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MODEL STUDY OF AMPHIBIOUS BREAKWATERS

by

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ABSTRACT

Curves have been developed from laboratory experiments which indicate the effectiveness of various orientations of a type of model floating breakwater. Comparisons are shown between the model orientations and some arrangements of rectangular blocks. The major variables have been identified. The results presented herein are based upon a two-dimensional study in a 1 foot x 3 feet x 60 feet wave channel. The prototype conditions which have been represented in these model tests are:

(i) waves ranging as high as 7 feet with a 12 second period, 16 feet with a $6\frac{1}{2}$ second period, and 25 feet with a 10 second period;

(ii) water depths ranging from 30 to 60 feet;

(iii) a Navy Lighter pontoon structure 175 feet long and of unit width.

Breakwater efficiencies up to 90% were noted in a few cases for some of the shorter period waves. Qualitative observations indicated mooring stresses ranged from very small to zero in a large number of instances. These results are encouraging, but additional experiments and analyses are needed.

Introduction

The height of waves and breakers is of prime importance in amphibious military operations and is one of the factors controlling assault landings, cargo handling, salvage, etc. In addition, the feasibility of many construction operations along waterfronts and offshore is determined by wave height. Marginal and limiting wave and breaker heights have been established for many amphibious and marine operations. When the actual (or predicted) wave heights exceed the desirable heights for a given operation, the operation either must be postponed or proceed under unfavorable conditions unless the actual heights can be reduced sufficiently. A breakwater may be used to reduce wave heights.

Extensive information, both from theoretical analyses and from practical usage, is available on some forms of breakwaters. For amphibious operations many types of breakwaters are unsatisfactory. The two distinguishing characteristics of amphibious breakwaters are:

(i) Mobility - the ability to be transported from afar and set in operation in a matter of days or perhaps hours - is required.

(ii) limited life of the breakwater - perhaps only a few months or less - is satisfactory.

Thus rubble mounds, concrete blocks and the more permanent types are eliminated, as are the types which require extensive preliminary work at the site such as pile driving, elaborate moorings etc.

The major source of prototype information on amphibious breakwaters is in the accounts of the Normandy landings in 1944. The mobile breakwaters which were used were of two types: the Phoenix and the Bombardon. Successful breakwaters must resist the horizontal forces of waves. The Phoenix type was sunk to the bottom and was designed to withstand these forces by resistance to overturning and by friction on the bottom developed by the mass of the structure. The Bombardon type was floating and was designed to withstand these forces by use of the mooring system and momentum of the float (natural period of the structure long compared to the wave period). The fact that these structures were so large and expensive, yet failed during a storm shortly after installation led many to believe that mobile breakwaters would not prove practical.

A somewhat more obscure prototype attempt to utilize a floating breakwater was described in the U. S. Navy Civil Engineer Corps Bulletin ("Pontoon Break-water," 1948). A 7 x 30 N. L. pontoon drydock (50 feet x 175 feet deck area) was tested at various depths of submergence and with the deck inclined at various angles. The conclusions drawn from this study were that:

(i) Ocean swells could be made to break offshore (thus dissipating energy) by letting them run up the inclined deck.

(ii) The length of the structure must be considerably greater than the wave length.

More recently, a complete and detailed evaluation of the various mobile breakwaters based on laboratory and theoretical analyses was reported by Carr (1950), wherein it was concluded that:

(i) Pneumatic breakwaters (dissipation of the wave energy by diffusion of air upward from the bottom) were impractical and did not merit further consideration.

(ii) Wave motors (attempts to harness the energy of the waves) were not practical in the present stages of development.

(iii) Floating and submerged barriers, though reasonably effective, could not prove practical until better moorings were devised because of the large horizontal forces developed.

All of these previous studies do not rule out the possibility that some ideas have been overlooked or even that a smaller breakwater with a very large mooring system might have application for some of the details of amphibious operations such as providing landing boat lanes of relatively small extent through the surf zone or providing protection over a small area for construction operations such as oil well drilling.

Although the idea of floating breakwaters is old, the mathematical analyses of various relationships is not well advanced. Nevertheless, some qualitative conclusions can be inferred from present knowledge of waves which should aid in the development of successful floating breakwaters. Some empirical model tests were conducted to substantiate these conclusions.

Qualitative Analytical Considerations

The kinetic energy of waves is manifested by orbital motions of water particles. The orbit patterns for deep and shallow water waves are indicated in Figure 1. One can see that the orbits are practically the same from top to bottom in the very shallow water wave, but are much larger nearer the top in a deep-water wave. Accordingly, in order to be effective in shallow water, a breakwater must disrupt virtually all of the orbital motion from top to bottom; whereas, in deep water a large percentage of the orbital motion can be disrupted in a region comparatively close to the surface. The shallow water conditions are of most interest in amphibious operations.

A plain floating structure such as a barge, which extends over half a wave length will be acted upon by horizontal components of the orbital forces both in the direction of wave advance and opposite to it. Consequently, the forces in the mooring will be less than if the structure is very short compared to the wave length.

Considering the facts that (i) virtually all of the orbits from top to bottom must be disrupted, and (ii) stress on the mooring will be less if the structure is as long as practicable compared to the wave length, a solution was suggested namely, a structure having one end resting on the bottom and the other end floating with the projected length of the structure equal to at least half the wave length. A float may be brought to such an inclination by proper use of ballast.

An unlimited number of combinations of weight and distribution of ballast is possible for a given slope, i, of the model. In fact, the upper limit for weight of ballast approaches infinity as the distance from the submerged end to the resultant downward force of weight of float and ballast approaches zero. The lower limit for weight of ballast is a little more definite. The model may be brought to a position with one end floating and one end resting on the bottom by a small amount of ballast distributed throughout almost the entire length with only enough flotation left at one end to hold it up. A reasonable starting point for the ballasting, then, appears to be to make the density of the ballasted portion just equal to the density of water. In other words, the ballasted section would just displace its own weight of water.

Accordingly, the major variables which determine the breakwater efficiency were presumed to be:

(i) the characteristics of the waves, d/L and H/L.

(ii) the characteristics of the breakwater such as arrangement of mooring, shape of the structure, mass of the structure.

(iii) the relationships between certain characteristics of the structure and the wave characteristics such as h_1/L and D/d.

Empirical Procedure

Valid conclusions could not be justified on the basis of the above qualitative analysis only, so an experimental program was outlined to:

(i) Establish relationships between length and draft, and transmitted wave heights using rectangular blocks.

(ii) Determine the effects of grids and transverse cutoff panels attached to the bottom of rectangular blocks.

(iii) Test various orientations of a model sloping float combining the information gained from items (i) and (ii) above.

Quantitative determinations of the breakwater efficiency for various conditions of the variables were made. It should be noted that the breakwater efficiency actually is 1 minus H_t/H_i, and H_t/H_i is not a true transmission coefficient. The measure of breakwater efficiency is the wave height with the structure in place, divided by the wave height with no structure in place. Consequently H_i is the initial wave (using no breakwater), not the incident wave on the seaward side of the breakwater. This distinction is particularly important in shallow water where wave characteristics are changing with depth. Also the incident wave seaward of the structure becomes complicated by reflections from the structure.

Qualitative determinations were made of conditions of mooring and other factors which could not be measured readily.

Laboratory Equipment

The equipment consisted of a glass-walled channel, with a level bottom, 1 foot wide, 3 feet high and 60 feet long, with a wave generator at one end and an absorber beach at the other; a 2-channel Brush recorder recorded water surface profiles by means of wire resistance elements. A sketch of the equipment is shown in Figure 2. The blocks and models which were used are detailed in Appendix A.

The experimental procedure was to:

(i) Generate waves in the channel and record the characteristics of these initial waves on the Brush recorder.

(ii) Insert various test objects

(iii) Compare initial wave heights (before test objects were inserted) with heights transmitted past the test objects.

In each run, a series of about one dozen waves was recorded; then the wave machine was stopped and the water allowed to become quiet; then the succeeding run was started. Each combination of wave and float conditions was tested by three separate runs. Then the maximum and average wave heights were computed separately for each run. These in turn were averaged for the three runs to determine a single maximum and single average transmitted height for that condition. By this means experimental errors were believed to be reduced.

Preliminary Results

A. Rectangular Blocks: Blocks of various lengths were tested in three different depths of water at a constant wave steepness, H_i/L, and a constant d/L to show the relationships between the block-length to wavelength ratio, h_1/L, and the transmitted-initial wave height ratio, H_t/H_i. The blocks were tested both free floating, and restrained by a string (of length equal to 6d) which was secured at the bottom of the channel and to the bottom of the block. These results are presented in Table I and Figures 3, and 4.

The analyses of the records showed secondary waves in many cases and variations in transmitted height with distance away from the float. Both of these phenomena are illustrated in the facsimile record, Figure 5. The variation in heights is illustrated graphically in Figure 6. The period of the major transmitted wave was the same as the initial wave for all of the large number of records sampled for period. Close inspection of the secondary wave shown in Figure 5 shows that although it has the same period as the primary wave it travels at a different velocity and thus is of different wave length. The analysis of Figure 5 is summarized in Table II.

B. Cutoff Panels: Because the draft to depth ratios were found to be major variables, a series oftests was completed in which transverse wooden strips were rigidly attached underneath the wood blocks. For three arrangements tested, the overall thickness was made the same as the rectangular block thickness above, but since the volume of the block was decreased considerably, the draft was much deeper, and the freeboard correspondingly less. The results listed in Table III, when compared with curves of Figure 4, show that, on the basis of D/d, the floats with the cutoff panels were not quite as effective as the solid blocks, but the mass was very much less - an important consideration in prototypes. The measurements also suggested that addition of interior cutoff panels in addition to the end panels did not change appreciably the transmitted wave heights.

C. Initial Studies with Model Structure: With a view to possible prototypes readily available, the model structure chosen had the general characteristics of a Navy Lighter pontoon structure of unit width by 175 feet (30 pontoons) long - the longest standard pontoon strings now fabricated. The scale factor selected was 60. The primary aim of these investigations was to study the effects of the different variables. Therefore, an expensive, detailed model which corresponded exactly to prototype did not seem warranted at this time. If the results of these investigations proved promising, they could hardly be considered as more than possibilities for further experiments.

An indication of the prototype conditions represented by the experiments may be obtained by multiplying the linear dimensions H_i, d, L, and h_1 by 60. The prototype period is a function of the square root of the linear scale ratio and may be computed from the tabulated data by multiplying the model periods by $\sqrt{60}$ or 7.75. Thus at prototype depth of 30 feet the period range represented is about $6\frac{1}{2}$ to $12\frac{1}{2}$ sec; at depth 45 feet, from about 6 to 10 sec.; at depth 60 feet, from about 6 to 9 sec.

The effect of adding two model pontoon bridge strings as a cutoff panel also was investigated because of the conclusions in paragraph B above.

Ballasting of the pontoons to obtain the various orientations was simulated by adding lead strips which had been weighed under water. Initially, three conditions of ballasting were simulated: the first 18 of the 30 pontoons or 0.60 h_o, the first 22 or 0.73 h_1, and the first 26 or 0.87 h_1. As noted previously, the ballasted portion was weighted to just displace its own weight of water.

The preliminary results have been summarized for comparison Table IV.

Results Using Model Structure

Study of Table IV and the laboratory observations showed that the most promising orientations were those with the shoreward end of the float submerged.

Those with the seaward end submerged tended to orient at reduced slope under wave action so that much water passed over and under the float. Accordingly, a second "screening" investigation was undertaken to study the effects of changes in ballast, changes in position of mooring, use and position of cutoff panels, and effect of reversing the float and submerging the end with the cutoff panels. These selected orientations were marked as Cases I through XII, and are detailed in Appendix A.

This secondary screening was for three different depths and four different wave lengths, a total of twelve different wave conditions for each orientation. All the records were not analysed in detail; those for the three cases most effective for reducing wave heights being selected. For each wave condition the most efficient three orientations were among cases VII to XII, inclusive, showing the desirability of orientating the float at an angle and using the transverse cutoff panels. Accordingly a supplementary study was made to establish more clearly the effect of wave steepness for these last six orientations.

A. Quantitative Results: These results consisted of measurement of wave height, length and period for the initial condition without any model and for each orientation of the model (Cases VII through XII). The still-water slope of each orientation, i, also was recorded. These results have been listed in Tables V, VI, and VII. The results at gage station 22.0 (feet) are shown graphically for each of the six orientations in Figures 7 through 11.

Comparison of the wave heights at both gages shows that the initial heights at the gages are seldom equal nor are the ratios of H_t/H_i equal. The initial heights might be expected to vary because the waves are in shallow water. The transmitted heights might be expected to vary both because the waves are in shallow water and the gages are at different distances from the structure. In all cases the shore end of the structure was placed at station 28 (feet) and the gages placed at station 25.0 and 22.0 regardless of depth or wave length. An indication of the differences in H_t/H_i between gages may be seen by comparing Figure 8 with Figure 12.

Inspection of Tables V, VI and VII indicated that a relationship exists between the average H_t/H_i at each of the gages and h_1/L. For the range of h_1/L between about 0.75 or less and about 0.56, the average H_t/H_i is less, in general, at the distance shoreward from the shore end of the float equal to 1.03 h_1 (gage station 25.0); but for h_1/L either greater or less than this range, the average H_t/H_i is less at the distance equal to 2.06 h_1 (gage station 22.0). From these observations one can infer that the transmitted waves are changing shape to a stable form as they proceed shoreward. Accordingly, optimum breakwater efficiency at a point apparently requires that the breakwater be placed seaward of the point some distance depending primarily on h_1/L. A continuous history of the transmitted wave would be necessary to establish more definite relationships.

The periods of the initial and transmitted waves were equal within limits of measurement. Case VIII generally transmitted the most complex wave, so periods were measured for all conditions of Case VIII. The primary transmitted wave always could be identified and had the same period as the initial wave.

The true effect of the depth of water may be obscured somewhat by the arrangement of the parameters in Figures 7 through 11. Consequently, Figure 13 (Case VIII) has been plotted where the changes in depth appear to be relatively unimportant for d/h_1 between 0.17 and 0.34. The curves of wave steepness for H_t/H_i at values of the ratio h_1/L are reasonable when the variations in depth within the limits investigated are ignored. Similar graphs for Cases VII, IX, XI, and XII showed the same general trends. An explanation may be that although the slope of the float with the bottom, i, varied considerably, the projected length, $h_1 \cos i$, changed only 6 or 7%.

The effect of wave steepness is indicated clearly on all the graphs. The H_t/H_i generally decreased for decreasing steepness, H_i/L, at a given d/L. The notable exception is case XII, Figure 11, where this relationship was reversed at the larger values of d/L. The upper limit of wave steepness tested was selected arbitrarily as that steepness where disturbance at the crest was noticeable in the channel.

The most efficient orientations in general were Cases VII and IX which hardly can be separated. A graphical comparison of all cases is presented in Figure 14 for $H_i/L \approx .05$ and $d/h_1 = .26$.

B. Qualitative Results: Several variables did not lend themselves to numerical determination readily. The three most important of these appeared to be

(i) the stress on the mooring.

(ii) the actions of the submerged end of the model.

(iii) the amount of water which passed over the model.

Characteristics of the secondary waves also were noted in a qualitative manner. Many laboratory wave records show secondary waves presumably generated by the motions of the structure which were of different form at the two gages similar to those for the rectangular block as shown in Figure 5.

The ballasting of the model deserves more than passing consideration. The static forces on the float under still-water conditions are sketched below.

where R_1 = upward force at submerged end

R_d = resultant upward force of water displaced

W = resultant downward force of weight of float and ballast

Some of these forces are fixed in location. The force R_1 must be at the submerged end of the float. For a float of uniform section throughout its length the force R_d will be located in the middle of the submerged length. But the location of W may be varied within certain limits. If W is great enough to submerge one end, then x may not exceed c or the wrong end will submerge. Theoretically, the minimum limit for x is zero when W is infinite.

but practically, the limit is a short distance when very heavy ballast is concentrated near the end. From the sketch, for a given i and depth, R_d and c are determined. Then the static bending moments in the structure will increase as x decreases because W must be increased. Presumably the dynamic forces will at times act to increase these bending moments even more. Aside from impact forces which may be high if the submerged end raises from the bottom, then slams down as the next wave arrives, the bending moments in the structure resulting from both static and dynamic forces appear to be less for well distributed ballast.

The breakwater efficiencies for the ballasting tested probably were less than if heavier ballasting has been used as this arrangement allowed water to raise the submerged end and pass under as the waves advanced. Note from Tables V, VI, VIII that the submerged end did not stay on the bottom under any conditions.

The stress in the mooring was estimated as listed in the Code Key for Remarks, preceding Table V. Perhaps the most noteworthy cases were those in which the transport of the structure was seaward, i. e. no stress on the mooring. This occurence was observed for several conditions of various orientations. It was true for all the investigated conditions with Case VIII, and since the mooring was the only variable between Cases VIII and X, Case X was eliminated from the graphs and tabular summaries. Careful observation showed that under certain conditions the float moved seaward by means of a sort of ratchet action: when the crest of the wave reached the seaward edge (stern) of the model, the stern was raised and the bow tended to "dig in." Thus the shore-ward movement of the model was prevented, not by the mooring, but by the bow. As the crest of the wave passed the submerged end, it was raised and the following trough (with its seaward direction of water) caused a slight movement to sea. In this manner the model was transported seaward. The implications of this phenomenon for prototype installations are quite interesting because much more favorable mooring conditions are indicated than have been reported for other types of floating breakwaters. The fact that other orientations (except Case XII) were transported seaward some of the time suggests that a significant part of the horizontal force was being resisted by the submerged end even over the smooth wood-to-metal contact in the channel. Hence, the stress in the mooring for the cases which were not transported seaward probably was reduced. Particularly, comparing Cases VII and IX where the only variable was the mooring, (compare sketches in Appendix A) in the cases which were not transported seaward, the breakwater efficiencies are practically equal, indicating that the change in mooring had little effect. Considering that the transmitted wave height (all other conditions being equal) is a function of the change in slope of the model and considering that this change in slope could be limited only by the weight of the structure and the stress in the mooring acting as turning moments about the submerged end, the only instance in which the transmitted wave heights could be virtually equal is when the stress in the mooring is small.

Summary and Conclusions

Considerable data were collected and a large number of variables were investigated in this series of tests on model amphibious breakwaters. The primary aim of the laboratory program was to test certain general conclusions. Nevertheless, the data do cover reasonable prototype ranges. One of the variables which was not examined in the laboratory, but which probably had some effect was the natural period of pitch of the float for different cases. These data on natural periods were not available readily for the prototype and did not lend themselves to easy computation. However, the prototype is reasonably uniform throughout its length with regard to mass distribution. Therefore, dynamical similarity of model and prototype is more apt to follow geometrical similarity than in a craft which has large concentrated masses built in it such as the engines in a boat or amphibian vehicle.

Much wave channel work has found application to full scale applications and the general validity of the conclusions of this study appears reasonable. One point of concern, however, may be the uniform height, length, period and direction of the model waves compared to the non-uniform corresponding characteristics of waves in nature. Whereas the pitching of a craft, for example, is a function of individual wave characteristics, the efficiency of the breakwaters investigated here probably is a function of both individual and group wave characteristics - especially so because the length of the breakwater is appreciable compared to wave length. Therefore, the regular waves in the channel are less apt to mirror prototype conditions for group wave phenomena than for individual wave phenomena, because waves in nature are not regular - in height, length, period, or direction. Nevertheless, some valid conclusions may be formed on the basis of this study as follows:

(i) Considerable breakwater efficiency can be realized and the stress in the mooring can be reduced considerably by using a structure submerged at the shoreward end and floating at the seaward end.

(ii) The major variables affecting the efficiency of such a floating breakwater appear to be h_1/L, d/L, H_i/L, the characteristics of the float, and the distance shoreward from the float.

(iii) Cutoff panels at the end of the float are effective in increasing the breakwater efficiency but addition of interior panels does not appear to increase efficiency much over end panels alone.

(iv) The transmitted waves appear to be unstable in form and changing in characteristics as they proceed shoreward from the breakwater. The primary transmitted waves have substantially the same period as the initial waves, but do not necessarily travel at the same velocity. Secondary transmitted waves sometimes are generated and usually are more erratic than the primary.

(v) Of the model orientations tested, Case VII proved to be generally most efficient, but Case VIII was best with respect to moorings because it was transported seaward under all conditions tested.

Recommendations

On the basis of the above conclusions and a review of these experiments one can see that additional observations could have been made and that additional studies along these general lines probably would be fruitful. Specifically, these recommendations are submitted:

1. That some prototype confirmation of the general feasibility of using a sloping float be obtained, possibly by using a 2 x 30 (14 feet by 175 feet) Navy Lighter pontoon causeway. I.E. check the model observations in re ballasting, mooring and action of the float. Actual quantitative determinations of breakwater efficiency probably are not justified at this stage of the study because of the excessive effort and equipment which would be required.

2. That a three-dimensional model study precede full-scale tests if a limited number of prototype observations confirm the conclusions of this study.

3. That the weight on the submerged end be increased to reduce the flow of water under the float.

4. That for the prototype, a spud be considered for the submerged end.

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see U1527

SYMBOLS AND NOTATIONS

ave	average
d	depth of water - ft
D	draft - ft
dist	distance shoreward from shore end of float - ft
h_1	characteristic length of blocks - ft
H_i	initial wave height (without a test object in place) - ft
H_t	transmitted wave height (at a point shoreward of a test object) - ft
i	inclination of model from horizontal - degrees
L	average wave length between two measuring points - ft
L_o	deep-water wave length - ft (from Wiegel, 1948 - see references)
max	maximum
sta	station, distance from a reference point - ft
SWL	still-water level

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TABLE I DATA SUMMARY FOR RECTANGULAR BLOCKS

$H_i/L = 0.06$ $d/L = 0.167$ $d/L_o = 0.131$
$D = 0.125$

L	H_i	D/d	h_1	h_1/L	FREE H_t/H_i Max	FREE H_t/H_i Ave	RESTRAINED H_t/H_i Max	RESTRAINED H_t/H_i Ave	RESTRAINED Dist
1.79	.105	.40	.75	.42	.393	.279	.393	.292	4.75
			1.5	.84	.568	.467	.463	.411	4.0
			2.25	1.26	.517	.441	.441	.396	3.25
			3.0	1.68	.489	.419	.431	.372	2.5
3.0	.192	.25	.75	.25	.932	.850	.891	.829	4.75
			1.0	.33	.787	.736	.814	.751	4.5
			1.25	.42	.658	.586	.726	.658	4.25
			1.5	.50	.622	.513	.726	.612	4.0
			1.75	.58	.647	.528	.699	.586	3.75
			2.0	.67	.648	.544	.663	.581	3.5
5.1	.315	.15	1.5	.29	.952	.879	.897	.853	4.0
			2.25	.44	.882	.815	.854	.809	3.25
			3.0	.59	.755	.694	.821	.748	2.5
			4.5	.88	.732	.675	.662	.601	1.0

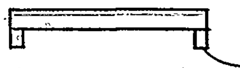
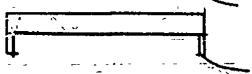
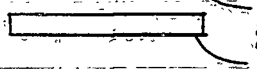
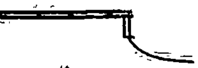
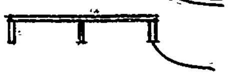
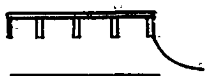
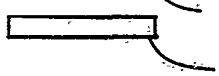
TABLE II Data Summary for Analysis of a Primary and Secondary Transmitted Wave - Restrained Rectangular Block

$d = 0.50$ $L = 5.9$ $H_i/L = 0.035$
$D = 0.125$ $h_1 = 4.5$
$T = 1.47$ for initial, primary and secondary transmitted waves at all measuring points

Dist	H_t/H_i max	H_t/H_i ave	Initial L	Transmitted L primary	Transmitted L secondary
.5	.870	.830	5.9	5.1	4.1
3.5	.820	.765			
5.0	.792	.707	5.9	5.9	6.3
8.0	.731	.698			

TABLE III Data Summary for Restrained Floats with Cutoff Panels

at d = 0.50 ft

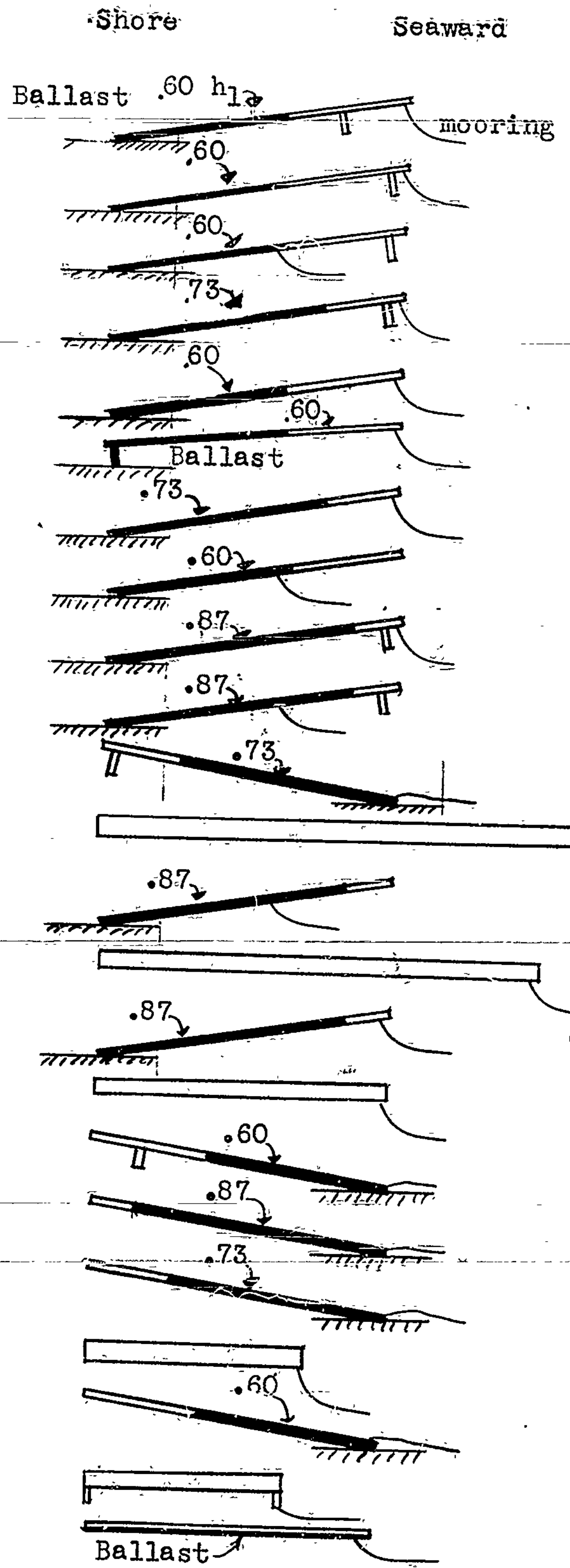
					$L = 3.0$; $H_i = .190$; $H_i/L = .064$; $d/L = .167$			$L = 5.97$; $H_i = .201$; $H_i/L = .034$; $d/L = .084$		
Sketch	h_1	D	D/d	Dist	h_1/L	H_t/H_i max	H_t/H_i ave	h_1/L	H_t/H_i max	H_t/H_i ave
	2.0	.324	.65	3.0	.67	.555	.495			
	2.0	.353	.71	3.0	.67	.470	.430	.34	.549	.488 *
	2.0	.125	.25	3.0	.67	.59	.565			
	1.5	.198	.40	3.5	.50	.496	.478	.25	.924	.849
	1.5	.198	.40	3.5	.50	.555	.485	.25	.936	.884
	1.5	.198	.40	3.5	.50	.573	.516	.25	.875	.836
	1.5	.125	.25	3.5	.50	.726	.612	.25	1.06	1.00

* Transport Seaward Estimated at .1 ft/sec.

Table IV Comparison of Preliminary Results

$L = 3$ ft $d = 0.50$ ft $H_i/L = 0.06$

Arranged in increasing order of ave H_t/H_i

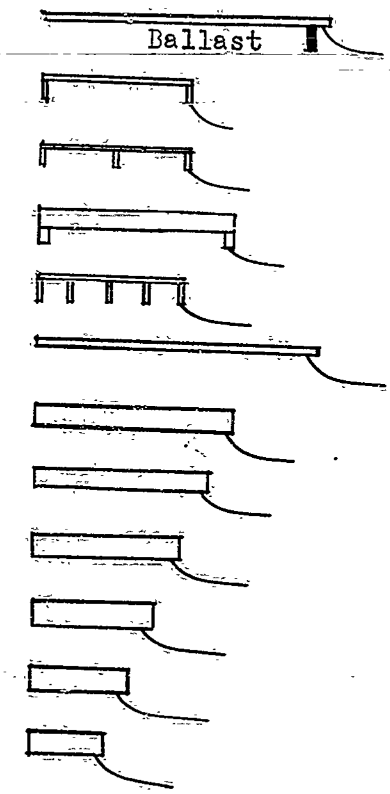


Case	h_1	D/d	H_t/H_i max	H_t/H_i ave	Dist
(Case XI)	2.9	-	.220	.152	6.0
(Case VII)	2.9	-	.209	.175	6.0
(Case IX)	2.9	-	.248	.181	6.0
	2.9	-	.300	.187	6.0
(Case II)	2.9	-	.305	.187	6.0
(Case XII)	2.9	-	.260	.208	6.0
	2.9	-	.333	.216	6.0
(Case IV)	2.9	-	.309	.241	6.0
(Case VIII)	2.9	-	.305	.245	6.0
(Case X)	2.9	-	.305	.245*	6.0
	2.9	-	.338	.282	6.0
	6.0	.25	.331	.289	**
(Case V)	2.9	-	.391	.293	6.0
	4.5	.25	.386	.359	**
(Case III)	2.9	-	.482	.369	6.0
	3.0	.25	.419	.375	**
	2.9	-	.424	.379	6.0
	2.9	-	.437	.382*	6.0
	2.9	-	.457	.388	6.0
	2.25	.25	.477	.406	**
	2.9	-	.518	.412	6.0
	2.0	.71	.470	.430	3.0
(Case I)	2.0	.125	.482	.445	6.0

* Transport Seaward

**Not Recorded

Table IV (cont)



h_1	D/d	H_t/H_i max	H_t/H_i ave	Dist
2.9	.55	.583	.466	6.0
1.5	.40	.496	.478	3.5
1.5	.40	.555	.485	3.5
2.0	.65	.555	.495	3.0
1.5	.40	.573	.516	3.5
2.9	.08	.553	.540	6.0
2.0	.25	.663	.581	3.5
1.75	.25	.699	.586	3.75
1.5	.25	.726	.612	4.0
1.25	.25	.726	.658	4.25
1.0	.25	.814	.751	4.5
.75	.25	.891	.829	4.75

Code Key for Remarks for Tables V, VI, VII

M: Mooring

- 0 Transport Seaward
- 1 Slack
- 2 Taut
- 3 Tugs every other wave
- 4 Tugs lightly, every wave
- 5 Tugs heavily, every wave

SE: Submerged End

- 0 Remains on bottom
- 1 Raises and lowers each wave
- 2 Bumps every other wave
- 3 Bumps lightly, every wave
- 4 Bumps heavily, every wave

WO: Water Over

- 0 None
- 1 Very little
- 2 Some
- 3 Much

2: Secondary Wave

- 0 Not apparent on record
- 1 Suggestion of
- 2 Definite, T = that of primary, but not in phase
- 3 Definite, T ≠ that of primary, but not in phase

0/1 etc. means 0 at gage sta 22.0, 1 at gage sta 25.0

Table V Data Summary for Model Orientations for d = 0.50 ft $d/h_1 = 0.17$ (h_1 = 2.92 ft) (Shore end of float at sta 28 for all conditions)

Case	Slope i^o	At Gage Sta 22.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	At Gage Sta 25.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	Remarks* M	SE	WO	2
L - 4.36		d/L - 0.115		d/L_o - 0.071				h_1 = 0.67		T = 1.04			
VII	11.6	.066	.023	.152	.121	.066	.023	.152	.136	4	1	0	0/1
VIII				.121	.091			.121	.106	0	1	1	3
IX				.136	.091			.167	.136	3	2	0	1
XI				.182	.152			.228	.182	1	3	0	0
XII				.288	.258			.318	.288	2	1	0	0
L = 2.94		d/L = 0.170		d/L_o = 0.134				h_1/L = 0.99		T = 0.82			
VII		.119	.040	.151	.109	.127	.043	.134	.110	3	3	1	1/3
VIII				.134	.084			.134	.087	0	3	2	2
IX				.176	.117			.189	.118	4	3	1	1
XI				.160	.117			.212	.134	4	1	3	3
XII				.437	.353			.418	.354	4	3	2	1

* See Code Key for Remarks

Table V (cont)

Case	Slope i^o	At Gage Sta 22.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	At Gage Sta 25.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	Remarks* M	SE	WO	2
L = 2.92		d/L = 0.171		d/L_o = 0.135				h_1/L = 1.00		T = 0.82			
VII		.177	.061	.209	.175	.189	.065	.286	.180	1	-	-	3
VIII													
IX													
XI				.220	.152			.328	.206	2	-	-	3
XII													
L = 3.09		d/L = 0.162		d/L_o = 0.125				h_1/L = 0.94		T = 0.82			
VII													
VIII		.191	.062	.305	.245	.202	.065	.288	.251	0	4	3	3
IX				.248	.181			.254	.183	3	3	2	3
XI													
XII				.260	.208			.259	.224	-	3	2	3
L = 4.36		d/L = 0.115		d/L_o = 0.071				h_1/L = 0.67		T = 1.04			
VII		.193	.044	.342	.301	.212	.049	.288	.266	1	3	2	0
VIII				.440	.398			.392	.354	0	3	2	3
IX				.343	.297			.288	.249	1	3	2	0/1
XI				.390	.350			.349	.329	0	-	1	0
XII				.466	.430			.425	.392	-	3	2	0/2
L = 4.80		d/L = 0.104		d/L_o = 0.060				h_1/L = 0.61		T = 1.20			
VII		.200	.042	.433	.395	.217	.045	.427	.367	4	3	2	0/1
VIII				.515	.446			.494	.425	0	4	3	1/3
IX				.432	.391			.425	.379	1	3	2	0
XI				.495	.465			.474	.438	1	3	1	0/1
XII				.472	.420			.499	.413	1	3	2	1
L = 6.08		d/L = 0.082		d/L_o = 0.039				h_1/L = 0.48		T = 1.65			
VII		.124	.021	.718	.661	.116	.019	.808	.732	4	3	0	0
VIII				.645	.627			.701	.679	0	3	0	0
IX				.734	.683			.816	.755	4	3	0	0
XI				.806	.790			.895	.852	0	3	0	0
XII				.586	.549			.667	.612	4	3	0	0

Table VI Data Summary for Model Orientations for d = 0.75 ft d/h_1 = 0.26

Case	Slope i^o	At Gage Sta 22.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	At Gage Sta 25.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	Remarks M	SE	WO	2
L = 3.02		d/L = 0.248		d/L_o = 0.227				h_1/L = 0.97		T = 0.78			
VII	17.7	.093	.031	.151	.108	.088	.029	.136	.114	4	3	0	1
VIII	16.0			.108	.075			.159	.102	0	3	0	3
IX	17.7			.161	.118			.171	.136	4	1	0	1/3
XI	18.2			.183	.140			.216	.182	4	1	0	1/3
XII	11.8			.269	.204			.273	.216	2	2	0	0/1

Table VI (cont.)

Case	Slope i°	At Gage Sta 22.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	At Gage Sta 25.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	Remarks M	SE	WO	2
L = 3.10		d/L = 0.242		d/L_o = 0.220				h_1/L = 0.97			T = 0.78		
VII		.158	.051	.139	.114	.171	.055	.158	.123	4	3	1	3
VIII				.252	.197			.258	.197	0	3	1	2
IX				.147	.110			.172	.129	4	3	0	2
XI				.196	.165			.216	.181	4	3	0	3
XII				.279	.215			.304	.234	2	2	1	1/3
L = 3.13		d/L = 0.240		d/L_o = 0.218				h_1/L = 0.93			T = 0.78		
VII		.268	.086	.300	.258	.262	.084	.368	.321	4	-	2	1/2
VIII				.362	.321			.428	.386	0	4	3	0/1
IX				.277	.216			.355	.309	3	4	2	1/2
XI				.264	.234			.314	.264	1	-	0	1/3
XII				.202	.169			.251	.238	2	3	2	3
L = 3.92		d/L = 0.192		d/L_o = 0.160				h_1/L = 0.75			T = 0.98		
VII		.196	.050	.372	.327	.190	.049	.374	.326	1	3	1	0/1
VIII				.444	.356			.442	.390	0	3	2	1
IX				Do.	VII			Do.	VII				
XI				.431	.394			.495	.415	0	3	1	0
XII				.436	.383			.447	.380	2	2	2	1
L = 4.25		d/L = 0.177		d/L_o = 0.142				h_1/L = 0.69			T = 0.98		
VII		.120	.028	.350	.316	.112	.026	.366	.322	3	2	1	0
VIII				.292	.275			.277	.250	1	3	2	1
IX				.342	.292			.321	.286	4	3	0	1
XI				.450	.416			.446	.384	-	2	0	0
XII				.484	.425			.429	.375	3	2	2	1
L = 4.34		d/L = 0.173		d/L_o = 0.138				h_1/L = 0.67			T = 1.00		
VII		.307	.071	.543	.507	.327	.075	.450	.392	0	4	2	0
VIII				.580	.554			.544	.495	0	3	3	0
IX				Do.	VII			Do	VII				
XI				.495	.457			.483	.453	0	3	1	0
XII				.518	.476			.488	.439	2	3	1	0
L = 5.21		d/L = 0.144		d/L_o = 0.103				h_1/L = 0.56			T = 0.91		
VII		.116	.022	.388	.336	.141	.027	.376	.312	5	4	0	0
VIII				.371	.345			.334	.291	1	3	2	1
IX				.383	.319			.340	.312	3	2	0	0
XI				.535	.449			.475	.411	0	3	0	0
XII				.517	.440			.440	.411	4	2	2	1/0

Table VI (cont.)

Case	Slope i°	At Gage Sta 22.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	At Gage Sta 25.0 H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	Remarks M	SE	WO	2
L = 5.30		d/L = 0.142			d/L_o = 0.101			h_1/L = 0.55			T = 1.16		
VII		.286	.054	.534	.498	.282	.053	.576	.534	0	3	2	0
VIII				.630	.580			.645	.609	0	3	3	1
IX				Do.	VII			Do.	VII				
XI				.660	.632			.659	.641	0	3	0	0
XII				.592	.530			.608	.557	4	3	2	0
L = 6.06		d/L = 0.124			d/L_o = 0.081			h_1/L = 0.48			T = 1.25		
VII		.190	.031	.700	.663	.185	.031	.755	.706	0	3	0	0
VIII				.668	.584			.718	.594	0	3	2	0
IX				Do.	VII			Do.	VII				
XI				.794	.747			.853	.810	0	3	0	0
XII				.684	.651			.707	.669	2	3	1	0
L = 6.13		d/L = 0.122			d/L_o = 0.079			h_1/L = 0.48			T = 1.31		
VII		.316	.052	.773	.700	.317	.052	.802	.735	0	3	1	0
VIII				.780	.718			.793	.773	0	3	2	1
IX				Do.	VII			Do.	VII				
XI				.810	.775			.875	.830	0	3	0	0
XII				.802	.706			.818	.755	2	3	2	1

Table VII Data Summary For Model Orientations for d = 1.00 ft d/h_1 = 0.34

Case	Slope i°	H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	H_i ft	H_i/L	H_t/H_i max	H_t/H_i ave	M	SE	WO	2
L = 3.03		d/L = 0.330			d/L_o = 0.320			h_1/L = 0.96			T = 0.74		
VII	23.9	.209	.069	.206	.144	.212	.070	.236	.184	3	2	0	3/2
VIII	21.8			.325	.292			.416	.377	0	3	2	1/3
IX	23.9			.187	.148			.251	.195	2	2	1	1/2
XI	24.7			.210	.177			.278	.231	0	3	0	1/3
XII	20.1			.201	.163			.260	.169	2	2	0	1/2
L = 3.90		d/L = 0.256			d/L_o = 0.236			h_1/L = 0.75			T = 0.88		
VII		.225	.058	.422	.369	.239	.061	.469	.372	0	3	1	1
VIII				.529	.457			.502	.448	0	3	3	1
IX				Do.	VII			Do.	VII				
XI				.506	.475			.497	.472	0	2	0	0
XII				.461	.430			.482	.410	4	3	1	0

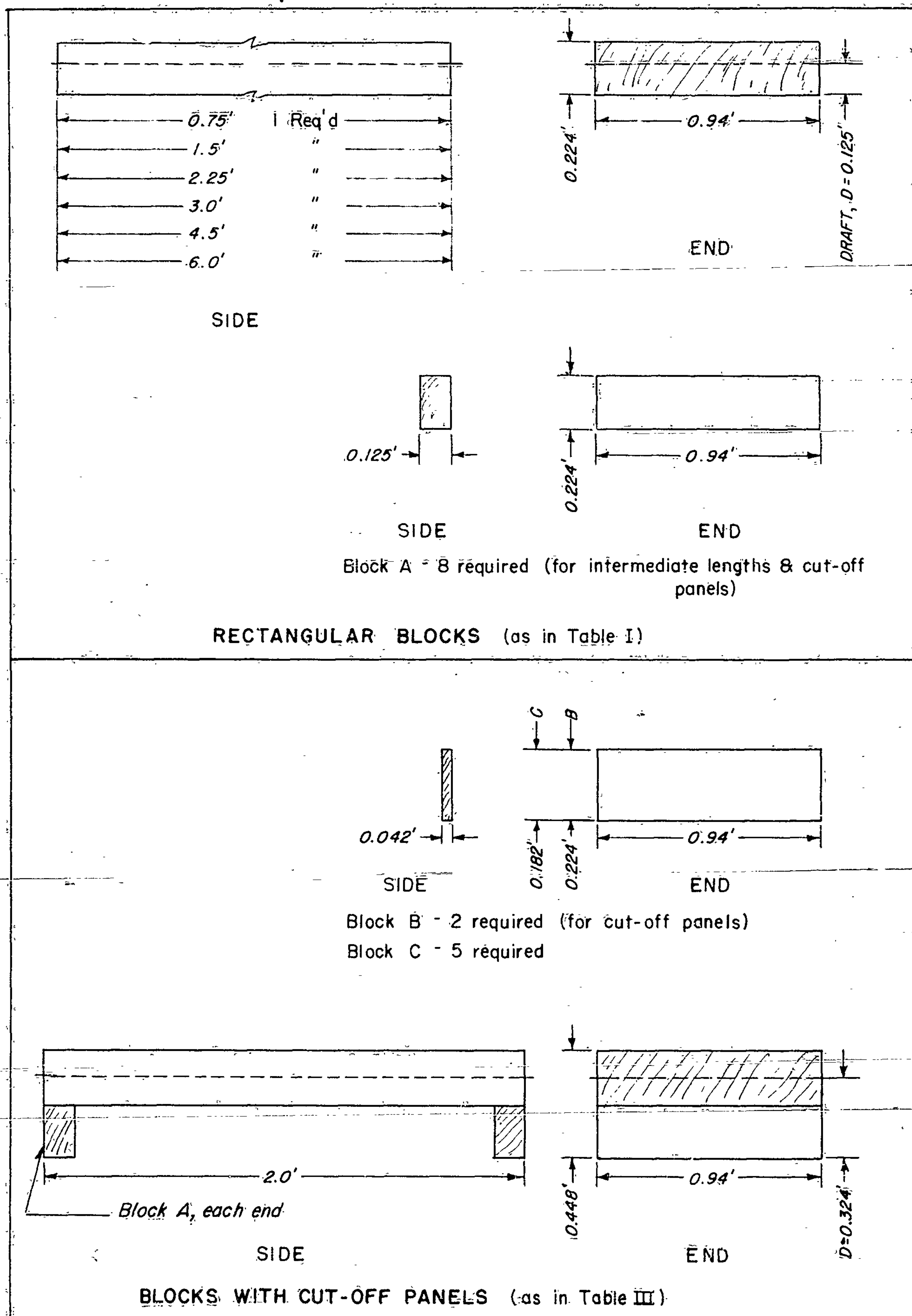
Table VII (cont)

$L = 5.09$ $d/L = 0.197$ $d/L_o = 0.166$ $h_1/L = 0.57$ $T = 1.04$

Case	Slope i^o	H_i ft	H_i/L	H_t/H_i max	ave	H_i ft	H_i/L	H_t/H_i max	ave	M	SE	V.O	2
VII		.375	.074	.672	.611	.381	.075	.677	.602	0	3	2	0
VIII				.707	.657			.684	.625	0	4	3	0
IX				Do.	VII			Do.	VII				
XI				.715	.672			.716	.675	0	3	2	0
XII				.695	.627			.738	.651	3	2	2	1

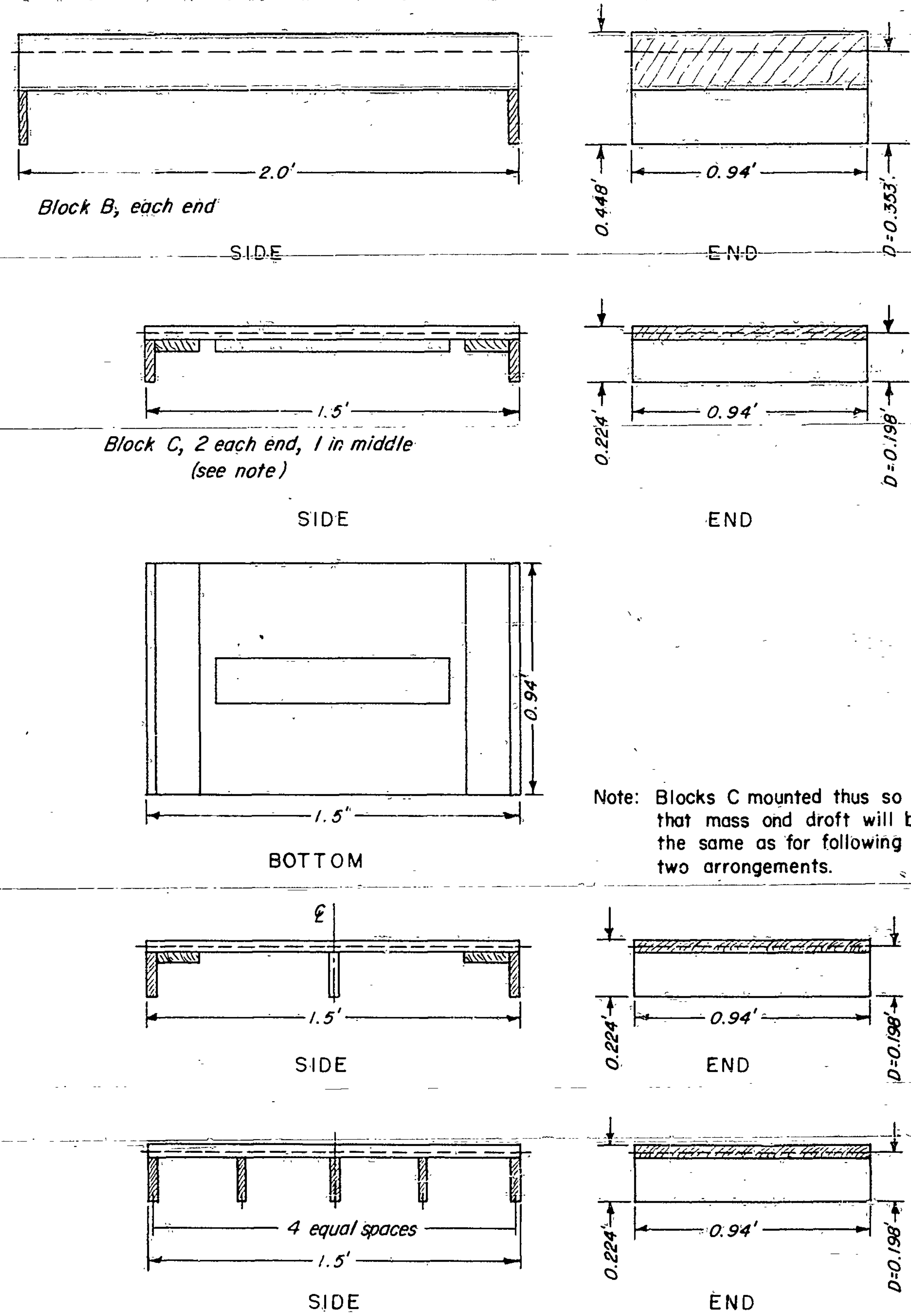
$L = 6.38$ $d/L = 0.157$ $d/L_o = 0.119$ $h_1/L = 0.46$ $T = 1.18$

Case	Slope i^o	H_i ft	H_i/L	H_t/H_i max	ave	H_i ft	H_i/L	H_t/H_i max	ave	M	SE	V.O	2
VII		.404	.063	.750	.720	.441	.069	.755	.715	0	3	2	0
VIII				.805	.738			.783	.709	0	3	3	0
IX				Do.	VII			Do.	VII				
XI				.864	.823			.797	.778	0	2	1	0
XII				.748	.713			.788	.688	4	4	3	0



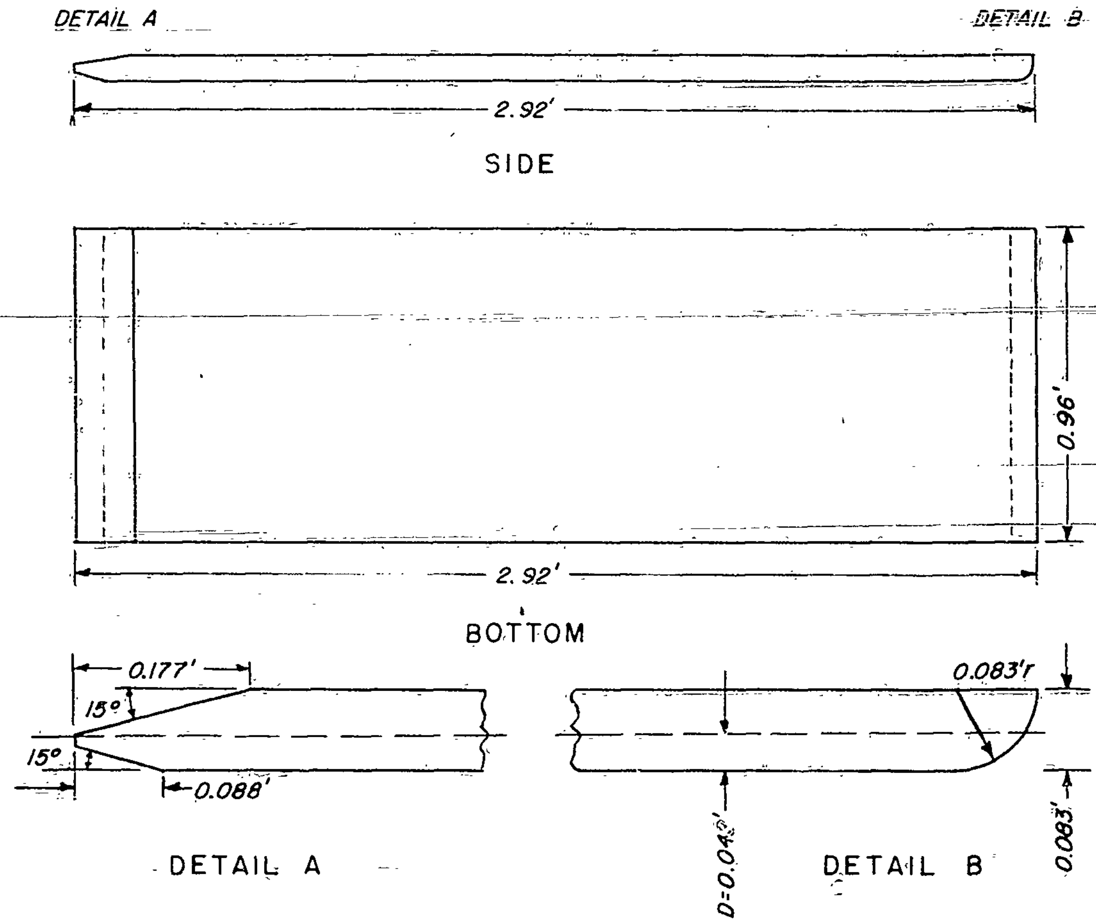
APPENDIX A - DETAILS OF FLOATS

DIMENSIONS IN FEET



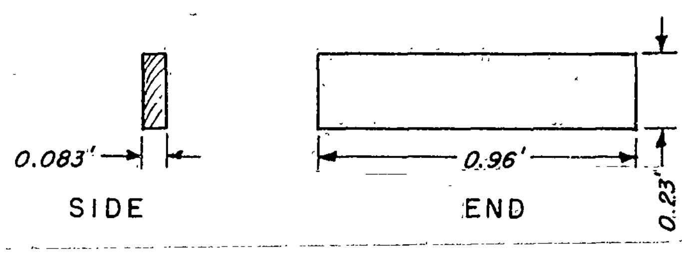
BLOCKS WITH CUT-OFF PANELS (cont.)

APPENDIX A (cont.)



MODEL OF NAVY LIGHTER PONTOON SECTION OF UNIT WIDTH BY 175' (30 PONTOONS) LONG

Model scale factor 1/60



MODEL OF NAVY LIGHTER PONTOON BRIDGE STRING 14' (2 PONTOONS) WIDE BY UNIT LENGTH

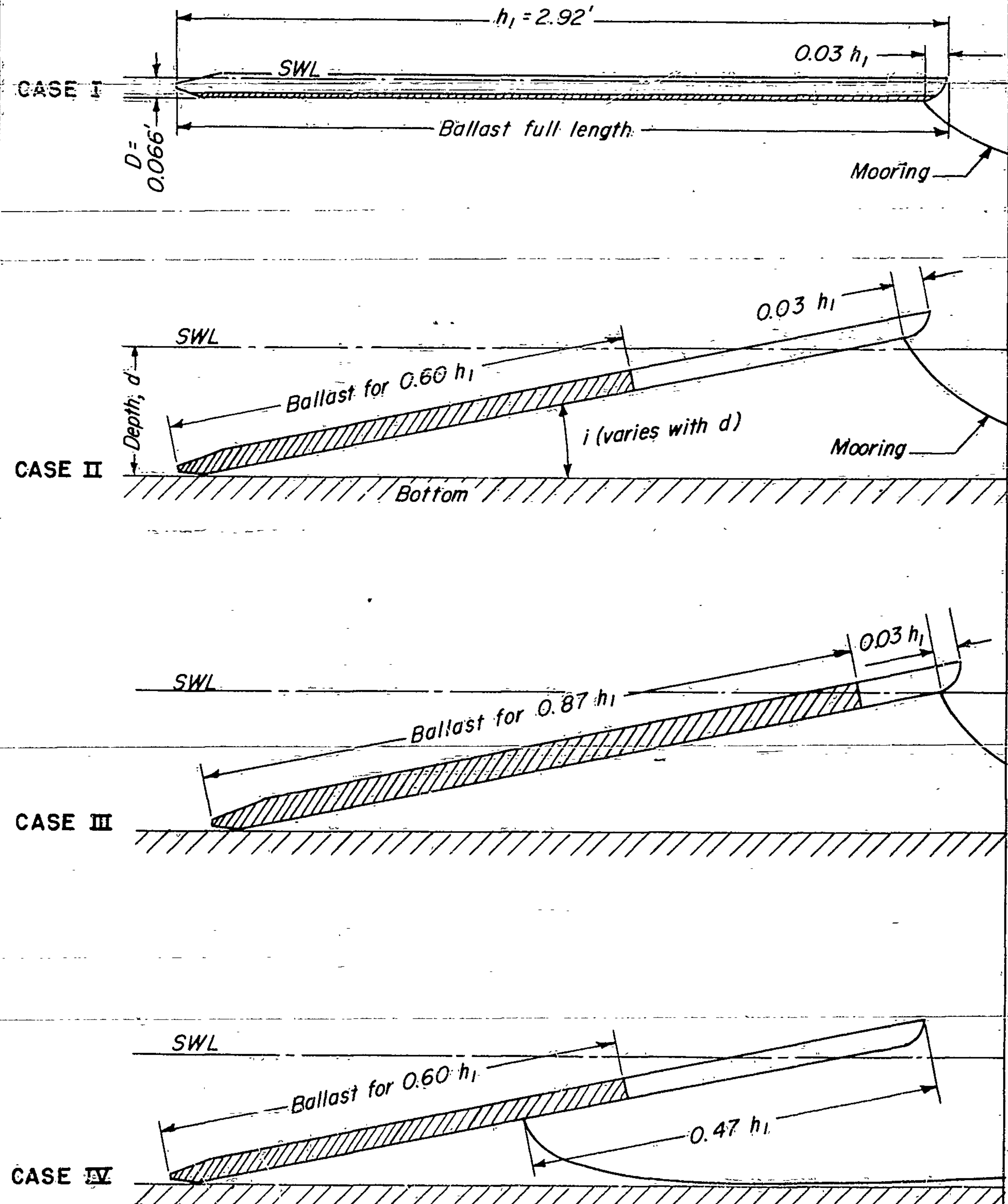
Note: Bridge string used on edge as cut-off panel

APPENDIX A (cont.)

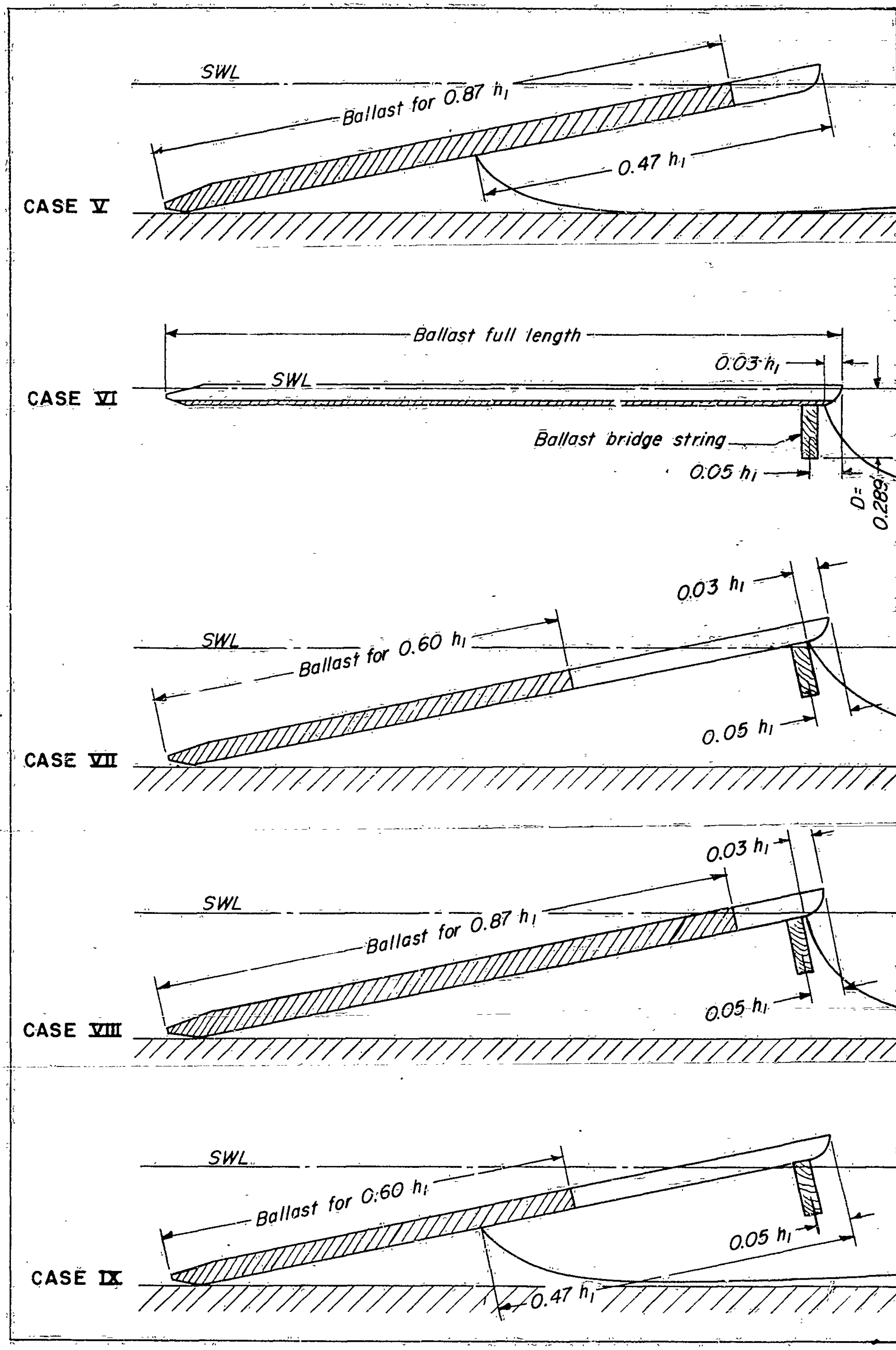
Details of orientations tested:

Note 1. Length of mooring = 6 x depth for all cases

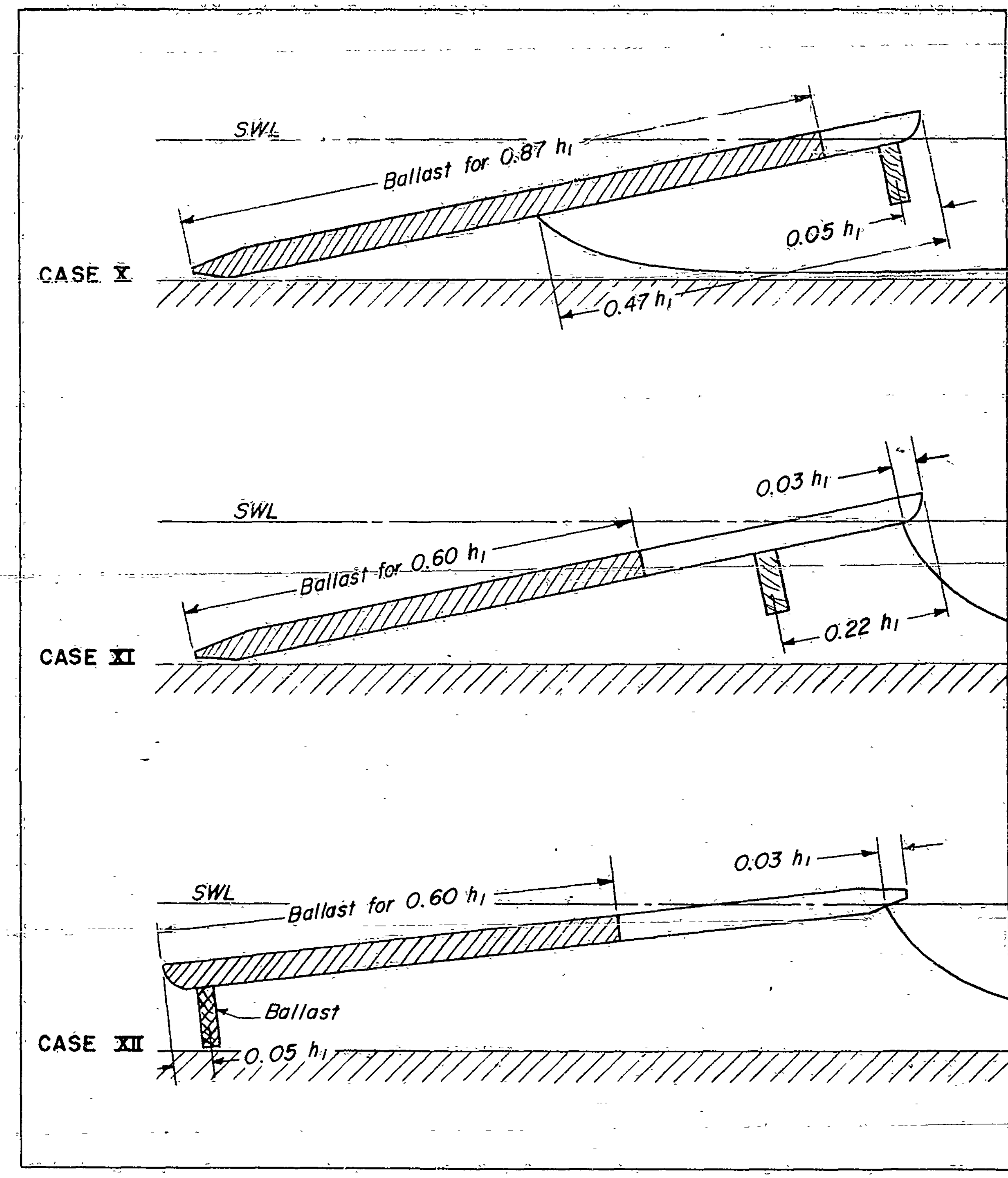
2. Except for Cases I and VI the density of the model over the ballasted length equals approximately the density of water.



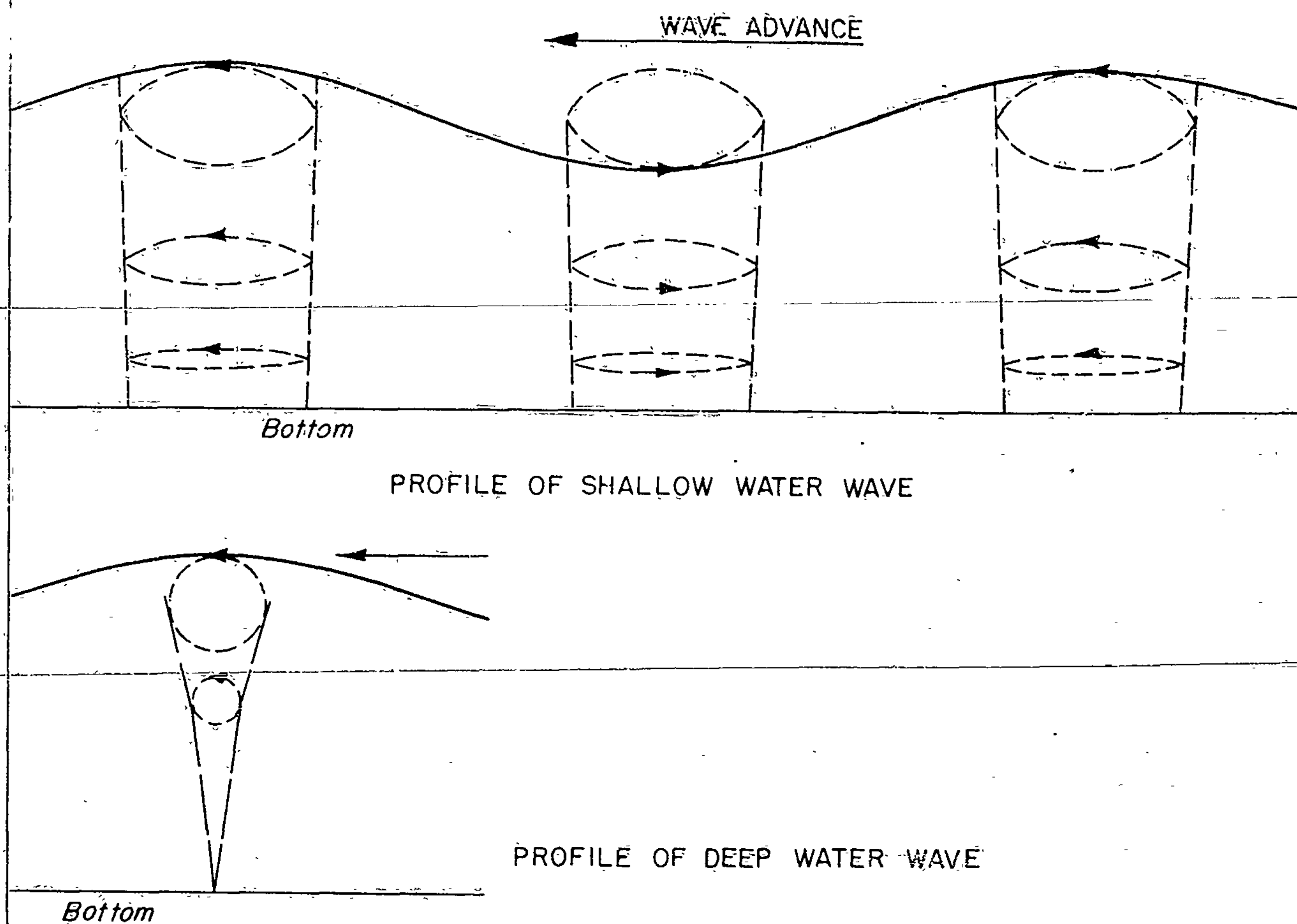
APPENDIX A (Cont.)



APPENDIX A (Cont.)

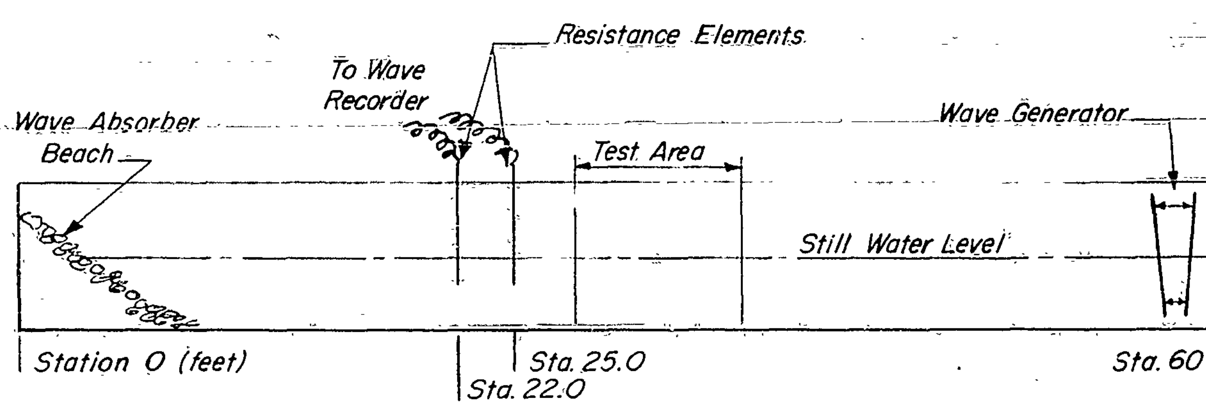


APPENDIX A (End)



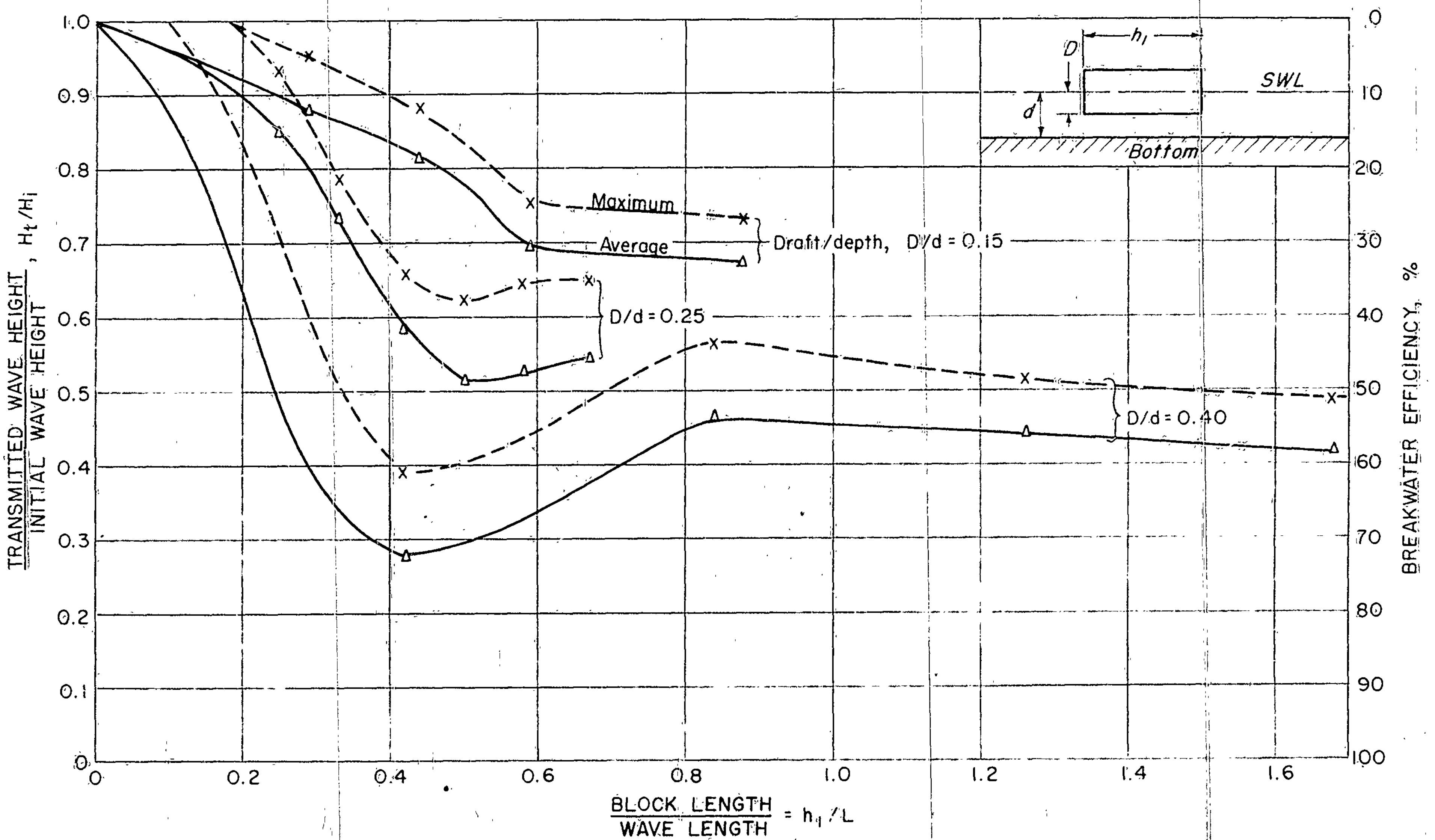
ORBITAL PATTERNS OF WATER PARTICLES

FIGURE 1



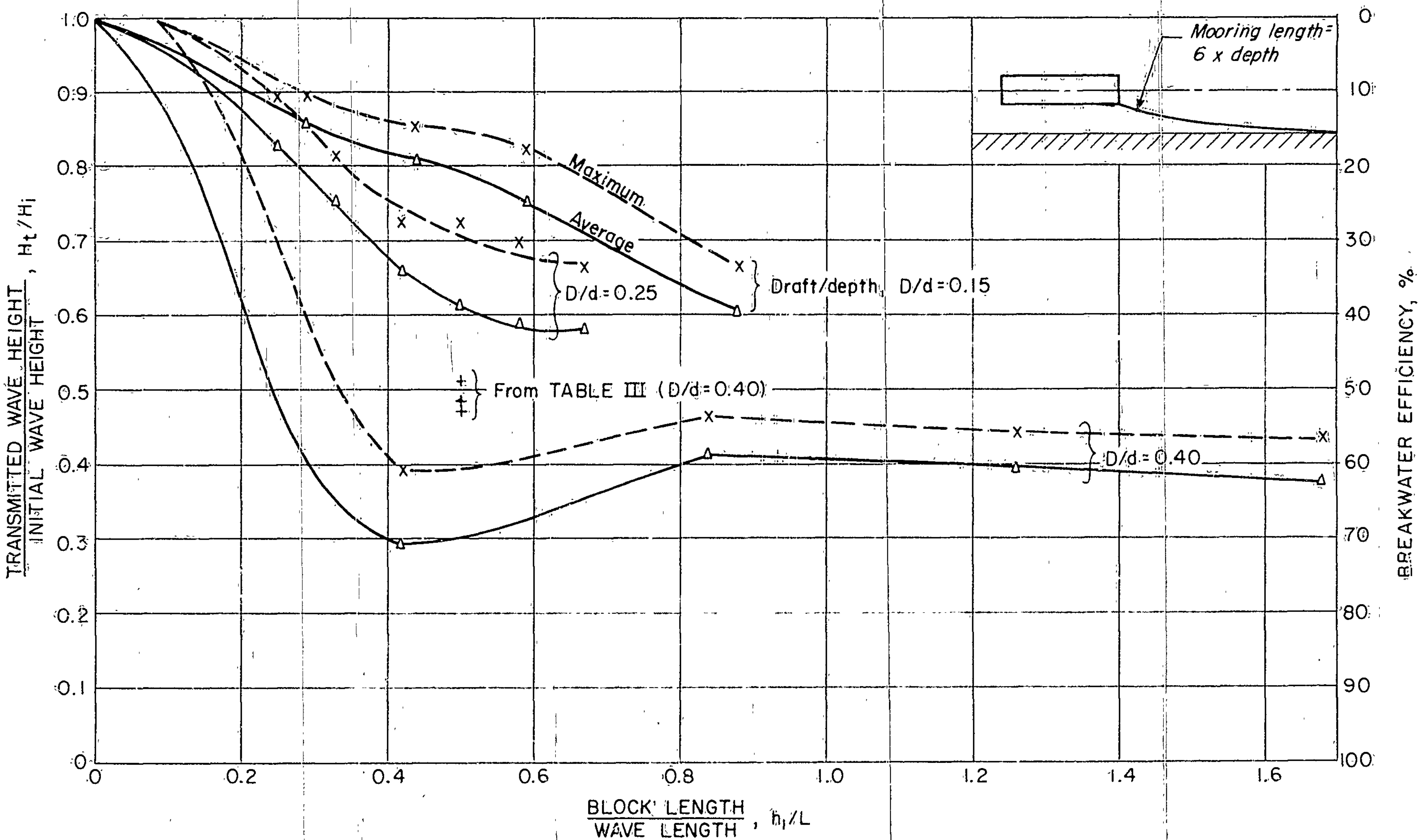
SKETCH OF THE EQUIPMENT SET-UP

FIGURE 2



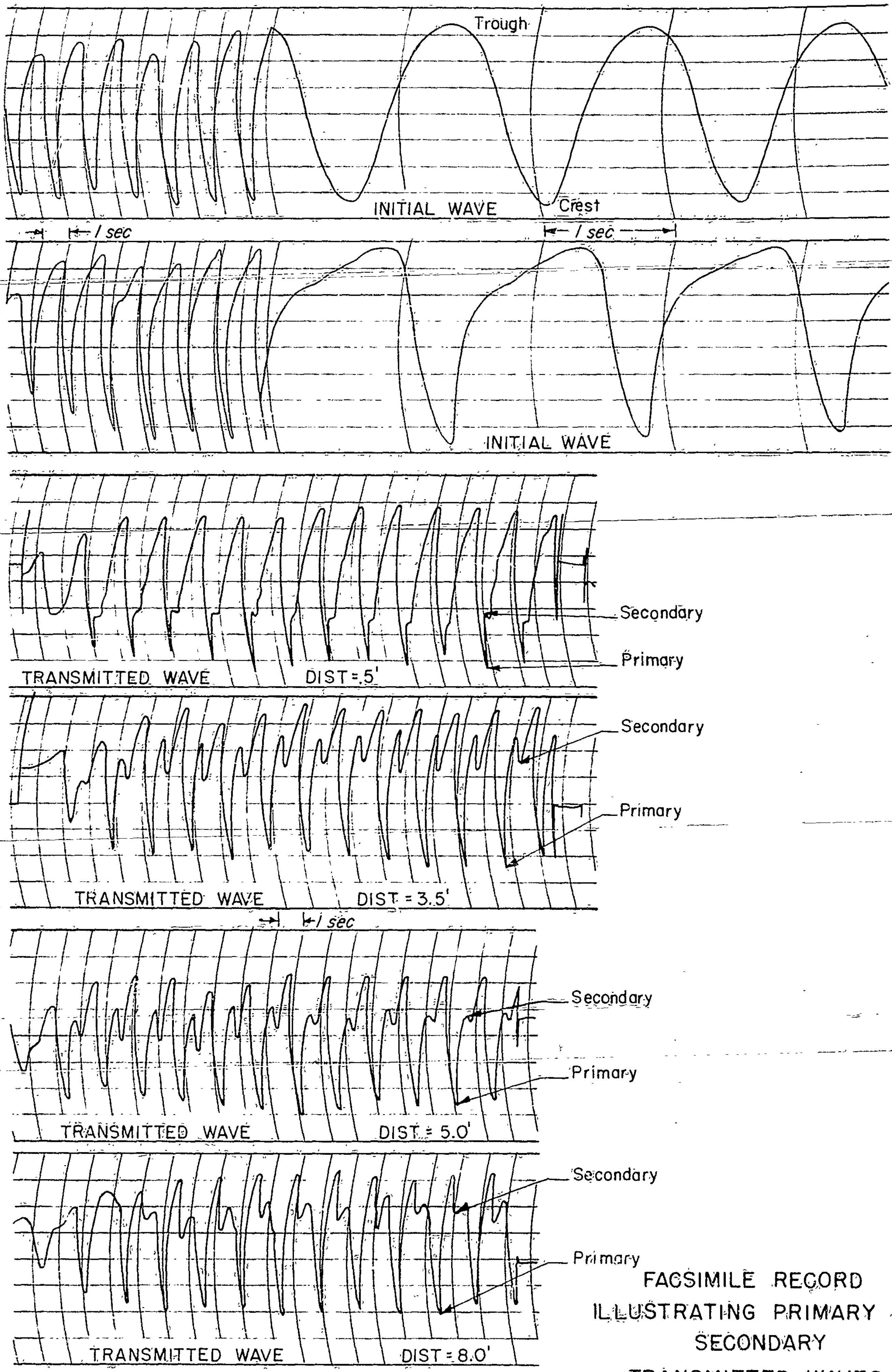
BREAKWATER EFFICIENCY CURVES
FREE FLOATING RECTANGULAR BLOCKS (from TABLE I)

FIGURE 3



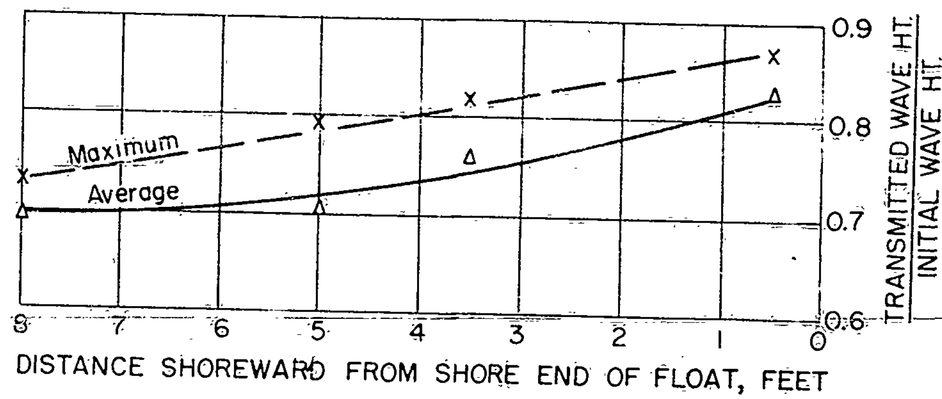
BREAKWATER EFFICIENCY CURVES
RESTRAINED RECTANGULAR BLOCKS (from TABLE I)

FIGURE 4



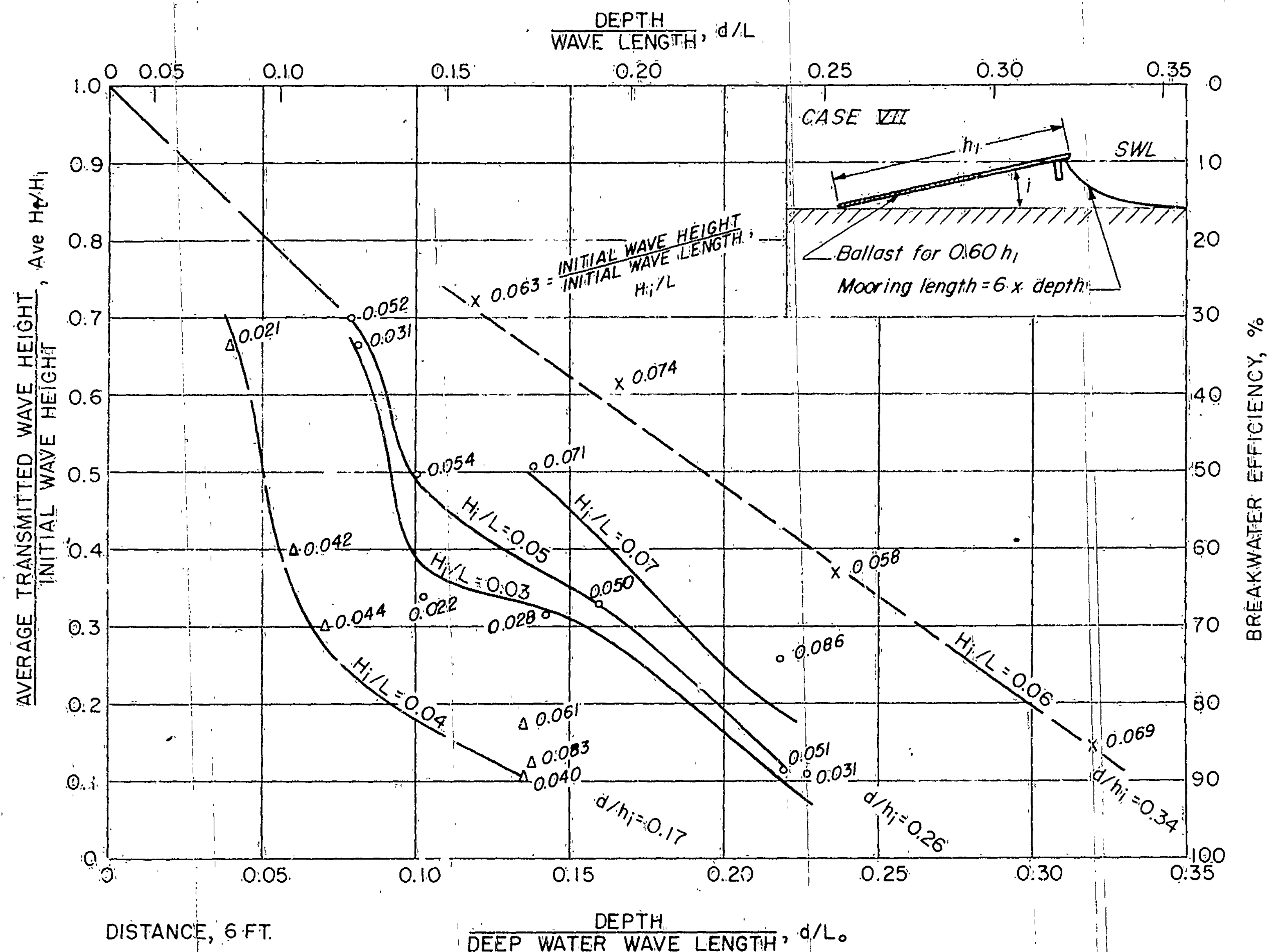
FACSIMILE RECORD ILLUSTRATING PRIMARY & SECONDARY TRANSMITTED WAVES

FIGURE 5



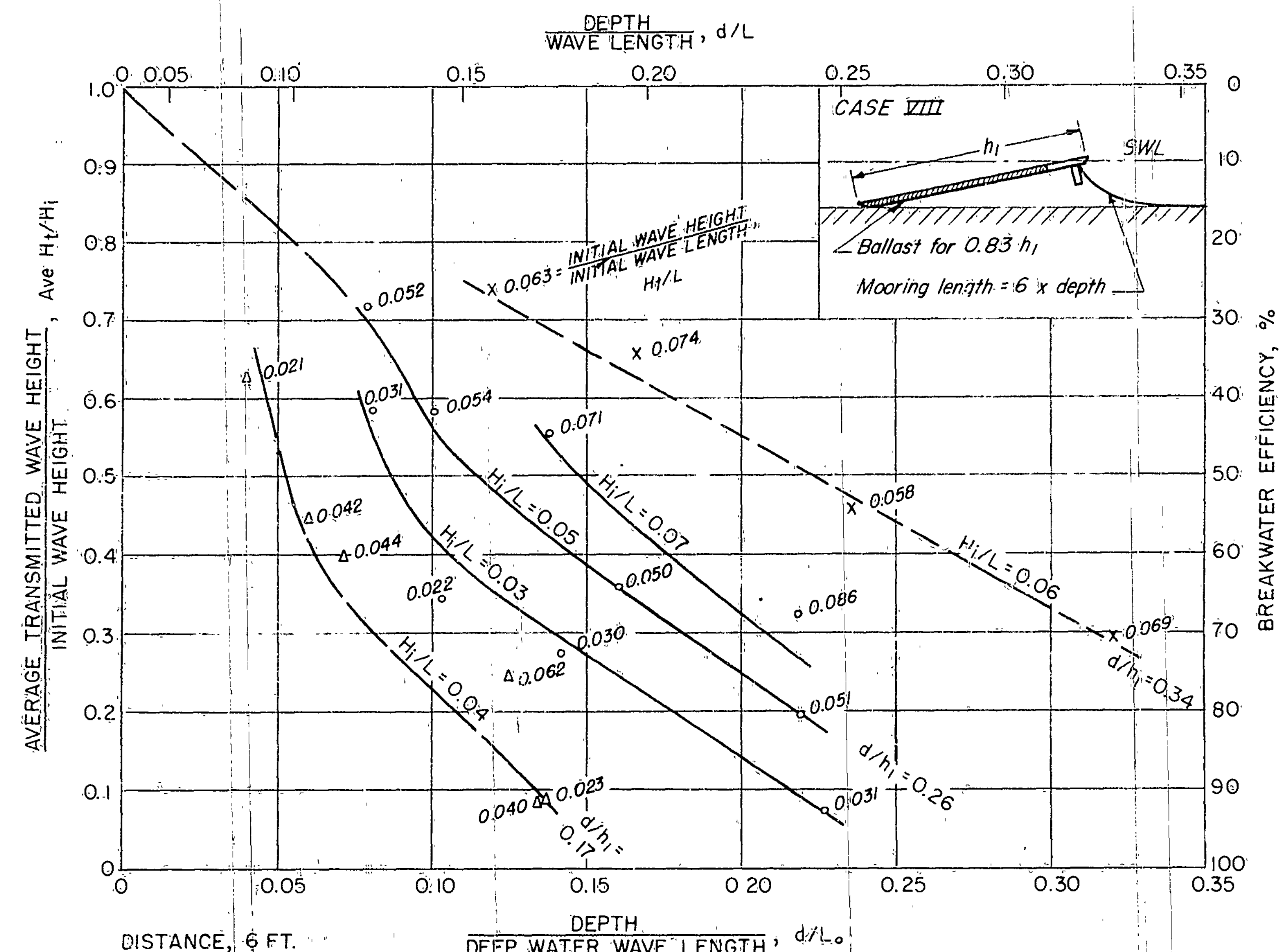
VARIATION OF H_t SHOREWARD FROM FLOAT (from TABLE II)

FIGURE 6



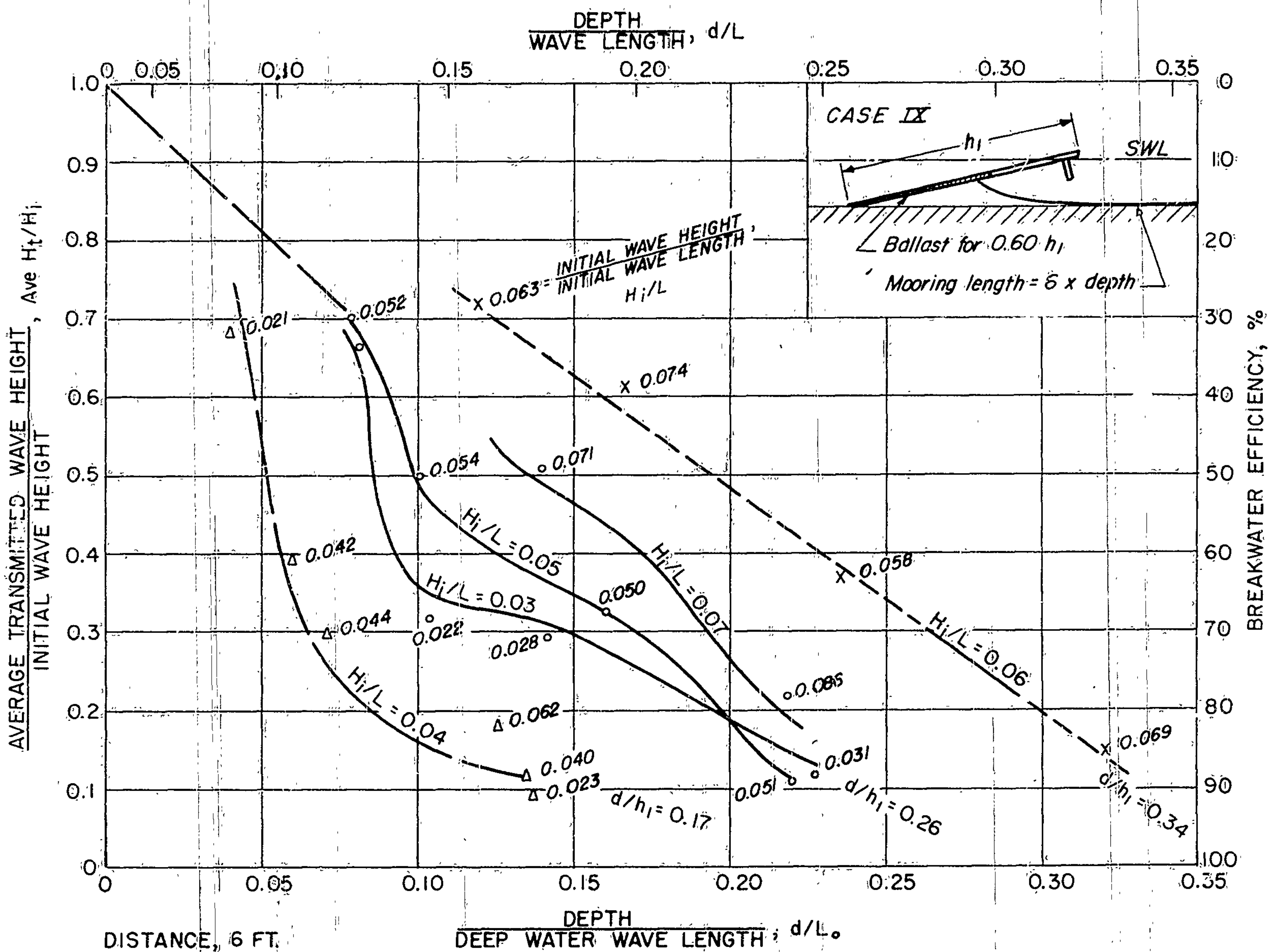
BREAKWATER EFFICIENCY CURVES - CASE VII (from TABLES V, VI, VII)

FIGURE 7



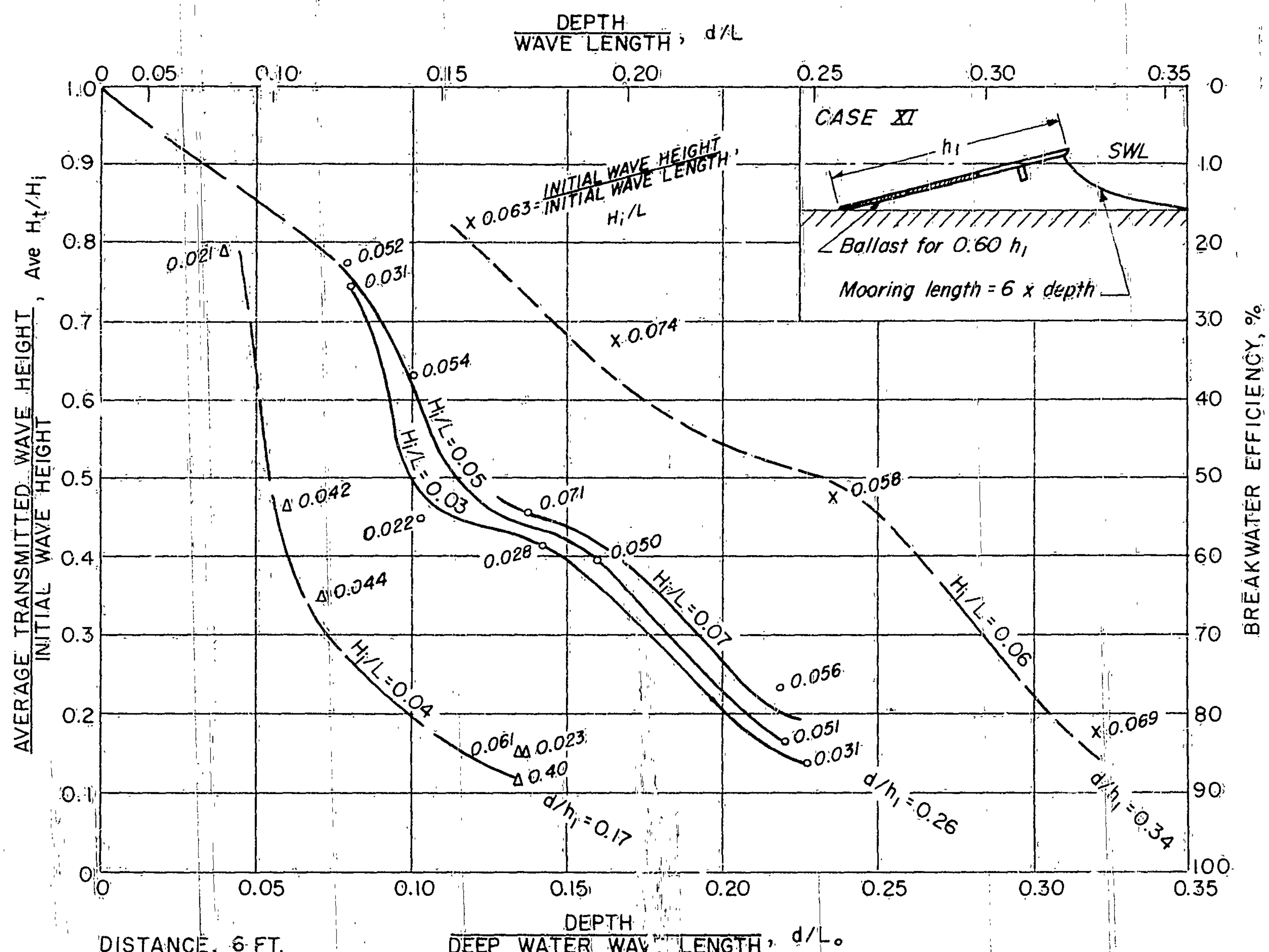
BREAKWATER EFFICIENCY CURVES - CASE VIII (from TABLES V, VI, VII)

FIGURE 8



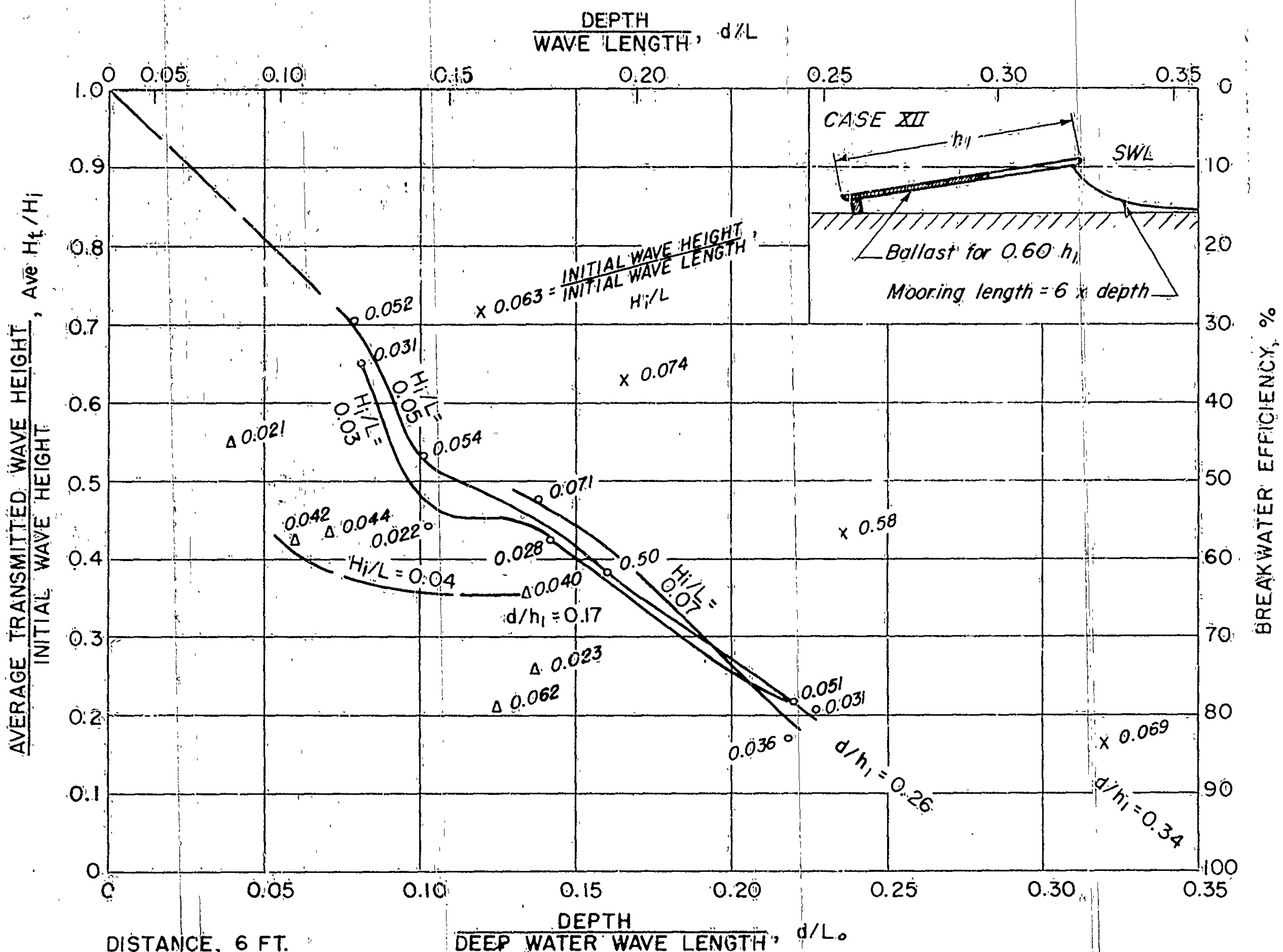
BREAKWATER EFFICIENCY CURVES - CASE IX (from TABLES V, VI, VII)

FIGURE 9



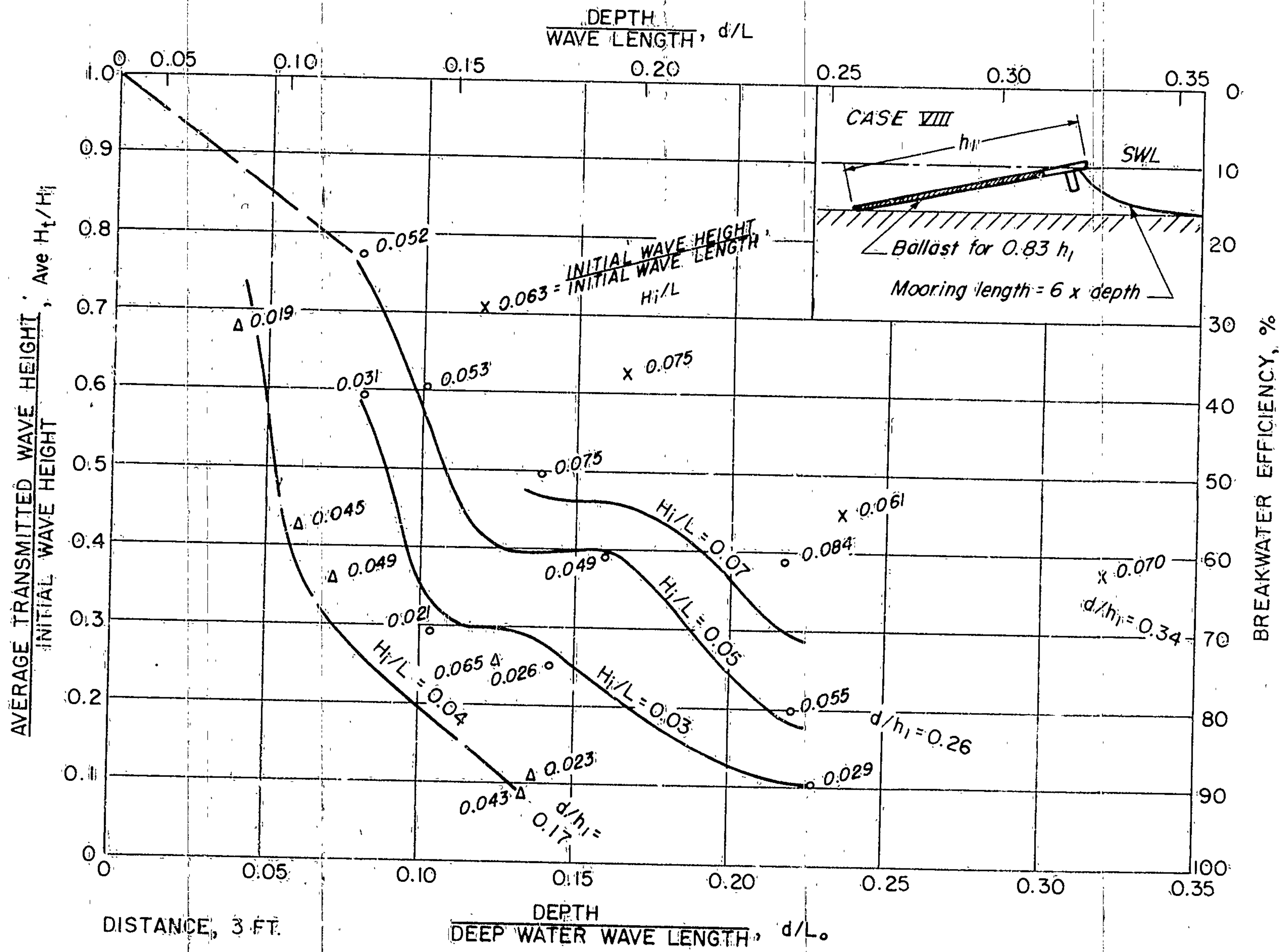
BREAKWATER EFFICIENCY CURVES - CASE XI (from TABLES V, VI, VII)

FIGURE 10



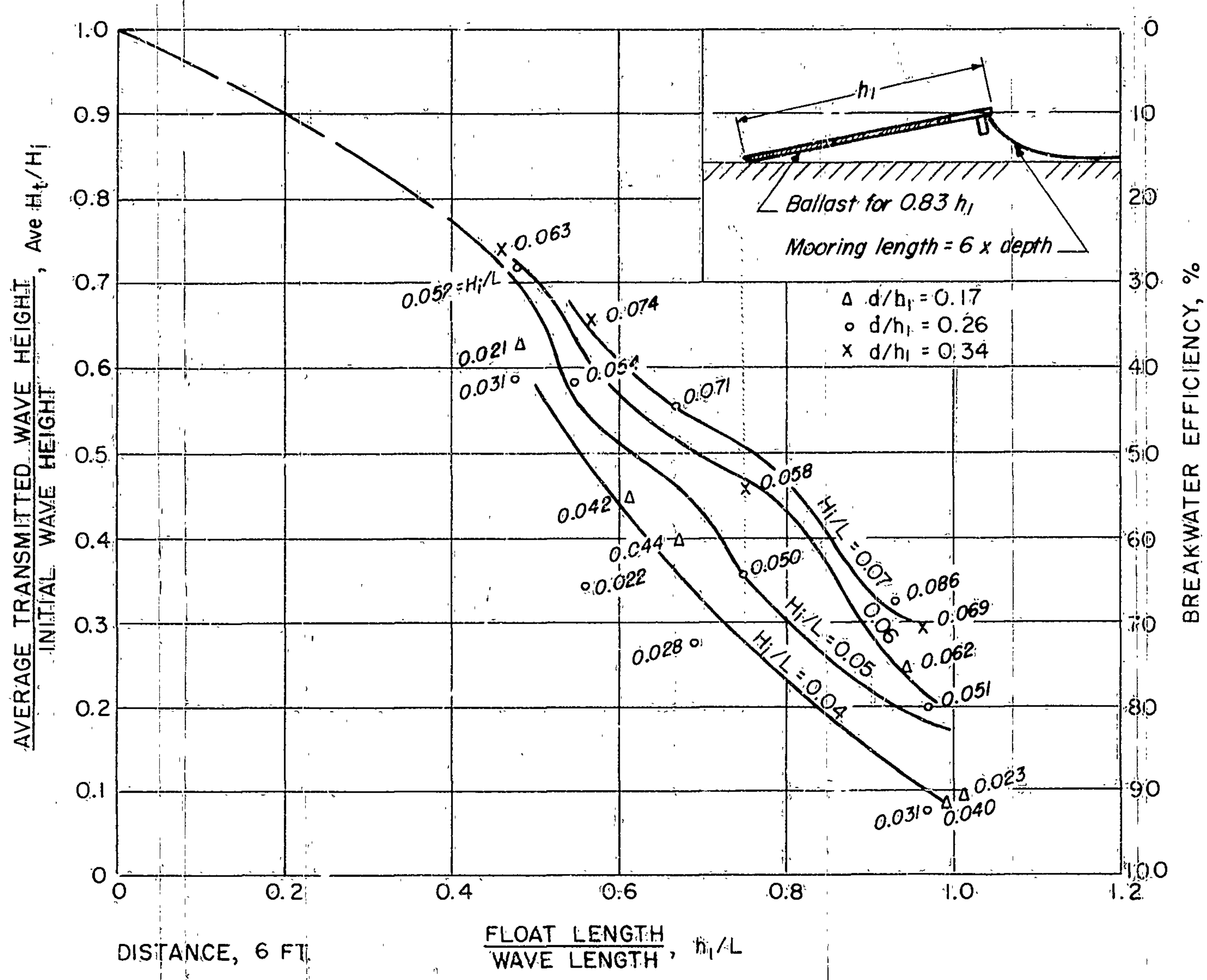
BREAKWATER EFFICIENCY CURVES - CASE XII (from TABLES V, VI, VII)

FIGURE 11



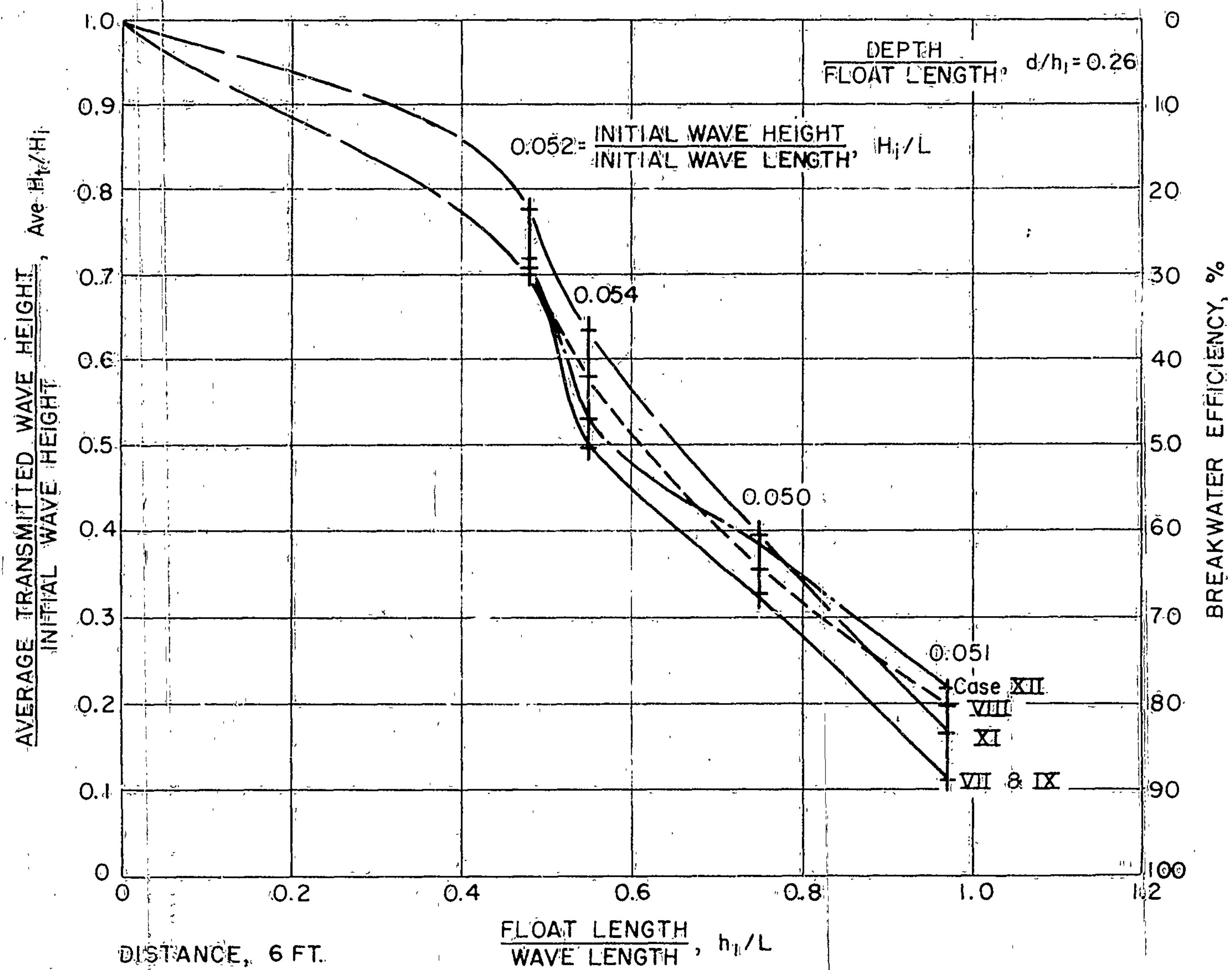
BREAKWATER EFFICIENCY CURVES - CASE VIII (from TABLES V, VI, VII)

FIGURE 12



EFFECT OF DEPTH - CASE VIII (from TABLES V, VI, VII)

FIGURE 13



COMPARISON OF EFFICIENCIES AT $H_i/L \cong 0.05$, $d/h_1 = 0.26$ (from TABLE VI)

FIGURE 14

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