CHAPTER 46

WAVE DAMPING IN HARBORS

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GENERAL

The purpose of harbors is to give the maximum shelter to vessels to prevent damage or allow greatest ease in loading or unloading. Small craft are most effected by short period waves, while commercial craft are more effected by long period waves or surge. Small craft require that the wave action be reduced to about 1 foot or less in height to prevent damage at moorings. To obtain quietness within the harbor, it is essential to prevent energy from entering the harbor, or, by absorbing it, after it enters. Energy can enter through three sources: through the entrance, by overtopping, or by transmission through the structures. The entrance to the harbor should be made as small as possible to reduce the amount of energy entering yet it must be wide enough to provide navigation ease and safety. The optimum width of the entrance depends on the type of harbor, the amount of traffic, size of the vessels, and entrance conditions.

Assuming the layout of the harbor structures as being fixed, several methods may be used to obtain maximum quietness. Porous breakwaters may be sealed. If a narrow channel is feasible, flat channel side-slopes protected by a rubble cover layer will dissipate a large portion of the energy. Wave energy reaching the interior may be absorbed by suitably placed stone wave absorbers or dissipators. Discussion of some recent pertinent studies follows.

EFFECT OF HARBOR OSCILLATIONS

It was considered that before proper absorbing measures could be devised for small craft harbors it was necessary to obtain a better understanding of the reaction of small craft to various oscillations. Therefore, through the Engineering Studies Program of the Corps of Engineers, a contract was entered into with the California Institute of Technology to perform such a study. This study consists of three phases:

1. The investigation of the motions of simple bodies elastically moored to a fixed support and subjected to standing waves having depth to wave length ratios which range from the limits of deep water to shallow water waves.

2. The study of the motion of simple bodies elastically moored to floating platforms which are in turn moored to fixed supports. This mooring arrangement has some of the features of a typical marina mooring system.

3. The investigation of the wave induced oscillations in basins of arbitrary shape.

Phase 1 of the study has been completed, a report[1/] has been prepared by Dr. Fredric Raichlen who is presenting a paper on the subject at this conference.

Upon completion of this portion of the study, further investigation will follow at the U. S. Army Engineer Waterways Experiment Station to determine practical methods of absorbing the energy causing the critical oscillations.

WAVE ABSORBERS

The effect of flat channel side slopes on wave dissipation in a harbor has been investigated by hydraulic model. The one discussed herein was constructed to a scale of 1 to 100 for an entirely artificial facility on a relatively exposed coast. Tests were made using a depth of 24 feet below LLW with no breakwaters, with an arrow head system of rubble mound breakwaters and with a parallel system of rubble mound breakwaters. The layout with a 24 foot depth had a width between breakwater heads of 420 feet. Additional tests were made with a 34-foot depth and 530 feet between the centerline of the breakwater heads. In all cases, the channel was 120 feet wide at the bottom and all wave absorbing slopes were 1 on 5. Figure 1 shows the elements of the model, and Figure 2 is a photograph of the model. On Figure 1, the parallel breakwaters are shown in a solid line and the arrow head position of the breakwaters is shown in broken line. Table 1 shows the plans tested in the model.

An extremely high degree of damping was obtained using the narrow channels and the flat side slopes. Increasing the channel depth to 35 feet had insignificant effect on the damping characteristics. This is shown on Table 2, "Effects of Plans", which gives data obtained for waves 10 feet in height, a 10-second period, and approaching directly into the entrance channel. Figure 3 is a data plot of the most effective plans for the 24-foot depth, using waves 10 feet in height, with 6-, 10-, and 14-second periods. This shows that, after the wave entered the entrance channel, the difference in period had no significant effect on the damping. The plot on Figure 3 also shows that within the mooring basin there is also little difference in effect between the arrow head and parallel breakwaters. Figure 4 shows similar data for the 35-foot depth. Lower waves are obtained in the inner portion of the entrance channel with the parallel breakwaters. It is also of note that experience indicates parallel jetties cause a lesser degree of sedimentation than the arrow head. This is more significant when the range of tide is relatively large.

1/ "Wave Induced Oscillations of Small Moored Vessels" by Frederic Raichlen, Report No. KH-R-10, W. M. Keck Laboratory, California Institute of Technology, October 1965.

TABLE 1

PLANS TESTED

Plan	Description
1	No breakwaters, curved spending beaches paved, 24-foot depth.
2	Arrow head breakwaters 420 ft. between ℄ at heads. 24-foot depth. Curved spending beaches paved.
2A	As plan 2 except 3 thicknesses of 1/4 in. stone on all spending beaches.
2B	As plan 2A except 1/2 in. stone on curved spending beaches.
2C	As 2A except 3/4 in. stone on curved spending beaches.
2D	As 2A except 1/2 in. and 3/4 in. stone on curved spending beaches.
3D	Parallel breakwaters, 420 ft. between ℄. 3 thicknesses of stone on all spending beaches. 1/4 in. stone on wave spending beach, 3/4 in. and 1/2 in. on curved spending beaches.
4	Arrow head breakwaters, 530 ft. between ℄ at head. 35-foot depth. All spending beaches paved.
4D	As 4 except 3/4 in. stone on seaward half and 1/2 in. stone on harborward half of curved spending beach.
5D	As plan 4D except breakwaters parallel.

TABLE 2 - EFFECT OF PLANS

10 ft., 10 sec. wave from ENE

Plan	Spending Beaches	Breakwaters	W	Depth	Gage	1	2	3	4	5	6	7	8	9	10	11	12
1		N		24		8.4	8.6	6.6	3.7	1.5	2.0	1.8	1.5	1.7	2.2	1.0	1.0
2			420'	24		10.2	11.0	4.0	2.7	14.	1.1	0.6	0.7	0.6	0.9	0.7	0.7
2A	*		420	24		10.1	9.4	5.9	1.5								
2B	*		420	24		9.5	9.9	6.9	1.2								
2C	*		420	24		10.8	10.4	7.2	1.3								
2D	*		420	24		10.2	9.2	5.6	1.0	0.3	0.2	0.2	0.3	0.3	0.2	0.2	0.2
3D	*	P	420	24		9.5	8.8	6.1	1.0	0.2	0.1	0.2	0.3	0.3	0.3	0.3	0.2
4			530	35		9.0	7.3	4.4	2.4	1.1	0.5	1.5	1.5	1.6	1.4	1.2	1.0
4D	*		530	35		10.2	8.7	4.9	1.5	0.3	0.2	0.6	0.4	0.5	0.4	0.2	0.3
5D	*	P	530	35		9.4	8.6	6.7	1.7	0.3	0.3	0.6	0.5	0.5	0.4	0.3	0.4

Note: * Rubble beaches, all others paved.
P Parallel breakwaters, all others arrow head.
N No breakwaters.
W Width between heads of breakwaters.

Comparison of 2 to 2D and 4 to 4D show value of rubble beaches.

Comparison of 2D to 3D and 4D to 5D show effect of arrowhead and parallel breakwaters.

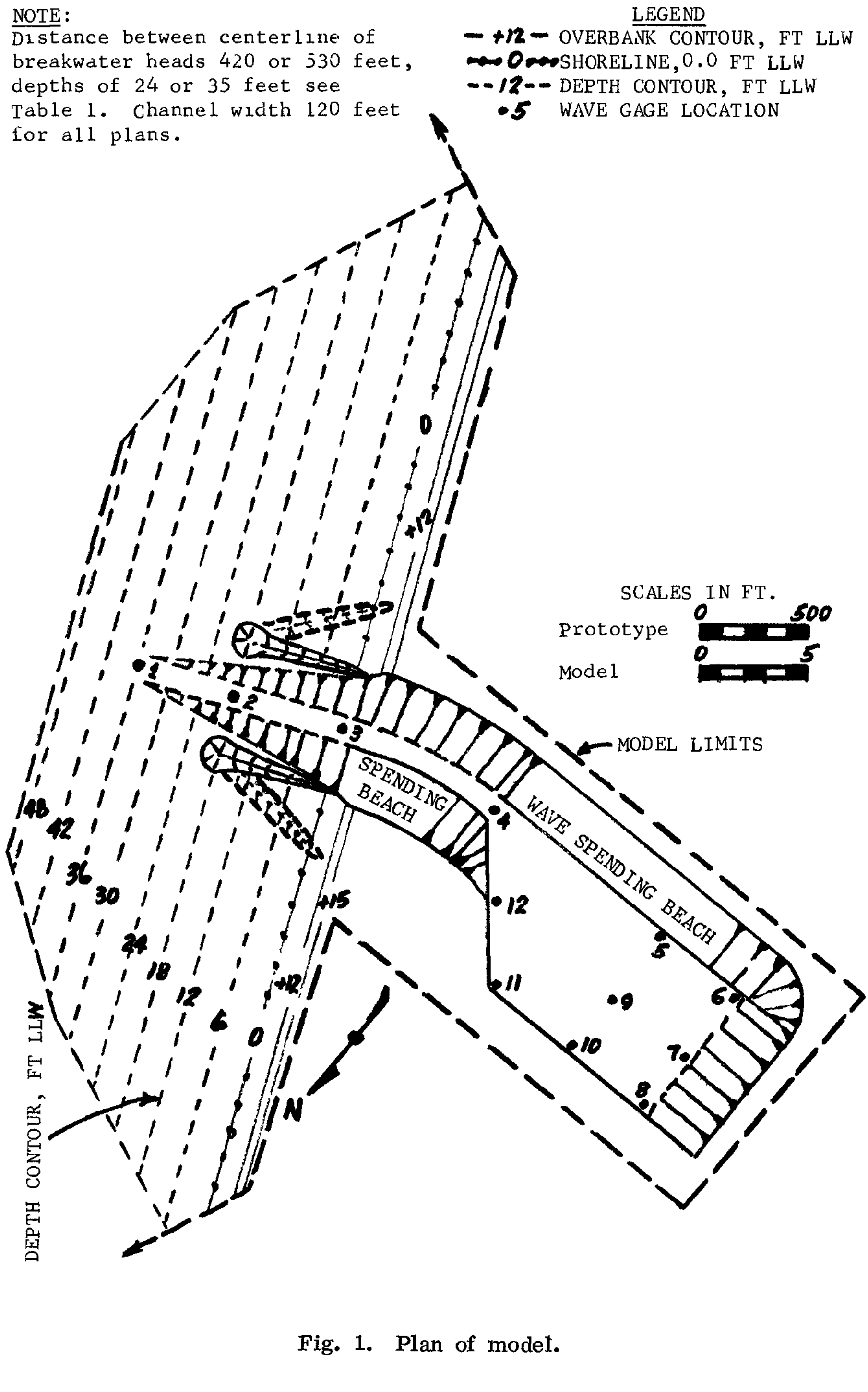


Fig. 1. Plan of model.

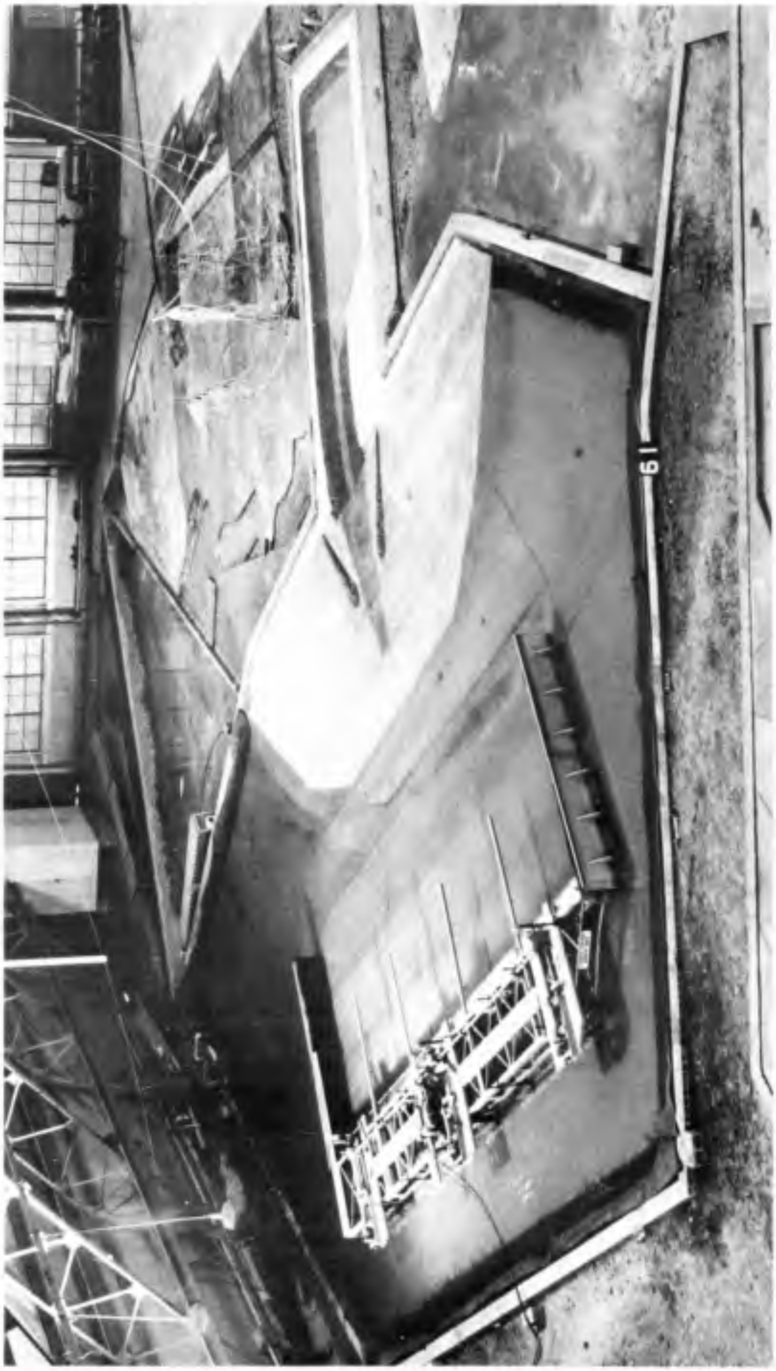


Fig. 2. Photograph of model.

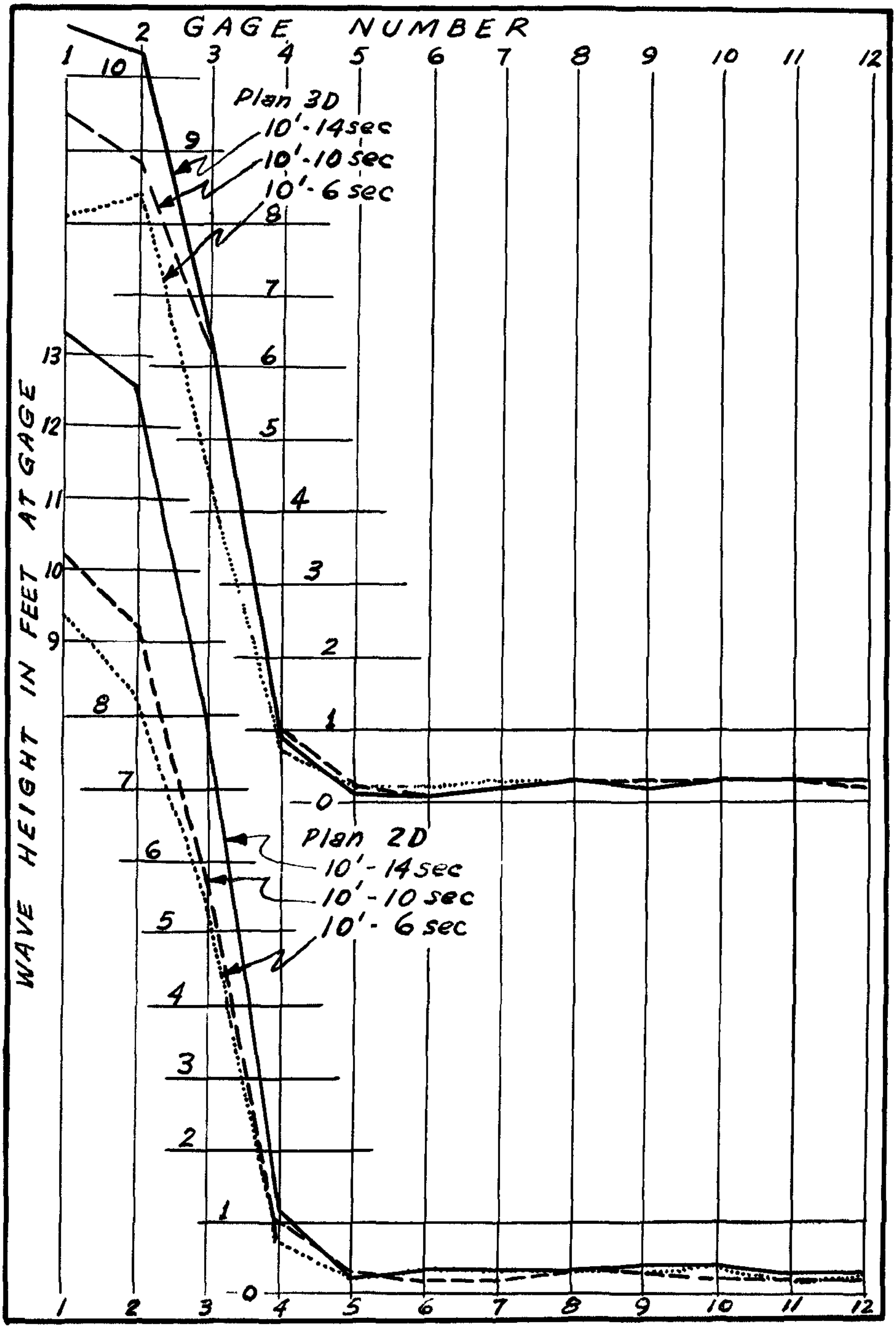


Fig. 3. Effect of wave period - 24-ft. depth.

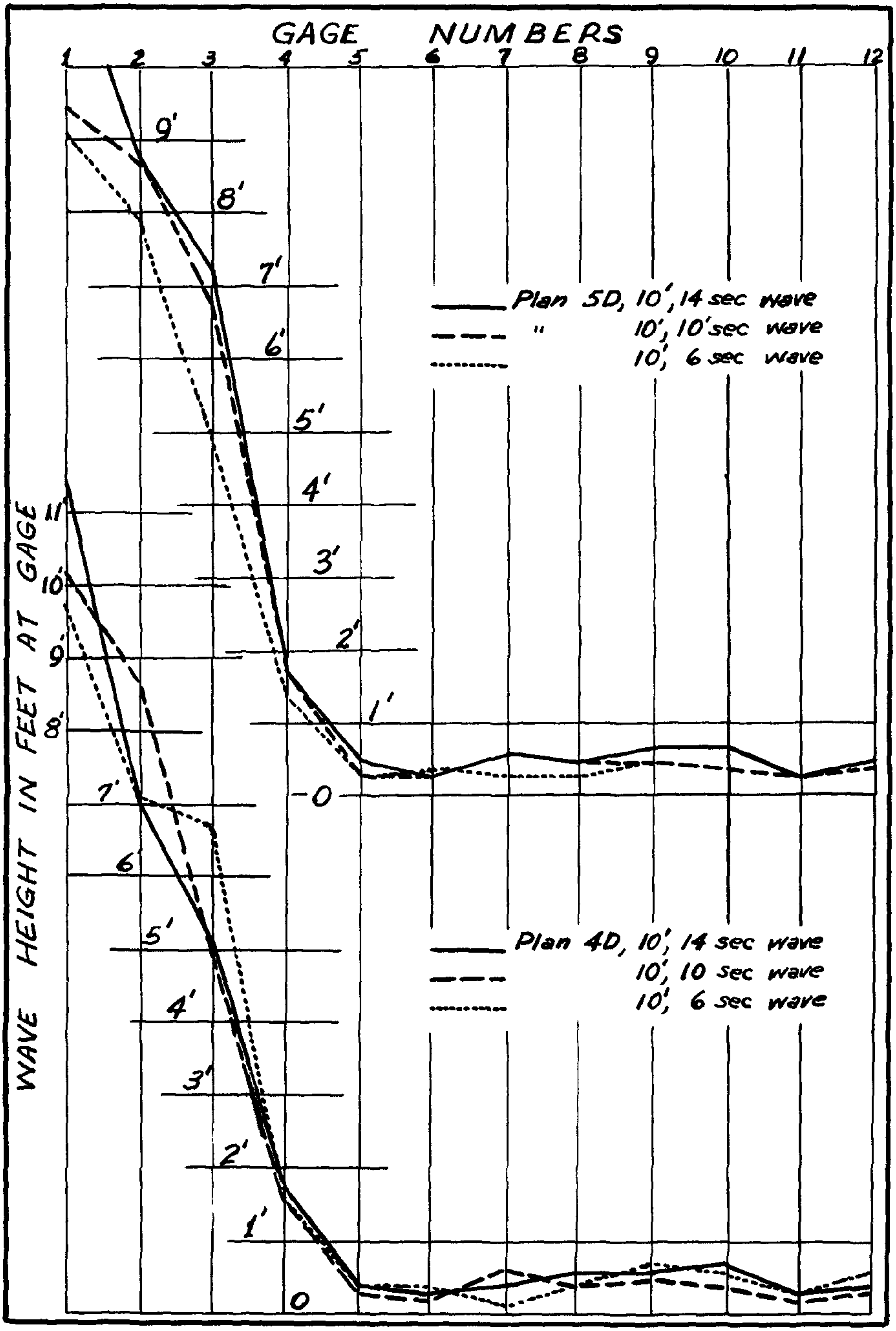


Fig. 4. Effect of wave period - 35-ft. depth.

In order to devise an effective comprehensive program of research, all existing data on the subject should be analyzed and evaluated while critical aspects of research and experimentation on specific projects continue. On this basis a contract was made with National Engineering Science Company to make a preliminary study of wave absorbers. The study was made and a report[2/] prepared. It was found that wave absorbers work effectively in a harbor with a small entrance and become less effective in the case of a harbor with a large entrance. A critical survey of different kinds of wave absorbers was presented. The report indicated that sloped wave absorbers with three layers of large rocks is most efficient and economical. It was also shown that wave transmission through a rock fill breakwater is smaller in small-scale models than in the prototype, and therefore greater wave reflection is obtained in the model than in the prototype. The report developed several new theories. They are:

1. A theory for wave agitation in a rectangular basin subjected to incident irregular waves, taking into account the effect of a wave absorber.

2. A theory for optimization of rock size for wave absorbers and similitude of wave reflection.

3. A theory giving the coefficient of reflection for a permeable vertical wall in front of a vertical quay.

4. A theory for optimization of long wave energy absorption within a harbor.

5. A theory for a progressive wave filter.

The report also stated that the scale effects of wave transmission through a rubble breakwater, which is related to phenomenon of energy absorption by a rubble wave absorber, is insignificant for model scales from about 1 to 20 to 1 to 35.

In 1959, a hydraulic model study[3/] was conducted at the U. S. Army Engineer Waterways Experiment Station to determine if navigation conditions in Gary Harbor, Indiana would be adversely affected by waves reflected from an adjacent vertical-walled bulkhead which was proposed for construction. A test program was devised to determine whether the bulkhead would reflect a high percentage of the wave energy into the navigation lanes, and if it did, to determine the proper length, position, and type of wave absorber needed to reduce the heights of the reflected waves to an acceptable level. Tests were accomplished on two types of models: (a) a 1:150 scale, fixed bed, three-dimensional harbor model; and (b) 1:50 scale, two-dimensional models, designated section models.

2/ "Wave Absorbers in Harbors" by Bernard LeMehaute, National Engineering Science Company, June 1965.

3/ "Waterways Experiment Station Technical Report No. 2-509, "Location and Design of Wave Absorber, Gary Harbor, Indiana", June 1959.

From tests on the 1:150 scale model it was determined that the proposed vertical bulkhead would reflect waves that would be hazardous to navigation, and that a 4,450-foot long rubble wave absorber would have to be placed along the structure to reduce heights of reflected waves in the navigation channel. It was also found that a 375-foot long rubble breakwater, located 675 feet east of the slip, would be required to reduce current velocities in the vicinity of the slip entrance. See Figure 5 for layout of the harbor model.

Tests were then conducted on the 1:50 scale models, installed in a flume, to determine the energy absorbing characteristics of 4 layers or 2 layers of armor stone on various slopes. It was found that for the waves used in this study an absorber composed of 2 layers of quarry stone armor on a 1 on 3.2 slope was the most economical approach to insure that heights of waves reflected from the proposed bulkhead into the navigation areas would not be greater than 2 feet.

The data from the section models are of major interest to the purpose of this paper as they were used to design the absorbers and determine their absorbing characteristics. The tests were conducted in a 94-foot long, glass sided wave flume, one foot wide, with a wave generating machine at one end and the test section at the other. The test section was 1.5 feet deep and 1 foot wide. The tests were performed in accordance with the Froude's model law Typical plans tested are shown on Figure 5 taken from Reference 3.

The study was directed toward the determination of a reflection coefficient. The proportion of wave energy absorbed by a structure can be determined by the equation

$$E_a = 1 - (H_r/H_i)^2 \tag{1}$$

where H_r is the reflected wave height, H_i is the incident wave height, and E_a is the percentage of wave energy absorbed. The term H_r/H_i is referred to as the reflection coefficient. It was shown by Keulegan[4] that the reflection coefficient may be determined from the equation

$$H_r/H_i = \frac{H_l - H_n}{H_l + H_n} \tag{2}$$

where H_l is the wave height measured at a loop point (one-half wave length from structure), and H_n is the wave height measured at a node point (one-fourth wave length from structure). It was necessary to modify the Keulegan equation for this study since it had been derived assuming sinusoidal waves of small height while the model tests utilized trochoidal waves of appreciable height. It was estimated from previous tests that waves reflected from an impervious vertical wall have reflection coefficients of about 0.95 rather than 1.00, due to friction loss. Based

4/ "A Method of Determining the Form of Oscillatory Waves Reflected from a Breakwater" by G. H. Keulegan, U. S. National Bureau of Standards, Washington, D. C., 1950 (unpublished).

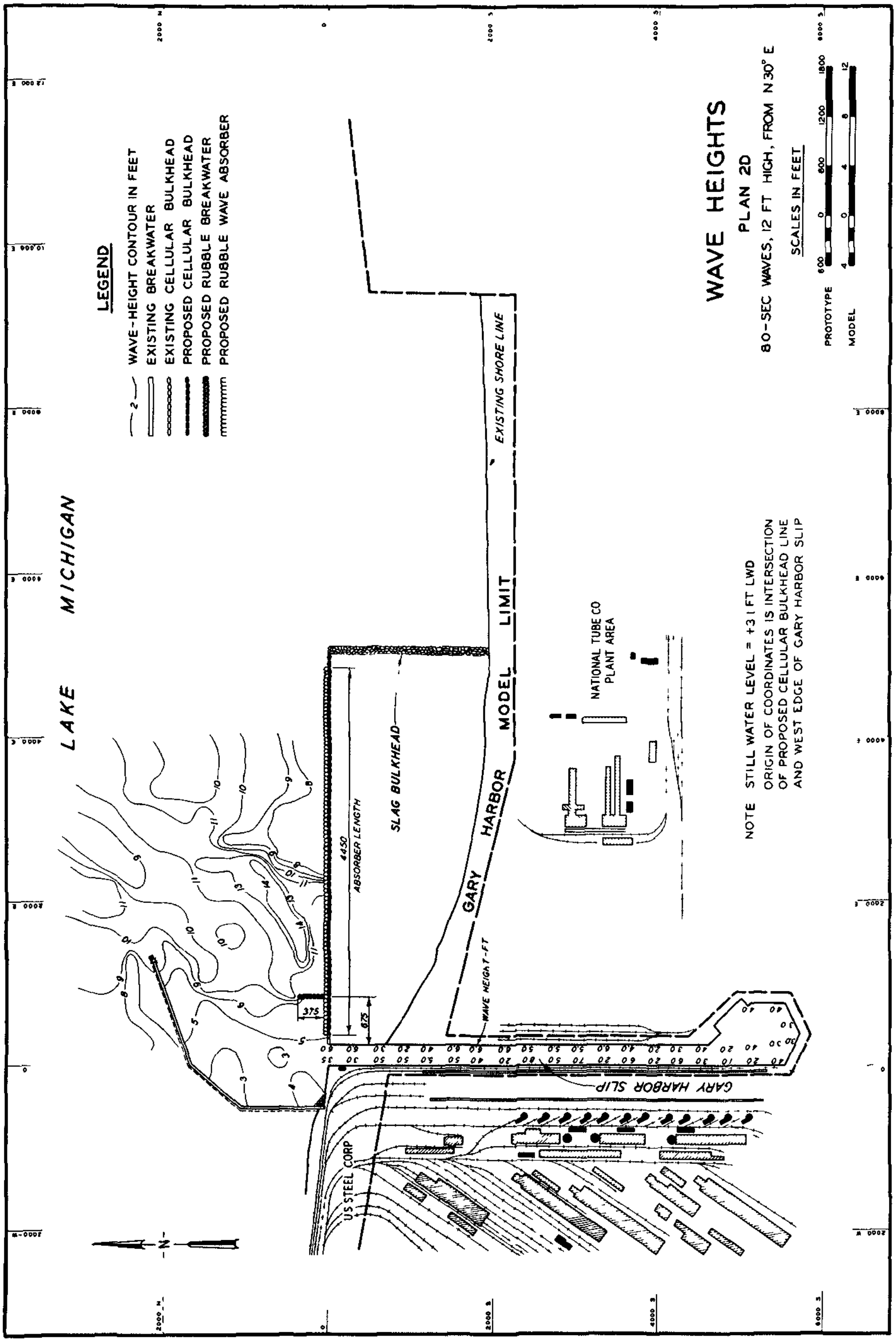
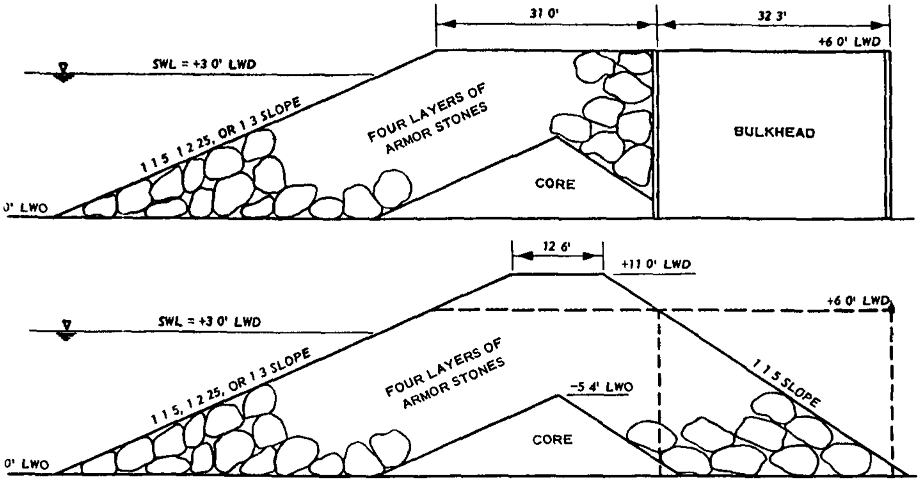
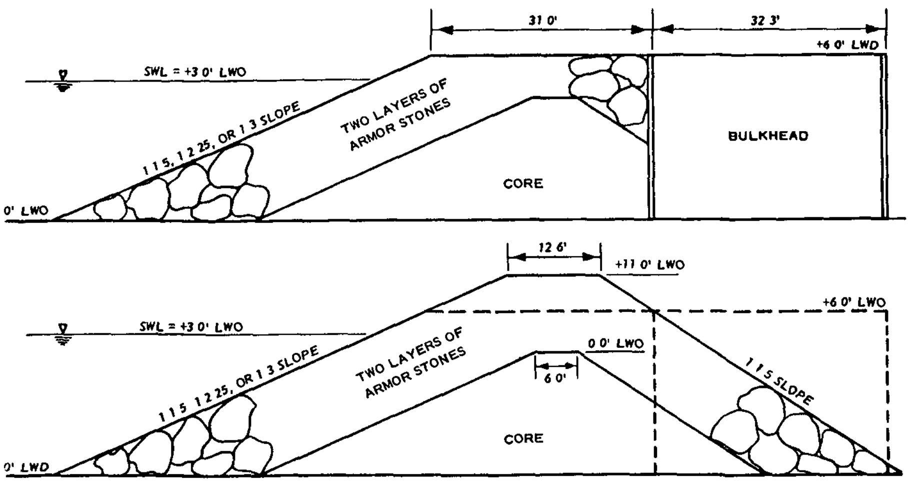


Fig. 5. Gary Harbor model.



Details of rubble-mound bulkhead test section A (lower figure), and sheet-steel-pile bulkhead with a rubble wave absorber (upper figure), using four layers of quarrystone armor units.



Details of rubble-mound bulkhead test section B (lower figure), and sheet-steel-pile bulkhead with a rubble wave absorber (upper figure), using two layers of quarrystone armor units.

Fig. 6. Section models - Gary Harbor, Ill.

on a reflection coefficient of 0.95, and measurements of H_1 and H_n for waves reflected from a vertical wall, values of an experimentally determined coefficient (k) were derived for use in the Keulegan equation. The values of k in the equation

$$H_r/H_i = k \frac{H_1 - H_n}{H_1 + H_n} \tag{3}$$

were found to be a function of wave steepness (H/λ), where λ is wave length.

The results of tests to determine the energy absorbing characteristics of the wave absorber type bulkheads are presented in Table 3. The reflection coefficients determined from the tests of Section A (see Figure 6) are plotted against wave steepness, Figure 7. A similar plot for Section B is shown on Figure 8.

WAVE TRANSMISSION

Wave energy transmission through structures may cause serious disturbance in a harbor, especially one servicing small craft. The problem and correction of Redondo Beach-King Harbor was reported[5/] to the 9th Conference on Coastal Engineering.

Dr. LeMehaute's findings on scale effects of wave transmission were verified at the Waterways Experiment Station by a scale model of Dana Point Harbor, California. Several aspects of the study were checked at a scale of 1 to 5 at the Coastal Engineering Research Center; at a scale of 1 to 50 in a wave flume at the Waterways Experiment Station; and a scale of 1 to 100 in the three-dimensional model of the harbor. The model reproduction of energy transmission and reflection was acceptable at the 1 to 50 scale. In the 1 to 100 scale model, energy transmission was less than for the larger models. Therefore, the 1 to 100 scale model breakwaters were modified in such a way as to achieve similitude with respect to wave transmission.

To supplement the work done by Dr. LeMehaute, a model investigation is being undertaken at the Waterways Experiment Station by Dr. Adel Kamel. This work is to determine energy transmission characteristics of various rubble structures. Initial tests will utilize a steady state discharge, various values of discharge, water depth, structure dimensions and porosity, and unit shape and size. Upon defining the variables and determining their extent by steady flow, tests using waves will be undertaken.

There are cases where existing harbor structures are satisfactory except for transmission of energy or sediment through the structures themselves. The Corps of Engineers remedied two cases by the following method. The jetties at the entrance to Mission Bay, California,

5/ "On the Design of Small Craft Harbors", by Charles E. Lee, Office, Chief of Engineers, 9th Conference on Coastal Engineering, Lisbon, 1964.

TABLE 3

Wave-reflection Characteristics of Rubble Absorbers

d ft	T sec	H ft	H/λ	k	H_r/H_i cotα = 1.5	cotα = 2.25	cotα = 3
				Test Section A			
20	10	5.0	0.021	1.56	0.80	0.66	0.43
20	10	7.5	0.031	1.61	0.70	0.64	0.40
20	7	7.5	0.046	1.47	0.58	0.26	0.19
20	5	6.2	0.059	1.22	0.32	0.20	0.14
30	10	10.0	0.034	1.71	0.87	0.55	0.27
30	10	12.5	0.043	1.65	0.85	0.47	0.23
30	7	10.0	0.053	1.32	0.47	0.25	0.11
30	7	12.5	0.066	1.31	0.40	0.19	0.13
				Test Section B			
20	10	5.0	0.021	1.56	0.86	0.70	0.42
20	10	7.5	0.031	1.61	0.90	0.67	0.42
20	7	7.5	0.046	1.47	0.70	0.34	0.25
20	5	6.2	0.059	1.22	0.30	0.28	0.11
30	10	10.0	0.034	1.71	1.02	0.64	0.31
30	10	12.5	0.043	1.65	0.90	0.61	0.37
30	7	10.0	0.053	1.32	0.51	0.26	0.18
30	7	12.5	0.066	1.31	0.51	0.18	0.21

Note. d = depth of water at toe of slope (ft).
T = wave period (sec).
H = wave height (ft).
λ = wave length (ft).
k = experimentally determined coefficient.
H_r = reflected-wave height (ft).
H_i = incident-wave height (ft).
α = angle of rubble slope.

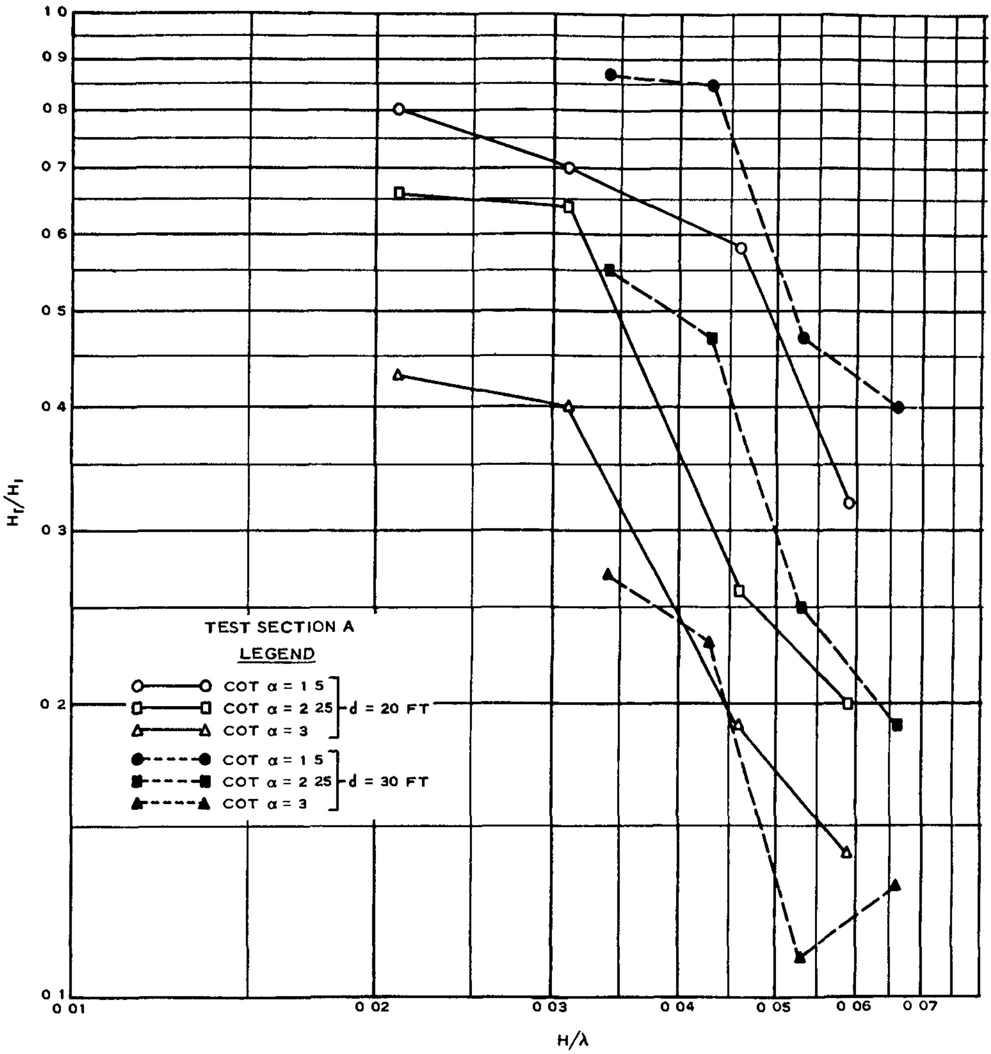


Fig. 7. Experimentally determined coefficient of reflection for absorber composed of four layers of armor stones.

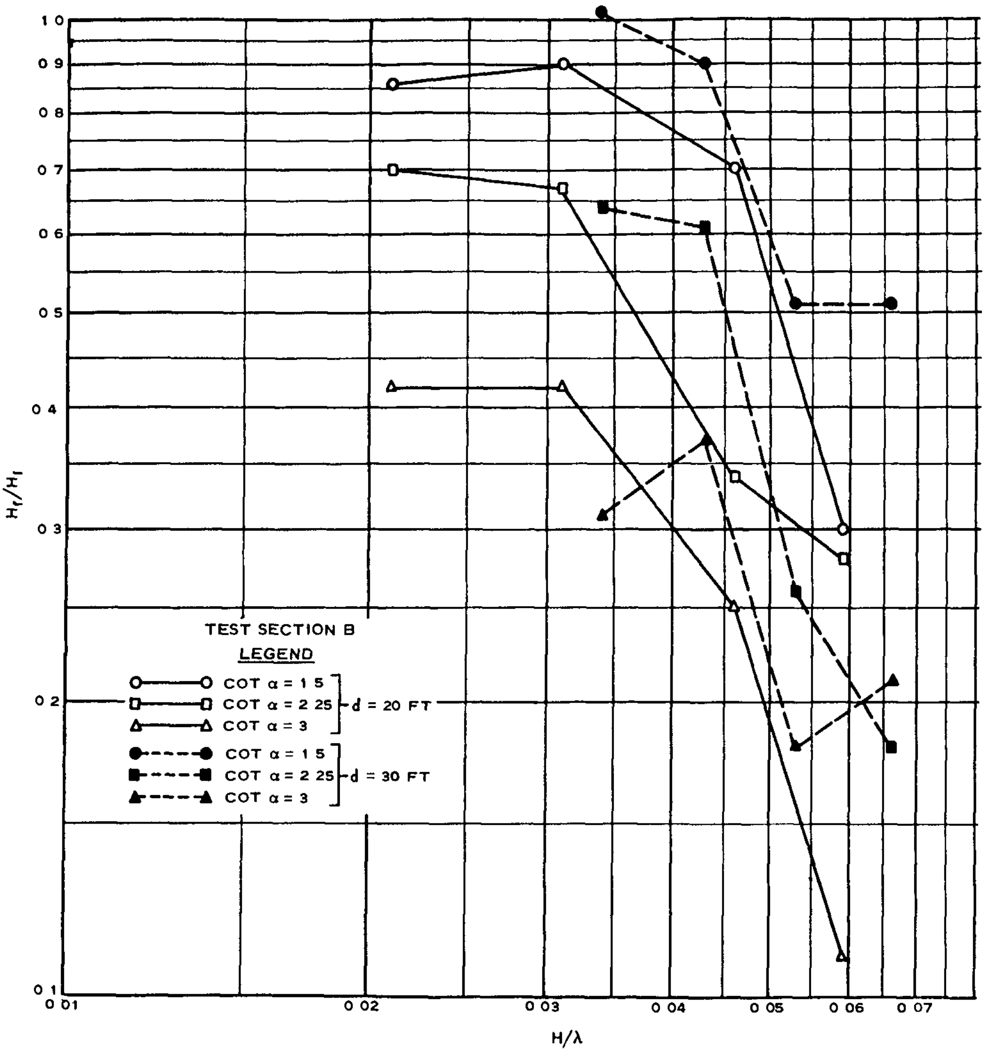


Fig. 8. Experimentally determined coefficient of reflection for absorber composed of two layers of armor stones.

contained a sand-tight core extending from the bottom to MLLW. This core was protected by an armor of large stones weighing from 1 to 15 tons each, and extending to 14 feet above MLLW. To seal the armor stone so that it would be sand-tight, 2½ inch holes were drilled on 6 foot centers along the centerline of the jetty. Grout was pumped through a 1½ inch rigid pipe nozzle to form a cone extending from the core stone to elevation +6 feet MLLW. These cones overlapped to form a sand-tight seal. The grout used was a composite of sand, cement, illite clay, water and calcium chloride. This correction method was also used at Marina del Rey, California, when it was found that energy was being transmitted through the outer 1000 feet of the south jetty and creating undesirable conditions in the entrance.

CONCLUSIONS

There is much to be determined regarding wave energy absorption and wave energy transmission through structures. Some data have been presented and assuredly there are data available that has not been presented to the general engineering profession. The Corps of Engineers plans to continue their investigations and present reports on them. It is sincerely hoped that others will continue their dissemination of knowledge on this subject.

The data presented herein was obtained from research or experimental programs of the Corps of Engineers conducted at our laboratories or by others through contact. The Chief of Engineers has granted approval to use the data. Conclusions and opinions expressed herein are those of the author and may not necessarily be those of the Corps of Engineers.