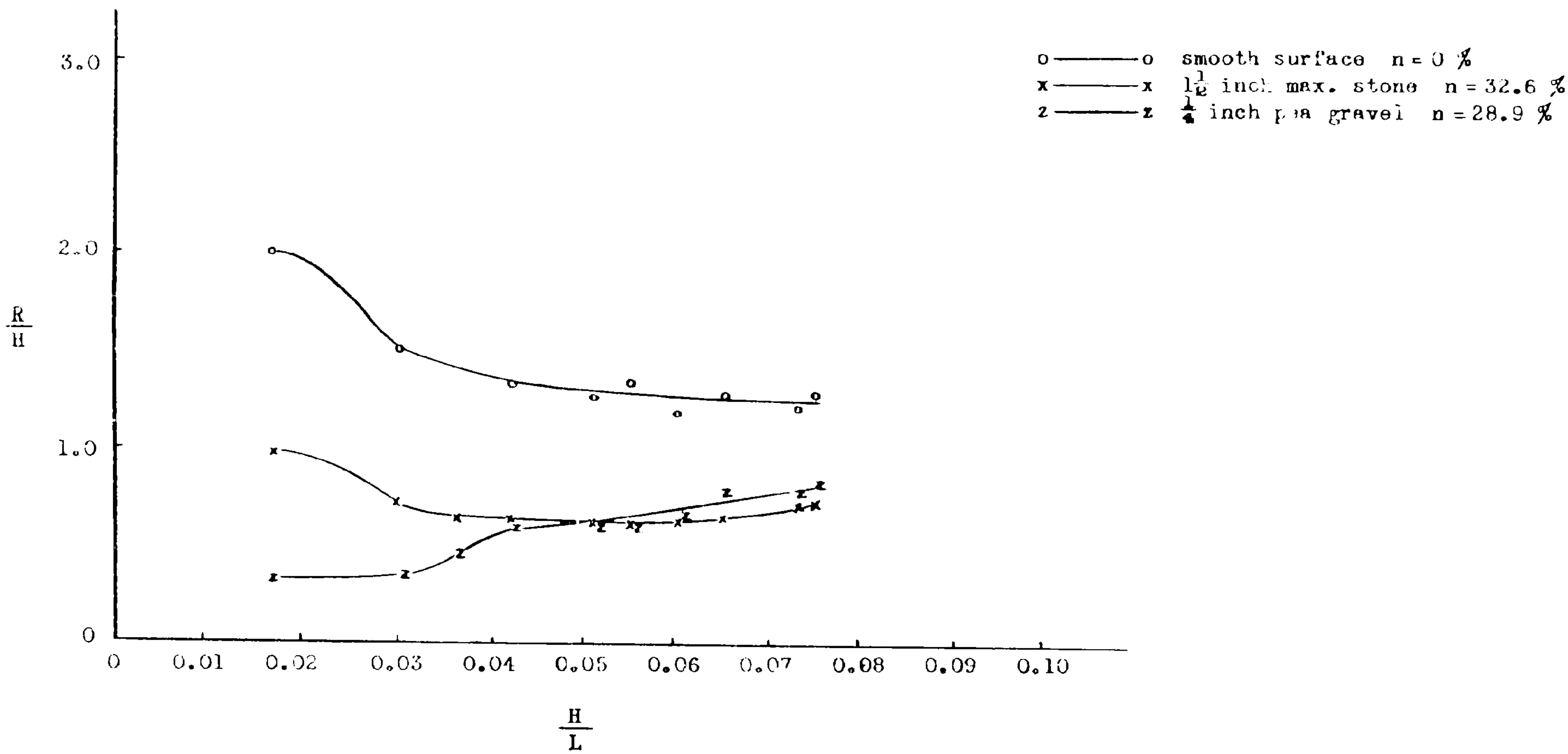
R = vertical rise (from s.w.l.)

H = uniform wave height

ϕ = angle of slope

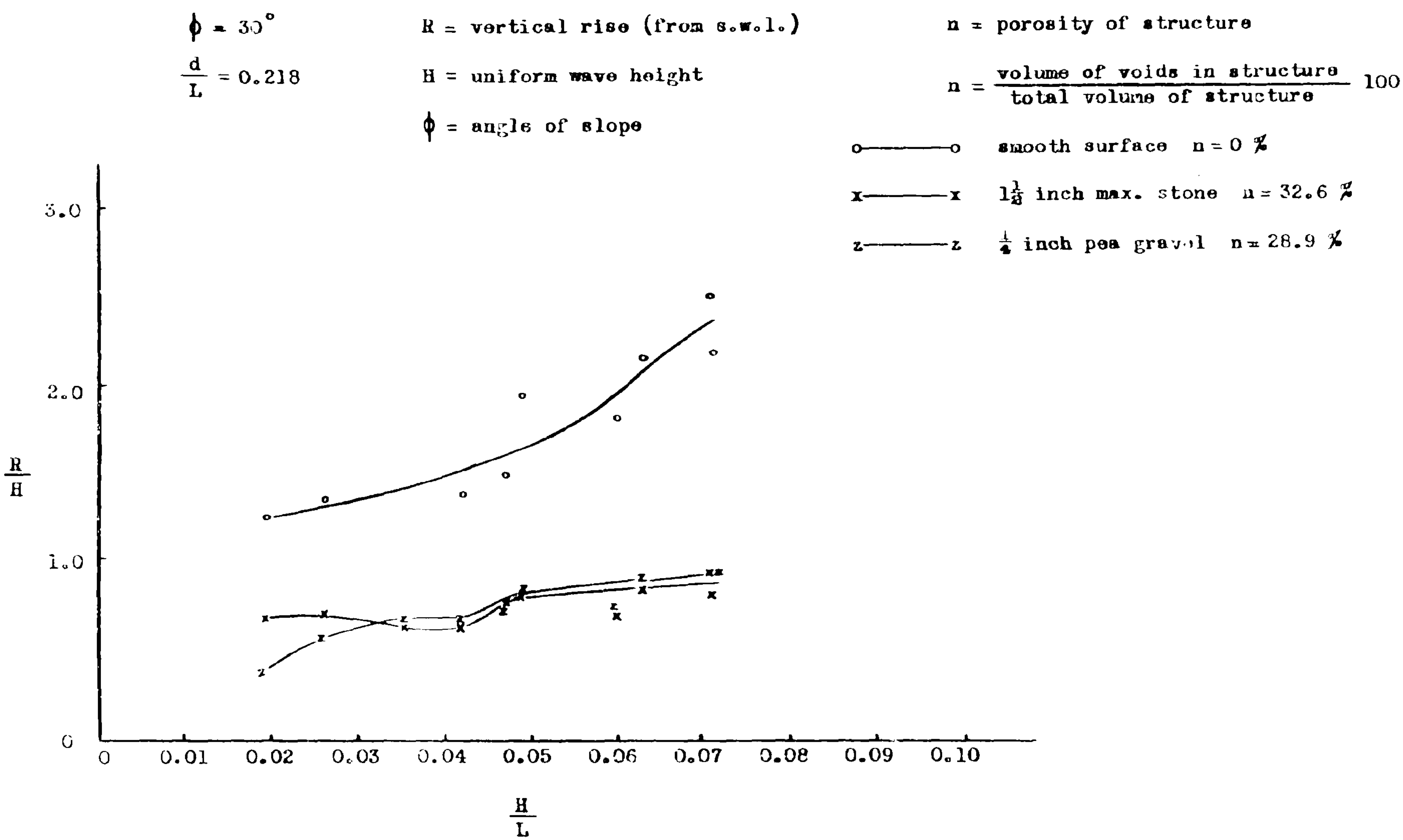
n = porosity of structure

$$n = \frac{\text{volume of voids in structure}}{\text{total volume of structure}} 100$$

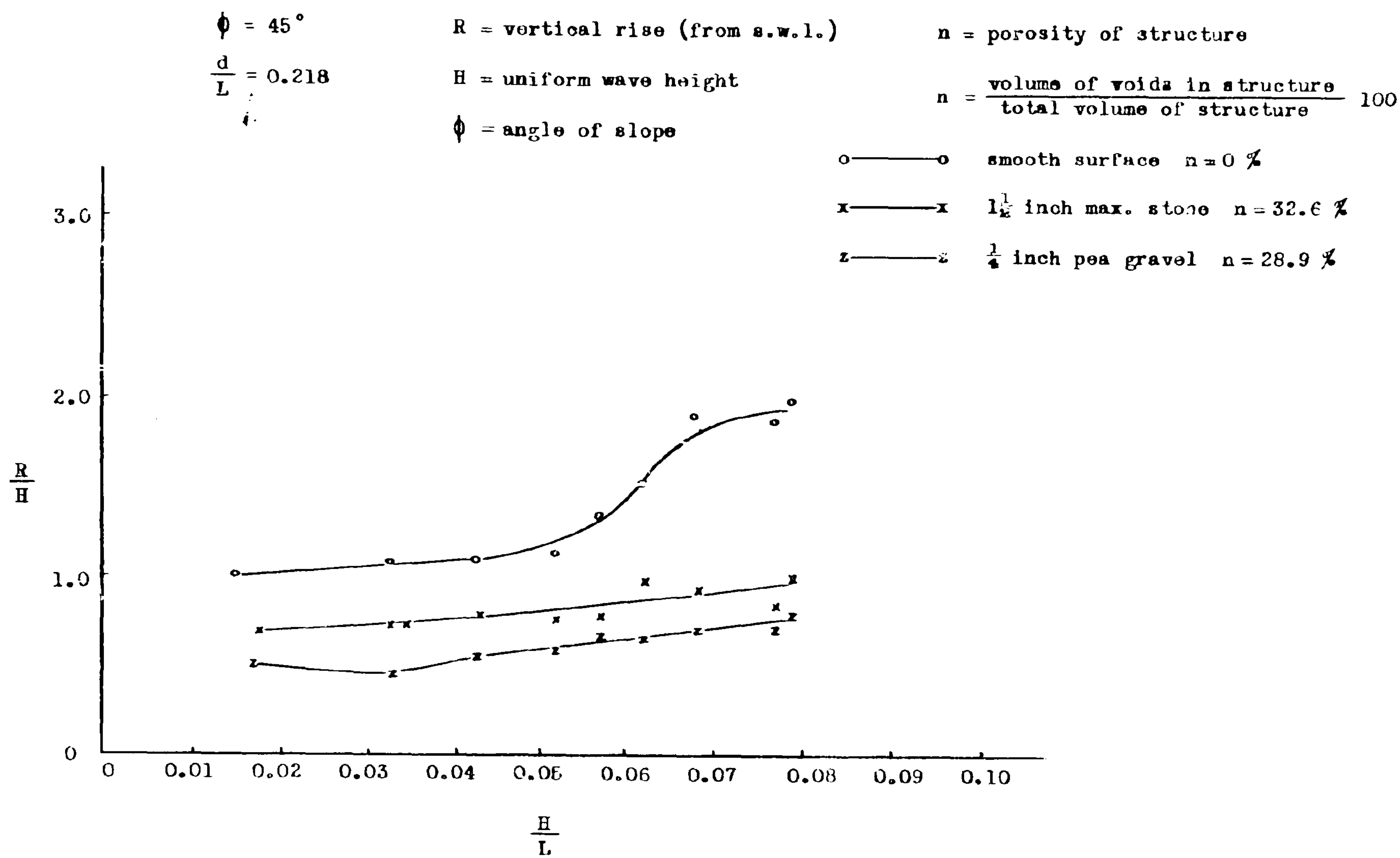


WAVE RUN-UP ON SLOPING STRUCTURES

Figure 12

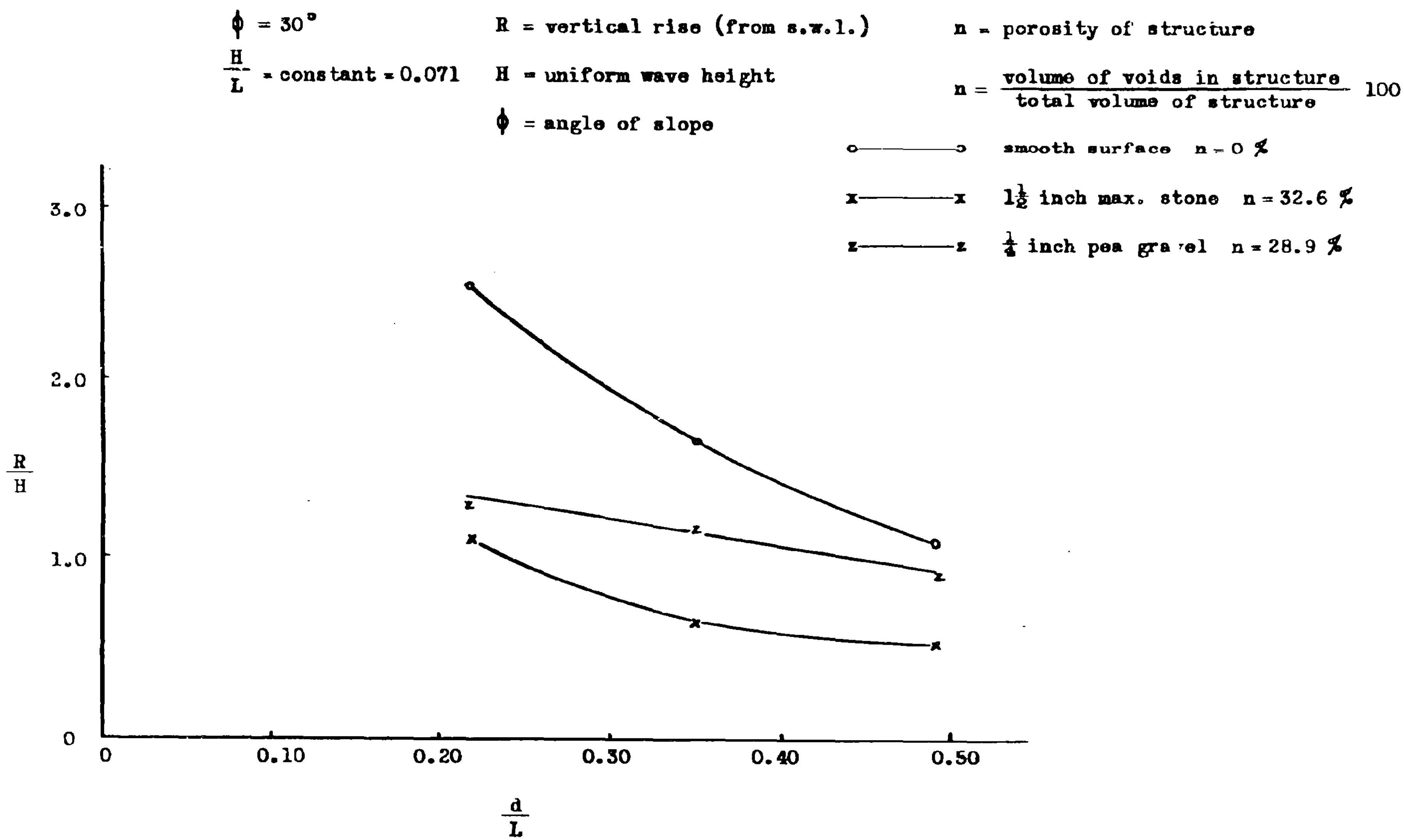


WAVE RUN-UP ON SLOPING STRUCTURES
Figure 13



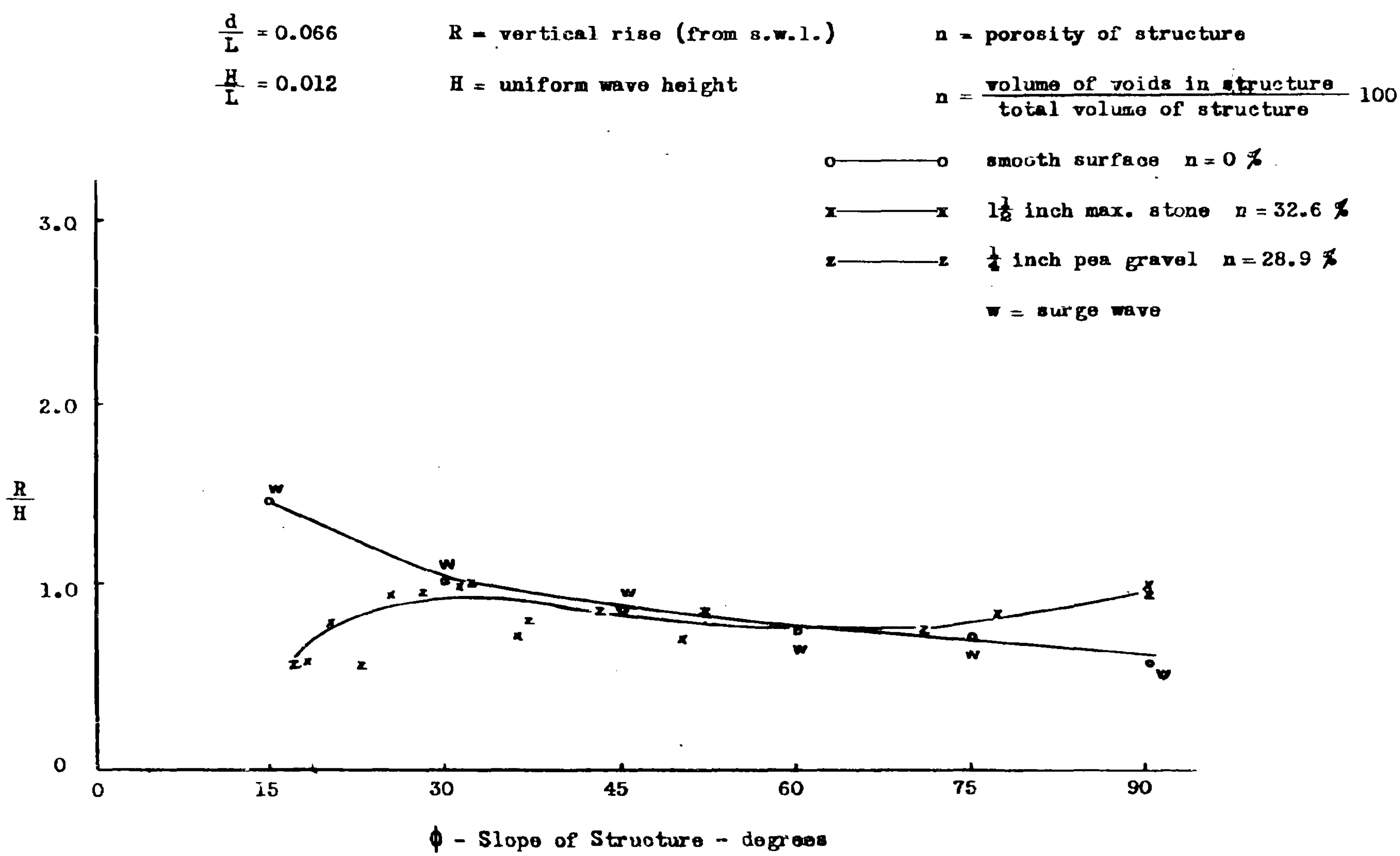
WAVE RUN-UP ON SLOPING STRUCTURES

Figure 14



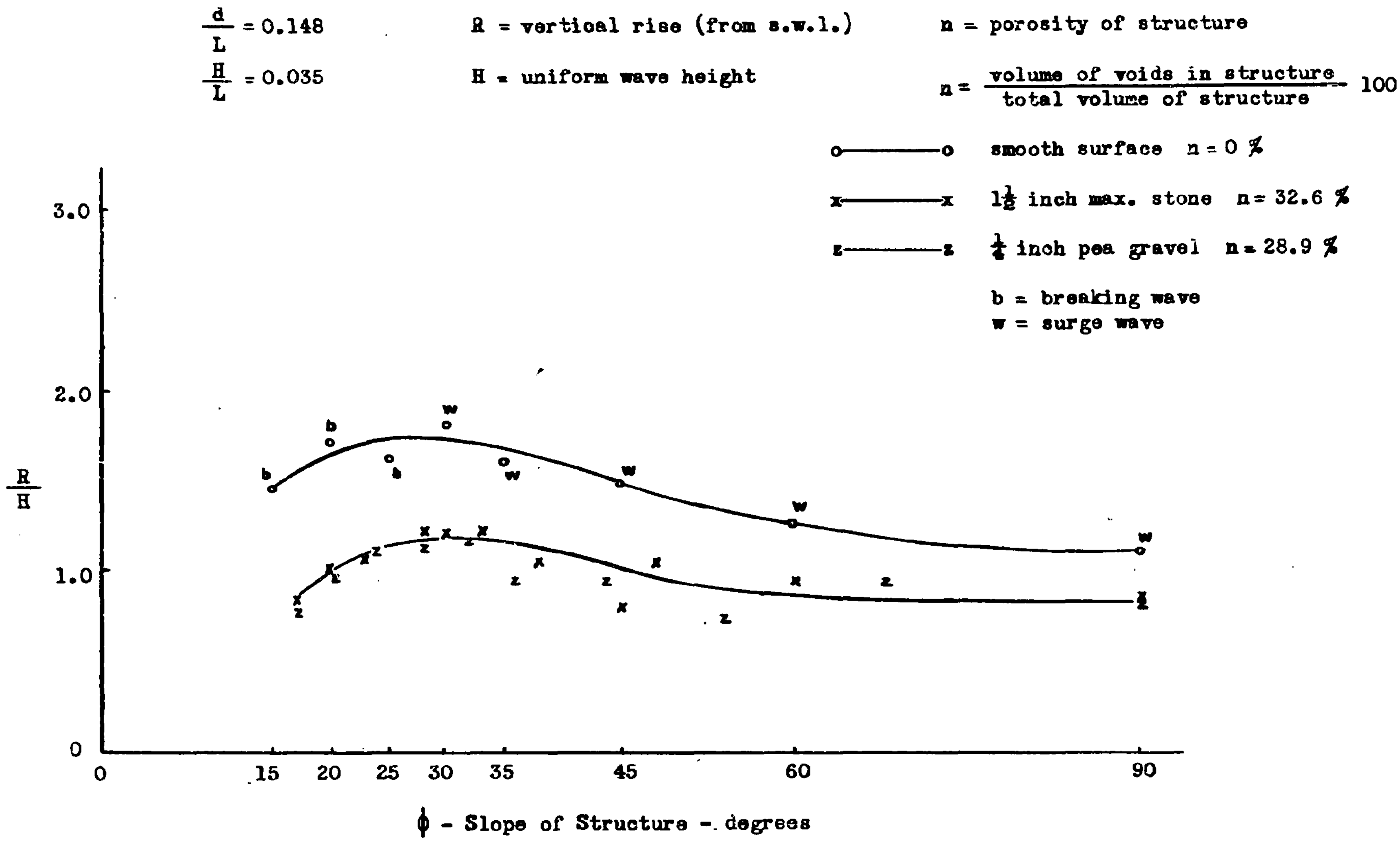
WAVE RUN-UP ON SLOPING STRUCTURES

Figure 15



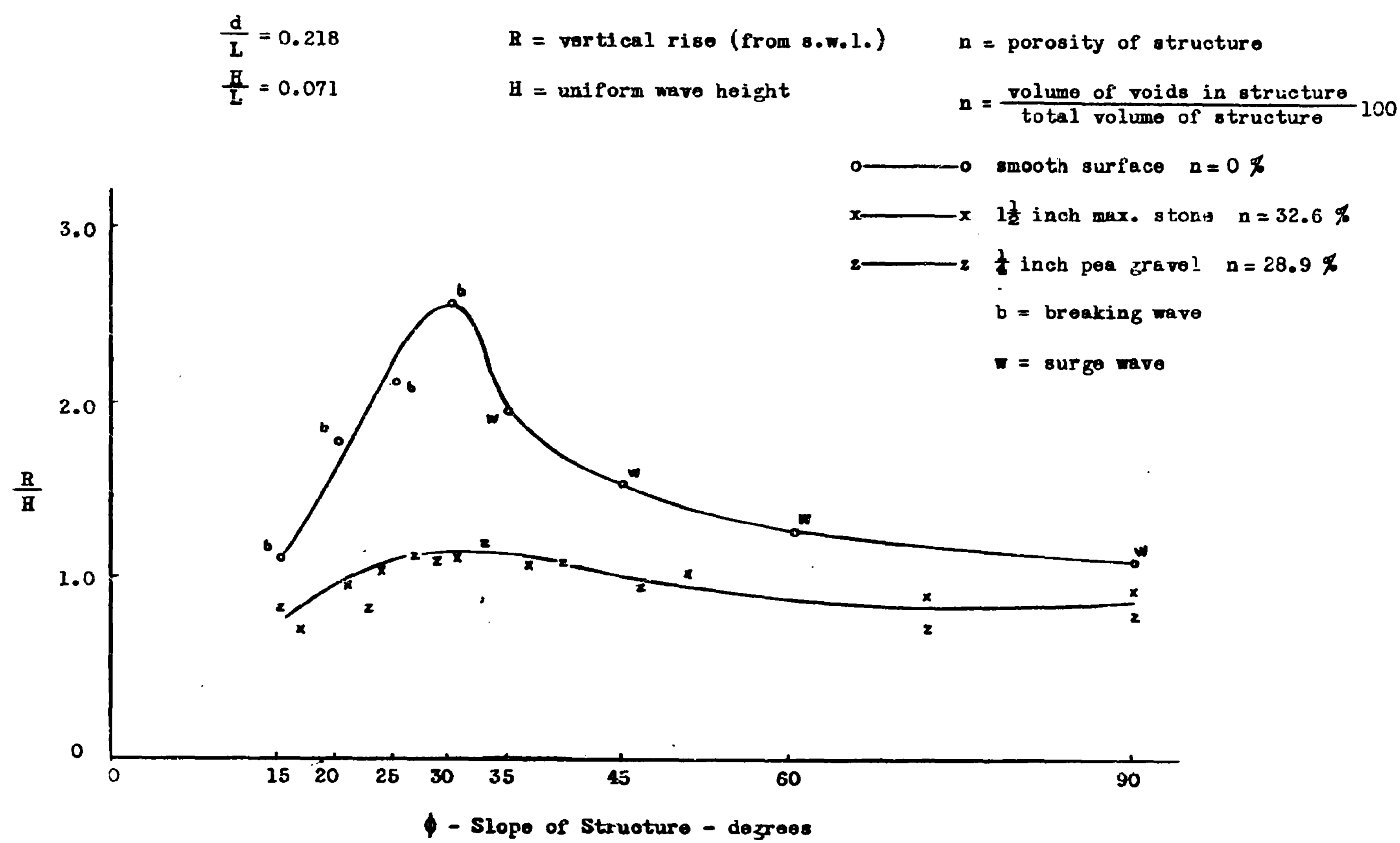
WAVE RUN-UP ON SLOPING STRUCTURES

Figure 16



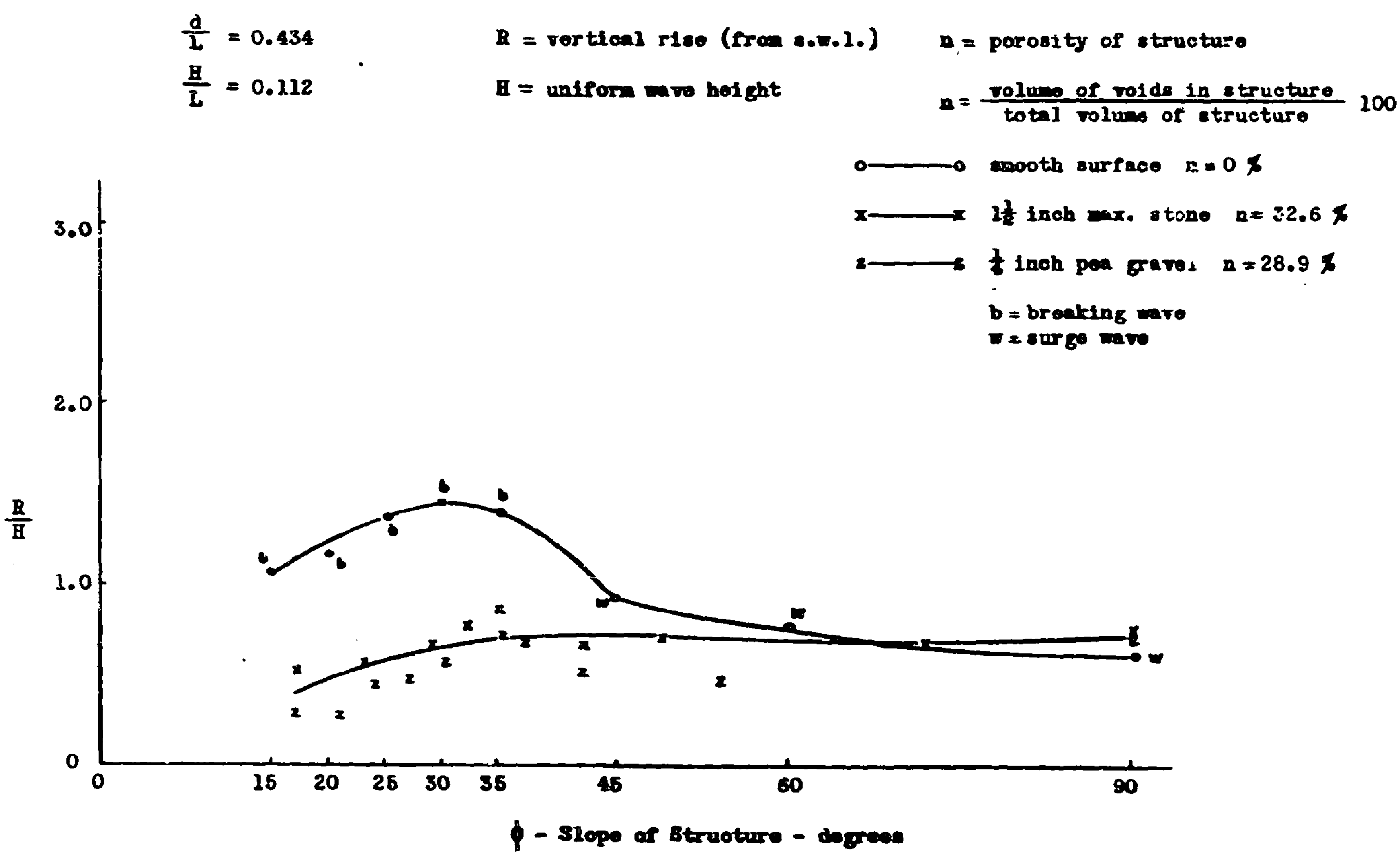
WAVE RUN UP ON SLOPING STRUCTURES

Figure 17



WAVE RUN-UP ON SLOPING STRUCTURES

Figure 18



WAVE RUN-UP ON SLOPING STRUCTURES
Figure 19

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