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UNIVERSITY OF MINNESOTA

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AN EXPERIMENTAL STUDY OF WAVE ABSORBERS

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PREFACE

Contract Nonr-710(05) between the University of Minnesota, St. Anthony Falls Hydraulic Laboratory, and the David Taylor Model Basin, Navy Department, provides for an experimental investigation of certain types of laboratory equipment necessary for studies involving gravity waves.

This report presents the results of large-scale experimental studies of two types of wave absorbers. The studies were conducted to procure information which would assist in the design of prototype wave facilities.

The project is under the general direction of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory. C. E. Bowers was project leader on the study. John B. Herbich conducted most of the experimental work with the assistance of Jurgen Ziegler. Manuscript preparation was performed under the direction of Loyal A. Johnson.

ABSTRACT

Large-scale experimental studies were conducted on two types of wave absorbers, as an extension of earlier small-scale work. The first absorber, and the one of primary interest, was a discontinuous permeable absorber with a surface slope of 12 degrees. Two types of permeable materials--(a) crushed rock and (b) rectangular bars--were investigated. Several modifications of the basic design were studied, including various thicknesses of permeable layer. On the basis of the experimental studies, an optimum thickness of permeable layer was selected. The use of the rectangular-bar construction was recommended.

Brief tests were run on the second type, a short absorber, which was being considered for use around the periphery of a rotating-arm basin. The tests indicated that a surface slope of 15 degrees and a thin layer of permeable material produced the best results. The absorber was restricted to a very short length and produced high reflection coefficients, but it materially reduced the settling time of the basin.

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d - Water depth.

H - Wave height.

H_I - Incident wave height.

H_ℓ - Wave height at loop.

H_n - Wave height at node.

H_R - Reflected wave height.

L - Wave length.

$R = \frac{H_R}{H_I}$ - Measured coefficient of reflection.

s - Thickness of permeable layer.

t - Time.

T - Wave period.

$-_m$ - Model dimension.

$-_p$ - Prototype dimension.

AN EXPERIMENTAL STUDY OF WAVE ABSORBERS

I. INTRODUCTION

Experimental results obtained in large-scale studies of two types of wave absorbers are presented herein. The studies were an extension of earlier small-scale work, the results of which were presented in St. Anthony Falls Hydraulic Laboratory Project Report No. 44 [1]*. The objective of both studies was to obtain information which would assist in the design of wave absorbers in proposed laboratory facilities to be constructed by the Navy Department.

Two types of absorbers were studied in the large-scale tests. The first of these, and the one of primary interest, was a discontinuous-slope permeable absorber with a length approximately equal to the length of the longest waves which would be encountered in a proposed maneuvering basin. The second was a very short absorber for use around the edges of a rotating-arm facility.

Of primary interest in the studies of the first absorber was the selection of a design which would result in a low coefficient of reflection and occupy a minimum of space. The range of wave conditions for which the facility was to be designed are:

wave length 3 to 40 ft
wave steepness 1/100 to 1/15 (0.01 to 0.067)
water depth 20 ft

The Sponsor had indicated that the absorber length preferably should not exceed 35 ft.

During the small-scale studies, tests were conducted on various types of absorbers with both permeable and impermeable surfaces and of various shapes. With a fixed depth of water, data were obtained on the coefficient of reflection as a function of both wave length and steepness. It was found that wave steepness was one of the primary parameters; many of the steep waves would break as they traveled onto the absorber, dissipating much of their energy and resulting in a relatively low coefficient of reflection. Very flat waves had no perceptible breaking action and were characterized by higher reflections.

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*Numbers in brackets refer to List of References on p. 19.

Initially, tests were conducted on absorbers with a continuous or single slope from the bottom of the channel to a point well above the water surface. The reflection coefficient was found to be a function of slope, with low reflection coefficients associated with flat slopes. Data were obtained for the impermeable type as well as for permeable types constructed of crushed rock, wire mesh, or rectangular bars. The permeable types were superior to the impermeable absorber for all comparable test conditions. It was also noted that with material such as gravel and crushed rock an increase in porosity resulted in a decrease in reflection coefficient. Tests with the crushed rock and gravel also indicated that reflection data varied if the rock were removed and relaid, particularly with the larger sizes. Apparently this was due to variations in porosity of the individual models. A narrow-size gradation resulted in the highest porosity (52 per cent) and lowest reflection coefficients. Very high porosities (93 to 99 per cent) were obtained with wire mesh and perforated plates, and good absorption was achieved; however, their cost was excessive and it was decided to discontinue further study of these materials. Consideration was then given to a precast concrete-bar design which produced a porosity of about 70 per cent; wood and Lucite were used to construct the models. This construction had good absorbing qualities and was selected, together with crushed rock, for further study.

Small-scale tests were then conducted on absorbers of various lengths and with varying thicknesses of permeable material over an impermeable surface. For wave lengths equivalent to 40 ft it appeared necessary to use an absorber with a length of at least 35 ft, and that best results could be obtained with a discontinuous type similar to that shown in Fig. 1. The small-scale tests indicated that a 12-degree slope was best for the desired operating conditions. Flatter slopes are desirable but with a fixed length a decrease in slope was accompanied by an increase in reflections from the submerged, vertical face of the absorber, due to the increase in height of this face. Thus, the 12-degree slope was the best compromise for the wave lengths and allowable absorber length of the proposed installation.

Tests with a parabolic surface indicated that this variation of the basic design was not sufficiently beneficial to warrant further study.

The small-scale tests also indicated that the thickness of the permeable layer should have a dimension of 5 ft or less (prototype) and this figure was used as a basis for the large-scale tests.

Assuming a fixed slope and selected wave characteristics, it was thought that a decrease in thickness of the permeable layer would be accompanied by an increase in reflection coefficient. While this general trend did exist, there were variations in the curve which complicated the selection of an optimum thickness. It was thought that some of these effects resulted from addition and cancellation of reflections from various parts of the absorber. For example, reflections from the front face of the absorber may be in phase or 180 degrees out of phase with respect to an impulsive wave created by water returning down the sloping surface following the initial breaking uprush. Variations in wave length would change this phase relationship. Likewise, variations in the thickness of the permeable layer, by retarding the initial uprush and subsequent return flow, would change the phase relationship even though the wave length was fixed.

The small-scale tests had been conducted in a channel 6 in. wide and 40 ft long, with a water depth of 1 ft. The large-scale tests were conducted in a channel 9 ft wide and 250 ft long, with a water depth of 4.5 ft. Thus, the scale ratio between the two was 1:4.5. The scale ratios relating these models to the prototype were 1:20 and 1:4.45.

II. EXPERIMENTAL PROCEDURE

The experimental absorber in the large-scale tests was placed at a distance of about 112 ft from the hinged-plate wave generator, as shown in Fig. 2. Waves of the desired length and steepness were generated continuously until the reflection measurements were complete. After the generator had been in operation long enough to produce stable conditions, a capacitive wave probe was traversed over a distance of at least one-half wave length at a location about 25 ft away from the absorber. This produced a record on a paper-tape recorder of the standing wave resulting from addition of the incident and reflected waves. Letting H_ℓ = height at the loop of the standing wave, H_n = height at node of standing wave, H_I = height of incident wave, H_R = height of reflected wave, and R = reflection coefficient, it can be shown that

$$R = \frac{H_\ell - H_n}{H_\ell + H_n} = \frac{H_R}{H_I} \quad \text{and} \quad H_I = \frac{H_\ell + H_n}{2}$$

This development is based on the assumption of a sine wave profile for both incident and reflected waves. The wave shape is not always sinusoidal, and as a result the reflection coefficients are sometimes only approximate values, but the results are considered to be sufficiently accurate for a study of this type.

Usually, reflection data were obtained for about four different wave lengths and five different values of wave steepness. Reflection coefficient was plotted as a function of wave steepness for individual wave lengths. Figure 5 illustrates a typical plot. Faired curves were drawn through the data and these curves used to plot reflection coefficient as a function of relative wave length (length/depth) for selected value of wave steepness. In some instances the summary data were tabulated and average reflection coefficients determined for the range of wave conditions of primary interest, H/L = 0.02 to 0.05 or 0.06.

One basic model was used for the major portion of the large-scale tests, as shown in Fig. 1. Variations of this basic design were tested as follows (dimensions are for 1:4.45 scale model):

1. Permeable material consisting of crushed rock, with a thickness of layer s of 13.5 inches.
2. Same as No. 1, with addition of a layer of permeable material down vertical face of absorber.
3. Permeable material corresponding to precast-concrete bars, spaced to produce a porosity of 68.5 per cent, and with thicknesses of 1.12 in., 3.37 in., 4.50 in., 5.62 in., 6.75 in., 7.85 in., 10.10 in., and 13.5 inches.
4. Permeable material corresponding to precast-concrete bars, using a sloping layer with a thickness of 13.5 in., plus a permeable layer down the front face.
5. Permeable material corresponding to precast-concrete bars, with a thickness of 7.85 in., on the sloping surface. An impermeable extension was added to this unit, extending to the bottom of the channel, and producing the equivalent of a continuous absorber. Objective was to provide an indication of the magnitude of reflections from the front vertical face of the absorber by comparing reflection data both with and without the lower sloping section.

Other tests were also conducted on a very short absorber for a rotating-arm facility. These are listed and discussed in another part of this report.

III. EXPERIMENTAL RESULTS

A. Crushed-Rock Absorbers

Brief tests were conducted on the crushed-rock absorbers, using a thickness of permeable layer of 13.5 in., both with and without a layer of about the same thickness down the face of the absorber. The crushed rock varied in size from 1.75 to 2.50 inches. The results of these tests are summarized in Table I. In general, the results indicate good absorbing qualities, although the reflection coefficient is slightly higher than that achieved with the square-bar construction. It was also noted that the over-all quality of the water surface was rougher than with the bar-type absorber; this effect was caused by short-crested, short-length reflections from the absorber. These apparently are caused by local variations in slope or porosity associated with a crushed-rock absorber.

TABLE I

REFLECTION COEFFICIENT FOR CRUSHED-ROCK
ABSORBER, 12-DEGREE SLOPE, $s = 13.5$ IN.

L_m	Wave Steepness H_I/L	Average Reflection Coefficient	
		Permeable Front	Solid Front
3.25 ft	0.02 to 0.05	0.068	0.072
5.5 ft	0.02 to 0.04	0.062	0.068
8.0 ft	0.02 to 0.05	0.051	0.042
Average		0.060	0.061

The crushed rock used in these tests was very uniform in size, in order to obtain a high porosity, and was quite expensive. Estimates of the cost of obtaining prototype material in the narrow-size gradation indicated that there would be very little saving as compared to the rectangular-bar construction. Material with a normal distribution, prepared with commercially available screens, could be obtained at lower prices; however, on the basis of the small-scale tests it was believed that higher reflection coefficients would result. As a result, the crushed rock was eliminated from further consideration for this absorber. In other installations, if ample length is available and if the material can be obtained commercially in the desired sizes, crushed rock is worthy of consideration. For a wide absorber, however, the uniformity of absorption probably would not be as good as a bar-type installation.

B. Bar-Type Absorbers

Experimental tests were conducted on the bar-type absorbers using eight values of thickness of permeable layer, all with an impermeable front, plus one test with a permeable front. Figure 4 illustrates one of the models in this series. In addition, some data were obtained with zero thickness or an impermeable surface. Figure 1 illustrates the basic model and the bar material.

Tests with a permeable layer on both the front vertical face and the 12-degree sloping surface indicated that some benefit was derived from the vertical layer. For example, the average reflection coefficient for three values of wave length and four values of wave steepness was 0.052 for the permeable front as compared to 0.063 for the impermeable front. Subsequently, other tests with an impermeable front and a lesser thickness of the sloping, permeable layer produced an average coefficient of 0.053; it was concluded that the permeable front was probably beneficial but would not be justified on the basis of the increased cost and complexity of construction.

Table II is a summary of the data obtained on the bar-type absorber with an impermeable front and with a thickness of permeable layer ranging from 0 to 13.5 inches. The data cover four wave lengths and up to seven values of wave steepness.

In Table III the data have been averaged over the range of wave steepness of primary interest, $H_I/L = 0.02$ to 0.05. This was done to assist in comparison of the reflection coefficient for various values of thickness s. Similarly, Table IV presents average values for a range of wave steepness between 0.01 and 0.05. An inspection of Tables III and IV indicates that the thickness of permeable layer should be in excess of 1.12 in. and that relatively low coefficients were achieved with thicknesses of 3.37 and 7.85 inches.

To assist in further comparisons of these two values of thickness, Tables V and VI were prepared. A comparison of the data in these tables indicates that the 7.85-in. thickness results in the lower coefficients. A similar comparison can be made in the graphical presentation of Fig. 6; here, reflection coefficient is plotted as a function of wave steepness for the range of relative wave lengths of primary interest ($0.15 < L/d < 1.5$).

Figures 7 and 8 are graphs of the data presented in Table II, with reflection coefficient plotted as a function of thickness of permeable layer. The trends are similar to those pointed out above, generally indicating that a thickness of 7.85 in. is desirable. Of interest is the fact that the shape of the curves varies considerably with wave length but only to a minor extent with wave steepness. As pointed out earlier, this is probably due to addition and cancellation of reflections from various parts of the absorber. In one instance, a wave length of 8.0 ft and thickness s of 3.37 in., the reflections are considerably lower than they are for shorter waves; this is the opposite of what would be expected, unless cancellation occurs.

Also of interest is the fact that for some wave conditions the reflections are lower for an impermeable surface than for one layer of bars ($s = 1.12$ in.). As one would expect, a breaking wave travels farther up the slope on an impermeable surface than on a permeable incline and as the water travels back down the incline it can create a fairly severe wave. For some conditions, the phase relationship may be such that the energy in the backflow is dissipated to some extent by the uprush of the next wave, reducing the reflected wave. For other wave conditions, the backflow probably encounters the water surface and generates a wave before the next wave breaks, producing a high reflected wave. Or, the wave created by the backflow may be in phase with reflections from the vertical front of the absorber, producing a high reflection.

In Fig. 9 reflection coefficients are plotted as a function of relative wave length for an impermeable absorber and for a permeable layer 7.85 in. thick. For some values of wave steepness and wave length, the impermeable absorber produces reasonably low reflections but for others high reflections result. There are variations in reflection coefficient with the permeable unit but they are smaller in magnitude and the average reflection coefficient is about 0.6 that of the impermeable unit.

With regard to an optimum thickness of permeable layer for the prototype unit, it was recommended that a value equivalent to 7.85 in. (2-ft.,

TABLE II

COEFFICIENT OF REFLECTION AS A FUNCTION OF WAVE STEEPNESS AND THICKNESS OF PERMEABLE LAYER FOR SELECTED WAVE LENGTHS

L_m	H_I/L	Thickness of Permeable Layer in inches (1:4.45 Scale Model)								
		0	1.12	3.37	4.50	5.62	6.75	7.85	10.10	13.50
3.0 ft	0.005	0.360	--	0.120	0.140	0.170	--	0.160	0.140	0.200
	0.010	0.120	0.240	0.100	0.120	0.140	0.130	0.120	0.115	0.150
	0.020	0.105	0.115	0.070	0.080	0.085	0.085	0.065	0.065	0.090
	0.030	0.105	0.090	0.050	0.050	0.075	0.055	0.045	0.040	0.065
	0.040	0.090	(0.065)	0.040	0.045	0.075	0.070	0.055	0.040	0.073
	0.050	0.100	--	--	0.045	--	0.090	--	0.050	0.060
	0.060	--	--	--	--	--	--	--	--	0.085
4.5 ft	0.005	0.260	0.360	0.180	0.110	0.100	--	0.090	0.170	0.180
	0.010	0.190	0.220	0.150	0.090	0.080	--	0.070	0.125	0.120
	0.020	0.140	0.100	0.100	0.080	0.070	--	0.055	0.075	0.070
	0.030	0.110	0.050	0.070	0.065	0.070	--	0.050	0.050	0.050
	0.040	0.100	0.035	0.050	0.045	0.055	--	0.040	0.040	0.040
	0.050	0.100	0.035	0.045	0.040	0.040	--	0.040	0.035	0.040
	0.060	--	--	0.050	0.050	--	--	0.040	--	0.045
5.5 ft	0.005	0.250	0.380	0.210	0.165	0.140	0.095	0.090	0.180	0.100
	0.010	0.090	0.240	0.150	0.130	0.110	0.085	0.080	0.110	0.065
	0.020	0.070	0.120	0.090	0.090	0.085	0.050	0.060	0.055	0.065
	0.030	0.075	0.095	0.065	0.075	0.070	0.040	0.040	0.040	0.060
	0.040	0.090	0.080	0.050	0.065	0.065	0.035	0.035	0.030	0.050
	0.050	0.110	0.075	0.050	0.050	0.060	0.030	0.030	0.030	0.040
	0.060	0.140	0.070	0.040	0.040	0.070	--	0.020	0.030	0.030
8.0 ft	0.005	0.380	0.340	0.065	0.155	0.220	0.220	0.125	0.100	0.175
	0.010	0.210	0.110	0.050	0.120	0.180	0.170	0.115	0.090	0.140
	0.020	0.085	0.070	0.050	0.080	0.115	0.105	0.090	0.100	0.100
	0.030	0.075	0.100	0.040	0.060	0.090	0.075	0.075	0.085	0.075
	0.040	0.045	0.075	0.050	0.065	0.080	0.075	0.065	0.090	0.060
	0.050	0.080	0.060	0.060	0.060	0.075	0.090	0.065	0.080	0.055
	0.060	0.140	0.045	0.070	0.040	0.060	--	0.060	0.050	--

TABLE III

AVERAGE VALUES OF COEFFICIENT OF REFLECTION FOR H_I/L BETWEEN 0.02 AND 0.05 FOR FOUR SELECTED WAVE LENGTHS

		Thickness of Permeable Layer in Inches (Model)								
L_m	H_I/L	0	1.12	3.37	4.50	5.62	6.75	7.85	10.10	13.50
3.0	0.02-0.04	0.100	0.090	0.053	0.058	0.078	0.070	0.052	0.048	0.077
4.5	0.02-0.05	0.112	0.055	0.066	0.057	0.059	0.052	0.046	0.050	0.050
5.5	0.02-0.05	0.086	0.092	0.064	0.070	0.070	0.039	0.041	0.039	0.054
8.0	0.02-0.05	0.071	0.076	0.050	0.066	0.090	0.086	0.074	0.089	0.072
Average H_R/H_I		0.092	0.078	0.059	0.063	0.074	0.061	0.053	0.057	0.063

TABLE IV

AVERAGE VALUES OF COEFFICIENT OF REFLECTION FOR H_I/L BETWEEN 0.01 AND 0.05 FOR FOUR SELECTED WAVE LENGTHS

		Thickness of Permeable Layer in Inches (Model)								
L_m	H_I/L	0	1.12	3.37	4.50	5.62	6.75	7.85	10.10	13.50
3.0	0.01-0.04	0.105	0.122	0.065	0.074	0.094	0.085	0.069	0.065	0.095
4.5	0.01-0.05	0.128	0.085	0.084	0.064	0.063	0.056	0.051	0.065	0.064
5.5	0.01-0.05	0.087	0.122	0.081	0.082	0.078	0.048	0.049	0.053	0.056
8.0	0.01-0.05	0.099	0.083	0.050	0.077	0.108	0.103	0.082	0.089	0.086
Average H_R/H_I		0.105	0.103	0.070	0.074	0.086	0.073	0.062	0.068	0.075

TABLE V

COEFFICIENT OF REFLECTION AS A FUNCTION OF WAVE STEEPNESS AND L/d RATIO FOR MODEL ABSORBER WITH s = 7.85 IN. (7 LAYERS)

L/d	Wave Steepness H_I/L			
	0.01	0.02	0.04	0.05
0.2	0.11	0.09	0.05	0.02
0.4	0.14	0.11	0.06	0.01
0.6	0.13	0.06	0.03	0.02
0.8	0.10	0.05	0.04	0.03
1.0	0.07	0.06	0.04	0.04
1.2	0.08	0.06	0.04	0.03
1.4	0.09	0.07	0.04	0.04
1.6	0.10	0.08	0.05	0.05
Average H_R/H_I	0.102	0.072	0.044	0.030

TABLE VI

COEFFICIENT OF REFLECTION AS A FUNCTION OF WAVE STEEPNESS AND L/d RATIO FOR MODEL ABSORBER WITH s = 3.37 IN. (3 LAYERS)

L/d	Wave Steepness H_I/L			
	0.01	0.02	0.04	0.05
0.2	0.13	0.10	0.06	0.05
0.4	0.17	0.12	0.09	0.06
0.6	0.10	0.09	0.04	0.04
0.8	0.10	0.08	0.04	0.04
1.0	0.15	0.10	0.04	0.04
1.2	0.15	0.09	0.05	0.05
1.4	0.07	0.06	0.03	0.03
1.6	0.06	0.04	0.02	0.03
Average H_R/H_I	0.116	0.085	0.046	0.042

11-in. prototype) be used. Actually, the results for a thickness of 3.37 in. were quite good and this unit would require less permeable material. However, the reflections were slightly higher, particularly for low values of wave steepness and it was concluded that the thickness of 7.85 in. should be used in an effort to obtain the lowest possible reflection coefficients.

Figure 10 illustrates the details of the prototype bar construction as developed by the Sponsor [2]. The bars are cast in panels and then placed in the absorber.

C. Comparison of Continuous and Discontinuous Absorbers

As noted in a preceding section, the absorber length was restricted to about 7.85 ft (model value) and it was found that a discontinuous absorber was more efficient than a continuous-slope unit of the same length; the latter would of necessity have a much steeper slope. There was some interest in the magnitude of reflections from the vertical front of the absorber and a brief test was conducted to obtain some additional data on this effect. A sloping, impermeable absorber with a 12-degree slope was added to the discontinuous absorber as shown in Fig. 11. This more than doubled the length of the absorber. Figure 11 also shows a comparison of average reflection coefficient with and without the lower section. The results indicate that the lower section was not beneficial for L/d values less than about 1.5 but above this value the difference between the reflection coefficients increased with an increase in wave length. The results are of interest only in a general way, as the restricted length of the prototype unit would not permit use of the lower section. However, if at some future date it is desired to use waves longer than those presently contemplated, the data may be of some value.

D. Comparison of Large and Small Models

Throughout the absorber tests there was considerable interest in the question of scale effect and the applicability of the model data to the prototype installation. The initial tests were conducted in the small channel (water depth 1 ft) and the remainder in the large channel (water depth 4.5 ft). Thus, the scale ratio between the two was 1:4.5 and the scale ratio of the small and large models with respect to the prototype was 1:20 and 1:4.45, respectively. Figure 12 illustrates comparative curves obtained in the two models, plus data obtained by the David Taylor Model Basin on a full-scale absorber section. While differences do exist, the over-all agreement is considered quite good and indicates that scale effects were of relatively minor importance.

The choice of rectangular bars as the main element in the permeable material may have had some bearing on the problem of scale effect, as the drag coefficient probably does not vary as widely as for some other shapes (such as circular rods) as a function of Reynolds number.

IV. ROTATING-ARM ABSORBER TESTS

Brief tests were conducted on a short absorber for possible use around the periphery of a proposed rotating-arm basin at the David Taylor Model Basin. The proposed basin will have a diameter of 260 ft and a water depth of 20 ft. It was requested that tests be conducted on permeable and impermeable absorbers with prototype radial lengths not to exceed 3.5 ft.

The magnitude of disturbances which might be encountered in the prototype facility is difficult to predict. The Sponsor indicated that waves up to 16 in. high, with wave lengths up to 56 ft, might be created by towed models. However, wave heights up to 8 in. were of primary interest.

It would have been desirable to test the absorbers in a model rotating-arm facility; as such a facility was not available, some comparative tests were conducted in the regular wave channels. Two types of tests were devised, one involving a measure of reflection coefficient for continuous operation of the wave generator, and the other involving a measure of the time required for the water to become quiet after a wave group had been generated. In many respects the latter test corresponds more closely to the actual prototype conditions, but both types should indicate the same trends. Neither test would provide data on the currents which might be created by the towed models.

A few tests were conducted in a small channel but the majority were conducted in the large wave channel using a water depth of 4.5 ft. The scale ratio was 1:4.45. The test program was as follows:

1. Impermeable beach with 5-degree, 10-degree, 15-degree and 20-degree slope. Maximum length, 0.786 ft (3.5 ft prototype).

2. Permeable bar-type beach with surface slope of 5 degrees, 10 degrees and 15 degrees, made up of 0.34-in. square bars spaced 0.34 in. apart, both normal and parallel to slope. The number of layers was varied from 1 to 3.

These absorbers were tested with wave lengths of 5 ft, 10 ft and 15 ft (approximate prototype values 22, 44 and 66 ft), and wave heights up to 3.6 in. (16-in. prototype).

The absorbers were placed 144 ft from the wave generator. A wire-mesh filter was placed 32 ft from the generator. Reflections and wave heights were measured 23 ft from the absorber.

Figure 13 is a photograph of one of the test absorbers.

Tables VII and VIII summarize the test data. Table VII includes data for both the regular reflection-coefficient tests and the settling-time tests. Considering first the reflection coefficients, it may be noted that the lowest coefficient measured was 0.20 and the maximum 0.70. This would indicate that all of the models are very poor as compared to conventional absorbers. In general, reflection coefficients for the 15-ft wave length are quite high for all the absorbers tested. For 5-ft and 10-ft wave lengths the permeable or bar-type absorbers produced lower reflections than the impermeable absorbers.

The trends indicated by the settling-time tests are similar. In these tests the generator was operated for 90 seconds and then stopped. The initial wave height (H_I) was measured while the generator was operating, and at short intervals after it was stopped. Curves were plotted of H/H_I as a function of time. In Table VII, the time required for the waves to recede to 0.4 and 0.2 times their initial value is shown. In Table VIII, data are given for the integrated area under the settling-time curve (Column A). In Column B of Table VIII, the area data have been divided by the comparable area for the best absorber tested. Thus, Column B indicates the relative area under the curve as compared to the best absorber and provides an easier means of comparing the absorbers. The best absorber was one with a 15-degree slope and two layers of bars, shown in Fig. 15.

Figure 14 is a graph showing the settling time for the 15-degree absorber plus similar curves for two other conditions. The other two curves

TABLE VII

SUMMARY OF DATA ON ROTATING-ARM ABSORBER
(1:4.45 Scale Model)

Absorber	Wave Length ft	H_I/L	Slope Degrees	Number of Bar-Layers	Wire Mesh Filter ft	Settling-Time Minutes $H/H_I = 0.4$	Settling-Time Minutes $H/H_I = 0.2$	Reflection-Coefficient $H_I/L = 0.01$	Reflection-Coefficient $H_I/L = 0.02$
Impermeable	5.0	0.018	5	0	4	3.5	6.0	0.70	0.55
↓	5.0	0.018	10	0	↓	3.0	7.5	0.55	0.50
	5.0	0.018	15	0		2.5	4.0	0.50	0.45
	5.0	0.018	20	0		2.5	7.0	0.65	0.60
	10.0	0.015	5	0		3.0	5.5	0.60	0.55
	10.0	0.015	10	0		1.5	3.0	0.45	0.40
	10.0	0.015	15	0		3.0	5.0	0.40	0.35
	10.0	0.015	20	0		1.5	4.0	0.20	0.20
	15.0	0.035	5	0		2.5	4.0	0.60	0.50
	15.0	0.035	10	0		1.5	2.5	0.45	0.40
	15.0	0.035	15	0		2.0	3.5	0.50	0.45
	15.0	0.035	20	0		2.0	4.0	0.45	0.40
Permeable (Bar-Type)	5.0	0.018	15	1		2.0	3.5	0.35	0.28
↓	5.0	0.018	15	2		1.0	2.5	0.28	0.28
	5.0	0.018	15	3		1.5	2.0	0.28	0.25
	10.0	0.015	15	1		2.5	4.0	0.36	0.32
	10.0	0.015	15	2		1.0	2.0	0.35	0.31
	10.0	0.015	15	3		1.0	2.0	0.28	0.25

<u>Note</u>:

Settling time is measured from time when wave generator was stopped until wave disturbances had subsided to ratio indicated. Ratio H/H_I equals wave height at indicated time divided by incident wave height when generator was operating.

TABLE VII (Cont.)

SUMMARY OF DATA ON ROTATING-ARM ABSORBER

Absorber	Wave Length ft	H_I/L	Slope Degrees	Number of Bar-Layers	Wire Mesh Filter ft	Settling-Time Minutes $H/H_I = 0.4$	Settling-Time Minutes $H/H_I = 0.2$	Reflection-Coefficient $H_I/L = 0.01$	Reflection-Coefficient $H_I/L = 0.02$
Permeable	15.0	0.035	15	1	4	1.5	2.5	0.43	0.41
(Bar-Type)	15.0	0.035	15	2	↓	1.5	2.5	0.41	0.41
↓	15.0	0.035	15	3		1.5	2.5	0.40	0.38
	5.0	0.018	10	2		2.0	3.5	0.46	0.42
	10.0	0.015	10	2		2.0	4.0	0.52	0.50
	15.0	0.035	10	2		1.5	3.0	0.56	0.53
None	5.0	0.018	-	-		6.5	10.5	0.80	0.75
↓	10.0	0.015	-	-		5.0	9.0	0.85	0.80
	15.0	0.035	-	-		2.5	6.0	0.90	0.85
	10.0	0.015	-	-	None	27.0	36.0	-	-

Note: Settling time is measured from time when wave generator was stopped until wave disturbances had subsided to ratio indicated. Ratio H/H_I equals wave height at indicated time divided by incident wave height when generator was operating.

TABLE VIII

SUMMARY OF MODEL DATA ON ROTATING-ARM ABSORBER

Planimetric Evaluation of Settling-Time-Test Graphs

Type	L ft	H_I/L	Slope Degrees	No. of Layers	Filter ft	A	B
Impermeable	5	0.018	5	0	4	62	2.46
	5	0.018	10	0		59	2.36
	5	0.018	15	0		46	1.82
	5	0.018	20	0		52	2.07
	10	0.015	5	0		55	2.77
	10	0.015	10	0		28	1.41
	10	0.015	15	0		27	1.36
	10	0.015	20	0		39	1.95
	15	0.035	5	0		40	1.33
	15	0.035	10	0		30	1.00
	15	0.035	15	0		35	1.18
	15	0.035	20	0		36	1.21
Permeable (Bar-Type)	5	0.018	15	1		37	1.46
	5	0.018	15	2		25*	1.00
	5	0.018	15	3		28	1.11
	10	0.015	15	1		42	2.14
	10	0.015	15	2		20*	1.00
	10	0.015	15	3		21	1.04
	15	0.035	15	1		27	0.91
	15	0.035	15	2		30*	1.00
	15	0.035	15	3		27	0.91
	5	0.018	10	2		37	1.46
	10	0.015	10	2		36	1.87
	15	0.035	10	2		23	0.79
None	5	0.018	90	-		116	4.60
	10	0.015	90	-		88	4.45
	15	0.035	90	-		48	1.61
	10	0.015	90	-	None	412	20.80

*Reference values used to compute column B.

Notes:

A - Planimeter reading between $H/H_I = 0.1$ and $H/H_I = 1.0$.

B - Readings reduced to ratio with respect to best absorber, for comparable wave lengths.

were obtained with the absorber removed, in which case the waves were completely reflected by a plain, vertical wall. For one of the latter tests a wave filter was in place near the wave generator and in the other test the filter was removed. As the wave-generator plate is a good reflector, the test without filter or absorber requires the longest time for the waves to settle out or become damped because the waves are continually reflected from the bulkhead and the generator plate. Addition of the filter greatly reduced the settling time and finally, addition of the absorber produces a further major reduction in settling time. No data were obtained with the absorber alone, that is with the filter removed. However, it is apparent that the absorber is quite beneficial for the 10-ft wave length, even though it does not compare favorably with a conventional wave absorber.

It may be noted in Fig. 14 that soon after the generator was stopped the wave height was higher than the incident wave height, that is, the ratio H/H_I was greater than unity. This results from addition of the incident and reflected waves, and the method of evaluating the wave height. Measurements were obtained with a single probe at a fixed distance from the absorber, giving a continuous indication of wave height at a point in the basin. Initially, addition of incident and reflected waves produced a height at the probe greater than the incident wave height, or $H/H_I > 1.0$. Variations in the longitudinal location of the probe would change the magnitude of the recorded wave height but in this instance the probe was fixed so that comparative data could be obtained. The wave height did not exhibit a steady decrease with time; rather there were oscillations in wave height, with a steady decrease in the average height. The oscillations in height result from the normal variation in wave height of the wave group. An average was taken of the wave height over an interval of about 10 sec. to determine H.

An inspection of Fig. 14 indicates that addition of the absorber reduced the settling time of this channel to about one-fourth that which was obtained without the absorber.

V. SUMMARY

Experimental tests were conducted in a large-wave channel on a discontinuous, permeable-type wave absorber to obtain information which would assist in the design of a prototype unit. The length of the 1:4.45 scale absorber was 7.92 ft and the surface slope was 12 degrees. Waves up to 8 ft long were used in most of the tests. The results indicated that a permeable layer on the 12-degree slope was desirable and that the thickness should be on the order of 7.85 in. (2-ft, 11-in. prototype). A lesser thickness, 3.37 in., also gave good results but the reflection coefficients were slightly higher and considerable variation in reflection coefficient was obtained for various wave conditions. As a result, a thickness corresponding to 7.85 in. is recommended for the prototype. The porosity of the permeable material used in the large-scale tests was 68.5 per cent, but various modifications associated with the development of the prototype design resulted in a porosity of 67 per cent.

Tests were performed in the large channel using two types of permeable material---crushed rock and rectangular bars. The latter type is recommended for the prototype.

Tests were performed on absorbers of very short length for use around the periphery of a rotating-arm basin. The length of the model absorber was initially specified as 0.785 ft. It was found that a 15-degree surface slope with two layers of rectangular bars produced the best results. The spacing of the bars was such that a porosity of about 70 per cent was obtained.

LIST OF REFERENCES

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[2] Brownell, W. F., Asling, W. H., and Marks, W. A 51 ft Pneumatic Wavemaker and a Wave Absorber. The Navy Department, David W. Taylor Model Basin Report 1054, August 1956. 41 pages.

[3] Bowers, C. E. and Herbich, J. B. Preliminary Data on Square-Bar Absorbers. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-25, December 1954.

[4] Bowers, C. E. and Herbich, J. B. Preliminary Data on Crushed-Rock Absorbers. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-26, December 1954.

[5] Herbich, J. B. Preliminary Data on Bar-Type Wave Absorbers. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-31, May 1955.

[6] Herbich, J. B. and Bowers, C. E. Notes on Testing Technique for Tests of Wave Absorbers at the St. Anthony Falls Hydraulic Laboratory. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-33, May 1955.

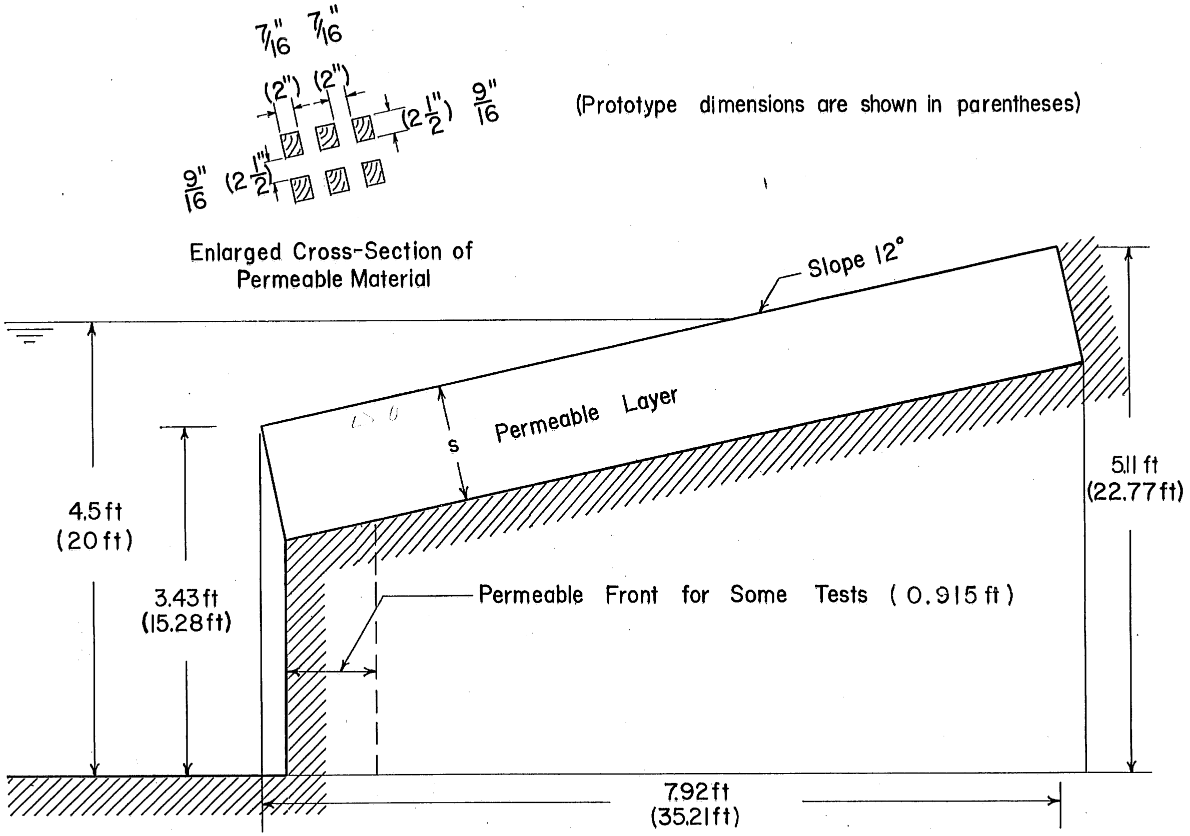
[7] Bowers, C. E. Comparative Experimental Data on a Continuous and a Discontinuous Absorber. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-36, June 1955.

[8] Bowers, C. E., Herbich, J. B., and Ziegler, J. Experimental Model Study of Absorber for Rotating-Arm Basin. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-38, July 1955.

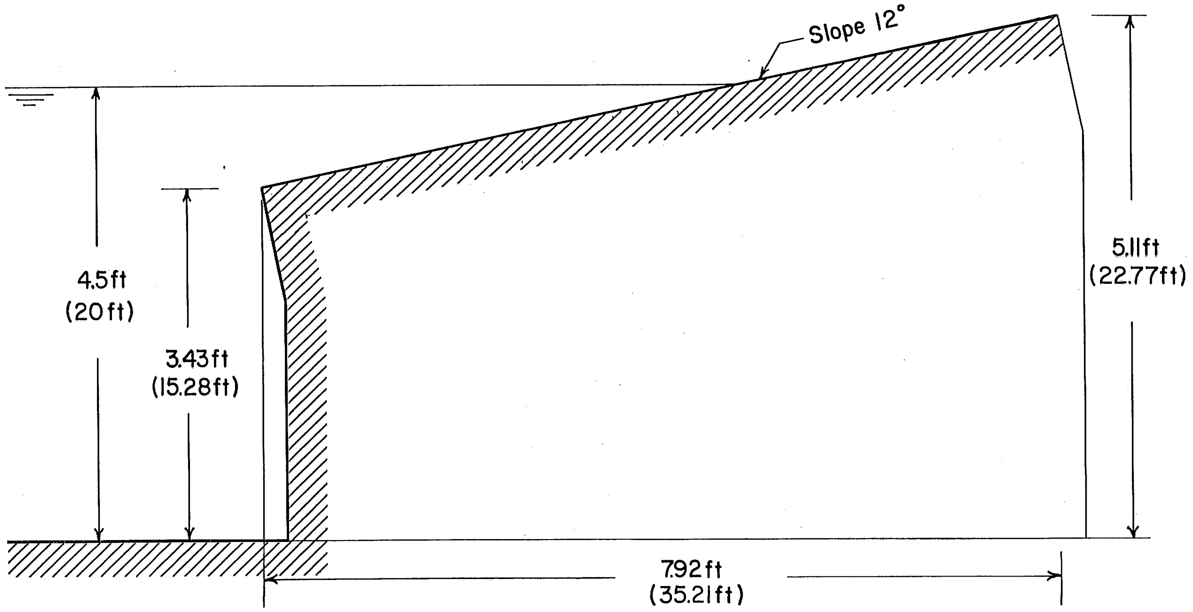
[9] Herbich, J. B. Model Study of Discontinuous Permeable Absorber With and Without Impermeable Headwall. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Memorandum M-42, October 1955.

FIGURES

(1 through 15)



(a) Permeable Absorber



(b) Impermeable Absorber

Fig. 1 – Sketch of Discontinuous-Slope Absorber

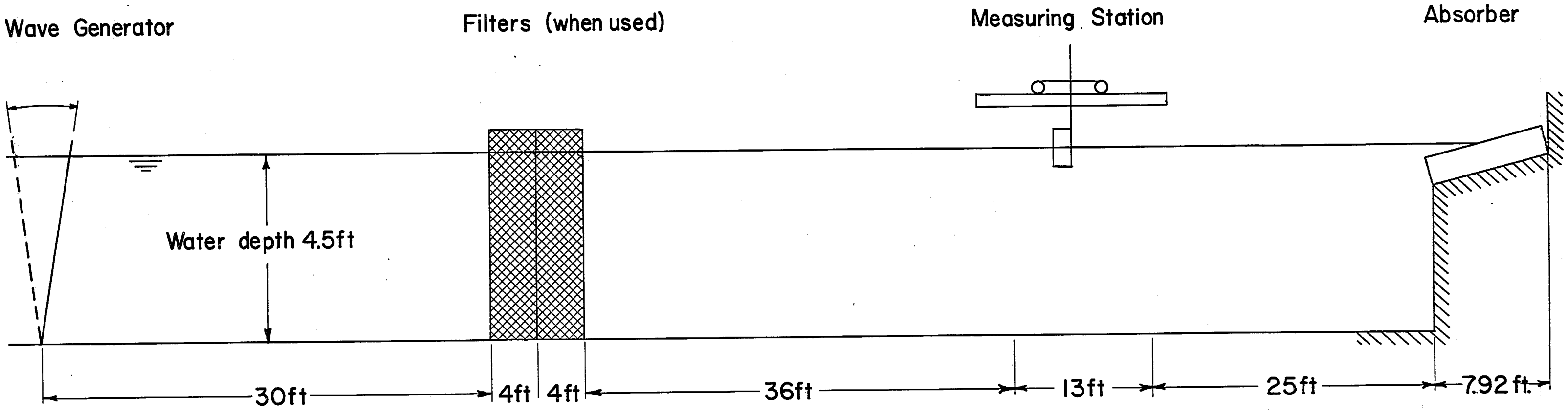
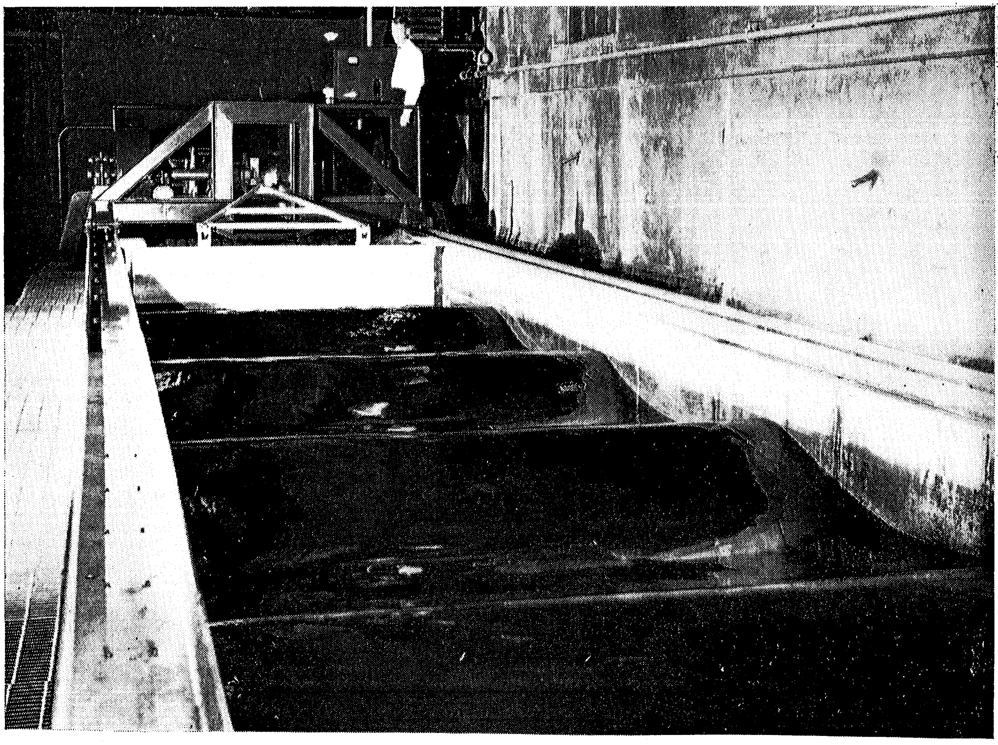


Fig. 2 - Sketch of Test Setup



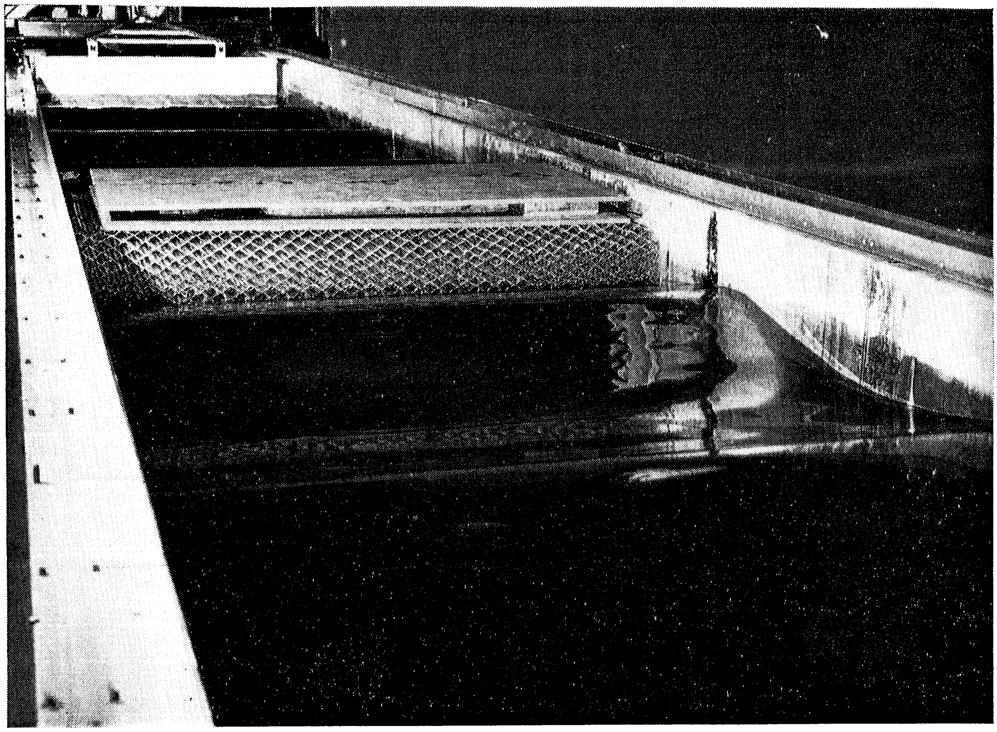


Fig. 3 - Views of Wave Generator and Filters Used in Tests

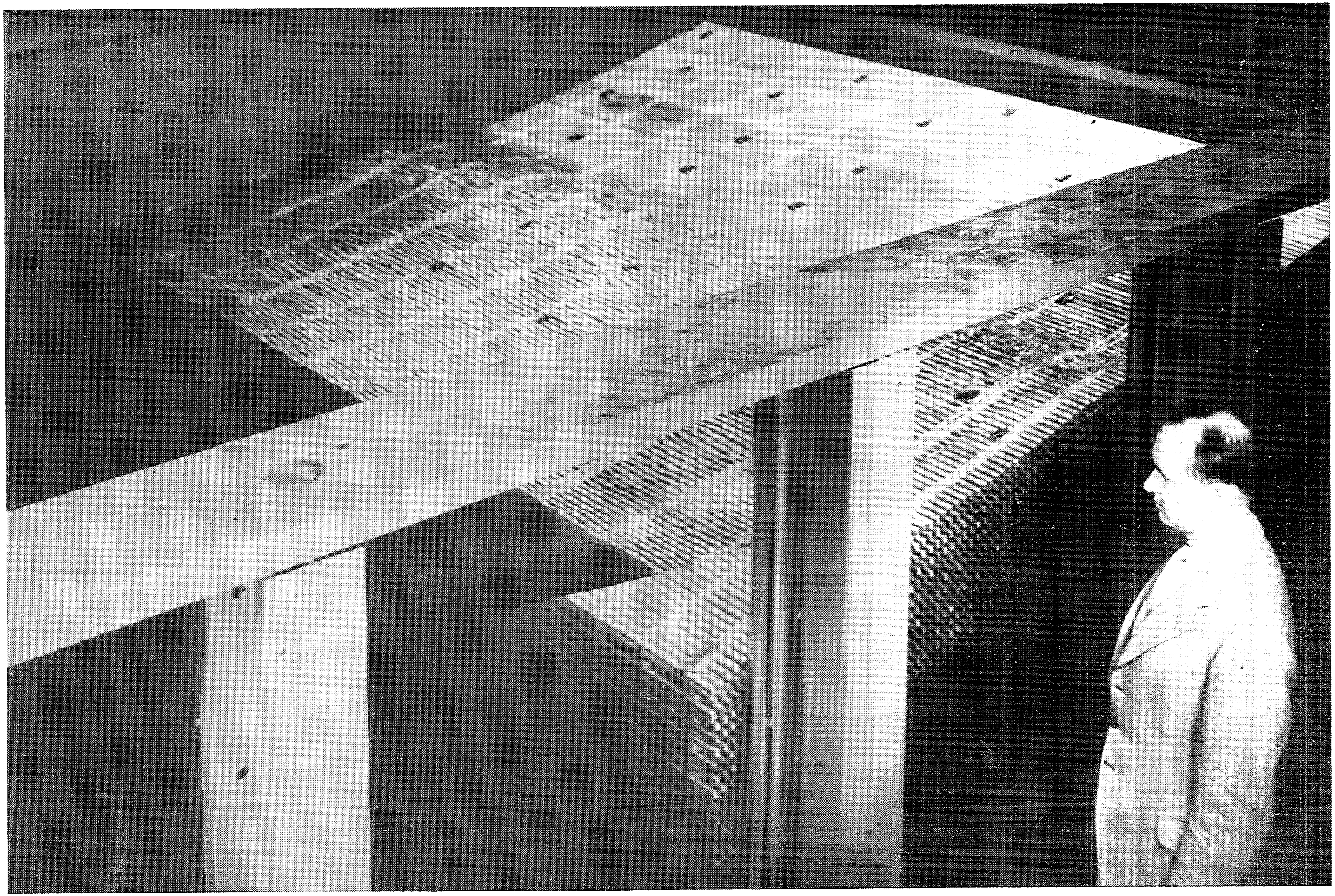
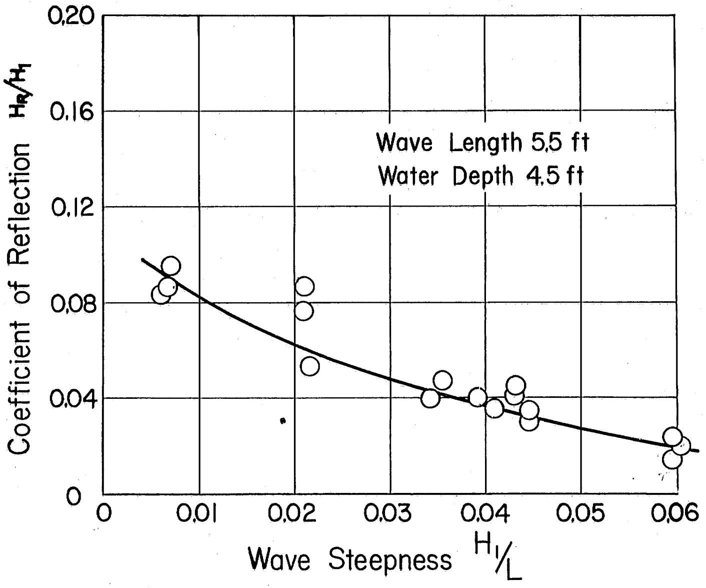
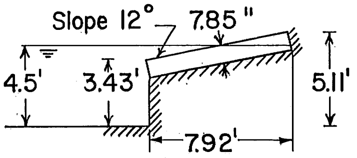


Fig. 4 - **Photograph of Bar-Type Absorber with Waves 8 ft Long and 0.4 ft High**



ABSORBER CHARACTERISTICS

Type: Permeable, Discontinuous
Thickness of Permeable Layer 7.85 in
Seven Layers of Bars
Slope 12 Degrees
Porosity 67 Percent
Channel Width 9 ft



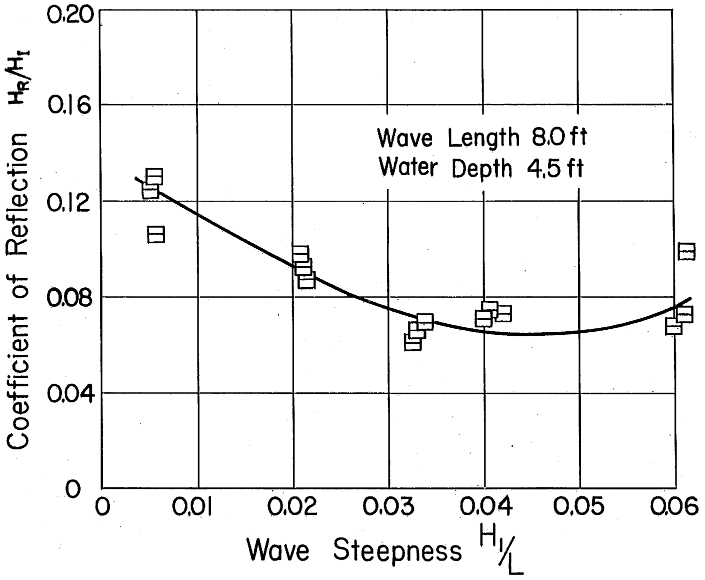


Fig. 5 – Typical Graphs of Reflection Coefficient as a Function of Wave Steepness

ABSORBER. CHARACTERISTICS

Permeable, Discontinuous

Number of Layers	Total Thickness, Permeable Layer	Symbol
3	s = 3.37"	○
7	s = 7.85"	□

Slope 12°
Porosity 67%
Channel Width 9ft

WAVE CHARACTERISTICS

L/d 0.15—1.5
Water Depth 4.5 ft

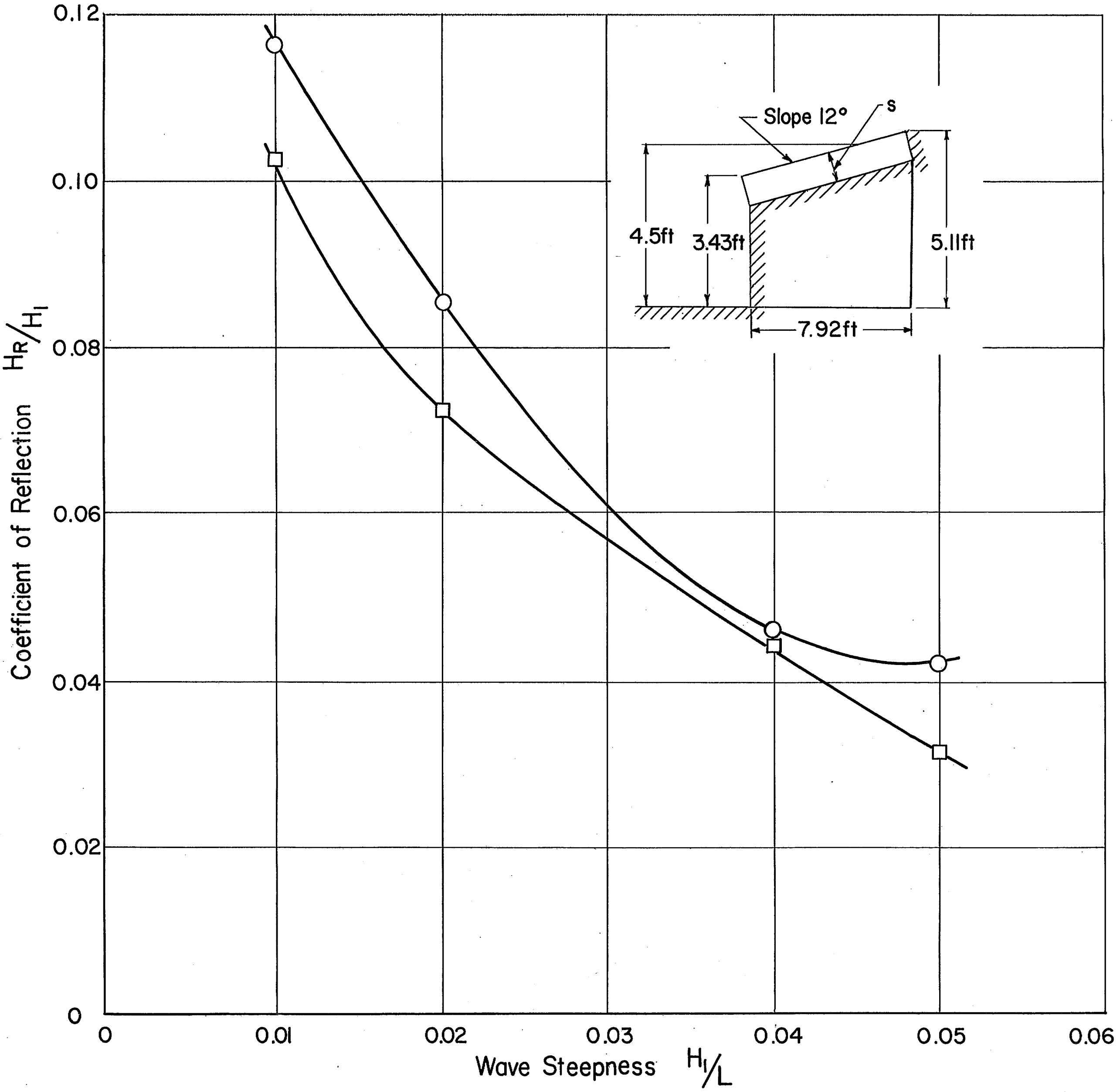


Fig. 6 – Comparison of Average Reflection Coefficient for Permeable Layers 3.37 in. and 7.85 in. Thick

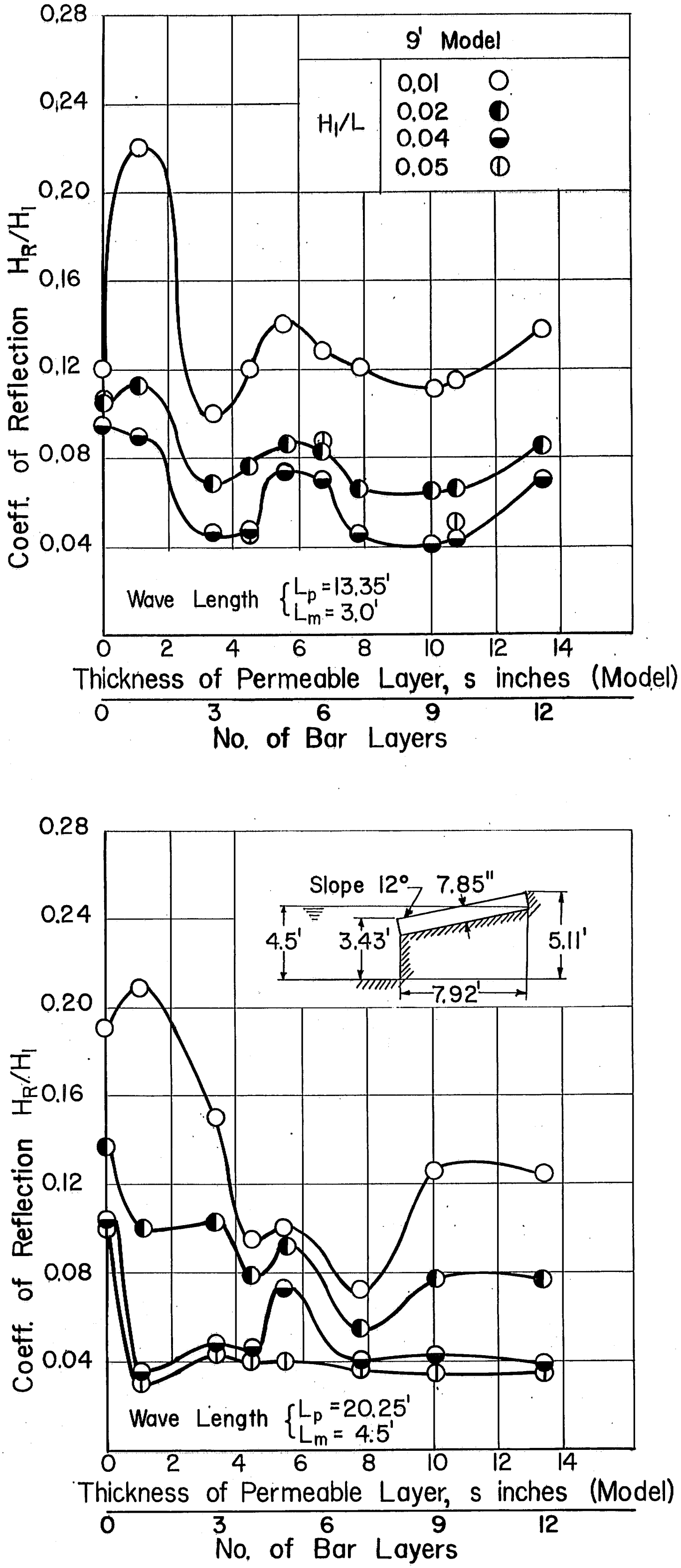


Fig. 7 - Reflection Coefficient as a Function of Thickness of Permeable Layer, for Bar-Type Absorber, (L_m = 3.0 ft and 4.5 ft)

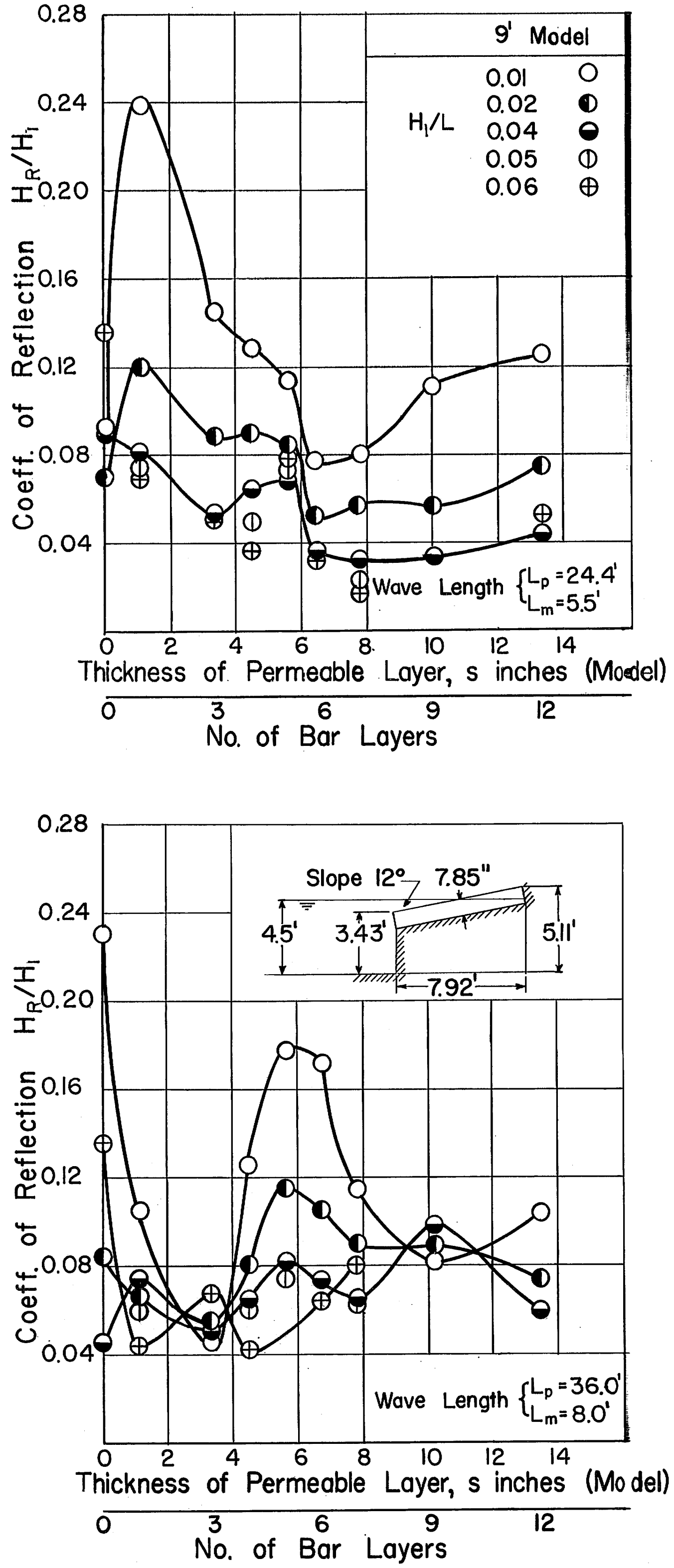


Fig. 8 - Reflection Coefficient as a Function of Thickness of Permeable Layer, for Bar-Type Absorber, (L_m = 5.5 ft and 8.0 ft)

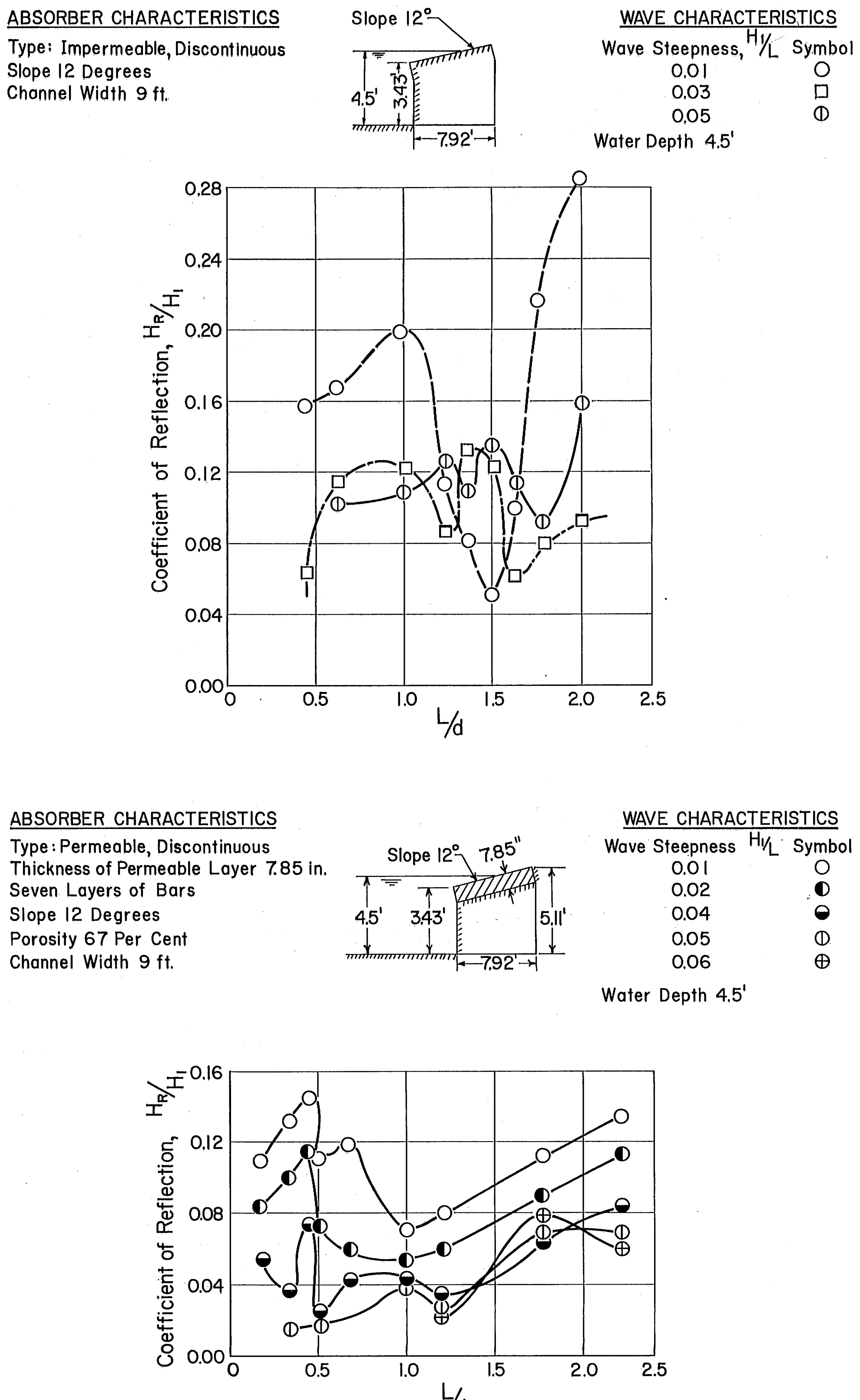
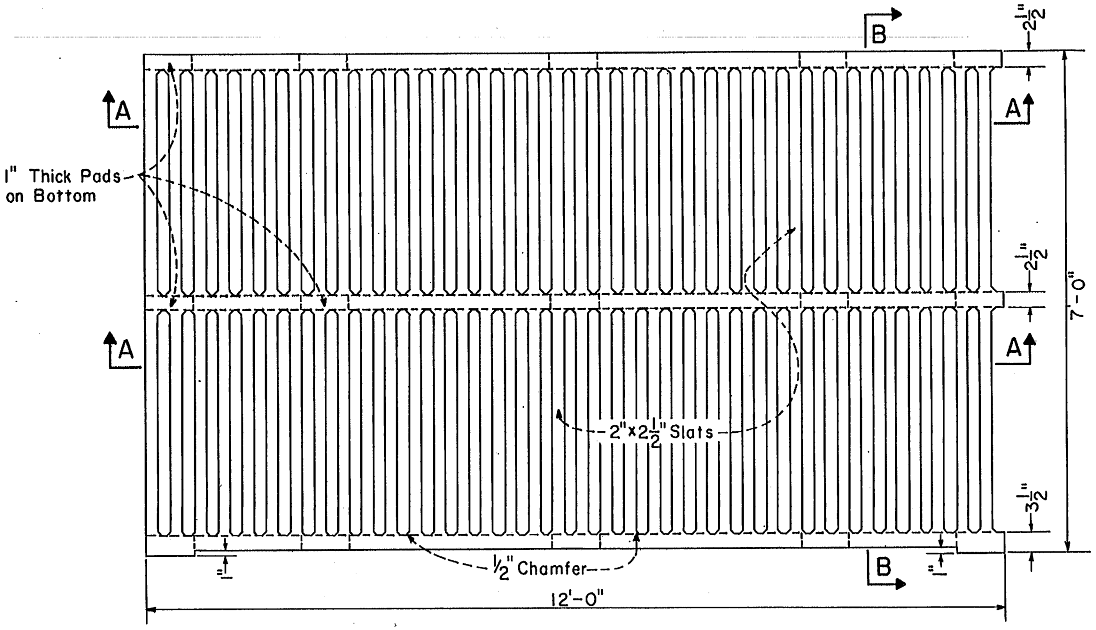
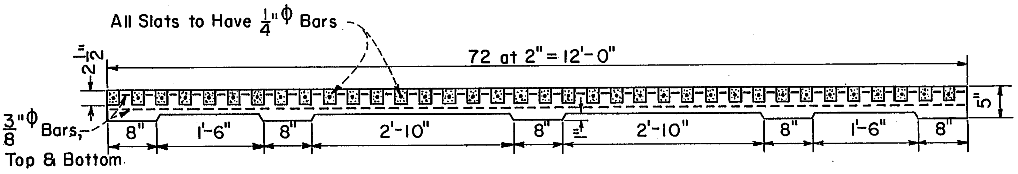


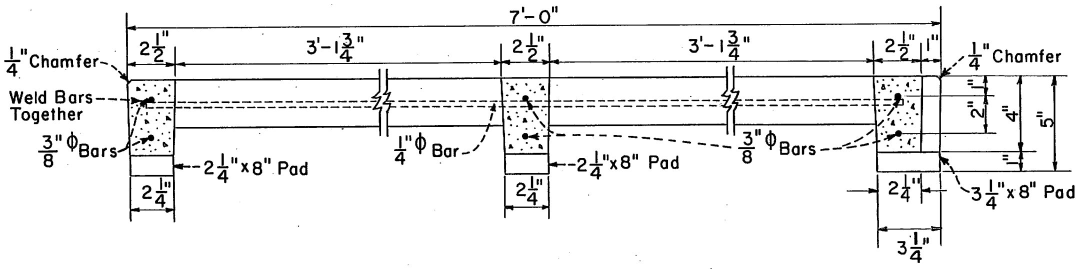
Fig. 9 - Reflection Coefficient as a Function of Relative Wave Length, for Impermeable Absorber and Permeable Unit with Thickness of 7.85 inches



PLAN



SECTION A-A



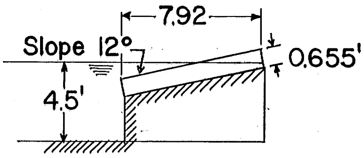
SECTION B-B

Fig. 10 - Details of Prototype Bar Construction (From Reference No. 2)

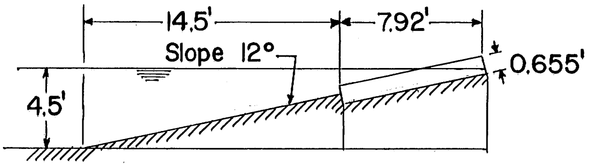
ABSORBER CHARACTERISTICS

Absorber A
Discontinuous, Permeable
Thickness of Permeable Layer 7.85 in.
Seven Layers of Bars
Slope 12 Degrees
Porosity 67 Percent
Channel Width 9 ft.

Absorber B
Continuous, Partly Permeable
Same as Absorber A Except
Impermeable Beach Added in Front



Absorber A



Absorber B

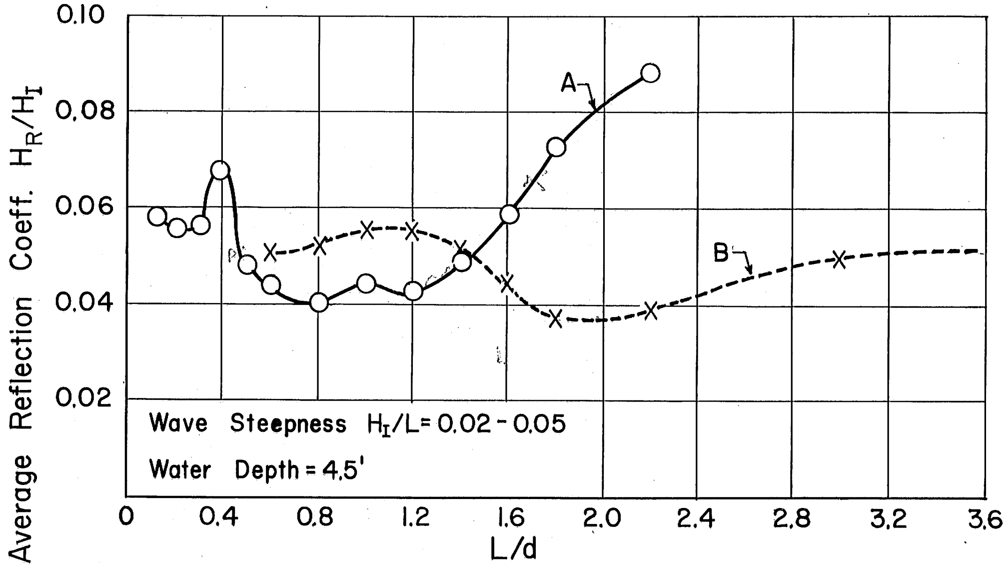


Fig. 11 – Comparative Reflection Coefficients for Continuous and Discontinuous Absorbers

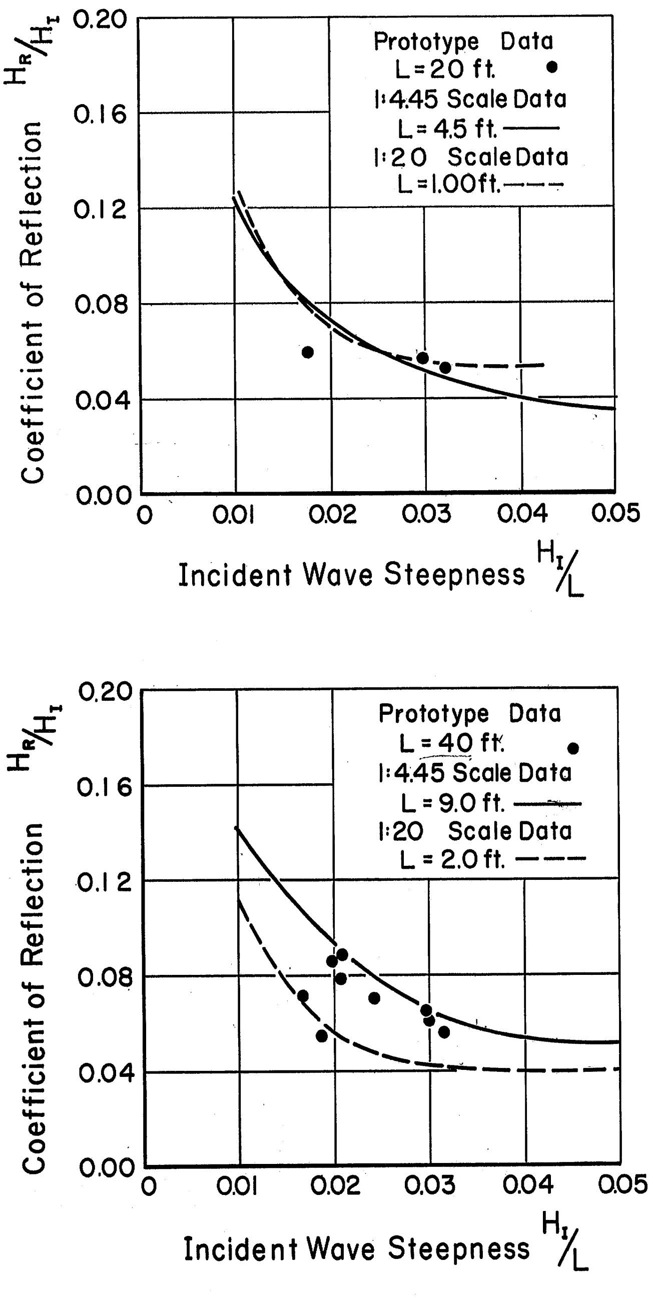


Fig. 12 – Comparison of Reflection Data Obtained in Two Models and a Prototype Absorber

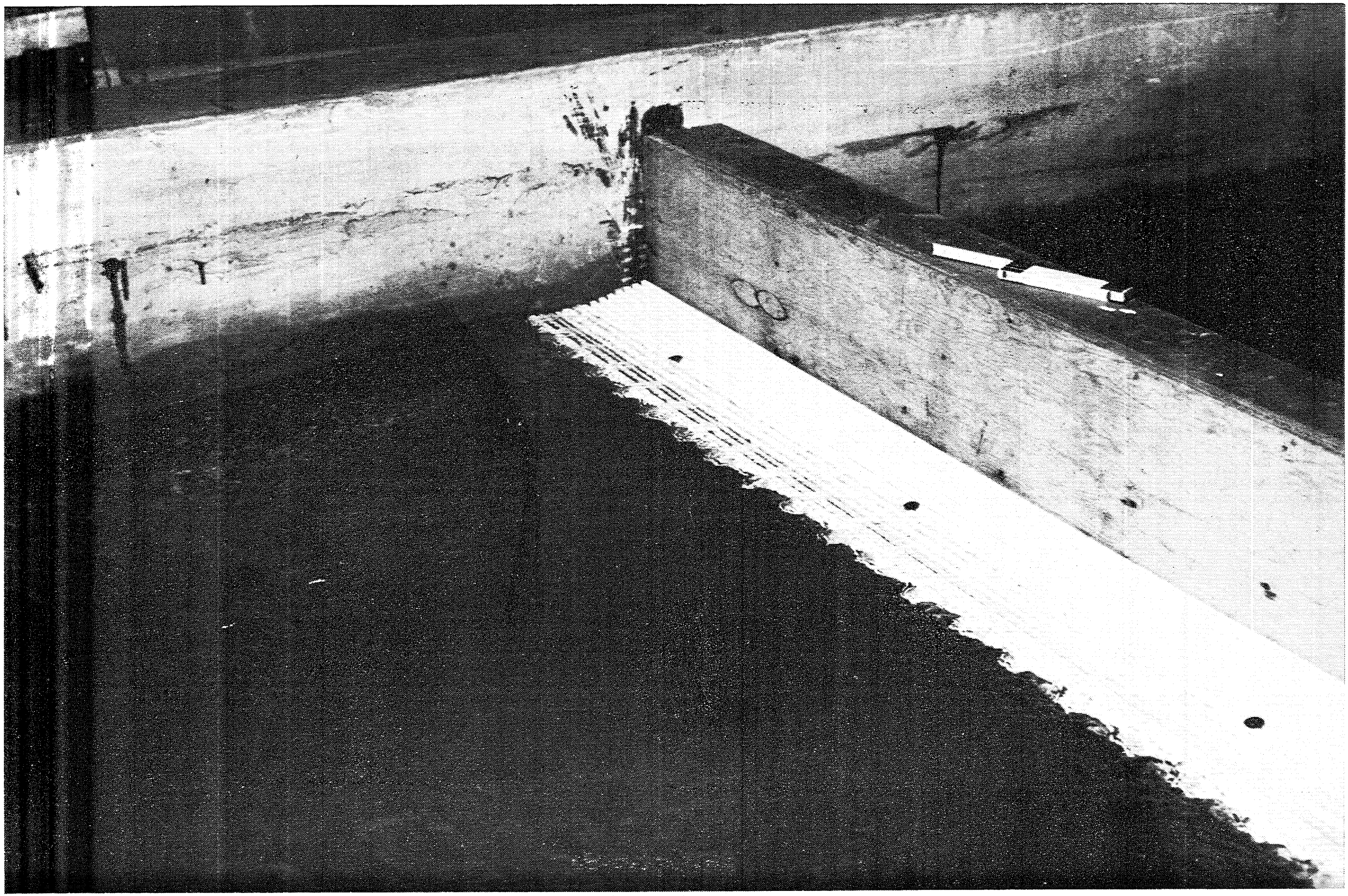


Fig. 13 - Photograph of Model of Rotating-Arm Absorber with Incident Waves 5 ft Long and 0.1 ft High; Slope - 15 Degrees, Two Layers of Bars

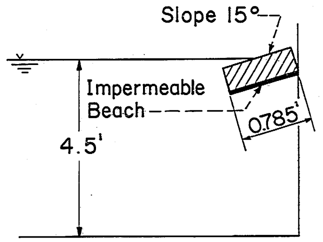
ABSORBER FOR ROTATING ARM FACILITY

ABSORBER CHARACTERISTICS

Type: Permeable, Discontinuous
Thickness of Permeable Layer = 1.35 in.
Two Layers of Bars
Distance Between Generator and Absorber = 144 ft.
Recording Station is 23 ft. from Absorber
Channel Width = 9 ft.

WAVE CHARACTERISTICS

Length	L = 10.0 ft.
Steepness	H_I/L = 0.015
Water Depth	d = 4.5 ft.



TEST CONDITIONS

Absorber	Filter	Symbol
Bar Type	Yes	– – □ – –
Vertical Wall	Yes	—△—
Vertical Wall	No	–··◇··–

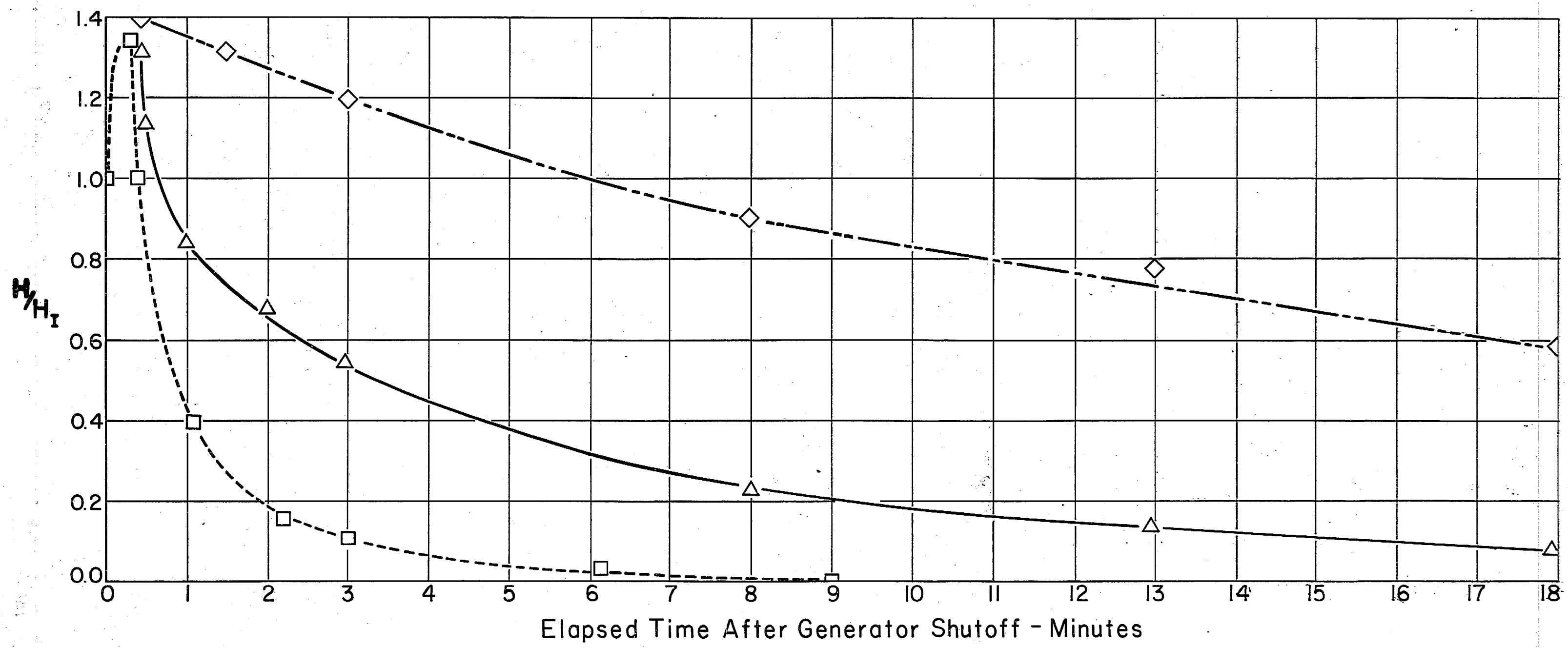


Fig. 14 - Variation of Wave Height in Test Channel after Generator is Stopped, as a Function of Time

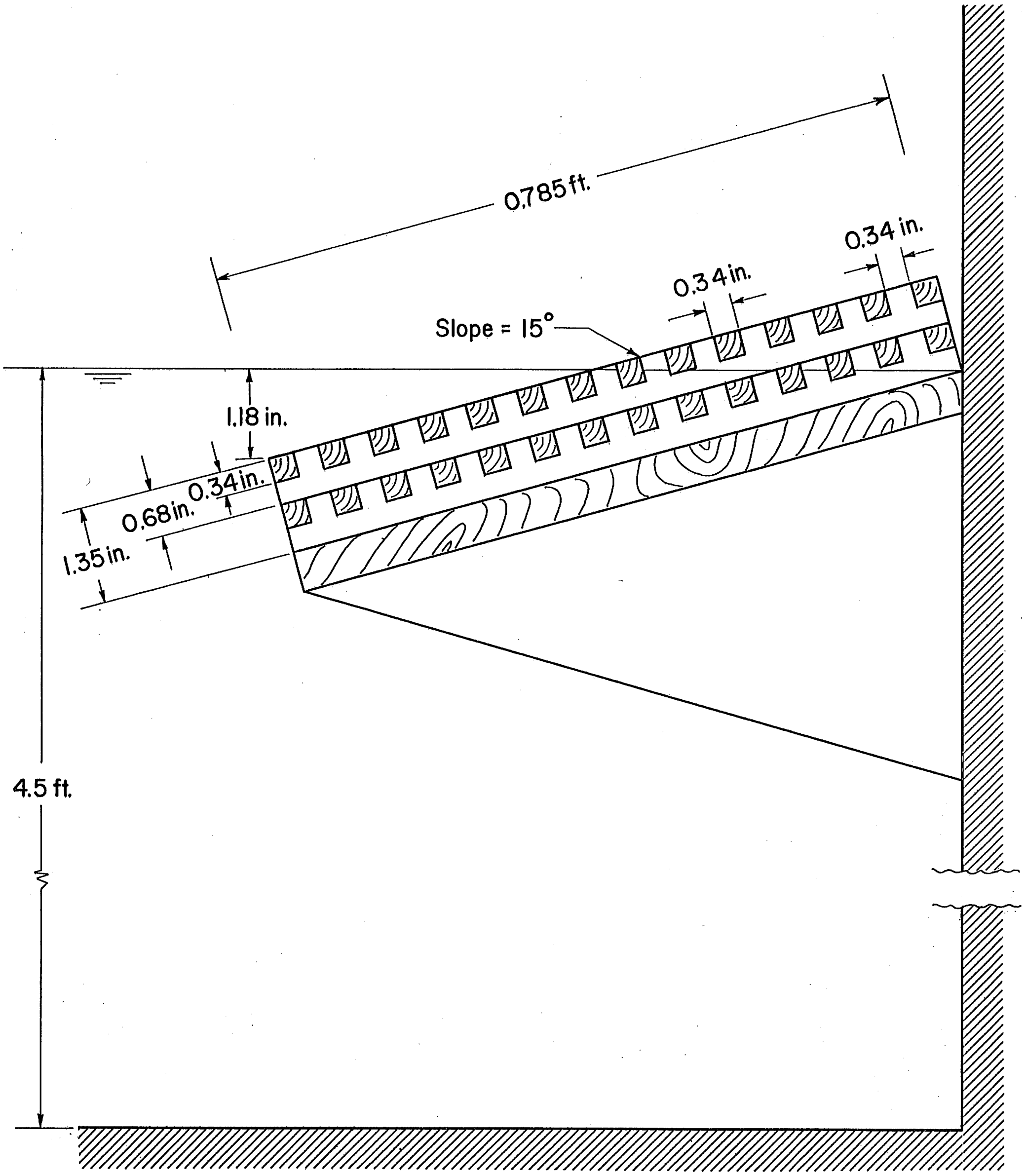


Fig. 15 - Sketch of Recommended Design of Absorber for Rotating-Arm Basin (Dimensions for 1:4.45 Scale Model)

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