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MOORING CABLE FORCES CAUSED BY WAVE ACTION ON FLOATING STRUCTURES

BY

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SYMBOLS AND NOTATION

$_{A}$	average
d	depth of water - feet
D	model draft - feet.
F	horizontal cable force at bottom - pounds (force)
F_A	average maximum force
F_M	absolute maximum force
H_i	incident, undisturbed wave height (without test object in place) - feet
H_t	transmitted wave height (shoreward of object) - feet
H_t/H_i	transmission coefficient
λ	model length in direction of wave travel - feet
L	wave length - feet
$_{M}$	[illegible]
S	[illegible] - cable length/depth - no dimensions

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ABSTRACT

Experiments have been conducted to determine the forces in mooring cables caused by wave action on floating structures. Empirical data are presented in graphical form showing the relationship of these forces to the several variables involved. All data are presented in tabular form, and a few typical cases are extrapolated to prototype conditions. Quantitative measurements were made of the horizontal cable force exerted by the mooring cable on a force meter at the bottom, the surface time history of the waves transmitted past the structure, and the surface time history of the waves without the model in the water. The major variables are established and the results are summarized in dimensionless plots. The models used were a cylinder, a rectangular block and a model of a military floating breakwater, the Bombardon. The two dimensional study was conducted in a 1 foot by 3 foot by 60 foot wave channel in the Fluid Mechanics Laboratory of the University of California, Berkeley.

INTRODUCTION

The problem of providing adequate moorings for floating objects has existed since the beginning of water borne travel. In order to design an adequate mooring system, it is necessary to predict the order of magnitude of maximum force that will be exerted on the system. In most cases, the problem of providing adequate moorings is negated by mooring the object in a sheltered position so that it is not subject to the large forces imposed by ocean waves.

When a sheltered position is not readily obtainable, the moored object may be subjected to large wave forces. The purpose of this study was to investigate the effect of such large wave forces upon the mooring system of a floating object and to correlate such effects with certain easily determined quantities, such as, wave length and height, depth of water, and model form characteristics.

HISTORY

The most notable attempt to moor any number of floating objects of appreciable size in large waves was made in the English Channel off the coast of Normandy, France, immediately following "D" day, in June 1944. At this time a considerable number of floating breakwaters were secured in place to provide an artificial harbor. A few days after the harbor had been completed, a storm of magnitude unexceeded in the previous forty years (during this time of year) caused the mooring systems of the breakwaters to fail, and the entire system of breakwaters was swept away. Had this failure occurred a few days earlier, the result would have been even more militarily disastrous than it was.

There are also several reported instances of large ships dragging their anchors and breaking their anchor chains when subjected to the forces caused by large storm waves, and serious economic losses have been incurred in this manner. Recent considerations of possible methods of drilling for offshore oil indicate that it might be possible to support an adequate drilling operation from a floating barge. The mooring system of such a barge must necessarily be stable in order to insure a successful operation.

QUANTITATIVE ANALYTICAL CONSIDERATIONS

Wave energy is manifested in the kinetic and potential energy of the individual water particles(1)*. If an object is moored in trains of water waves in such a manner that the object can interrupt the motion of the individual particles, the object will necessarily dissipate some of the wave energy that would normally have been transmitted past the structure. This reduction in transmitted energy can be achieved by reflection or by turbulence. If the energy is reflected, a force will be exerted on the structure. This force will either cause an increase of linear and/or angular momentum of the structure.

Insofar as a floating breakwater is concerned, it is advantageous for this force to act on the momentum of the structure and thus reduce the force in the mooring system of the structure. Conversely, for cases of the drilling barge, whose displacement with respect to the still water level must be small, most of the forces should be transmitted to the mooring system of the barge.

It can be shown that for certain conditions the momentum of the structure can account for only a given percentage of the force and that above a certain limiting wave condition the percent of wave force imparted to the mooring system will increase rapidly. Since wave energy is proportional to wave height squared, it is seen that any reduction of wave height requires a correspondingly greater reduction of wave energy, and therefore, that correspondingly larger forces will be exerted on the object.

The amount of energy manifested in a given stratum of water for a given wave condition is described by the relative depth of the water. For deep water ($d/L \gg 0.5$) most of the wave energy is concentrated relatively close to the surface; while for shallow water ($d/L \ll 0.5$) the energy is more evenly distributed with respect to depth. By using H_i/L it is possible to describe the wave form.

Because the individual water particles exert force on the structure, it can be inferred that if the structure is long compared with the wave length there will be a series of positive and negative force contributions along the length of the object, with a small resultant force acting over a large area. Conversely, for a relatively small ratio of model length to wave length, one might expect a larger resultant force to be exerted. Therefore λ/L, the ratio of model length to wave length, should be a parameter.

While relative depth determines the slope of the energy gradient at any one depth, the draft of the model will determine the amount of energy to which the model will be exposed. Hence, a combination of draft and depth (D/d) is used as a parameter in combination with d/L.

Statistical analysis of ocean wave records has shown that for an open

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* Numbers in parentheses refer to References at end of report.

ocean wave condition, the maximum wave height of a given sample of waves can be expressed by a constant, times the average wave height of the sample[2, 3, 4]. Past experience indicates that valuable data can be obtained from laboratory experiments where wave length and height are held constant, even though ocean wave records indicate a random distribution of length and height. Thus, even though the laboratory study indicates a maximum force (for the seaward cable only) of approximately twice the average force, it is entirely possible that for prototype conditions the maximum force could be expressed as any reasonable number times the average force.

EMPIRICAL PROCEDURE

A series of experiments was planned to cover a wide range of the major variables in order to obtain quantitative results. The purpose of the experimental study was to determine the mooring cable forces caused by wave action and to identify the major variables influencing these forces.

Quantitative measurements were made of the horizontal cable force (hereinafter called "force") exerted on the cable force meter at the bottom, the incident wave surface time history with the model out of the water, and the surface time history of the waves transmitted past the structure. It should be emphasized that the incident surface time history was measured with the model out of the channel and that the actual surface time history of the waves incident upon the model was complicated by reflections from the front of the model. No data were taken when the incident surface time history was complicated by reflections from the model which were then returned to the model by reflection from the generator.

For each wave height and mooring condition, three trials of data were taken and the results were averaged. It is expected that this averaging procedure reduced the scatter of experimental points.

LABORATORY EQUIPMENT AND PROCEDURE

The laboratory equipment consisted of a steel and glass wave channel 1 foot wide by 3 feet deep by 60 feet in length, with a wave generator at one end and an absorber beach at the opposite end. A damping device was located near the generator in order to damp out any reflected waves (Figure 24). Parallel wire resistance elements[5] were used to measure the incident and transmitted wave heights, and a special force meter was designed to record the mooring cable force. All data were recorded on a two channel Brush Recording Oscillograph (Figure 26). Brush Universal Analyzers (Figure 26) provided the necessary power supply and amplification facilities for the force meter and for the resistance elements. It was also necessary to use an external gain and a centering device to improve on the external circuit of the Brush Oscillograph used to record wave heights. This is also shown in Figure 26. The improvements afforded by this addition were; improved gain and centering control, and no zero drift.

To simplify instrument construction, it was decided to build a force meter which would measure the horizontal pull that the cable exerted at its bottom mooring. Hence, as noted before, any value presented herein as force is the horizontal cable force as measured at the bottom of the wave channel, and corresponds to a horizontal anchor pull.

The principle of the Wheatstone bridge was used to design the force meter. This principle (Figure 28) states that for four equal resistances, connected as shown in the drawing, with the input as indicated, the voltmeter (recorder) will give no reading; but if the ratio of resistances in the opposite arms of the bridge stays the same, and adjacent resistances are varied, the recording oscillograph will show a reading.

The meter (Figures 27, 28) was composed of a metal base plate and a cantilever stainless steel beam, which was supported laterally by a vertical piece of steel projecting from the front of the base plate. Upon this beam four Baldwin 120 SR4 strain gages were mounted, two to a side, as seen in Figure 28. These gages consisted of carefully matched 120 ohm resistances in the form of several lengths of wire about 5/8 inch long, pasted to a piece of hard paper.

The gages were attached to the steel bar, using a special cement. When the bar was bent, the extreme fibers of the metal and the wire of the strain gage deformed as a unit, and the bridge was unbalanced. As the bridge is unbalanced, the recording oscillograph records the change in voltage drop across the arms of the bridge.

After the gages had been mounted on the bar, approximately thirty feet of four conductor shielded wire was attached to the strain gages, and the shielding was attached to the metal base plate. The strain gages were then covered with a layer of okonite tape, and one coat of neoprene rubber precoat and seven coats of neoprene rubber maintenance coat were applied to the taped area on the bar. The meter was thus ready for operation, being completely waterproof.

Using the above-described equipment, the experimental procedure was as follows:

1. Waves were generated in the channel and the initial undisturbed surface time history was measured.

2. A model was inserted in the channel.

3. The height of the waves transmitted past the model was measured.

4. The horizontal force exerted by the cable on the force meter at the bottom was measured.

This was done for several models and for a series of wave lengths, wave heights, and water depths. After each run sufficient time was allowed for the water to become quiescent before the next run was started. A scope of 6 was used in all experimental runs. For the two cable mooring, the only force measured was that in the seaward cable.

RESULTS OF THE EXPERIMENTAL INVESTIGATIONS

Rectangular Block:

The variation of force is presented as a function of four parameters, λ/L, D/d, d/L and H_i/L. These data are presented in Figures 4, and 6-14, and in Tables I and II. The plot of breakwater efficiency and transmission coefficients as a function of wave steepness shows no real efficiency variation with steepness. The plot of transmission coefficient and efficiency as a function of λ/L shows that both mooring systems exhibit the same efficiency characteristics for values of λ/L greater than 0.56. However, below this value, the block with seaward and leeward moorings is the more efficient.

If the model is moored with one cable*, the force on the mooring cable will increase at an increasing rate as wave steepness increases; while when the model is moored both seaward and leeward, the force variation is almost linear with steepness. With the two cable moorings the absolute maximum force is little different than the average maximum force. This is shown in the sample record in Figure 22.

For one cable, a comparison of the average maximum force for each case with the absolute maximum force for each condition can be made from observation of Figures 4 and 6. It is seen that the absolute maximum force is approximately twice the average maximum force.

The several crossplots of force as a function of ratio of model length to wave length indicate that above a certain value of λ/L the force will be small, but that for ratios below this critical value the force will become larger and will increase rapidly as λ/L becomes smaller. The critical values of λ/L can readily be determined from the graphs.

The ratio of draft to depth, D/d, indicates the extent to which the model is exposed to wave energy. As this ratio is increased (for constant d/L), the corresponding mooring forces become larger. This is confirmed by the studies made with the Bombardon and the cylinder. Figure 20 shows the effect of D/d for the Bombardon, using the same relative depth.

An interesting phenomenon was observed for the block when it was moored with one cable only. For some wave conditions the force in the cable was exerted only every three or four waves. It is believed that this can be explained in the following manner. At the beginning of the cycle the cable is taut; as soon as a wave crest passes the block, the resultant hydrodynamic force on the block shifts to the seaward direction, and the force in the cable - along with the hydrodynamic force - tends to accelerate the block seaward. As the block is thus put in motion, the wave forces must first stop the block's seaward motion and then accelerate it shoreward again before another cable force will be recorded. A typical "cyclic" force record is shown in Figure 21.

*Hereafter, one-cable designation applies to a single cable on the seaward side; two-cables designates moorings on the seaward and leeward sides with force measured only in the seaward cable.

Bombardon Floating Breakwater:

The Bombardon floating breakwater was used in "Operation Overlord", the invasion of Normandy, France, in June 1944. The basis of design of the structure was to make its natural period long compared with the wave period, so that resonance effects would be small and energy dissipation could be achieved through utilizing the momentum of the structure.

As the wave force is applied to the structure, little force is transmitted to the mooring system. For very long waves (small λ/L), the structure is not efficient as a breakwater, and large stresses are set up in the mooring system. It can be ovserved (Figure 15) that efficiency does not vary appreciably with steepness, while Figure 16 shows that efficiency is definitely a function of λ/L. Apparently the Bombardon exhibits the same tendencies as the block insofar as the critical values of λ/L are concerned. The graphs indicate that the mooring cable force increases at an increasing rate as wave steepness increases, but that the resultant forces are less than those obtained for the block and cylinder. It should be emphasized that the force on the Bombardon mooring is reported as force in pounds, and not as a dimensionless number.

Cylinder:

Of the three test models, the mooring system of the cylinder was subjected to the largest forces for the given range of variables. This might be due to the fact that the mass of the cylinder is approximately three times larger than that of either the block or the Bombardon. Since oscillatory flow sets up the necessary conditions for impact forces to be exerted, the larger mass of the cylinder indicates larger mooring cable forces due to its increased momentum.

Figure 20 shows the comparison of force as a function of steepness for all of the models for given relative depth.

CONCLUSIONS

1. Using the experimentally determined data, it might be possible to predict the order of magnitude of mooring cable forces for structures of the Bombardon, rectangular block* and cylindrical shapes.

2. The several parameters, d/L, λ/L, D/d and H_i/L can be used to describe the force on the mooring system for a floating object subject to wave action.

3. If the moored object has both seaward and leeward anchors, the mooring cable force will be much larger than the force in the case where one cable is used.

4. Although all variables were held constant for the case of a single mooring line, the force varied. The maximum force was found to be approximately twice the average force.

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* See numerical example, Appendix I.

REFERENCES

1. WIEGEL, R.L., An analysis of data from wave recorders on the Pacific Coast of the United States; Trans. Amer. Geophys. Union, Vol. 30, No. 5, pp 700-704, Oct. 1949.

2. SEIWELL, H.R., Results of research on surface waves of the Western North Atlantic, Papers; Phys. Ocean. Met., Vol. 10, No. 4. 56 pp. 1945.

3. PUTZ, R.R., Statistical distributions for ocean waves, Trans. Amer. Geophys. Union, Vol. 33, No. 5, pp. 685-692, October 1952.

4. LONGUET-HIGGINS, M.S., On the statistical distribution of the heights of sea waves, Sears Found., Jour. of Marine Res., Vol. XI, No. 3, pp. 245-266, Dec. 1952.

5. MORISON, J.R., Measurement of heights by resistance elements; Bull. Beach Erosion Board, Corps of Engrs. U.S. Army, Wash., D.C. Vol. 3, No. 3, July 1, 1949, pp. 16-19.

APPENDIX I.

NUMERICAL EXAMPLES.

Steps to be followed in using model study data to predict prototype forces in seaward cable with a rectangular block.

1. Given: λ, L, d, H, D, S.

   Compute: λ/L, H/L, D/d

2. Determine:

   $\frac{F_M}{\lambda D w}$ for seaward cable only (Figure 6)

   $\frac{F_A}{\lambda D w}$ for two-cable mooring (force in seaward cable only) (Figure 7)

3. Compute total prototype force (horizontal component)

   B = barge width

   F_M prototype (B) = F_M model (λ D w) B-lbs

   F_A prototype (B) = F_A model (λ Dw) B - lbs seaward force.

All forces measured horizontally at bottom.

4. Compute total prototype force

$$F_{total} = \frac{F_P}{\cos\left(\sin^{-1}\left(\frac{1-D/d}{6}\right)\right)} \qquad (1)$$

COMPUTATIONS.

1. Assume: L = 500 ft., λ = 200 ft., d = 55 ft., H = 10 ft.
D = 10 ft., S = 6, B = 40 ft.

Compute: $\frac{\lambda}{L} = 0.40$ $\quad \frac{H}{L} = \sout{0.20}\ .02$ $\quad \frac{D}{d} = 0.18$

2. $\frac{F_M}{\lambda Dw} = 0.035$

$\frac{F_A}{\lambda Dw} = 0.10$

3. $F_M B = (0.035)(\lambda)(D)(W)(B)$

$= (0.035)(200)(10)(62.4)(40)$

$= 175,000$ lbs.

$F_A B = (0.10)(200)(10)(62.4)(40)$

$= 500,000$ lbs.

4. $\cos\left(\sin^{-1}\left(\frac{1-0.18}{6}\right)\right) = \cos 9.6°$

$\frac{F_M B}{\cos 9.6°} = 177,500$ lbs.

$$\frac{F_A B}{\cos 9.6°} = 506,000 \text{ lbs.} \qquad (2)$$

In each of the two cases sufficient mooring cable must be provided to take this load, that is,

(a) <u>Single seaward cable</u>

$\frac{177,500 \text{ lbs.}}{20,000 \text{ lbs/in}^2} = 8.875 \text{ in}^2$ of steel

(b) <u>Seaward cable force with seaward and leeward mooring</u>

$\frac{506,000 \text{ lbs.}}{20,000 \text{ lbs/in}^2} = 25.3 \text{ in}^2$ of steel

Anchor holding power will determine the number of cables that must be used.

TABLE I
SUMMARY OF RESULTS
RECTANGULAR BLOCK

						Type of Mooring							
						Single Cable					2 - Cable		
Run	T sec	L ft.	H_i ft.	$\frac{\lambda}{L}$	$\frac{H_i}{L}$	F_A lbs.	$\frac{F_A}{\lambda D w}$	F_M lbs.	$\frac{F_M}{\lambda D w}$	E %	F_A lbs	$\frac{F_A}{\lambda D w}$	E %
1	0.60	1.82	0.081	0.825	0.044	0.111	0.0079	0.209	0.0149	67	0.386	0.0276	63
2	"	"	0.047	"	0.026	0.052	0.0037	0.092	0.0066	70	0.356	0.0254	66
3	0.70	2.45	0.191	0.612	0.076	0.492	0.0350	0.888	0.0638	81	1.576	0.1130	77
4	"	"	0.094	"	0.037	0.242	0.0159	0.575	0.0411	65	0.914	0.0651	58
5	"	"	0.053	"	0.022	0.065	0.0047	0.149	0.0106	59	0.571	0.0407	60
6	0.85	3.39	0.228	0.442	0.067	0.914	0.0655	1.959	0.1390	39	3.670	0.2610	49
7	"	"	0.165	"	0.049	0.380	0.0271	0.888	0.0638	34	2.620	0.1830	46
8	"	"	0.101	"	0.030	0.243	0.0173	0.706	0.0505	27	1.760	0.1255	50
9	"	"	0.058	"	0.017	0.022	0.0016	0.269	0.0192	34	0.936	0.0668	45
10	1.05	4.58	0.273	0.328	0.060	2.310	0.1650	4.210	0.3010	10	7.280	0.5190	33
11	"	"	0.218	"	0.048	0.958	0.0680	1.850	0.1322	12	4.910	0.3500	24
12	"	"	0.154	"	0.340	0.391	0.0279	1.350	0.0964	3	3.870	0.0276	24
13	"	"	0.108	"	0.024	0.139	0.0099	0.419	0.0299	7	2.960	0.2110	40
14	"	"	0.059	"	0.013	0.095	0.0068	0.209	0.0149	13	1.430	0.1020	34
15	1.25	5.78	0.194	0.255	0.034	0.680	0.0485	1.850	0.1322	9	5.070	0.3620	9
16	"	"	0.138	"	0.024	0.227	0.0162	0.624	0.0445	5	3.730	0.2660	7
17	"	"	0.083	"	0.014	0.153	0.0108	0.888	0.0638	2	2.490	0.1770	16
18	"	"	0.042	"	0.007	--	--	--	--	7	0.848	0.0605	18

S = 6 D = 0.15 feet d = 0.835 feet
λ = 1.50 feet D/d = 0.18 T_i - (2 cables) = 0.18 pounds

TABLE II
SUMMARY OF RESULTS
RECTANGULAR BLOCK

						Type Mooring			
						1 cable		2 cables	
Run	T sec.	L ft.	H_i ft.	$\frac{\lambda}{L}$	$\frac{H_i}{L}$	F_A lbs.	$\frac{F_A}{\lambda D w}$	F_A lbs.	$\frac{F_A}{\lambda D w}$
25	1.29	4.86	0.158	0.309	0.033	0.740	0.0528	2.120	0.1510
26	"	"	0.158	"	0.033	0.740	0.0528	2.180	0.1553
27	"	"	0.096	"	0.020	0.321	0.0229	0.915	0.0652
28	"	"	0.049	"	0.010	0.058	0.0041	0.311	0.0222
29	1.00	3.60	0.061	0.417	0.017	0.034	0.0024	0.504	0.0359
30	"	"	0.118	"	0.033	0.307	0.0219	1.220	0.0869
31	"	"	0.161	"	0.045	1.300	0.0926	2.240	0.1595
32	0.86	2.97	0.151	0.505	0.051	0.716	0.0510	1.690	0.1204
33	"	"	0.098	"	0.033	0.160	0.0114	0.772	0.0550
34	"	"	0.048	"	0.016	--	--	0.302	0.0215
35	0.72	2.32	0.050	0.647	0.022	0.018	0.0013	0.279	0.0199
36	"	"	0.131	"	0.056	0.215	0.0153	0.706	0.0503

S = 6 D = 0.15 feet d = 0.500 feet
λ = 1.50 feet D/d = 0.30 w = 62.4 pounds

TABLE III
SUMMARY OF RESULTS
BOMBARDON

Run	T sec	L ft.	H_i ft.	$\frac{\lambda}{L}$	$\frac{H_i}{L}$	F_A lbs.	E percent
38	0.84	3.56	0.300	0.281	0.084	0.565	58
39	"	"	0.250	"	0.070	0.328	55
40	"	"	0.169	"	0.047	0.168	61
41	"	"	0.095	"	0.027	0.037	62
42	1.05	5.32	0.081	0.188	0.015	0.018	5
43	"	"	0.136	"	0.026	0.070	7
44	"	"	0.208	"	0.039	0.195	13
45	"	"	0.262	"	0.049	0.404	14
46	0.72	2.65	0.159	0.377	0.060	0.210	75
47	"	"	0.111	"	0.042	0.089	79
48	"	"	0.061	"	0.023	0.020	88

S = 6 D = 0.56ft. d = 1.50ft.

λ = 1.00' D/d = 0.373

TABLE IV
SUMMARY OF RESULTS
BOMBARDON

Run	T sec	L ft.	H_i ft.	$\frac{\lambda}{L}$	$\frac{H_i}{L}$	F_A lbs.	E percent
50	0.92	4.04	0.205	0.248	0.050	0.348	44
51	"	"	0.122	"	0.030	0.096	34
52	"	"	0.062	"	0.015	0.020	32
53	0.84	3.43	0.211	0.292	0.062	0.408	60
54	"	"	0.086	"	0.025	0.154	48
55	"	"	0.057	"	0.017	0.020	68
56	0.71	2.55	0.246	0.392	0.096	0.426	74
57	"	"	0.169	"	0.066	0.176	79
58	"	"	0.086	"	0.034	0.048	87
59	0.60	1.84	0.124	0.543	0.067	0.094	89
60	"	"	0.083	"	0.045	0.023	91
91	"	"	0.045	"	0.024	0.011	88

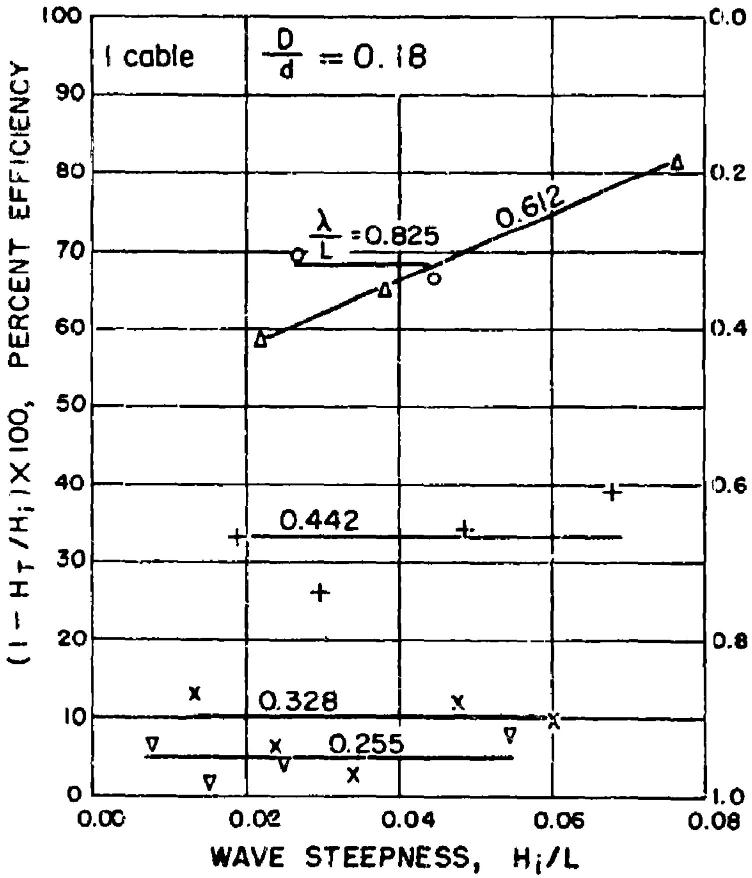
S = 6 D = 0.56 ft. d = 1.00 ft.

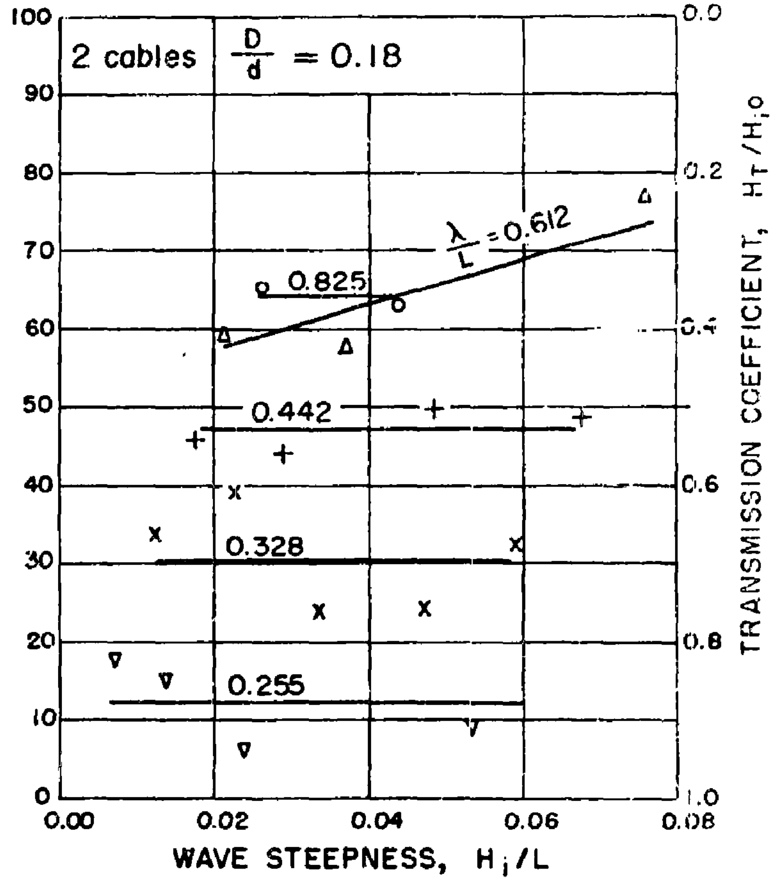
λ = 1.00 D/d = 0.56

TABLE V.
SUMMARY OF RESULTS
CYLINDER

Run	T sec	L ft.	H_i ft.	$\frac{\lambda}{L}$	$\frac{H_i}{L}$	F_A lbs.	$\frac{F_A}{\lambda D w}$	E percent
62	1.02	4.66	0.310	0.215	0.066	0.923	0.0296	-
63	"	"	0.305	"	0.066	0.604	0.0194	-
64	"	"	0.149	"	0.032	0.097	0.0031	-
65	0.86	3.57	0.220	0.280	0.062	1.056	0.0338	50
66	"	"	0.114	"	0.032	0.238	0.0077	48
67	"	"	0.029	"	0.008	0.070	0.0022	44
68	0.71	2.55	0.185	0.392	0.074	0.494	0.0158	-
69	"	"	0.130	"	0.051	0.216	0.0069	-
70	"	"	0.057	"	0.022	0.145	0.0046	-
71	0.58	1.71	0.108	0.585	0.063	0.124	0.0040	-
72	"	"	0.073	"	0.043	0.039	0.0012	-

$d = 1.00$ ft. $\lambda = 1.00$ ft. $D = \frac{\lambda}{2} = 0.50$ ft. $d/D = 0.50$





d = 0.835 foot   D = 0.15 foot   1.5-foot block

FIG. 1

FIG. 2

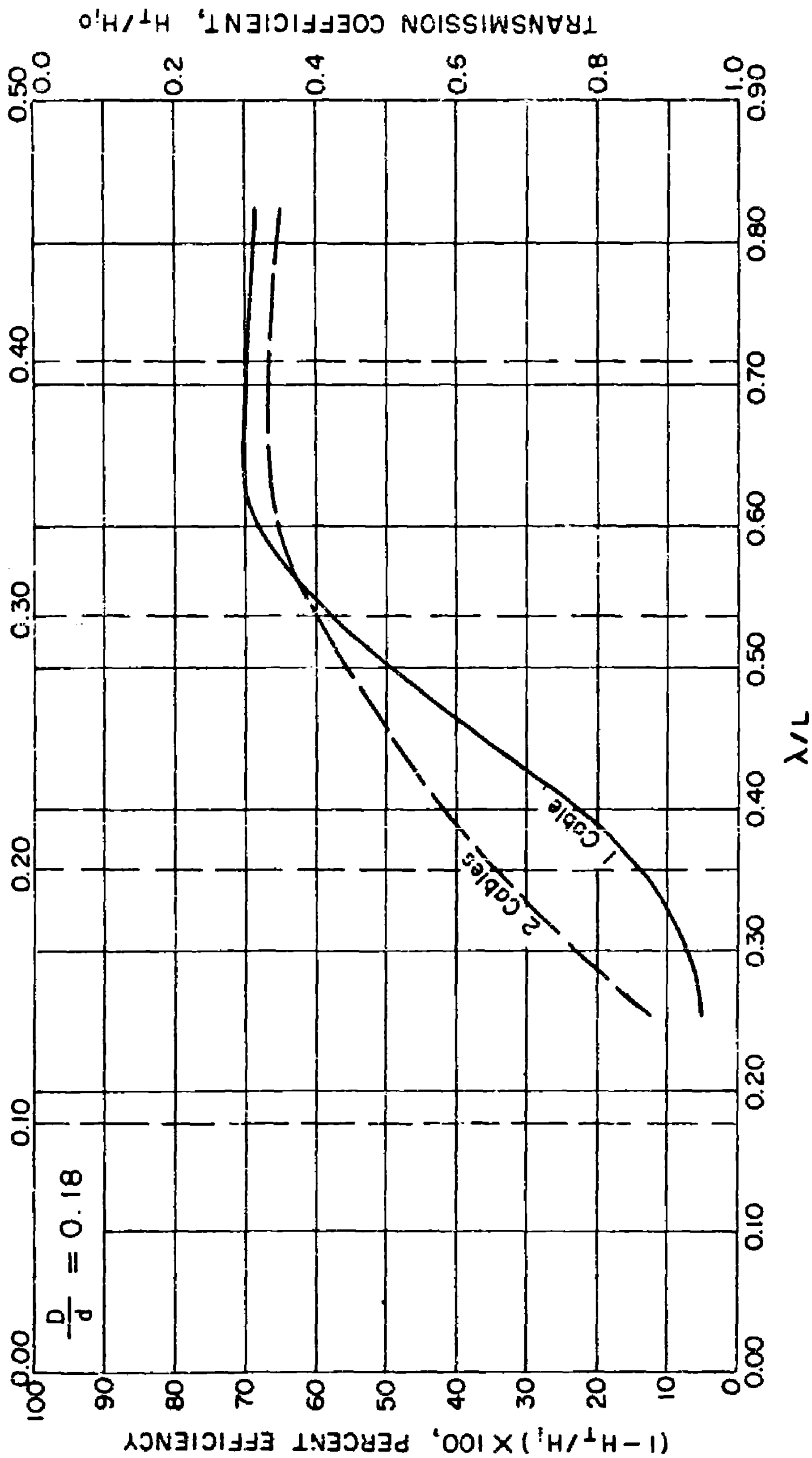
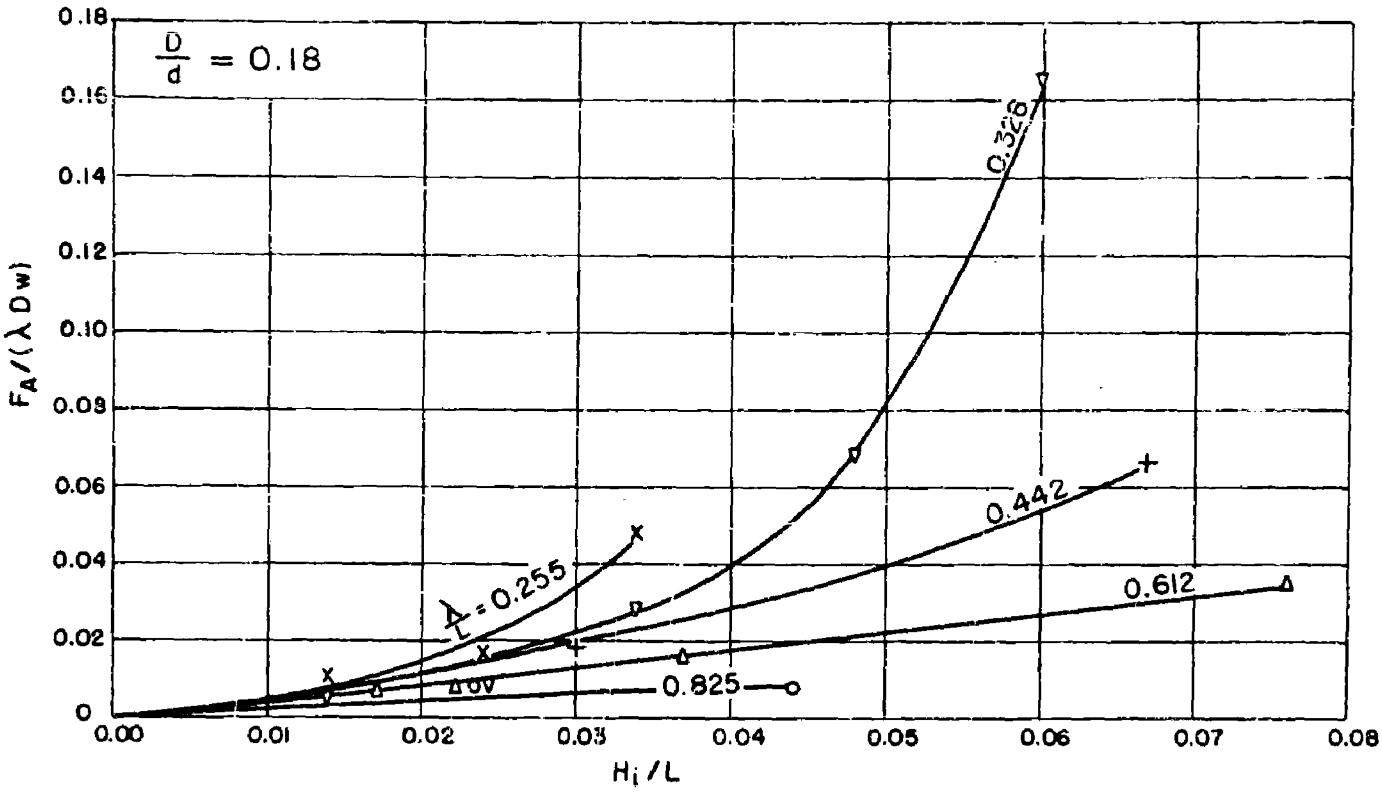
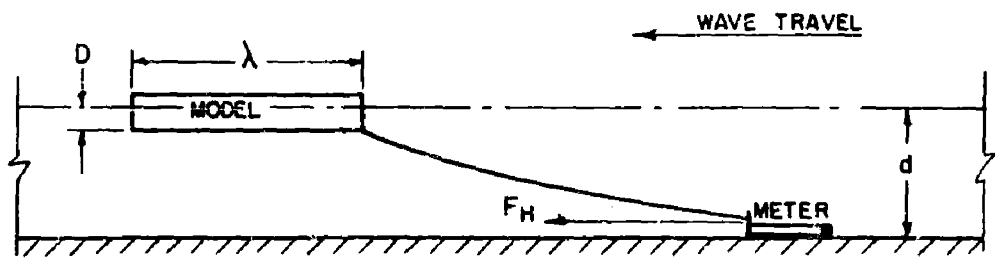

TRANSMISSION COEFFICIENT, H_T/H_I
d/L
λ/L
$(1 - H_T/H_I) \times 100$, PERCENT EFFICIENCY
$\frac{D}{d} = 0.18$
1 Cable
2 Cables
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.0
0.2
0.4
0.6
0.8
1.0
100
90
80
70
60
50
40
30
20
10
0

FIGURE 3



AVERAGE MAXIMUM FORCE AS A FUNCTION OF WAVE STEEPNESS

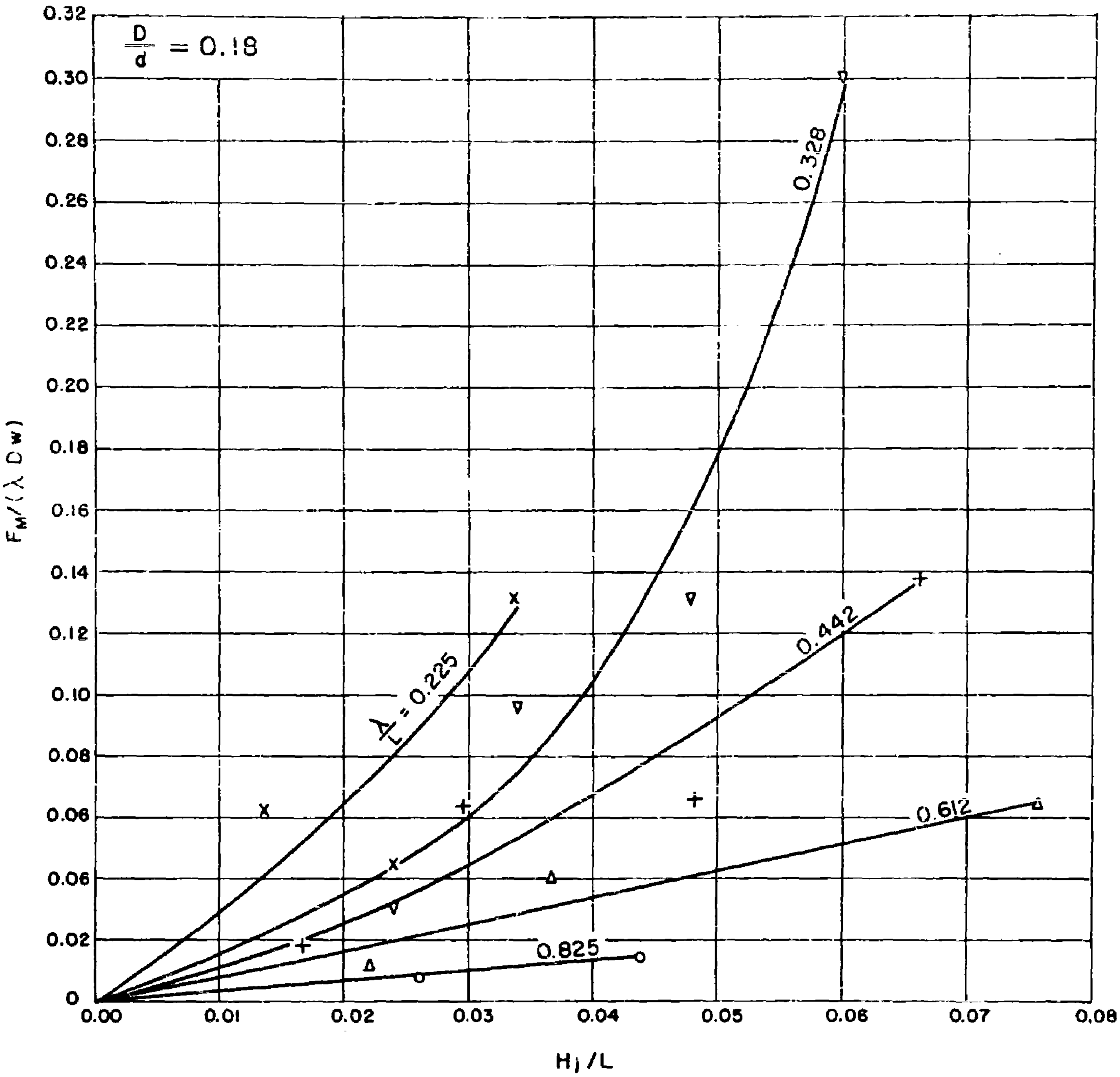
FIG. 4



Section of channel showing model, meter and mooring position. All force readings are F_H.

1.5-foot block, D=0.15, S=6, 1 cable

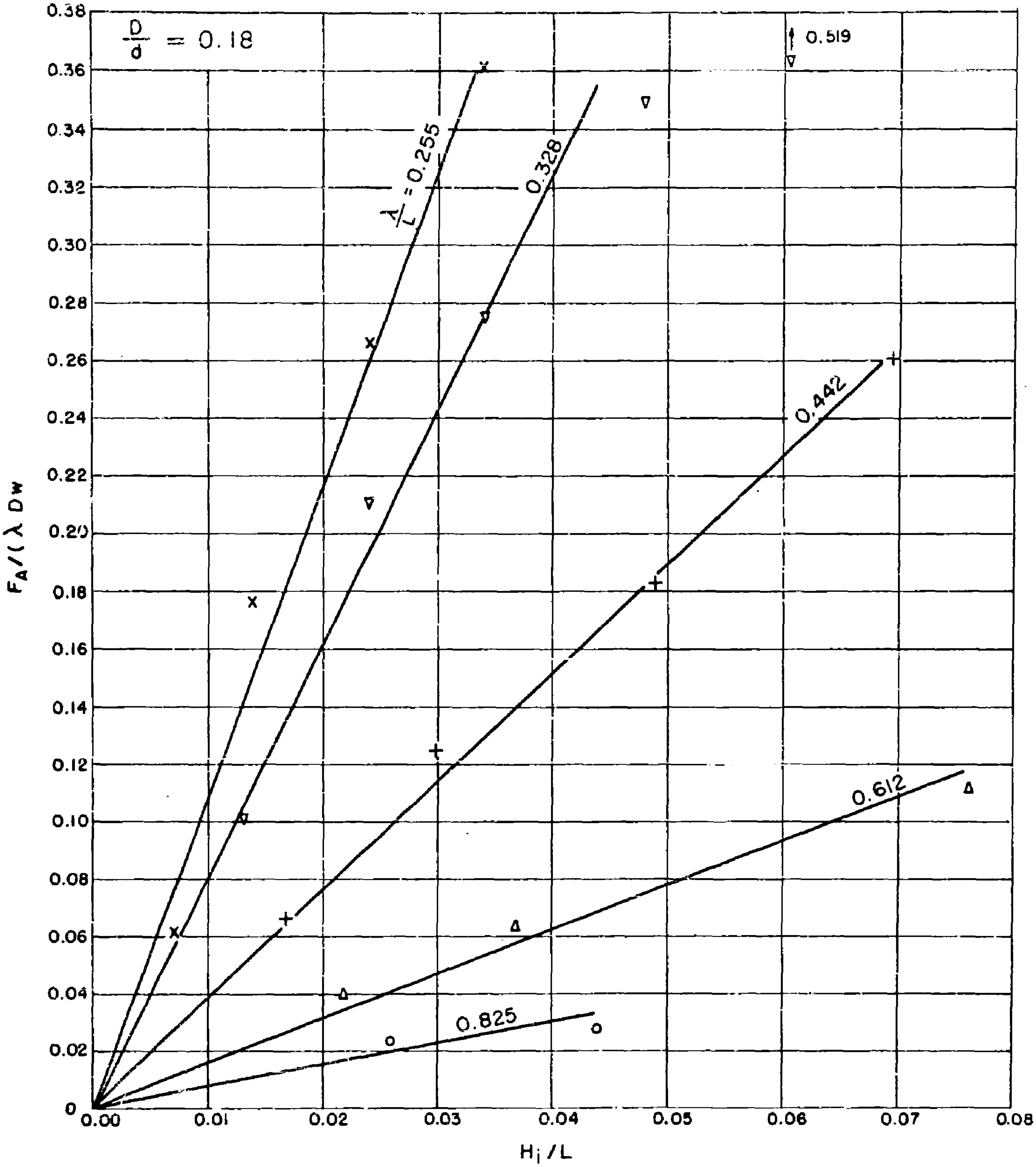
FIG. 5



d = 0.835, λ = 1.5, D = 0.15, S = 6, 1 cable

ABSOLUTE MAXIMUM FORCE AS A FUNCTION OF WAVE STEEPNESS

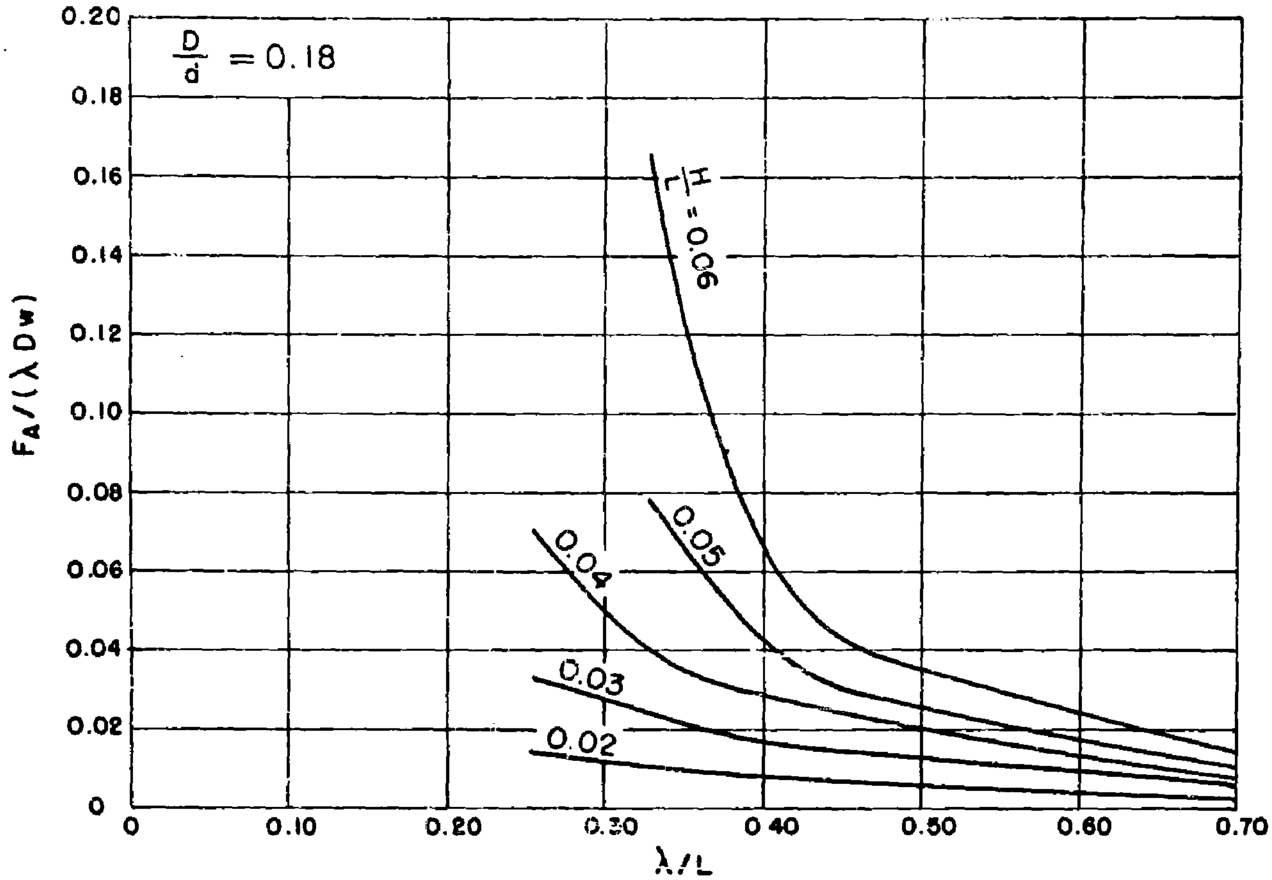
FIGURE 6



d = 0.835 foot, 2 cables

AVERAGE MAXIMUM FORCE AS A FUNCTION OF WAVE STEEPNESS, LEEWARD AND SEAWARD MOORINGS

FIGURE 7

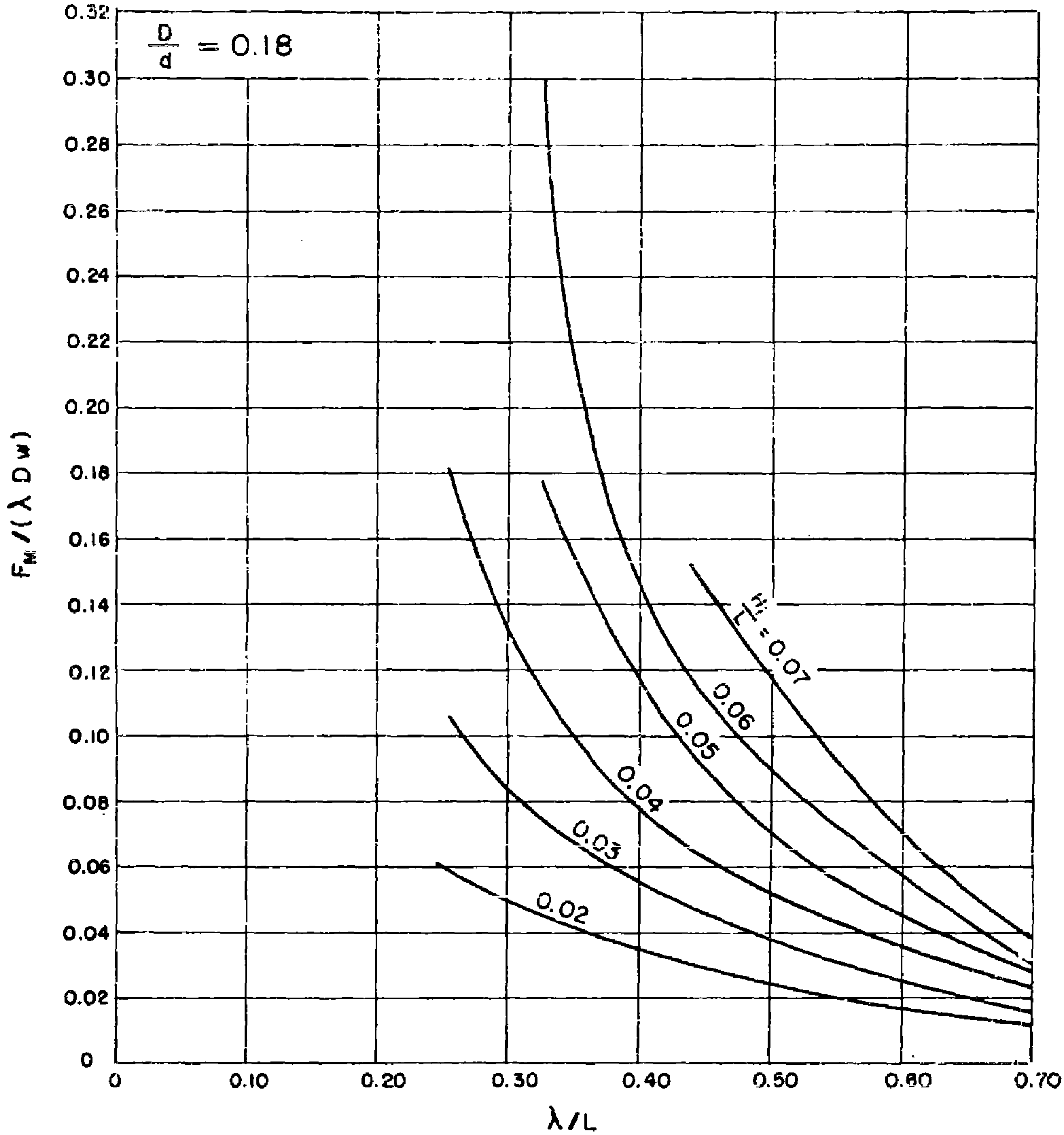


d = 0.835 foot, λ = 1.5 feet, D = 0.15, S = 6, 1 cable

AVERAGE MAXIMUM FORCE AS A FUNCTION OF THE RATIO OF BLOCK LENGTH TO WAVE LENGTH

CROSS PLOT FROM FIGURE 4

FIGURE 8

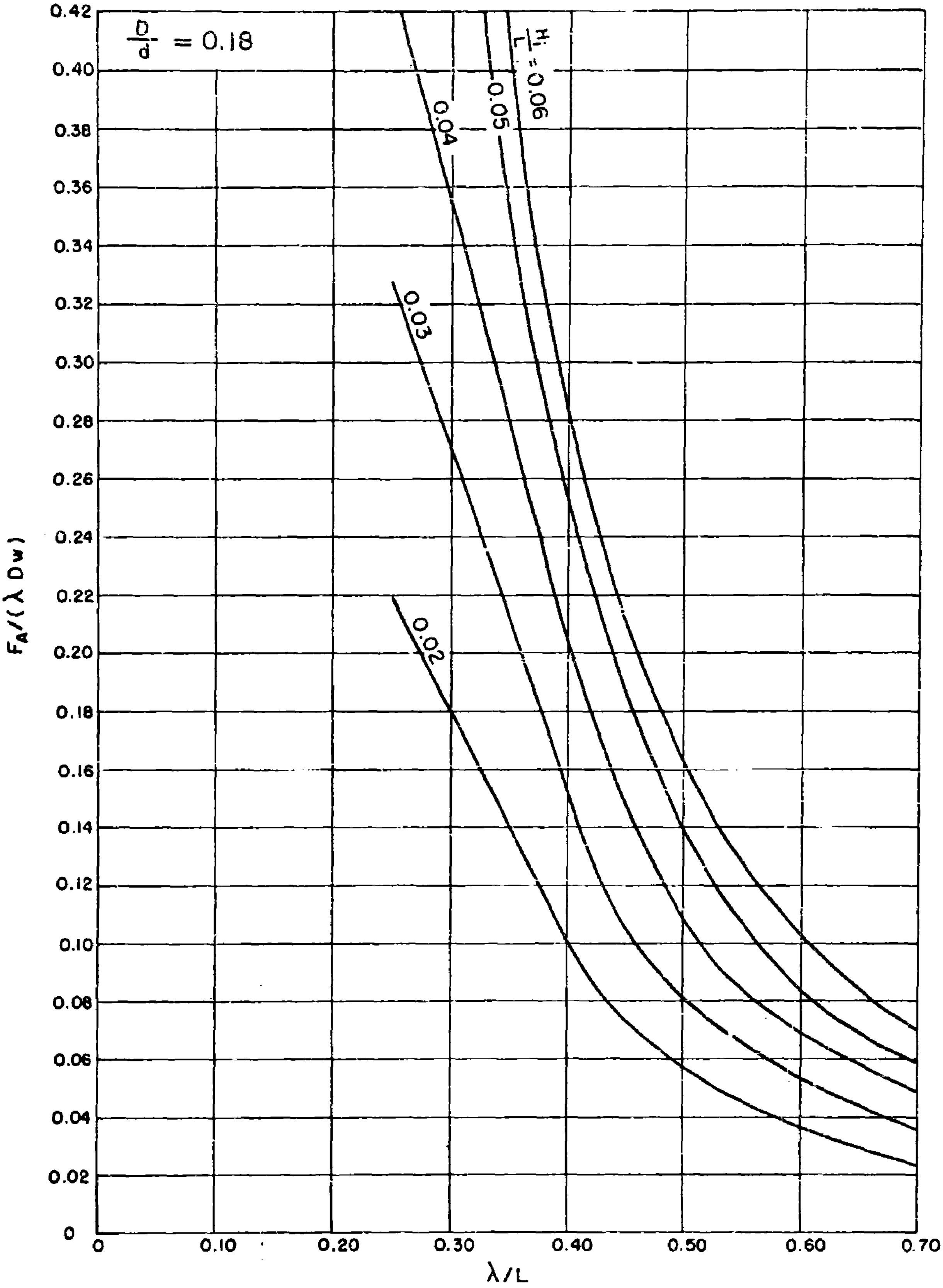


d = 0.835 foot, λ = 1.5, D = 0.15, S = 6, 1 cable

ABSOLUTE MAXIMUM FORCE AS A FUNCTION OF THE RATIO OF BLOCK LENGTH TO WAVE LENGTH

CROSS PLOT FROM FIGURE 6

FIGURE 9



d = 0.835 foot, λ = 1.5 feet, 2 cables

AVERAGE MAXIMUM FORCE AS A FUNCTION OF THE RATIO OF BLOCK LENGTH TO WAVE LENGTH

CROSS PLOT FROM FIGURE 7

FIGURE 10

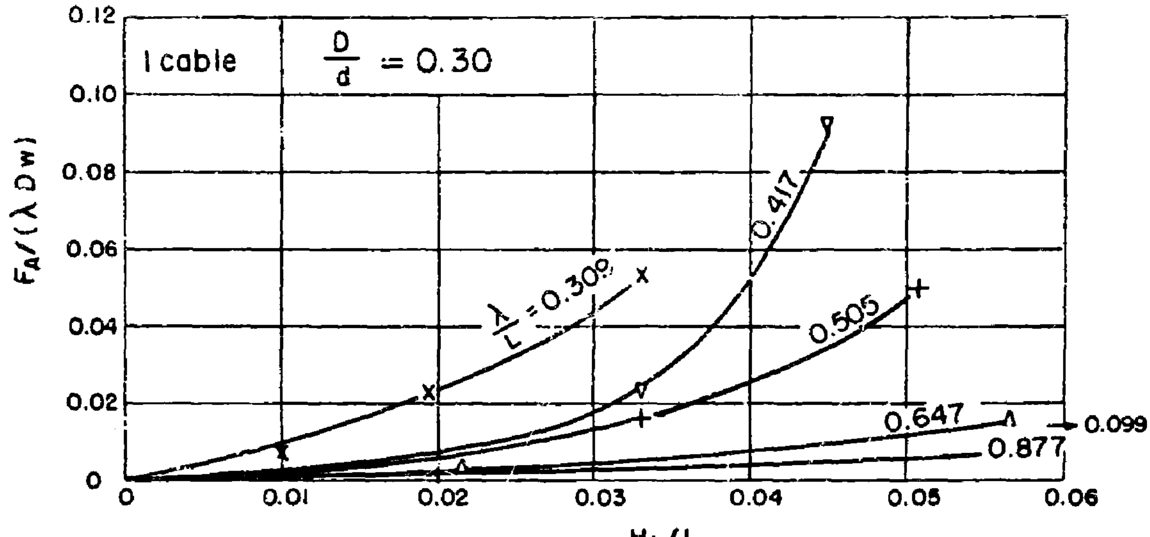


FIG. 11

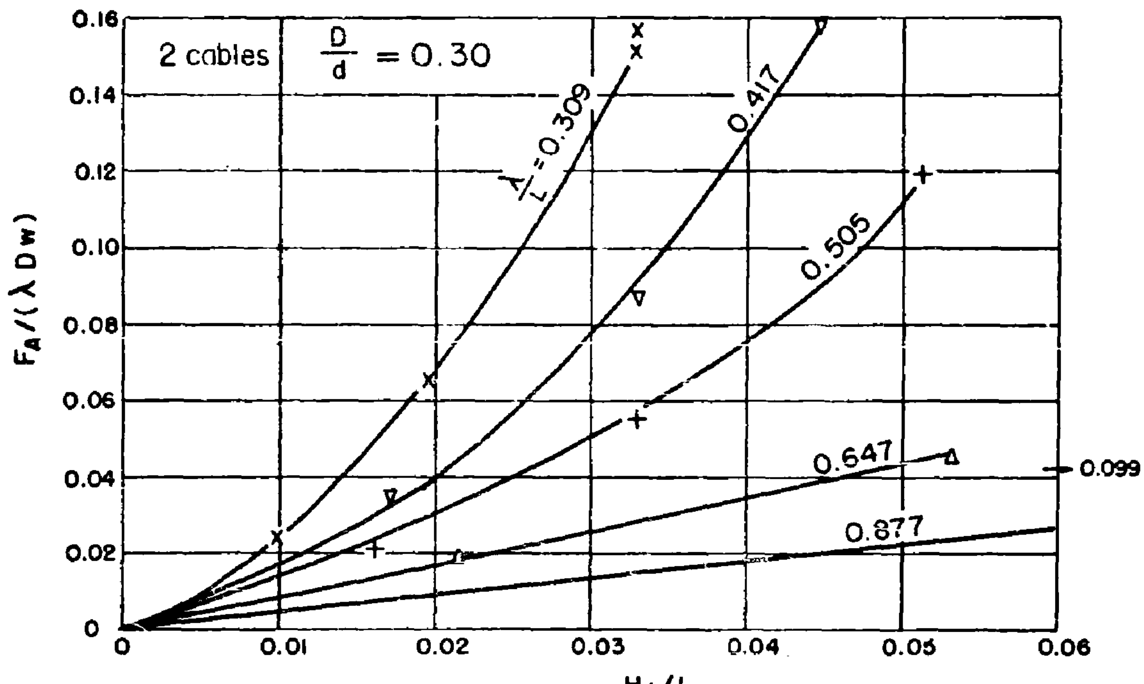


FIG. 12

d = 0.500 foot, λ = 1.5 feet, D = 0.15 foot, S = 6

AVERAGE MAXIMUM FORCE

AS A FUNCTION OF WAVE STEEPNESS

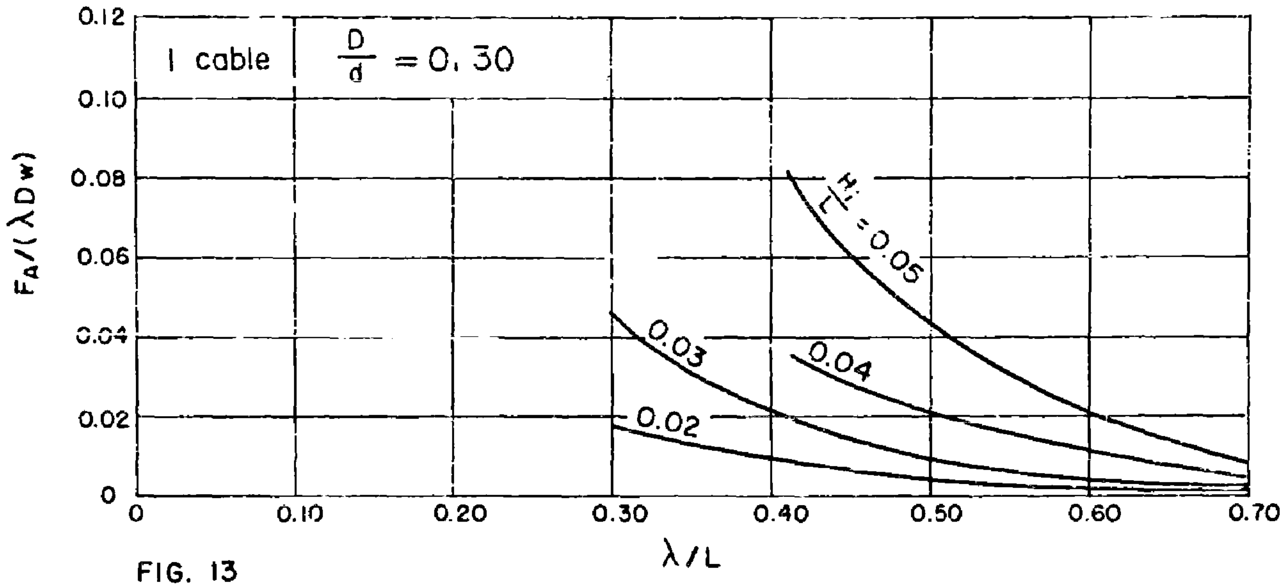


FIG. 13

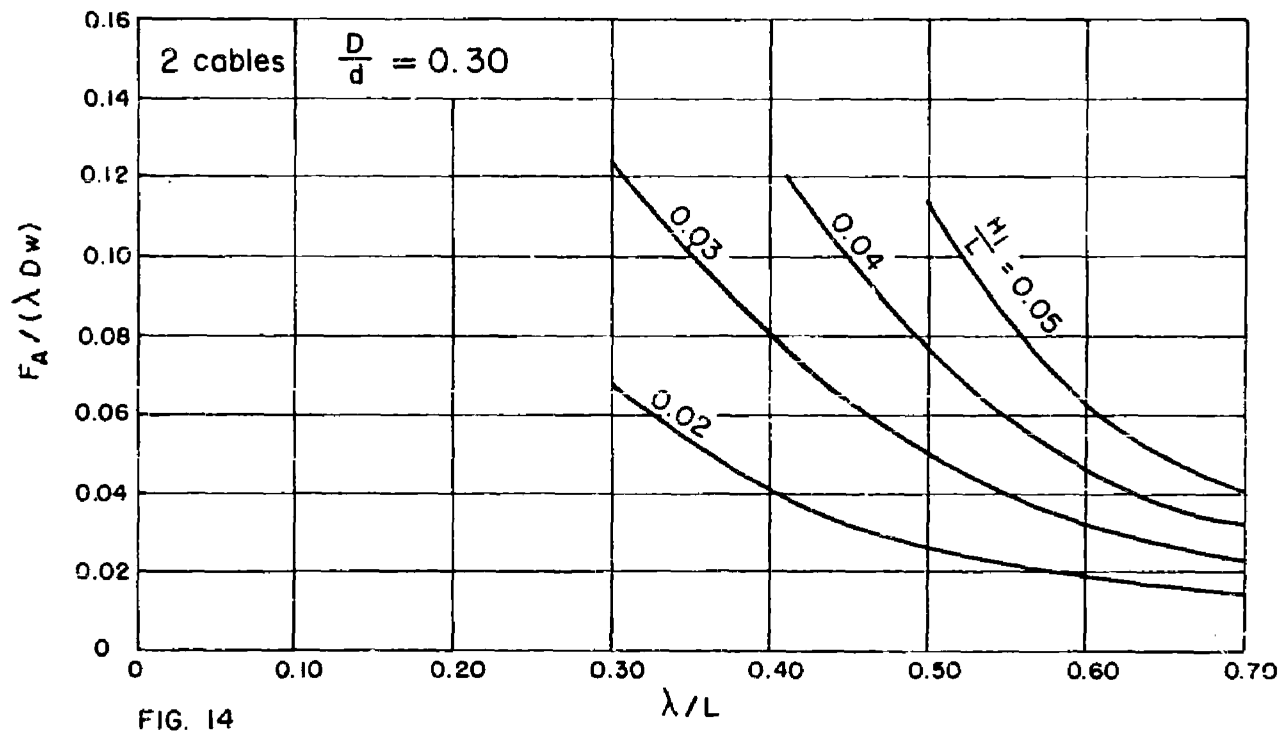
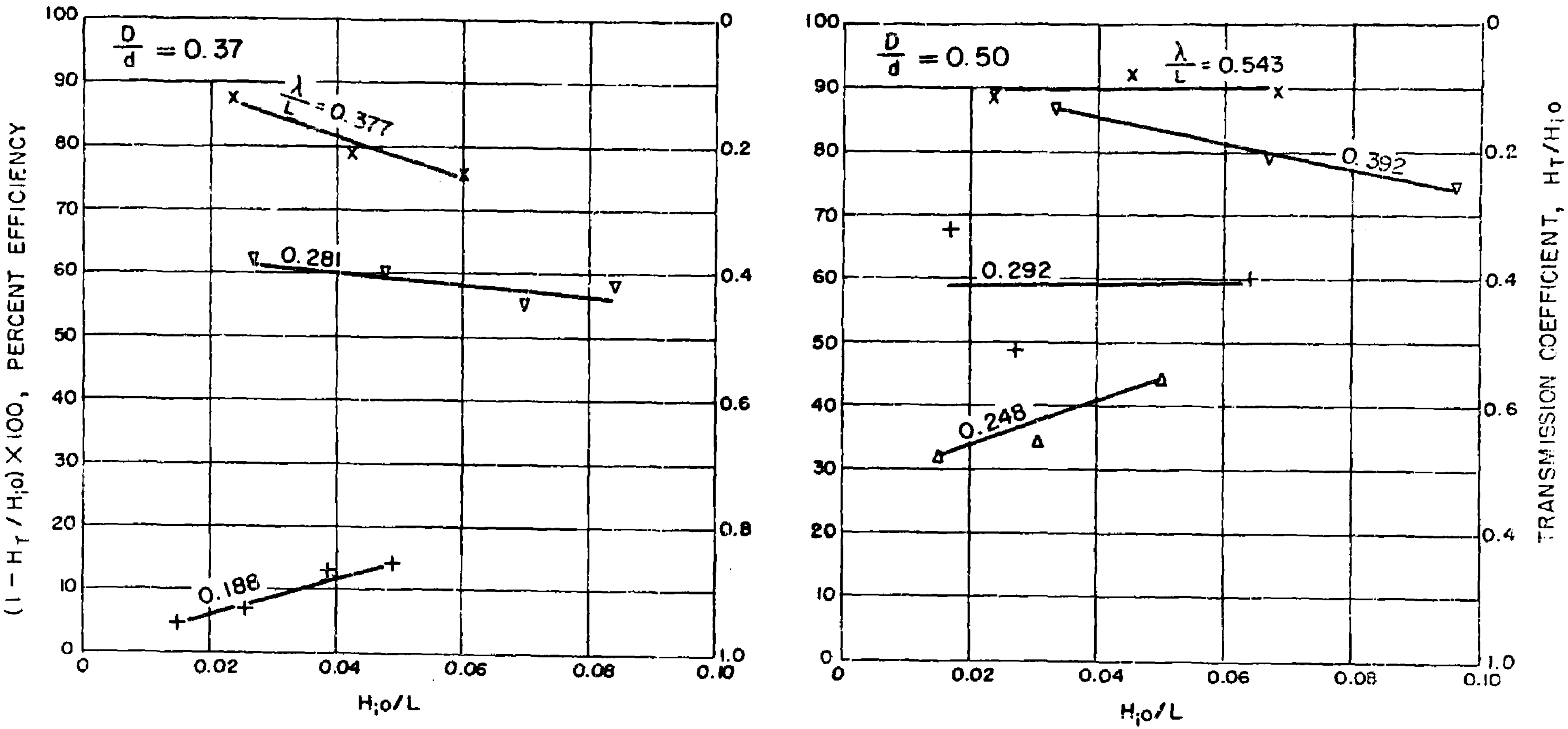


FIG. 14

d = 0.50 foot, = 1.5 feet

AVERAGE MAXIMUM FORCE AS A FUNCTION OF THE RATIO OF BLOCK LENGTH TO WAVE LENGTH

CROSS PLOT FROM FIGURES 11 & 12

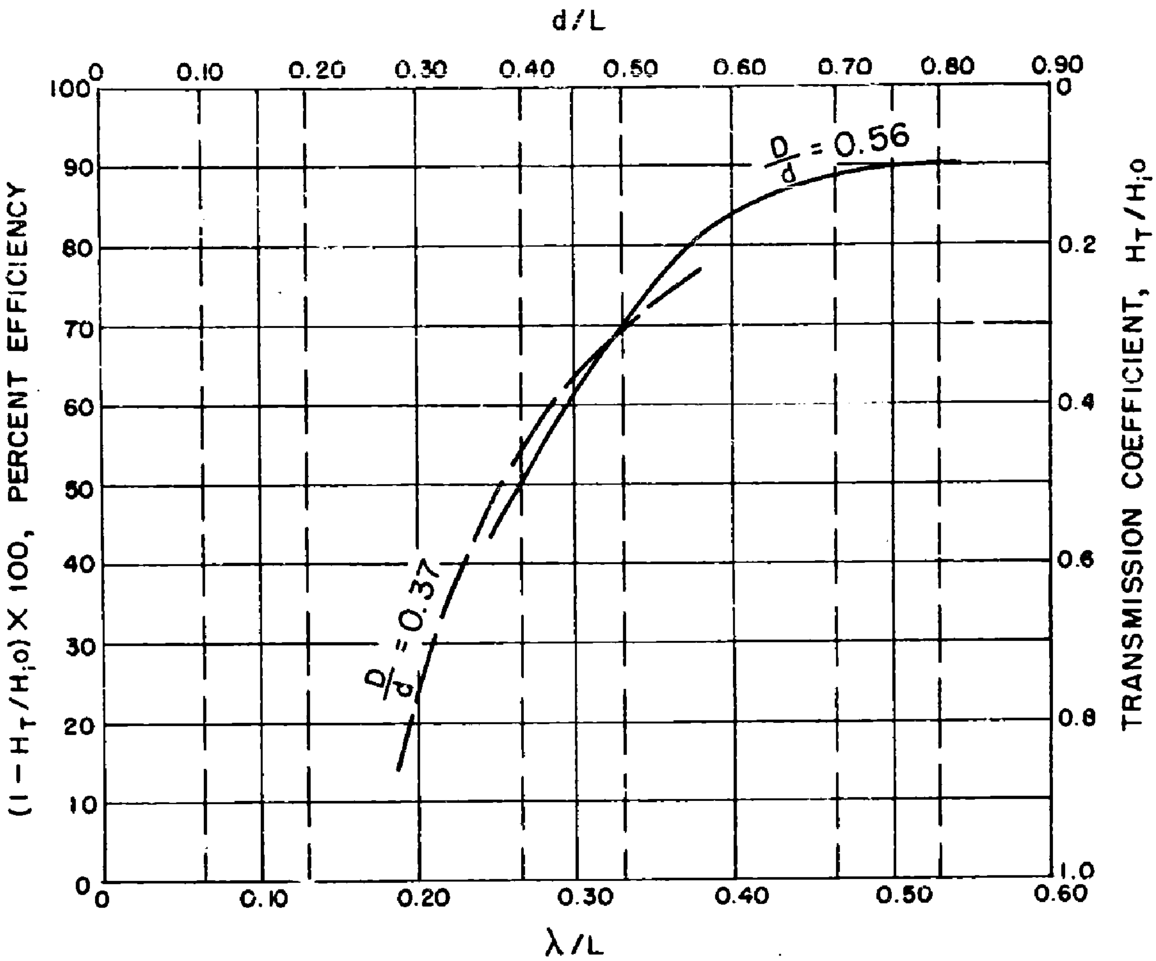


d = 1.50 feet, D = 0.56 foot, S = 6

BOMBARDON FLOATING BREAKWATER

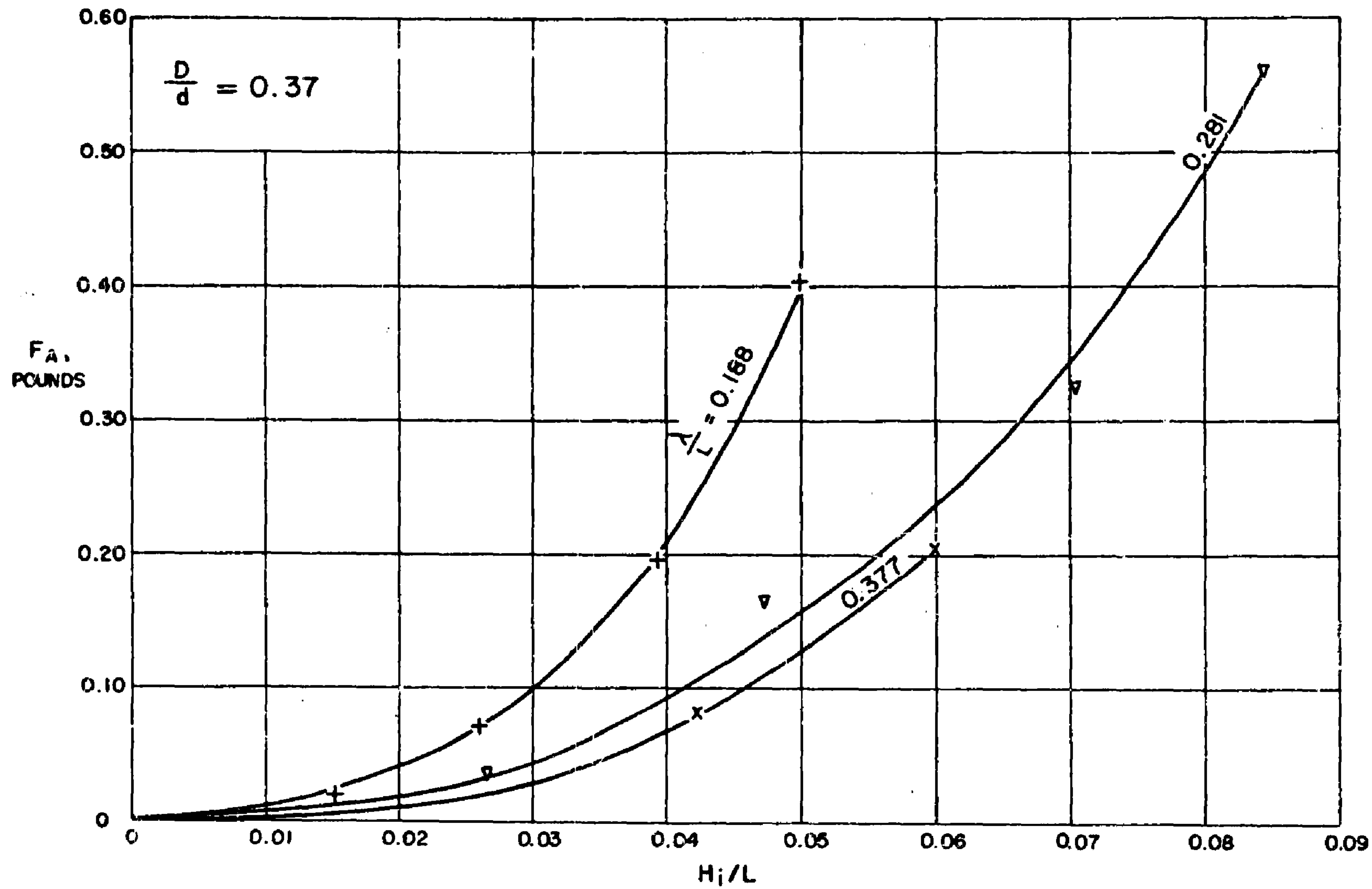
EFFICIENCY AND TRANSMISSION COEFFICIENT AS A FUNCTION OF WAVE STEEPNESS

FIGURE 15



EFFICIENCY AND TRANSMISSION COEFFICIENT
AS A FUNCTION OF THE RATIO
OF MODEL LENGTH TO WAVE LENGTH

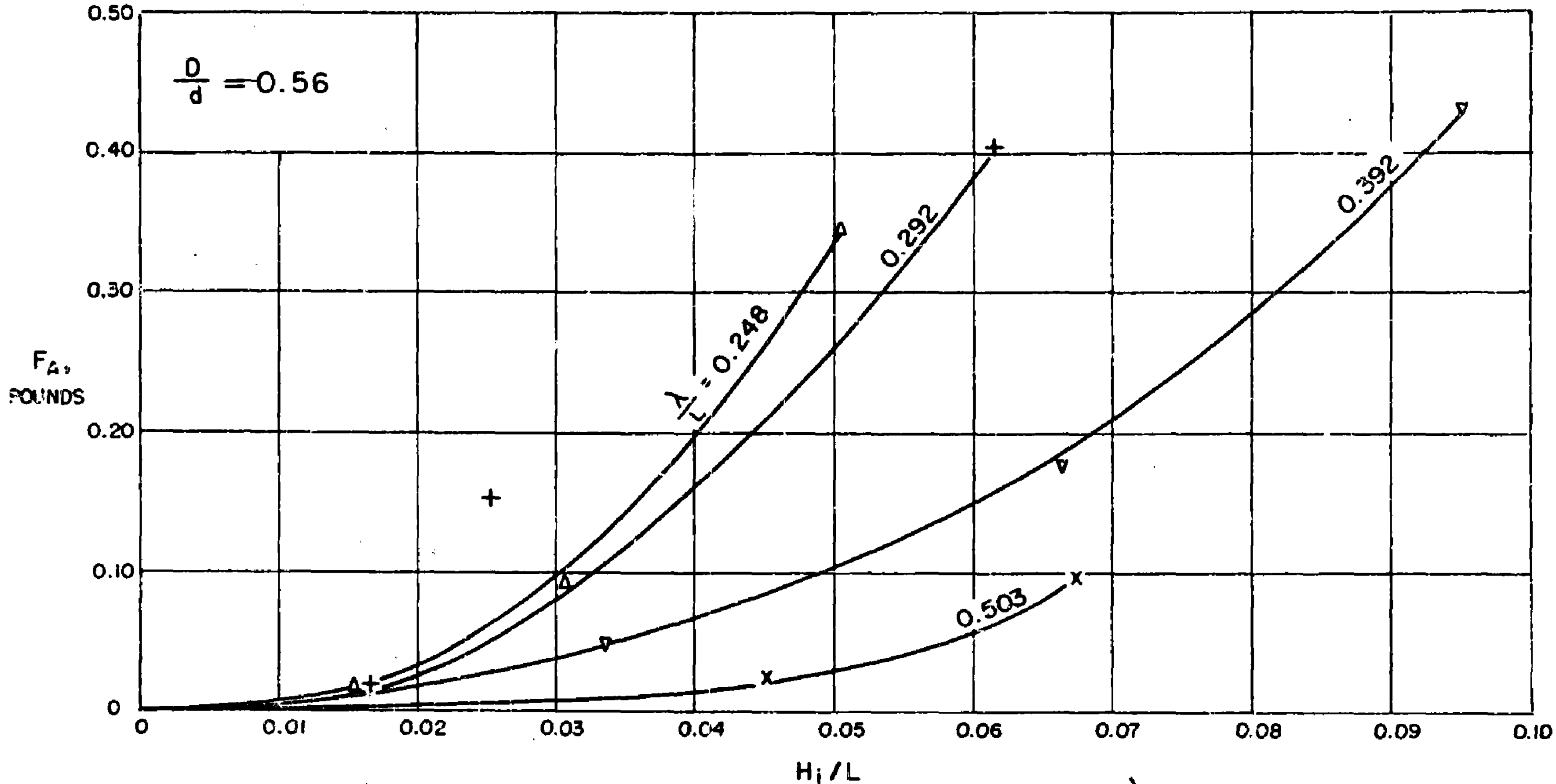
FIGURE 16



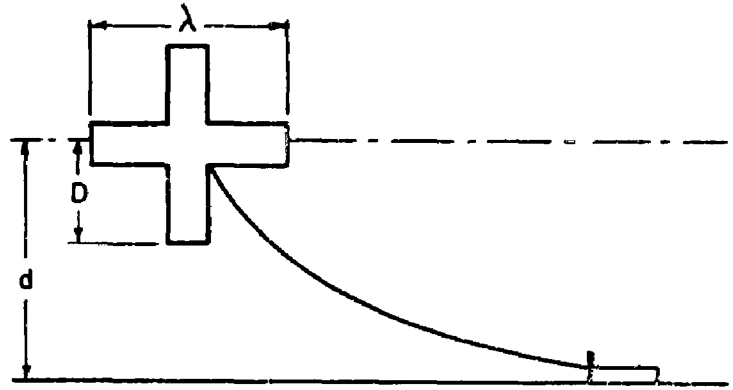
d = 1.50 feet, λ = 1.00 foot, D = 0.56 foot, S = 6, Bombardon

AVERAGE MAXIMUM FORCE AS A FUNCTION OF WAVE STEEPNESS

FIGURE 17

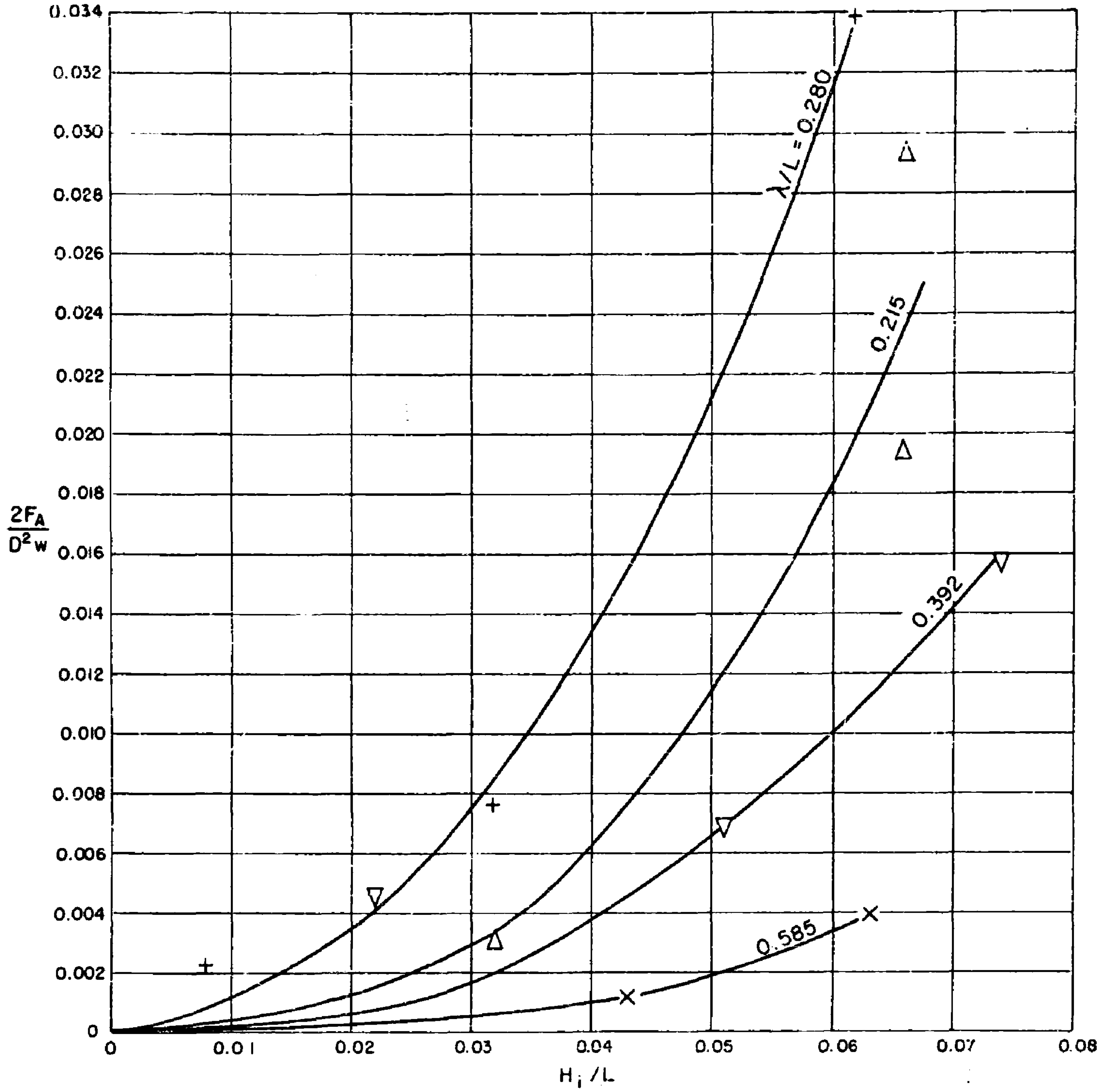


d = 1.00 foot, λ = 1.00 foot, D = 0.56 foot, S = 6



AVERAGE MAXIMUM FORCE
AS A FUNCTION OF WAVE STEEPNESS

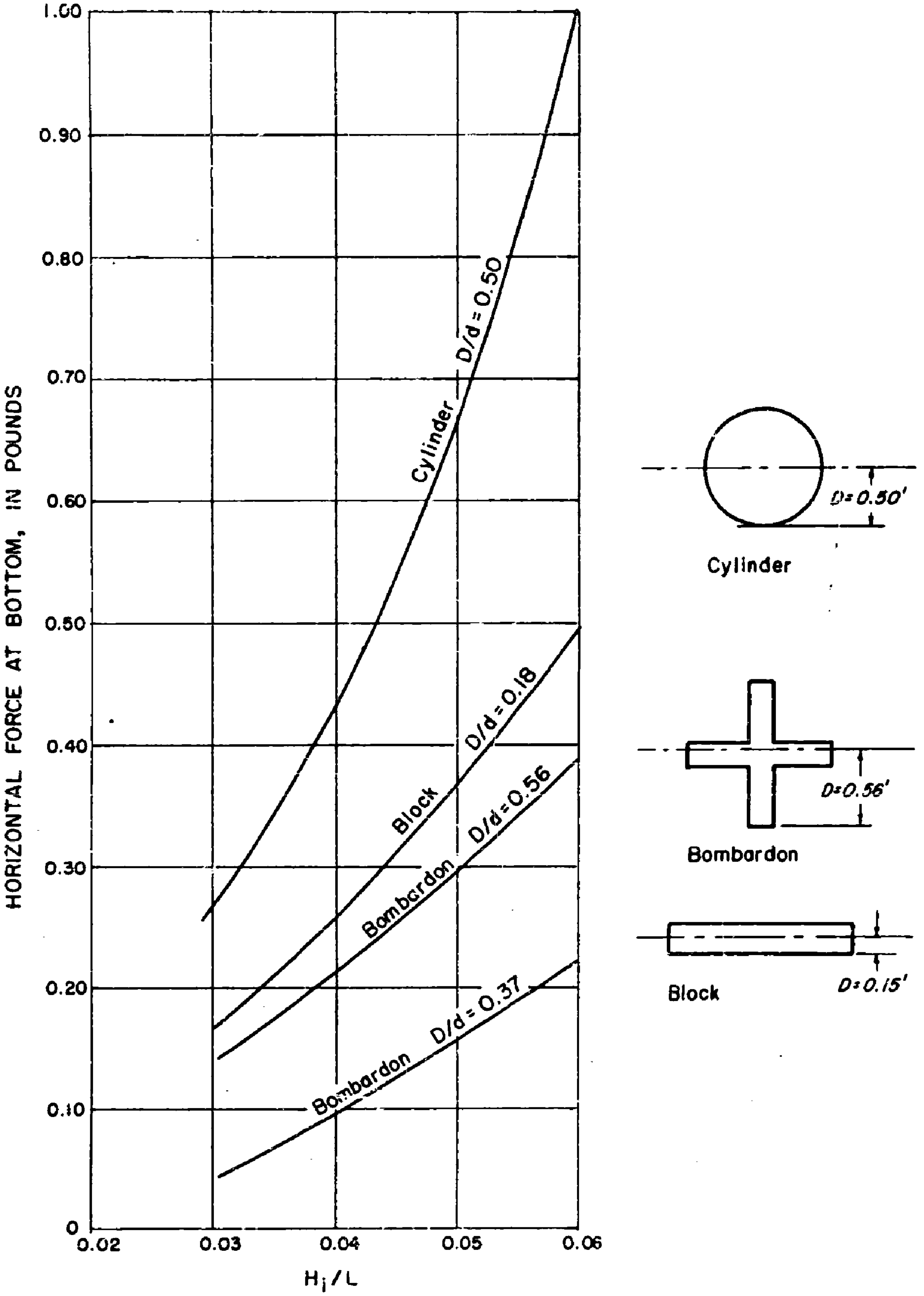
FIGURE 18



d = 1.00 foot, D = 0.50 foot, Cylinder, 1 cable

AVERAGE MAXIMUM FORCE
AS A FUNCTION OF WAVE STEEPNESS

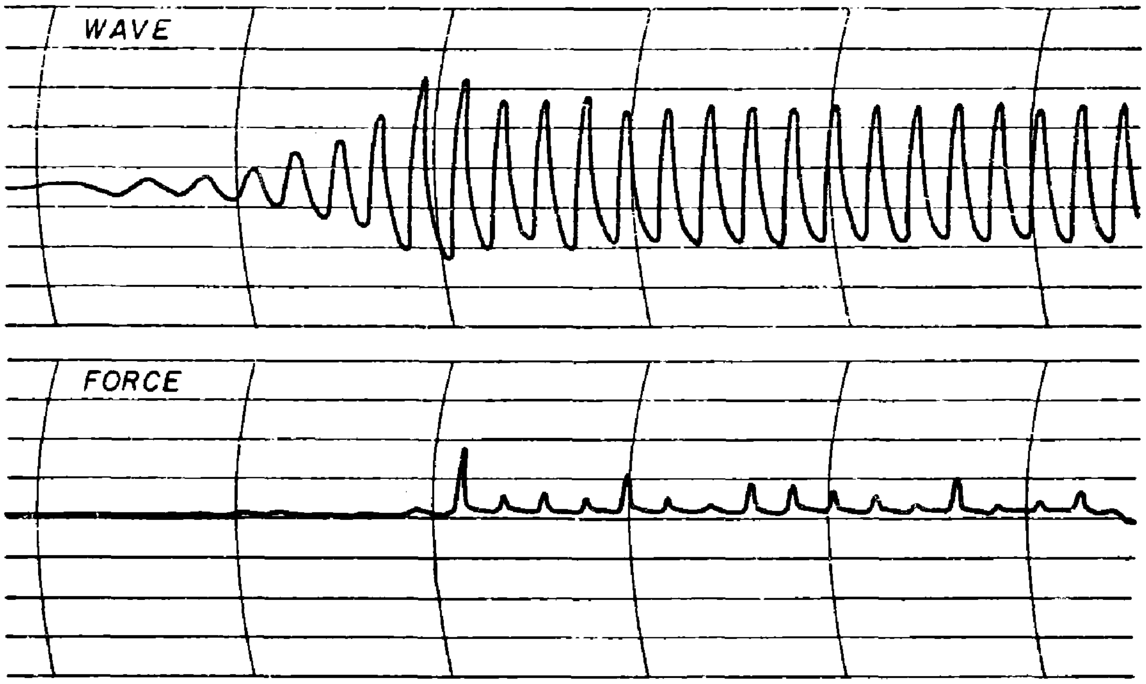
FIGURE 19



0.28 < d/L < 0.29, S = 6

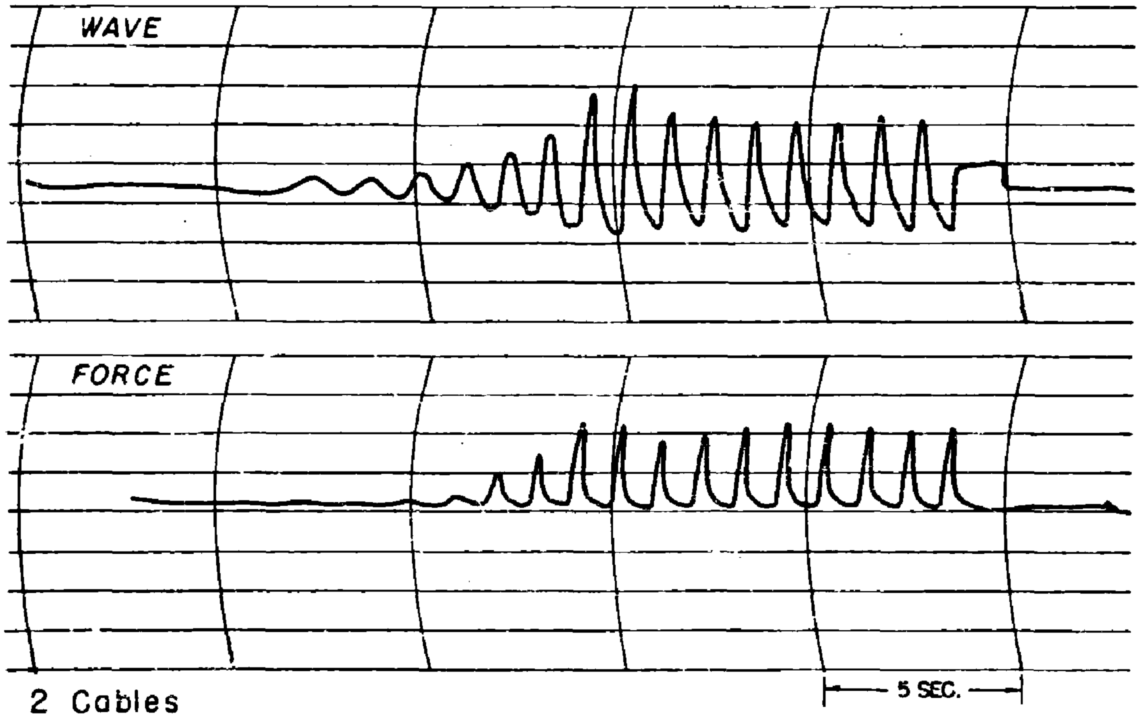
AVERAGE MAXIMUM FORCE
AS A FUNCTION OF WAVE STEEPNESS
COMPARISON OF THE THREE MODELS

FIGURE 20



I Cable

FIG. 21

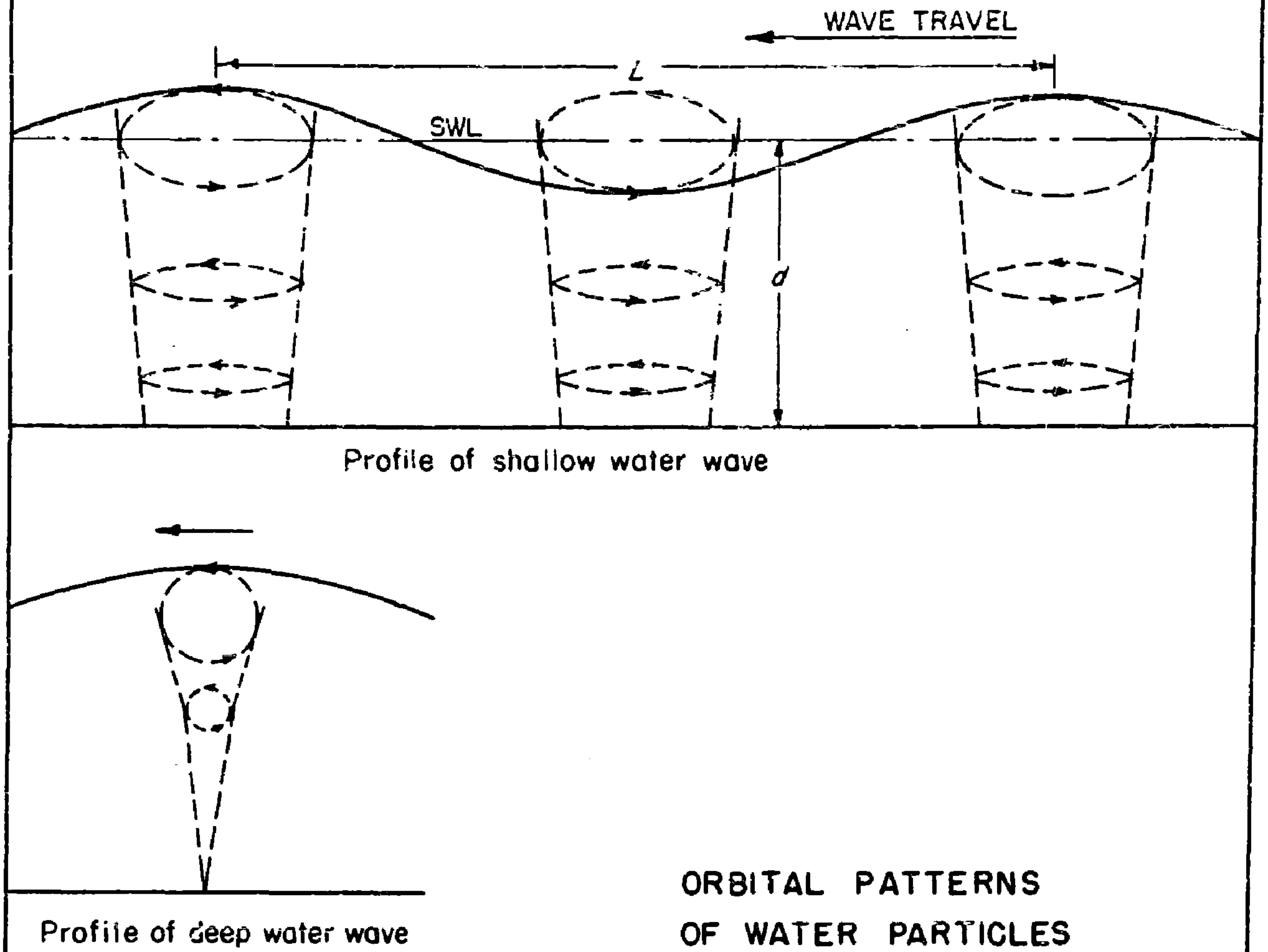


2 Cables

FIG. 22

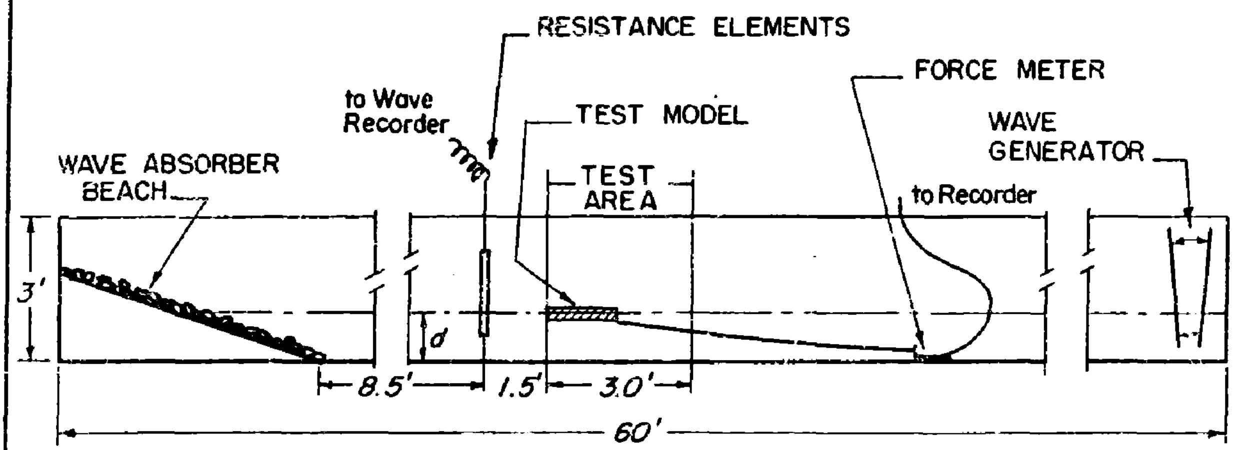
Run 12, d = 0.835 foot

SAMPLE RECORD



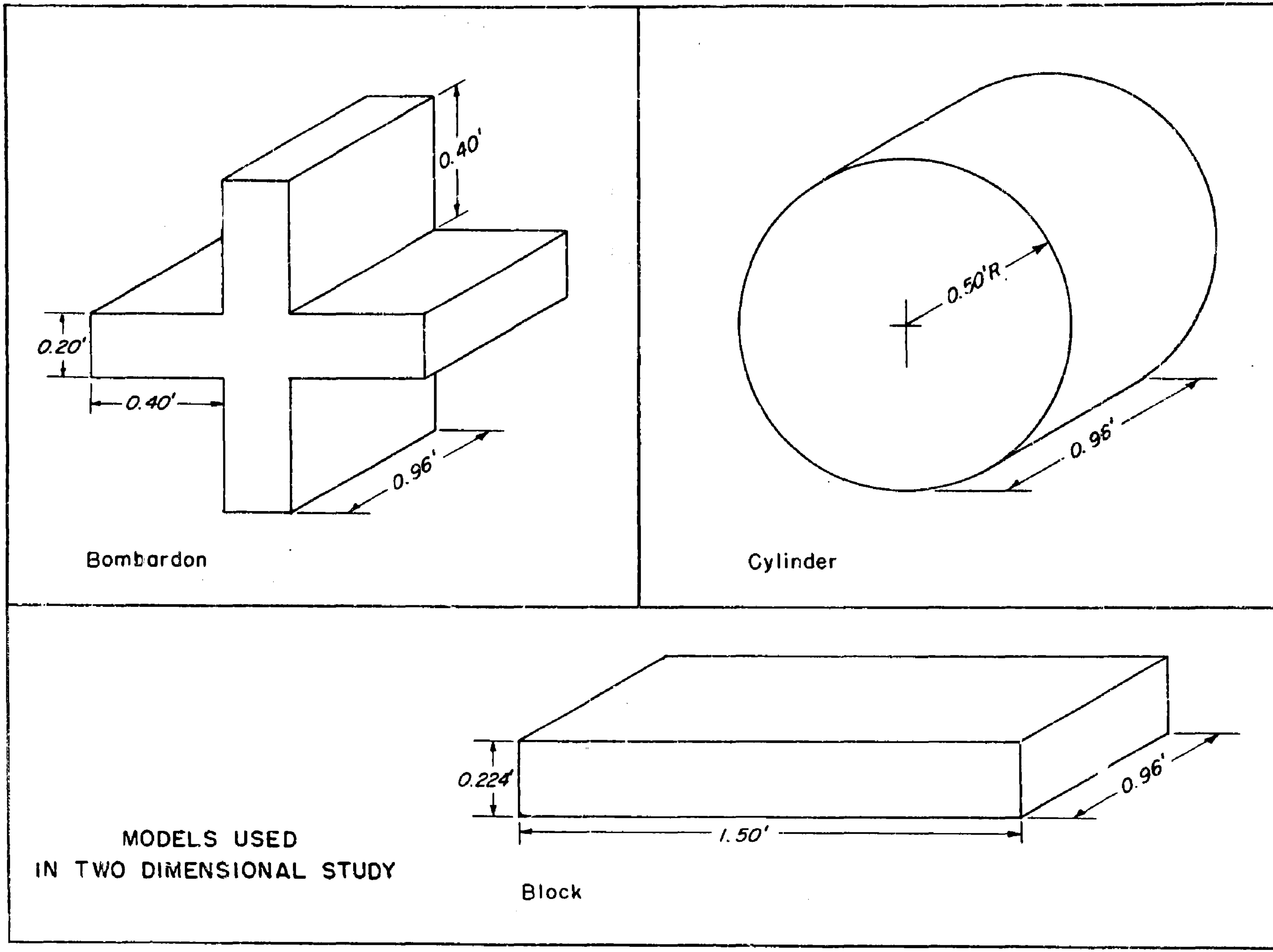
ORBITAL PATTERNS
OF WATER PARTICLES

FIG. 23



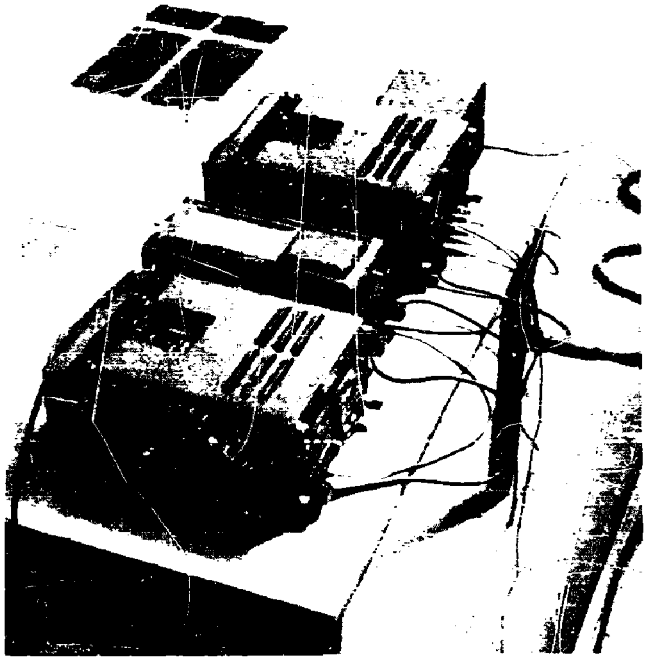
SKETCH OF EQUIPMENT IN CHANNEL

FIG. 24



MODELS USED
IN TWO DIMENSIONAL STUDY

FIGURE 25



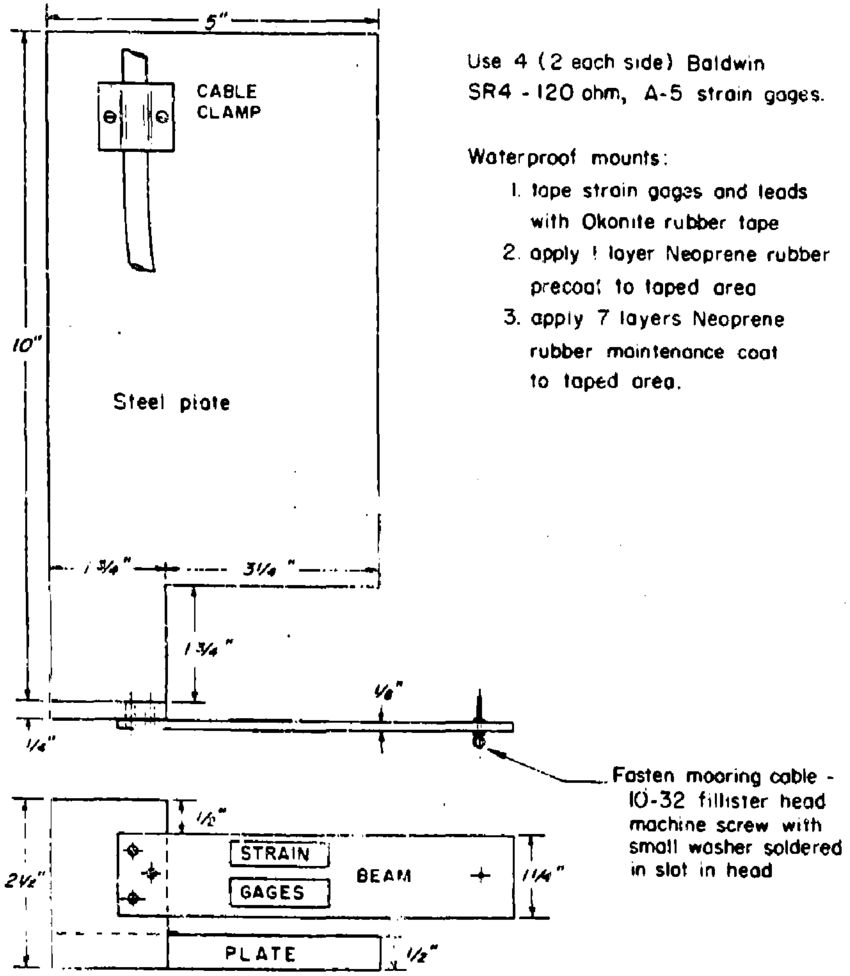
Recording equipment

FIG. 26

Cable force meter

FIG. 27

FIGURES 26 & 27

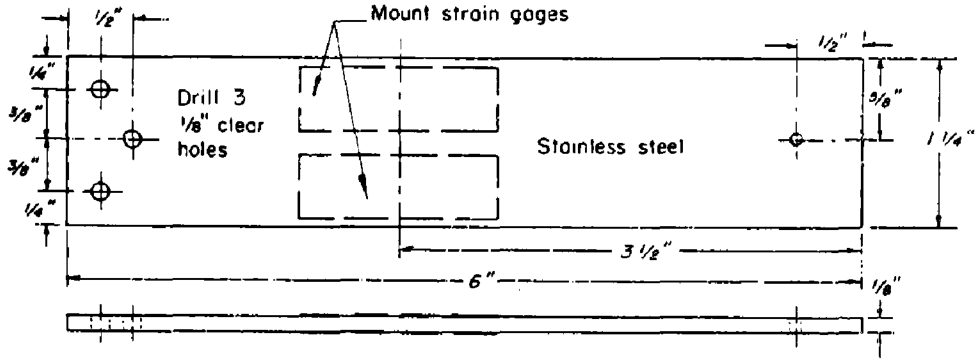


ASSEMBLY

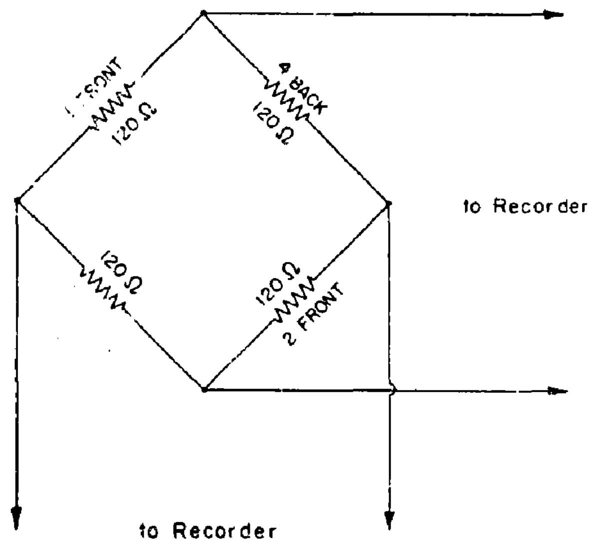
Use 4 (2 each side) Baldwin SR4 - 120 ohm, A-5 strain gages.

Waterproof mounts:

1. tape strain gages and leads with Okonite rubber tape
2. apply 1 layer Neoprene rubber precoat to taped area
3. apply 7 layers Neoprene rubber maintenance coat to taped area.



CANTILEVER BEAM



BRIDGE CIRCUIT DIAGRAM

MOORING CABLE FORCE METER

FIGURE 28