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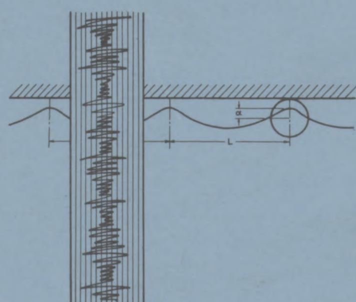
MODEL STUDY OF AN OFFSHORE DRILLING STRUCTURE

by
E.F. Brater and L.C. Maugh



Technical Report No. 6
Lake Hydraulics Laboratory
Department of Civil Engineering

Project 2092
Bethlehem Steel Company, Shipbuilding Division
Beaumont, Texas

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MODEL STUDY OF AN OFFSHORE DRILLING STRUCTURE

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BETHLEHEM STEEL COMPANY, SHIPBUILDING DIVISION
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MODEL STUDY OF AN OFFSHORE DRILLING STRUCTURE

INTRODUCTION

These model tests were undertaken to determine the horizontal forces, piling stresses, and drilling platform displacements produced in a proposed off-shore drilling structure by the action of waves. This information was needed to provide a basis for design and also to provide an indication of operating conditions. Measurements were made on a 1:50 scale model for various depths of water with waves of various periods and heights and with the barge in two different positions.

The study was made in accordance with a contract, dated September 30, 1952, between the University of Michigan, Ann Arbor, Michigan, and the Bethlehem Steel Company, Shipbuilding Division, Beaumont, Texas. The tests were conducted in the University of Michigan Lake Hydraulics Laboratory*.

The men most directly concerned with the model tests were Mr. E. C. Rechtin, General Manager, and Mr. J. E. Steele, Chief of Design, Bethlehem Steel Company, Shipbuilding Division, Beaumont, Texas. The model was designed on the basis of preliminary plans supplied by Mr. Steele. The test results were transmitted to Mr. Steele as they were obtained and the model operations and test sequences were arranged to meet the needs of the design group.

Consultations were also held with Mr. H. deLuce and Mr. D. F. MacNaught of the Central Technical Division, Bethlehem Steel Company, Quincy, Massachusetts. Their suggestions were very helpful in planning and conducting the tests.

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* The Lake Hydraulics Laboratory is a facility of the Engineering Research Institute and the Department of Civil Engineering of the College of Engineering.

Mr. J. R. Aikins and Mr. H. J. EnDean of the Gulf Research and Development Company, Pittsburgh, Pennsylvania, made helpful suggestions regarding the tests and also supplied some of the recording instruments used during the tests. Other personnel of the Gulf Oil Company who visited the laboratory during the tests were Mr. D. W. Gower of the Construction Department, Mr. W. D. Stine and Mr. C. W. Laas of the Producing Department, Houston, Texas, and Mr. O. W. Crisman of the Producing Department, New Orleans, Lousiana.

Mr. L. D. Stair, Research Associate in the Engineering Research Institute, worked with the authors on all phases of the testing program and in the preparation of the report. Dr. T. A. Hunter, Assistant Professor of Engineering Mechanics, assisted with the instrumentation and other phases of the work.

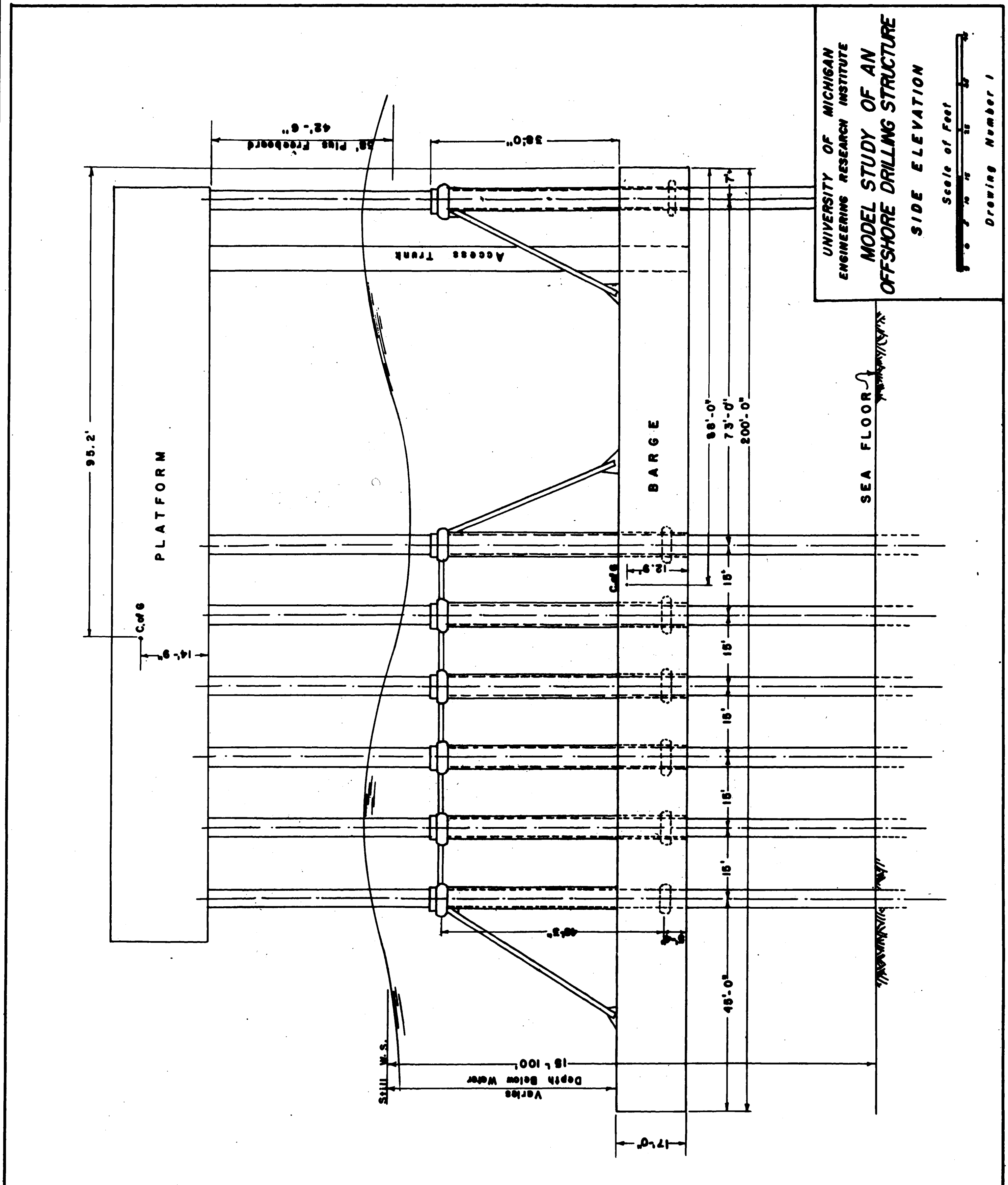
THE PROTOTYPE

The proposed structure is being designed for use in the Gulf of Mexico at water depths up to 100 feet. It is expected that storm waves as high as 35 feet will be directed against the structure. The wave period selected for design purposes was 12 seconds; the corresponding wave length in deep water would be 736 feet.

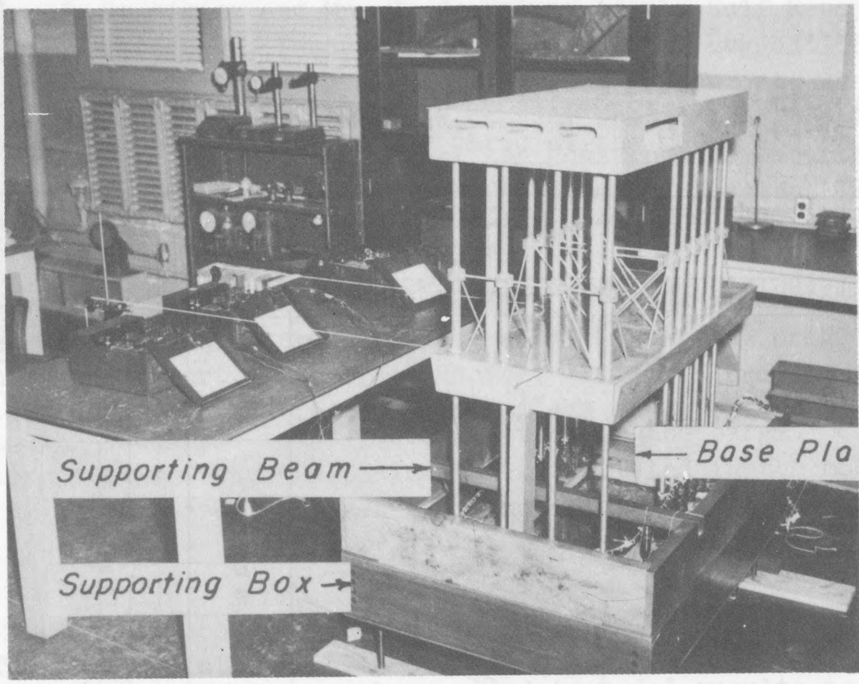
The structure consists of a movable barge 200 feet long, 88 feet wide and, 17 feet high and a drilling platform 165 feet long and 88 feet wide. During transit, the drilling platform is supported 40 feet above the deck of the barge by sixteen 48-inch tubes which are part of the barge superstructure. During operation, the platform is to be supported on sixteen 36-inch piles driven through the 48-inch tubes; at the same time the barge is lowered to a position below the water surface, where it is held in place by clamps located near both ends of the 48-inch tubes.

THE MODEL

The model was constructed to a scale of 1:50 in accordance with plans supplied by the Bethlehem Steel Company. Drawing 1 shows the general arrangement and dimensions of the model. Photographs of the model during assembly are shown in Fig. 1, p. 4.



Drawing Number 1



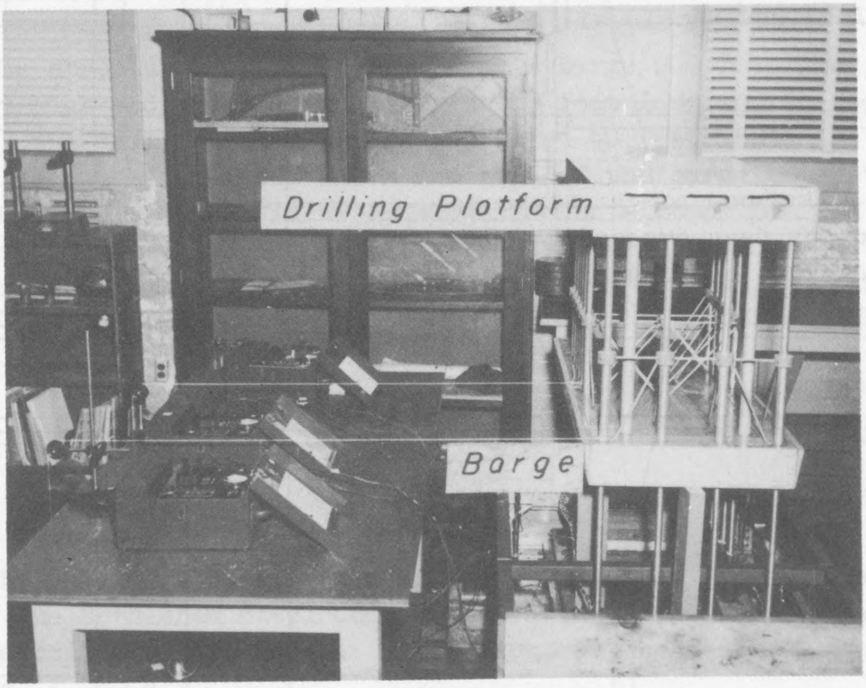


Figure 1. Model during Final Stages of Assembly.

Barge and Drilling Platform

In order to reproduce the stiffness of the prototype as accurately as possible, the internal bulkheads were designed and constructed to simulate those shown in detailed drawings supplied by the Bethlehem Steel Company. A drawing showing the internal construction of the model barge is given as Drawing 2, Appendix A, p. 23, and a photograph is shown in Fig. 2.

The weights of the barge and platform were reproduced to scale ($1:50^3$) by adding weights where necessary, placing them so as to duplicate the locations of the centers of gravity.

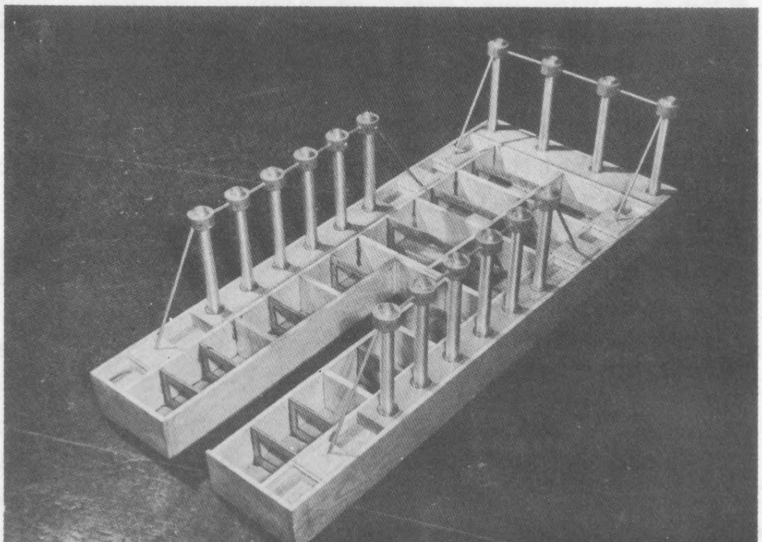


Figure 2. Interior of Model Barge.

Piling

It was decided to use aluminum for the model piling rather than steel in order to magnify the strains induced by the model forces. The prototype piling consisted of 36-inch-outside-diameter pipe having a wall thickness of 3/4 inch. The corresponding model dimensions were 0.72-inch diameter and 0.015-inch wall thickness. The 48-inch-outside-diameter tubes (Fig. 2) which will support the drilling platform while the structure is in transit and through which the piling will be driven when the structure is in place have the model dimensions of 0.96-inch diameter and 0.015-inch wall thickness. The construction of the model was delayed for some time until material having approximately these dimensions could be found. The problem was solved by reducing the wall thickness of standard aluminum tubing by a centerless grinding process*. The tubing used for the model piling had an outside diameter of 0.711 inch. The wall thickness of the tubes was measured and the deviations from 0.015 inch were found to be less than 0.001 inch for thirteen piles and just slightly greater than 0.001 inch for three piles. Figure 3a is a photograph showing the piling before assembly.

It was decided that the degree of fixity of the piling in the mud bottom might be simulated by restraining the model piling against rotation at a location corresponding to a point 40 feet below the mud line. This was accomplished by carefully driving the model piling into holes drilled in pieces of cypress 1-5/8 inches thick. The pieces of cypress were bolted to a 1/4-inch aluminum plate as shown in Figs. 1 and 3b. The fit between the aluminum tubes and the wood was as tight as could be obtained without injuring the piling. A similar tight fit was produced in the platform by drilling holes in hard wood 3 inches thick. Four strain gages were placed on each pile (Fig. 3a, p. 7) at a point 1.6 inches (80 inches in prototype) above the point where they emerged from their supports. When the piles were placed in the supporting plate the positions of the strain gages were oriented with the principal axes of the model.

The clamping arrangement for fastening the barge to the piling was simulated by placing four set screws in the corresponding locations at the top and bottom of the 48-inch supporting tubes. It was found that the eight set screws on each of the sixteen piles produced sufficient resistance to support the barge in any desired position without serious injury to the model piling.

* These tubes were prepared by the Central Specialty Division of the King Seely Corporation, Ypsilanti, Michigan, under the direction of Mr. Louis Chadwick.

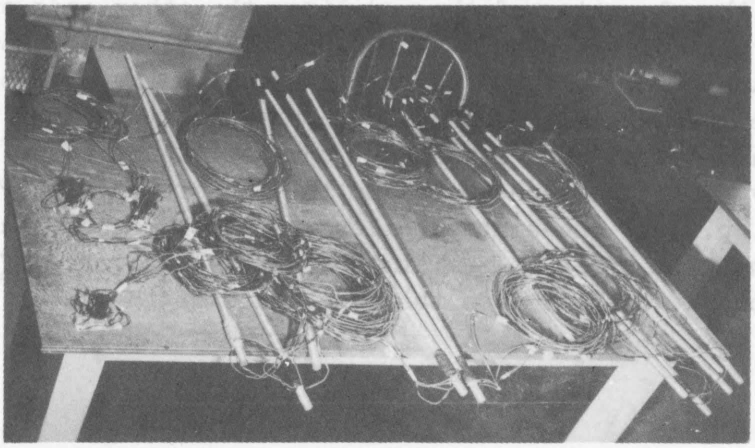


Figure 3a. Piling before Assembly.

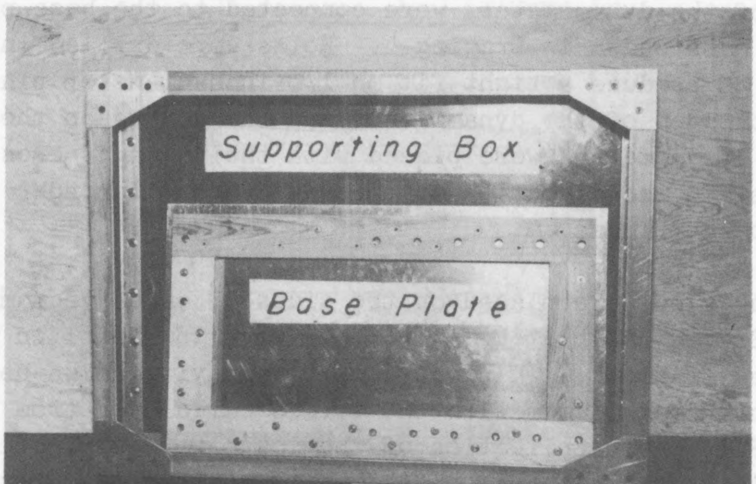


Figure 3 b. Base Plate and Aluminum Portion of Supporting Box.

Model Suspension

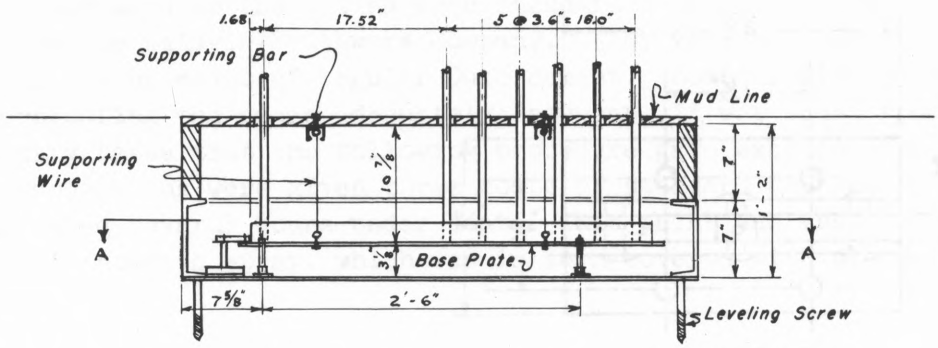
The model was suspended from four piano wires 11-1/2 inches long located as shown in Drawing 3. The suspending wires were supported by two small beams placed at the elevation of the mud line, the other ends of the wires being fastened to the base plate. One of the supporting beams is shown in place in Fig. 1. The beams were, in turn, supported by the walls of a box in which the base of the model was enclosed. The lower portion of this box was made of aluminum (Figs. 1 and 3a) and the upper portion was made of wood. The sea floor was simulated by nailing 1-inch boards to the top of the supporting box as shown in Fig. 5, p. 14. The sixteen piles passed through holes in these boards without restraint. In order to resist the overturning force of the waves, a weight of 115 pounds was placed on the base plate of the model.

Dynamometers

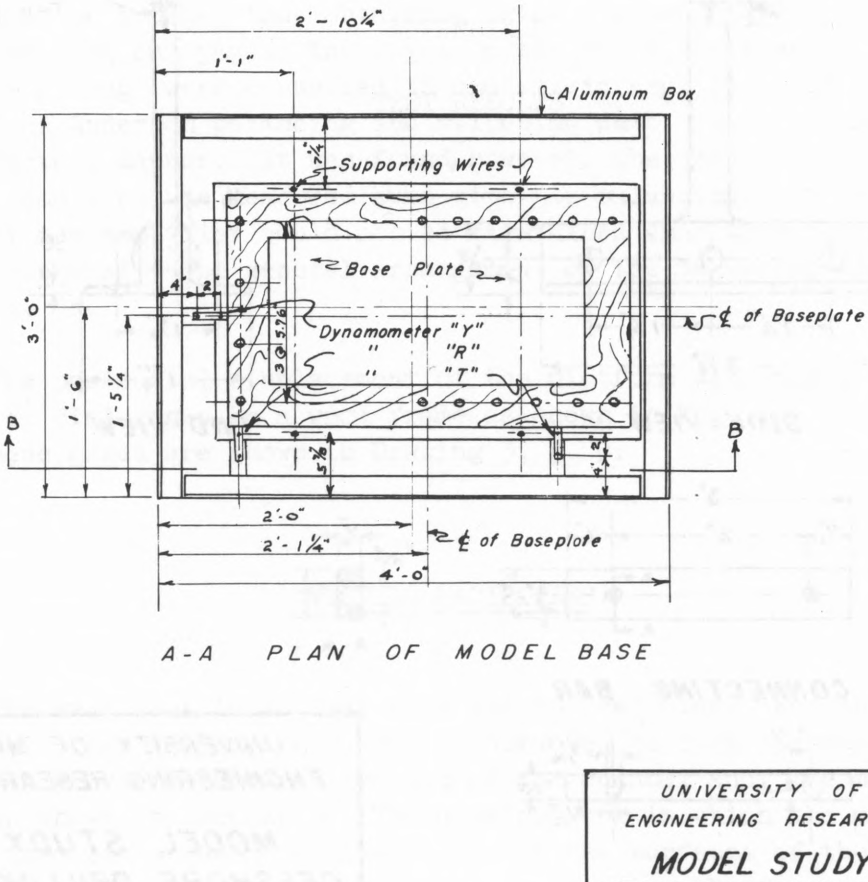
The horizontal displacement of the base plate of the model was restricted by three dynamometers located as shown in Drawing 3, p. 9. The dynamometers consisted of aluminum cantilevers having the dimensions shown in Drawing 4. They were fastened to the bottom of the rigid aluminum box shown in Fig. 3b. The upper ends of the dynamometers were connected to the base plate of the model by the aluminum bars shown in Drawing 4. Holes were drilled in the ends of these connecting bars to produce a tight fit on 1/8-inch-diameter pins, one of which was located on the top of the dynamometer and the others on the base plate of the model. The dynamometers were placed with their longer cross-sectional dimensions parallel to the direction of the wave forces in order to provide the maximum amount of stiffness.

Strain gages were placed on the sides of each dynamometer 1.72 inches from the top. Static calibrations were made with the model in place before and after each series of tests. This was done by applying known horizontal loads and comparing their magnitudes with the forces calculated from the strain gage measurements. Points of application of the loads were varied in both the horizontal and vertical directions in order to insure that the static tests covered the range of conditions produced by the waves. It was found that the calibration factor varied very little with the location of the point of application of the loads.

The calibration coefficient varied gradually from about 1.12 to 1.3 during the several months of testing. A calibration factor of 1.25 would indicate that the horizontal force computed from dynamometer readings was 80 per cent of the applied load.



B-B SECTION THROUGH MODEL BASE



A-A PLAN OF MODEL BASE

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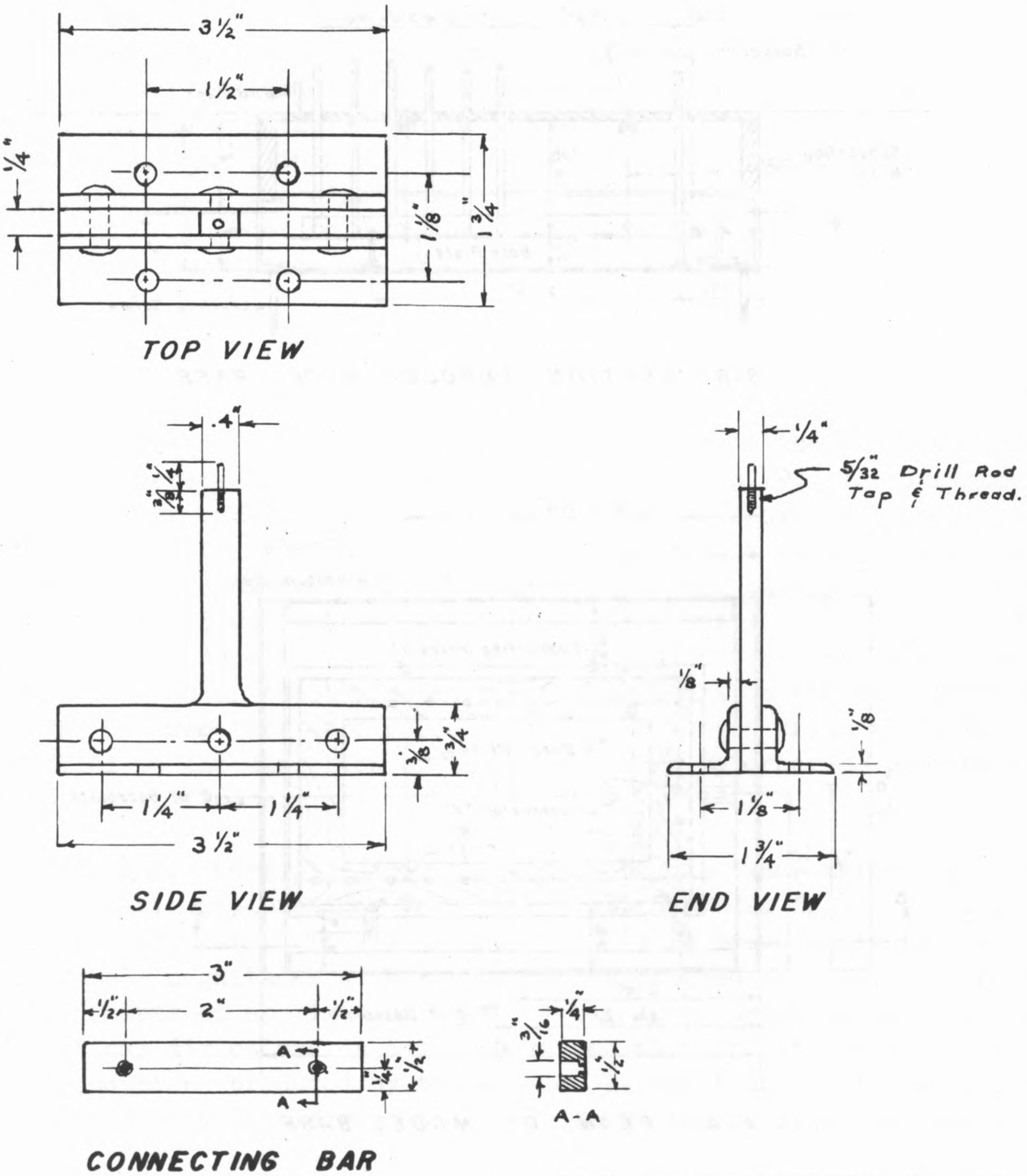
MODEL BASE DETAILS

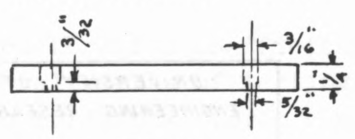
Scale of Feet

1 0 1 2

Drawing Number 3

DYNAMOMETER





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MODEL STUDY OF AN
OFFSHORE DRILLING STRUCTURE

DYNAMOMETER DETAILS

Scale : 1:2

Drawing Number 4

INSTRUMENTATION

The strain gages used on the dynamometers were standard A-7 resistance gages and those used on the piling were standard A-12 gages. The gages were obtained from the Baldwin-Southwark Company. They were attached to the dynamometers and piling by means of regular Duco cement. Some difficulty was encountered in waterproofing the gages adequately; however, it was found from a series of preliminary tests that the following procedure gave excellent results. The gages and connections were given three coats of standard Glyptal paint, each coat being dried several hours under heat. This paint was then covered with Krylon acrylic plastic spray, which was in turn covered with standard Permatex No. 1.

The strain gages on the two principal dynamometers (R and T), which measured the resultant wave forces, were connected directly to separate Brush strain amplifiers and the results were recorded by means of Brush oscillographs. The two gages on opposite sides of a dynamometer were attached to opposite arms of the Wheatstone bridge, thus obtaining twice the sensitivity that would have been obtained from one gage. The gages on the third dynamometer (Y) and those on eight of the piling were connected to one strain amplifier and oscillograph by means of an Anderson balancing and switching unit. This arrangement operated in a satisfactory manner. It was found, however, that the stress in the remaining piling could not be measured even with the balancing unit because the balancing of the amplifier could not be maintained when these additional piling gages were attached. The general arrangement of the measuring equipment is shown in Fig. 4a.

The horizontal displacement of the platform was obtained by mounting three Federal dial gages in a wood frame as shown in Fig. 4b. The exact locations of these gages are shown in Drawing 3, p. 9.

TESTING FACILITIES

The wave tank is 90 feet long and 55 feet wide. For these tests, a temporary wall, a-b in Drawing 5, was constructed to form a channel 14 feet wide. The wave machine was located at one end of the channel and, the model near the other end as shown in Drawing 5. The aluminum box in which the model was mounted was set in a pit at such an elevation that the surfaces of the boards which simulated the sea floor were at the same elevation as the floor of the tank.

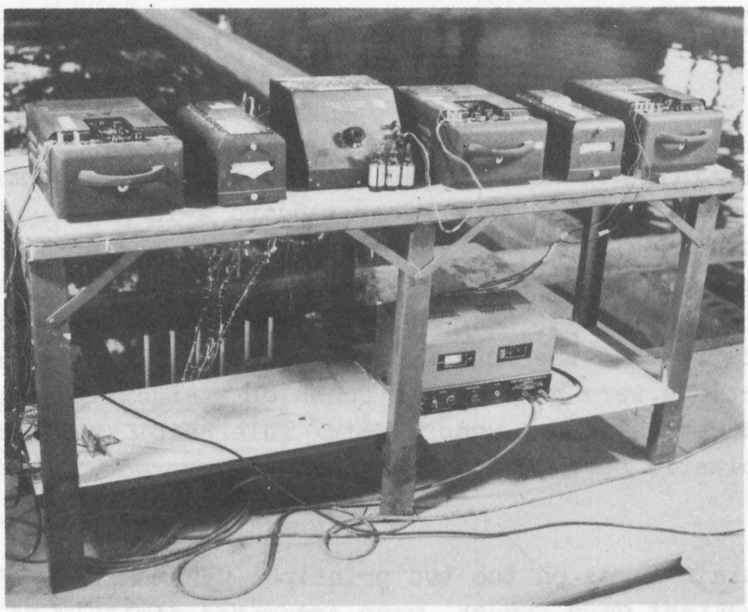


Figure 4a Recording Instruments and Amplifiers.

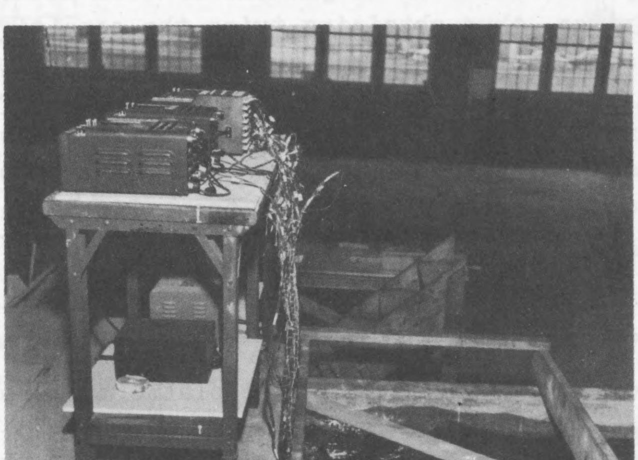
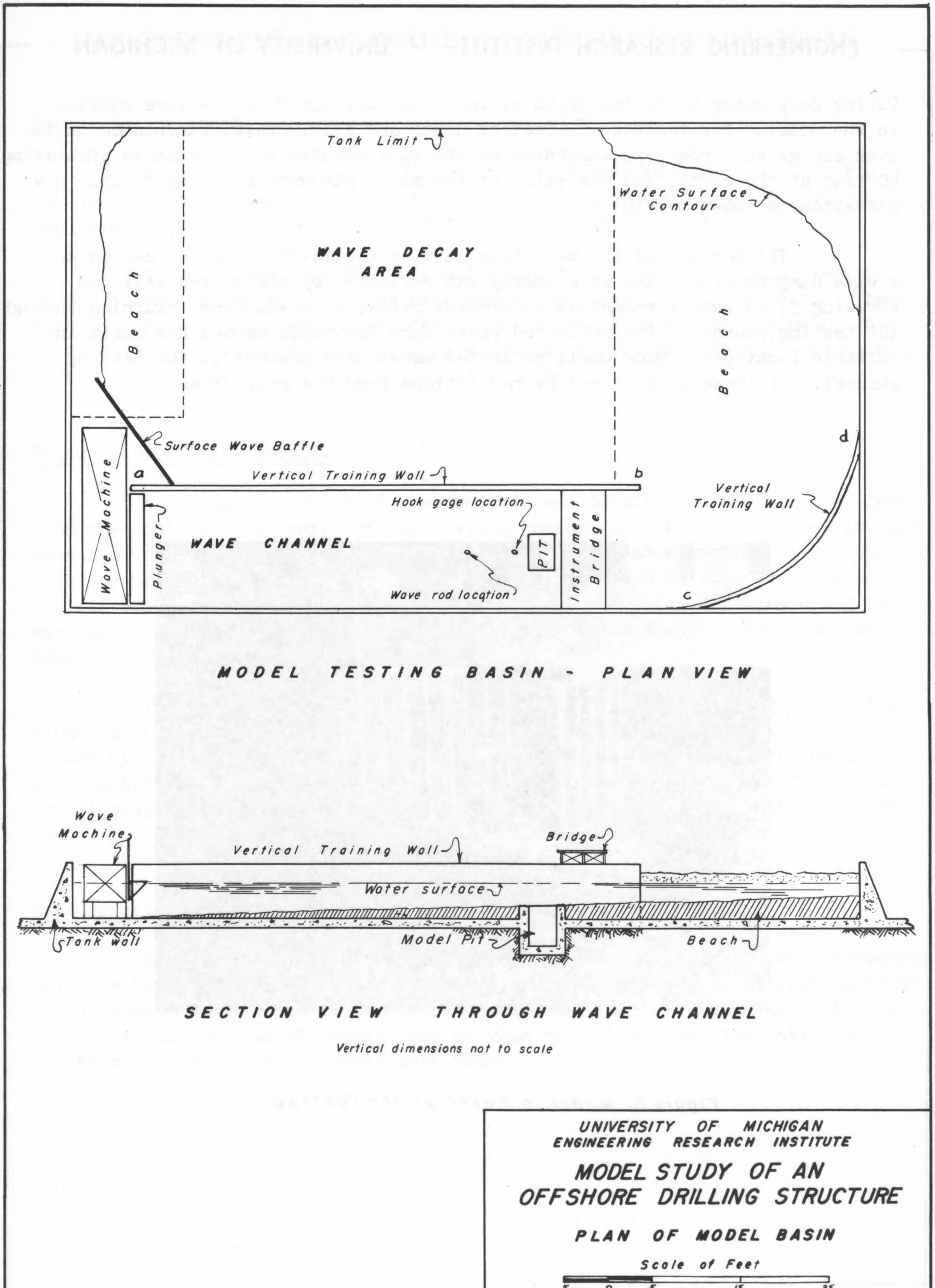


Figure 4b Displacement Gages


Tank Limit
Water Surface Contour
WAVE DECAY AREA
Beach
Beach
Surface Wave Baffle
a
b
c
d
Vertical Training Wall
Vertical Training Wall
Hook gage location
Wave Machine
Plunger
WAVE CHANNEL
PIT
Instrument Bridge
Wave rod location
MODEL TESTING BASIN - PLAN VIEW
Wave Machine
Bridge
Vertical Training Wall
Water surface
Tank wall
Model Pit
Beach
SECTION VIEW THROUGH WAVE CHANNEL
Vertical dimensions not to scale
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PLAN OF MODEL BASIN
Scale of Feet
5 0 5 15 25
Drawing Number 5

During deep-water tests the depth of water was uniform from the wave machine to the model. For tests at 62 feet of depth and less, gravel was placed in the tank and graded from zero thickness at the wave machine to a thickness simulating 40 feet at the model, and the walls of the model pit were built up to this new elevation as shown in Fig. 5.

The portion of the wave tank outside the 14-foot channel served as a wave-damping area. The wave energy was reflected by the curved wall c-d (Drawing 5) in such a manner as to prevent reflected waves from returning through the testing channel. The reflected waves were destroyed on beaches built in suitable locations. Some small reflected waves were present in the testing channel, but these were caused by reflections from the model itself.

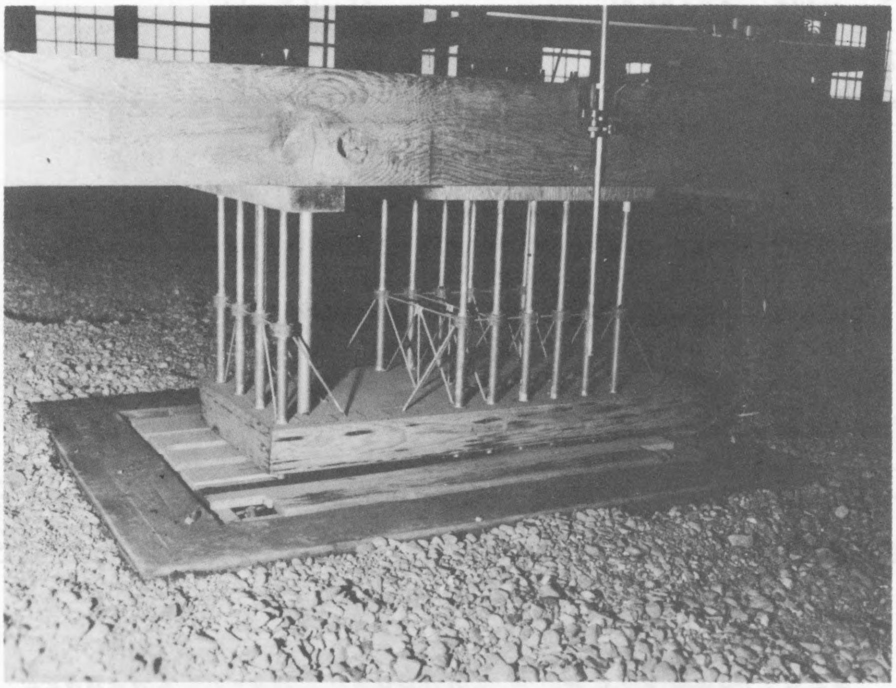


Figure 5. Model in Position for Testing.

Generation of Waves

Waves were generated by the plunger-type wave machine, shown in Fig. 6a. The speed of the plunger could be controlled to produce any desired wave period. The wave height was varied by changing the amplitude of the plunger.

It was found that the original plunger was unable to produce waves of sufficient height at the large wave periods required for these tests. Therefore, a larger plunger was constructed of plywood. With the new plunger, waves up to 0.35 foot were generated at a wave period of 1.65 seconds and wave heights up to 0.54 foot at a wave period of 1.23 seconds.

Measurement of Wave Heights

A continuous record of wave heights was obtained at a point 6.67 feet from the model at the center of the testing channel by means of an electrically operated wave rod. Readings were also taken at a location 1.67 feet from the model by means of a point gage. These devices are shown in Fig. 6b. A wave rod was also located at one side of the model for the purpose of comparing the wave profile at the model with the variations in the horizontal force on the model.

The wave rod acted as one resistance in a Wheatstone bridge. Variations in the water depth produced variations in the resistance, which were recorded by means of an oscillograph. The gage was calibrated by lowering and raising the wave rod known amounts in still water and noting the corresponding oscillograph readings. Calibrations were made before and after each series of tests.

Measurement of Wave Lengths

Wave lengths were determined by noting the positions of two consecutive wave crests. One point of observation was near the wave rod (6.67 feet in front of the model) and the other, one wave length nearer the wave machine. Observations were made by two observers, one of whom varied his position until the locations of simultaneous crests were found.

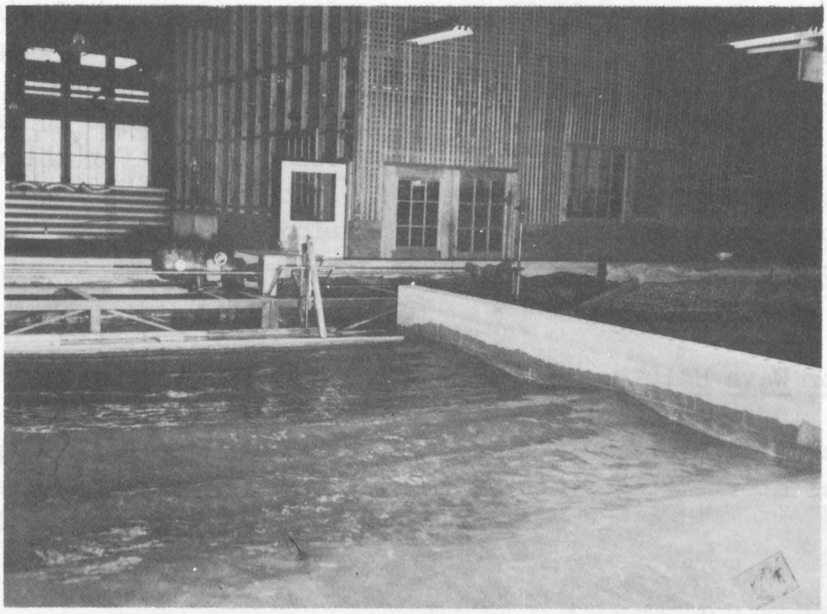


Figure 6a Wave Machine.

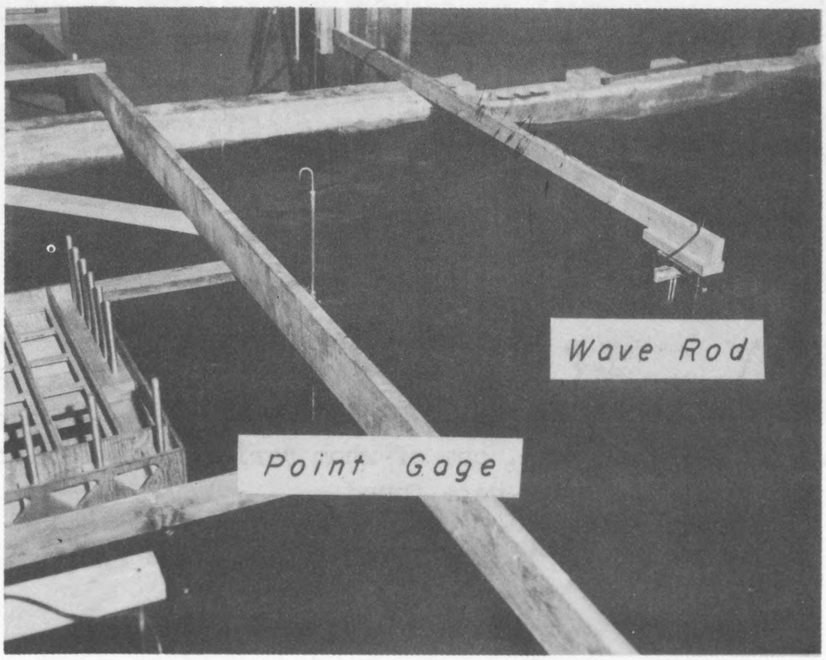


Figure 6b Wave Rod.

SCOPE OF THE TESTS

The variable factors in the tests were water depth, vertical positions of the barge and platform, wave period and wave height. During each series of tests the water depth and barge location were held constant. Tests were conducted with water depths of 100 feet, 62 feet, 40 feet, 20 feet, and 15 feet. With a water depth of 100 feet, tests were conducted with the bottom of the barge 41.5 feet above the mud line (center of barge at mid-depth) and with the bottom of the barge 3 feet above the mud line. For all other water depths the barge was placed only at the latter location. Figure 5 is a photograph showing the barge in this position.

During each series of tests, at least two wave periods were studied. In each case a wave period of approximately 1.65 seconds was used. This period corresponds approximately to a prototype period of 12 seconds. One or more shorter-period waves were also studied because it was possible to generate higher waves at the smaller periods.

For each wave period, waves of three or four different heights were projected against the model. The wave heights were varied from the maximum that could be generated to one having a prototype height of less than 10 feet.

TEST PROCEDURE

At the beginning of each series of tests the calibration of the dynamometers was checked as previously described (p. 8). The tank was then filled to the proper water-surface elevation. The zero readings of the displacement gages and the point gage were taken. The wave machine was set at the desired period and plunger amplitudes. The strain amplifiers were then balanced and the wave rod calibrated. After the instruments were set in operation, the wave machine was started and the test observations made.

During each test run, continuous records were obtained from the wave rod and from the two principal dynamometers (R and T, Fig. 3, p. 7). At the same time, another oscillograph channel, connected with a switch box, was used to obtain shorter-period records from dynamometer S, from eight piles (see Table I, p. 29), and from the auxiliary wave rod located at the side of the model. The piles for which stresses were measured during each test may be determined from

Table I, p. 29 and the locations of these piles may be determined from Drawing 2, p. 25. The time of beginning and ending of each of the above records was noted on the wave-height oscillograph chart. The three dial gages giving platform displacements were read and the value of wave height at the point gage was observed. Finally, the wave length was determined.

The wave machine was then shut down and the amplitude of the plunger changed to produce a wave of a different height. When all reflections had disappeared from the tank the procedure described above was repeated.

For each model setup the natural frequency of the model was determined with water in the tank. This was done by giving the model an initial impulse and recording the oscillations of the force in one of the dynamometers.

TEST RESULTS

The results of measurements made during the wave tests are given in Table 1, Appendix B, p. 27 to 31. The tabulated results are given in the order in which the tests were conducted. Values shown in Column 9 [(R + T) x factor] represent the total corrected horizontal force on the model in the direction of wave travel. Displacements of the platform are represented by the symbol, Δ, in columns 10-13. For water depths of 40 feet or greater, the values in Column 13, $(\Delta_1 + \Delta_2)/2$, are the total average amplitudes of the displacements in the direction parallel to the direction of wave travel. The displacements in one direction from the still-water position may be obtained by dividing tabulated values by 2. For water depths of 20 feet and 15 feet the breaking waves caused the displacements in the direction of wave travel to be much larger than those in the reverse direction. Therefore, the values given in Columns 10-13 for water depths of 20 and 15 feet are displacements in the direction of wave travel from the neutral position.

The locations of the piles referred to in Columns 14-22 may be found from Drawing 2, p. 25. It should be noted that these stresses were observed at strain gages placed 1.6 inches above the top of the base support.

The test results have also been presented in graphical form in Appendix B, Figs. 7-30, pages 33-56 Figures 7-12 are summaries of some of the test results. Complete sets of data for all tests are given in Figs. 13-30. The general arrangement used in presenting the graphs was to place those giving the total horizontal forces, the piling stresses, and the platform displacements in that order. Thus, in the summaries, Figs. 7 and 8 give forces, Figs. 9 and 10 deal with piling stresses, and Figs. 11 and 12 show displacements. In a similar manner the more detailed results for forces are given in Figs. 13-18, for stresses in Figs. 19-24 and for displacements in Figs. 25-30.

It should be noted that the summary graphs do not show the actual test results, but only the lines drawn through the resulting points. The measured values are all plotted in the more detailed graphs (Figs. 13-30). The reader must refer to these latter figures in order to determine the nature and extent of the extrapolation used to apply the results to a prototype wave height of 35 feet.

The straight lines drawn through the sets of experimental points give dependable comparative values of the test results and may be used to indicate the effect of the variables. However, actual numerical values read from these lines outside the range of the test values are subject to the uncertainty resulting from the straight-line extrapolation.

The summary curves indicate that the forces, piling stresses, and displacements increased as the water depth was decreased for the case where the bottom of the barge was located 3 feet above the mud line. A comparison of Figs. 13 and 14 indicates that moving the barge from mid-depth to a point near the bottom had little or no effect on the magnitude of the horizontal forces. The effect of wave period on the total horizontal forces is well illustrated by the results shown on Fig. 13, p. 39. It should be noted that the displacements and corresponding forces measured during static calibration tests were in very close agreement with the displacements and corresponding forces measured during the wave tests, thus indicating that consistent and dependable results were being obtained.

The results of the determinations of the natural frequencies of the model both in and out of water are presented in Table II, p. 32.

The results of the static tests, the calibration data for the wave rod, the oscillograph charts for all the tests, and many other data have not been included in this report but are on file in the University of Michigan Lake Hydraulics Laboratory.

CONVERSION OF RESULTS FROM MODEL TO PROTOTYPE

Horizontal Forces

Based on the Froude law, the conversion factors for force is the product of the cube of the length ratio and the ratio of the specific weights of the fluid. For these studies, this value would be

$$F_r = 50^3 \times 64/62.4 = 125{,}000 \times 1.025 = 128{,}000.$$

However, this conversion factor should be modified by the ratio of the model and prototype drag coefficients and the ratio of the model and prototype virtual-mass coefficients in proportion to the relative values of the drag forces and acceleration forces. It could be expected that the drag coefficient at the higher Reynolds numbers found in the prototype would be smaller than that of the model. Little is known about the variations in the virtual-mass coefficient. However, because the indications were that the drag force was less important than the acceleration forces, it was believed that for the present it would be necessary, for safety, to convert on the basis of the Froude law. The test results indicated the predominant force was that on the barge. Consequently, the use of larger piles than the 36-inch ones simulated in the model would produce only a small increase in forces over those measured in the model.

Piling Stresses

The conversion factor to be applied to model results to obtain prototype values is 50 if 36 x 3/4-inch piles are used and 21.2 if 48 x 1-inch piles are used. The development of these conversion factors is shown in Appendix C, p. 59. A procedure for comparing the stresses at the base of the piles with experimental values (1.6 inches above the base) is also given in Appendix C.

Platform Displacements

Model values of platform displacements may be converted to prototype values by multiplying by 833 if 36 x 3/4-inch piles are used and by 266 if 48 x 1-inch piles are used. Computations for determining these conversion factors are given in Appendix C, p. 59.

Natural Period

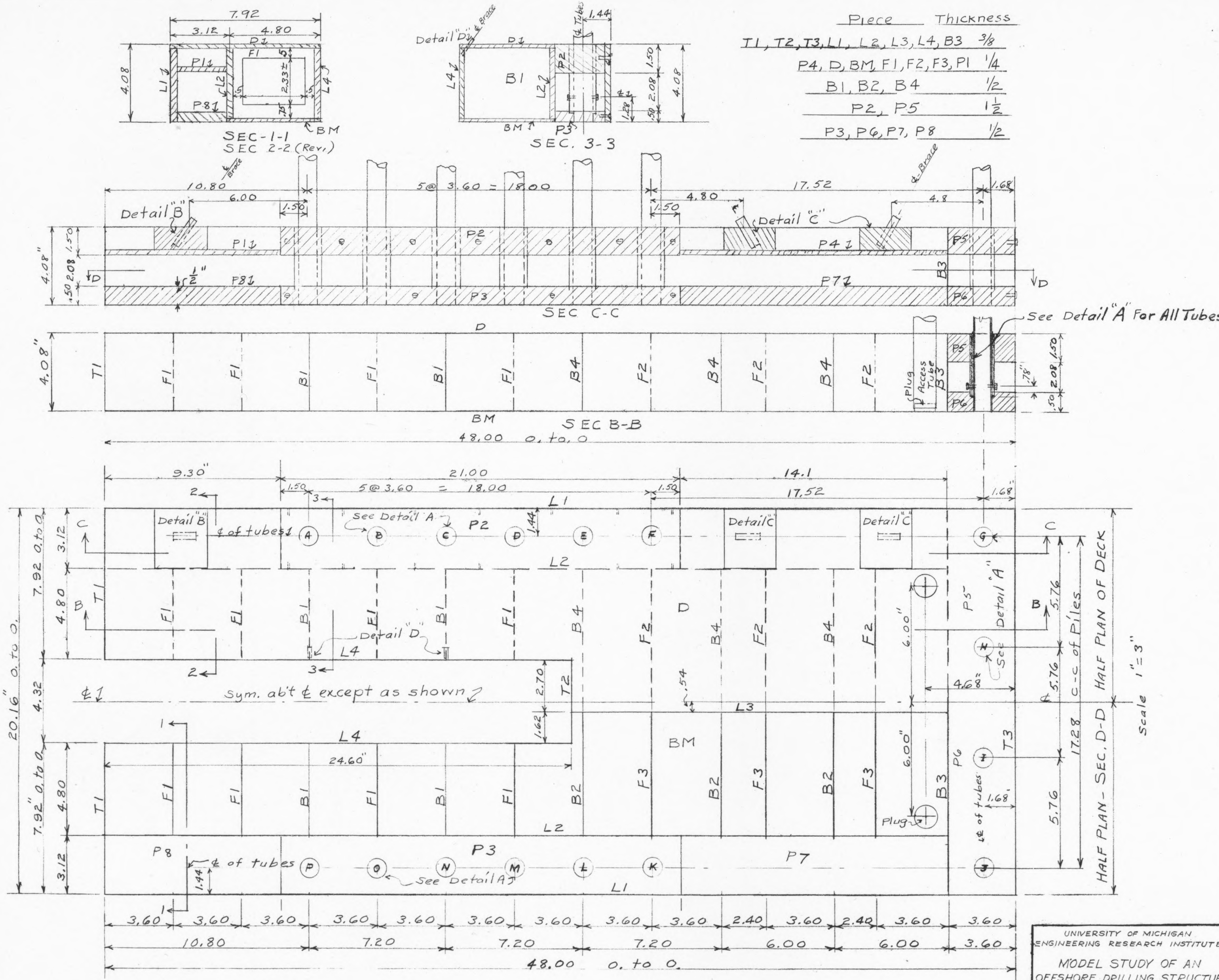
The conversion of national frequencies from model to prototype is discussed in Appendix C, p. 60

Magnification Factor

No correction of the experimental results has been made for the dynamic magnification effect. The magnification factor depends on the natural period of the structure, the wave period, and the amount of damping. The amount of damping in both model and prototype is uncertain. Therefore, there is no apparent advantage in attempting to correct for this effect. It is possible however, that the magnification factor may be higher in the prototype than in the model, thus resulting in prototype displacements and stresses which would be larger than those computed by means of the conversion factors shown above.

APPENDIX A

DRAWING 2



Piece	Thickness
T1, T2, T3, L1, L2, L3, L4, B3	3/8
P4, D, BM, F1, F2, F3, P1	1/4
B1, B2, B4	1/2
P2, P5	1 1/2
P3, P6, P7, P8	1/2

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BARGE DETAILS

Scale: 1:50 Date: Jan. 1, 1953

Drawing No. 2

APPENDIX B

TEST RESULTS

TABLE I. SUMMARY OF TEST RESULTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Test No.	Wave Period	Wave Height	Dyn. Reading in Lbs				Cal. Factor	R + T x Factor	Δ in Inches			$\frac{\Delta 1 + \Delta 2}{2}$	Piling Stress in Lbs/In.²									Avg. Pile Stress	Remarks
			R	T	Y	R + T			Δ1	Δ2	Δ3		A	C	D	E	F	G	J	K	P		
8	.97	17.8	2.62	5.28	.60	7.90	1.1	8.69	.096	.075	.011	.086		700	770	720	600	800	690	760	860	737	
9	.98	26.5	3.70	8.30	.94	12.00	1.1	13.20	.140	.100	.025	.120		1100	1140	1060	900	1180	950	1130	1290	1093	
11	.98	11.5	1.61	3.89	.39	5.50	1.1	6.05	.065	.049	.008	.057		530	580	510	480	570	420	500	600	523	
12	.98	22.3	3.20	7.30	.87	10.50	1.1	11.55	.130	.113	.017	.121		940	1060	900	800	1000	800	930	1140	946	
13	1.23	16.8	2.33	6.40	1.58	8.73	1.1	9.60	.124	.085	.029	.105		800	900	800	710	860	650	850	1020	824	
14	1.22	12.5	1.77	4.63	1.42	6.40	1.1	7.05	.092	.063	.025	.078		640	720	610	570	740	560	670	810	665	
15	1.22	9.3	1.41	3.90	1.18	5.31	1.1	5.85	.069	.051	.019	.060		500	550	450	430	510	400	500	600	493	
16a	1.23	20.1	3.66	6.05	1.77	9.71	1.1	10.7															
16b	1.23	22.2	4.02	6.97	1.97	10.99	1.1	12.08	.160	.104	.033	.130		1130	1300	1110	980	1100	950		1380	1136	
17a	1.44	17.3	2.01	5.07	.51	7.08	1.1	7.79															
17b	1.44	18.5	2.01	5.23	.79	7.24	1.1	7.96	.107	.068	.007	.087		750	890	700	620	620	620		900	728	
18	1.43	21.5	2.55	6.54	1.22	9.09	1.1	10.0	.130	.084	.011	.107		880	1030	880	700	830	680	880	1130	876	Depth of water 100 feet. Barge 41.5 feet above mud line.
19	1.25	27.0	4.08	9.86	1.97	13.94	1.1	15.34	.200	.139	.044	.169		1420	1500	1280	1180	1400	1170	1370	1650	1371	
20	1.44	8.1	1.05	2.27		3.32	1.1	3.65	.052	.027	.003	.040											
21	1.45	9.9	1.21	2.84	.55	4.05	1.1	4.46	.065	.036	.001	.050		410	490	400	300	400	300	450	570	415	
27	1.67	10.1	1.68	4.55	.98	6.23	1.1	6.85	.087	.059	.013	.073				550					580	565	
27a	1.67	6.5	1.28	2.88		4.16	1.1	4.57															
28	1.67	9.8	1.61	4.26		5.87	1.1	6.45															
28a	1.67	15.2	2.50	6.90	.98	9.40	1.1	10.30	.119	.081	.014	.100				750						750	
29a	1.63	17.5	3.00	7.10		10.10	1.1	11.10															
29b	1.63	13.0	2.50	5.67	1.18	8.17	1.1	9.00	.118	.083	.018	.098	700	700		680	630	710	600	640	740	675	
30a	1.63	12.3	1.93	4.87		6.80	1.1	7.48															
30b	1.63	9.8	1.89	4.10	.99	5.99	1.1	6.60	.079	.055	.013	.067	490	490		470	420	470	400	440	500	460	
31a	1.63	6.8	1.29	2.92		4.21	1.1	4.63															
31b	1.63	5.5	1.09	2.12	.40	3.21	1.1	3.54	.074	.037	.007	.037	300	300		290	270	300	230	300	320	264	

TABLE I. SUMMARY OF TEST RESULTS (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Test No.	Wave Period	Wave Height	Dyn. Reading in Lbs				Cal. Factor	R + T x Factor	Δ in Inches			$\frac{\Delta 1 + \Delta 2}{2}$	Piling Stress in Lbs/In.^{2}									Avg. Pile Stress	Remarks
			R	T	Y	R + T			Δ1	Δ2	Δ3		A	C	D	E	F	G	J	K	P		
32	1.63	7.6	1.30	2.35		3.65	1.23	4.48															
32a	1.63	6.5	1.21	2.23	.39	3.44	1.23	4.24	.017	.011	.003	.014	90	100		100	100	100	90	100	125	100	
33	1.60	12.3	2.31	4.05		6.36	1.23	7.82															
33a	1.60	10.5	1.91	3.65	.39	5.56	1.23	6.83	.025	.018	.004	.022	150	160		200	110	200	150	125	200	162	Depth of water 100 feet. Barge 3 feet above mud line.
34	1.60	15.0	3.02	5.75		8.77	1.23	10.80															
34a	1.60	13.6	2.62	4.95	.49	7.57	1.23	9.30	.035	.027	.006	.031	250	200		225	200	300	250	200	250	234	
35	1.20	23.0	3.70	6.20	1.18	9.90	1.23	12.19	.035	.030	.008	.033	250	250		350	280	350	300	270	310	295	
36	1.21	13.5	2.01	3.77	.67	5.78	1.23	7.10	.030	.020	.005	.025	175	175		175	175	225	200	190	200	189	
37	1.22	8.7	1.57	2.64	.47	4.21	1.23	5.17	.025	.016	.005	.020	150	130		130	130	200	150	150	190	154	
38	1.24	8.0	1.69	4.42	.39	6.11	1.30	7.95	.028	.017	.002	.023	280	260		230	220	230	200	220	300	242	
39	1.24	12.5	2.86	6.36	.39	9.22	1.30	12.00	.041	.027	.003	.034	420	350		400	350	400	350	350	480	387	
40	1.24	21.8	4.43	10.55	.47	14.98	1.30	19.45	.062	.045	.002	.053	700	650		700	550	650	620	620	750	655	
41	1.65	14.5	3.04	7.71	.39	10.75	1.30	14.00	.045	.033	.003	.039	500	420		500	400	450	450	500	575	474	Depth of water 62 feet. Barge 3 feet above mud line.
42	1.65	8.4	1.61	4.42	.39	6.03	1.30	7.85	.029	.016	.001	.023	290	290		230	250	250	230	225	350	264	
43	1.65	10.3	2.21	5.68	.39	7.89	1.30	10.25	.037	.022	.001	.030	350	340		350	300	310	300	370	400	340	
44	1.65	12.8	2.69	6.76		9.45	1.30	12.30	.043	.029		.036											
45	1.20	17.8	4.8	10.1	.98	14.9	1.30	19.4	.050	.038		.044	650	650	700		550	600	550	450	500	581	
46	1.20	22.5	4.8	11.4		16.2	1.30	21.1	.060	.043		.052											
47	1.20	16.0	3.8	8.7	.79	12.5	1.30	16.3	.049	.034		.042	550	500	600		500	550	500	450	550	525	
48	1.20	7.5	1.4	4.6		6.0	1.30	7.8															
48a	1.20	9.8	1.5	5.7	.47	7.2	1.30	9.4	.037	.026		.032	400	350	400		300	400	300	350	350	356	Depth of water 40 feet. Barge 3 feet above mud line.
49	1.60	3.5	1.0	2.8	.39	3.8	1.30	4.9	.019	.009		.014	175	150	150		125	125	125	125	200	146	
50	1.60	8.8	2.0	5.7	.47	7.7	1.30	10.0	.032	.018		.025	300	300	350		300	300	275	300	400	315	
51	1.60	12.3	3.2	7.3	.39	10.5	1.30	13.7	.050	.032		.041	550	450	575		450	450	400	425	525	478	

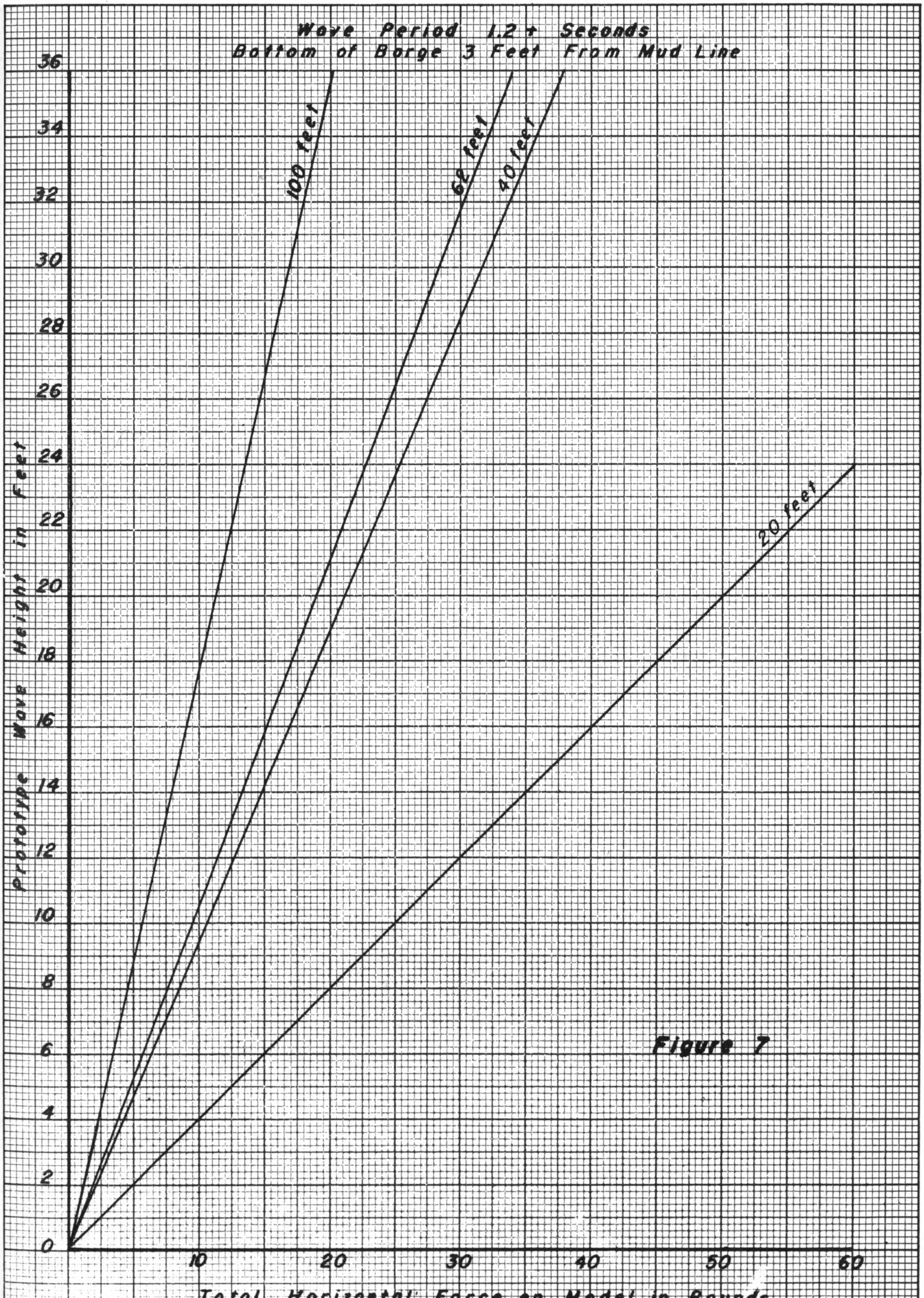
TABLE I. SUMMARY OF TEST RESULTS (concluded)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Test No.	Wave Period	Wave Height	Dyn. Reading in Lbs R	T	Y	R + T	Cal. Factor	R + T x Factor	Δ in Inches Δ1	Δ2	Δ3	(Δ1 + Δ2)/2	Piling Stress in Lbs/In.^{2} A	C	D	E	F	G	J	K	P	Avg. Pile Stress	Remarks
53a	1.66	8.0	3.6	9.7		13.3	1.30	17.7															
53b	1.66	13.0	5.6	13.8	1.38	19.4	1.30	25.2	.044	.025		.034*	750	600	675		600	600	450	600	750	627	
53c	1.66	14.0	5.2	16.6		21.8	1.30	28.3															
54a	1.25	5.0	2.4	6.5		8.9	1.30	11.5															
54b	1.25	8.0	2.8	8.9		11.7	1.30	15.2															
54c	1.25	16.0	6.0	21.1		27.1	1.30	35.2															
54d	1.25	17.0	5.6	24.3	1.96	29.9	1.30	38.9	.050	.040		.045*	1125		1200		1050	1050	680	600	1125	975	Depth of water 20 feet. Barge 3 feet above mud line. *Displacement in downstream direction only.
55a	1.25	3.0	1.6	4.8		6.4	1.30	8.3															
55b	1.25	6.3	3.2	7.3		10.5	1.30	13.6															
55c	1.25	15.0	7.2	20.2		27.4	1.30	35.8															
55d	1.25	12.0	7.2	15.4	1.96	22.6	1.30	29.4	.038	.032		.035*	600		600		675	900	600	600	600	653	
56a	1.25	4.5	2.0	4.5		6.5	1.30	8.5															
56b	1.25	9.5	4.4	10.9	.78	15.3	1.30	19.8	.035	.025		.030*	675		750		600	600	450	525	600	600	
57a	1.45	4.8	2.4	6.1		8.5	1.30	11.1															
57b	1.45	8.0	3.2	8.5		11.7	1.30	15.2															
57c	1.45	13.3	6.4	15.0		21.4	1.30	27.8															
57d	1.45	14.5	7.6	19.4	1.58	27.0	1.30	35.0	.053	.038		.045*	900		900		750	900	750	675	825	814	Depth of water 15 feet. Barge 3 feet above mud line. *Displacement in downstream direction only.
58a	1.45	4.0	1.6	4.1		5.7	1.30	7.4															
58b	1.45	8.5	4.0	11.3	1.18	15.3	1.30	19.8	.027	.024		.026*	675		750		600	600	525	525	600	610	

TABLE II

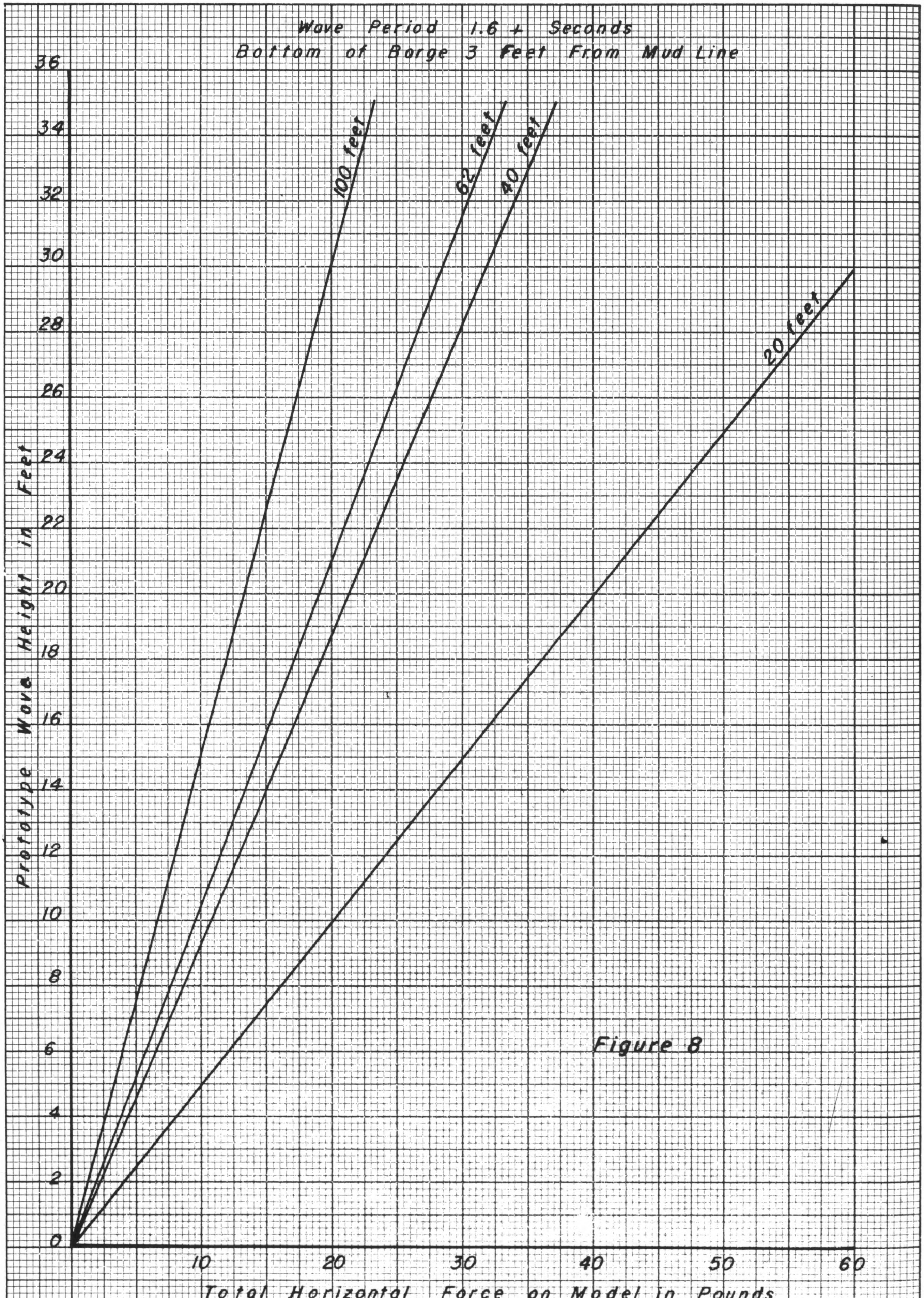
SUMMARY OF THE NATURAL FREQUENCIES OF THE MODEL
(Primary Mode)

Depth of Water (Prototype), Feet	Distance of Bottom of Barge above Mud Line (Prototype), Feet	Frequency of Model in Water, cycles/sec
100	41.5	3
100	3.0	4-1/2
62	3.0	4-3/4
40	3.0	5-1/4



Wave Period 1.2+ Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
62 feet
40 feet
20 feet
Prototype Wave Height in Feet
Total Horizontal Force on Model in Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
10
20
30
40
50
60

Figure 7



Wave Period 1.6 + Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
62 feet
40 feet
20 feet
Prototype Wave Height in Feet
Total Horizontal Force on Model in Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
10
20
30
40
50
60

Figure 8

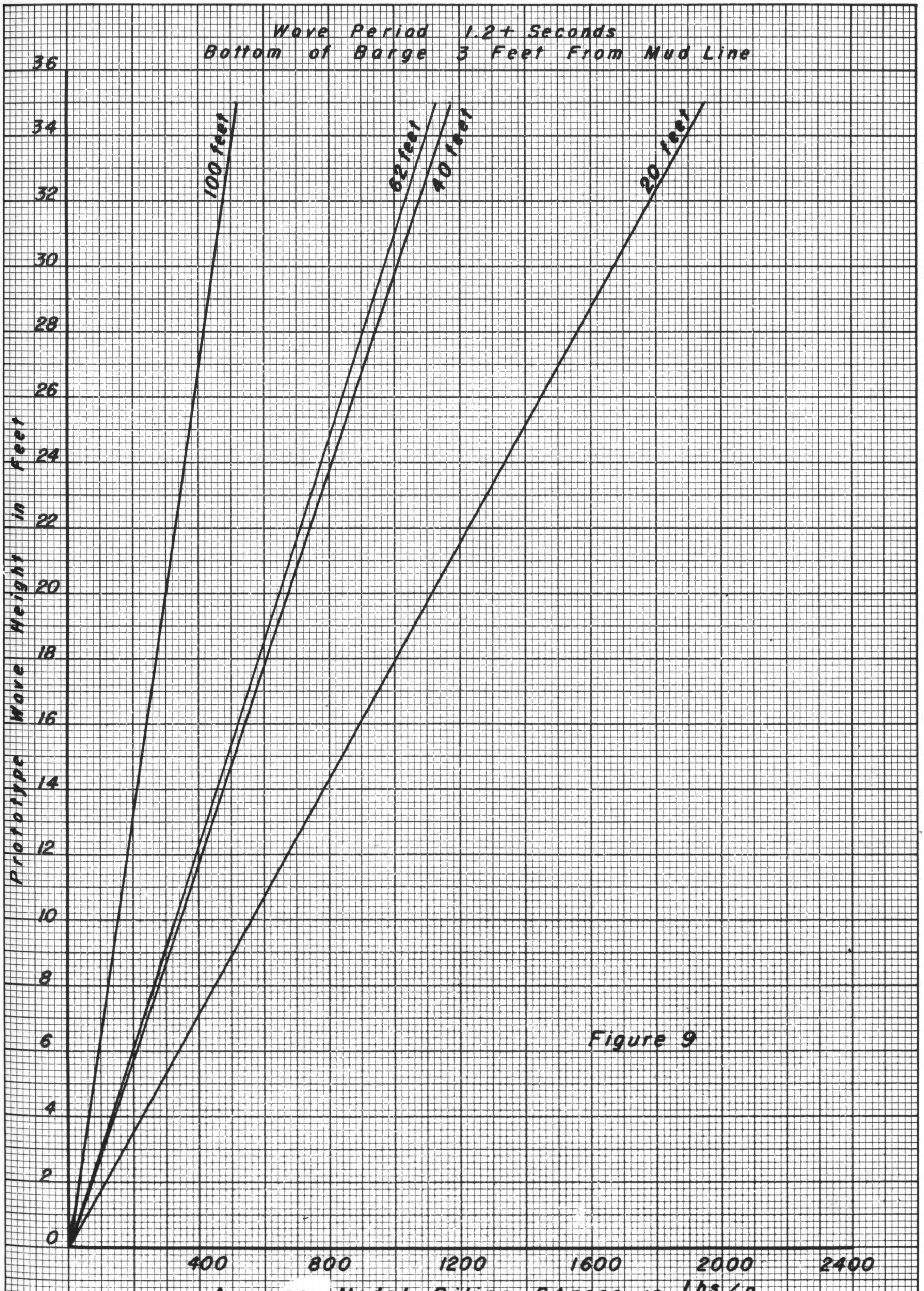

Wave Period 1.2+ Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
62 feet
40 feet
20 feet
Prototype Wave Height in Feet
Average Model Piling Stress in Lbs/In.2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
400
800
1200
1600
2000
2400

Figure 9

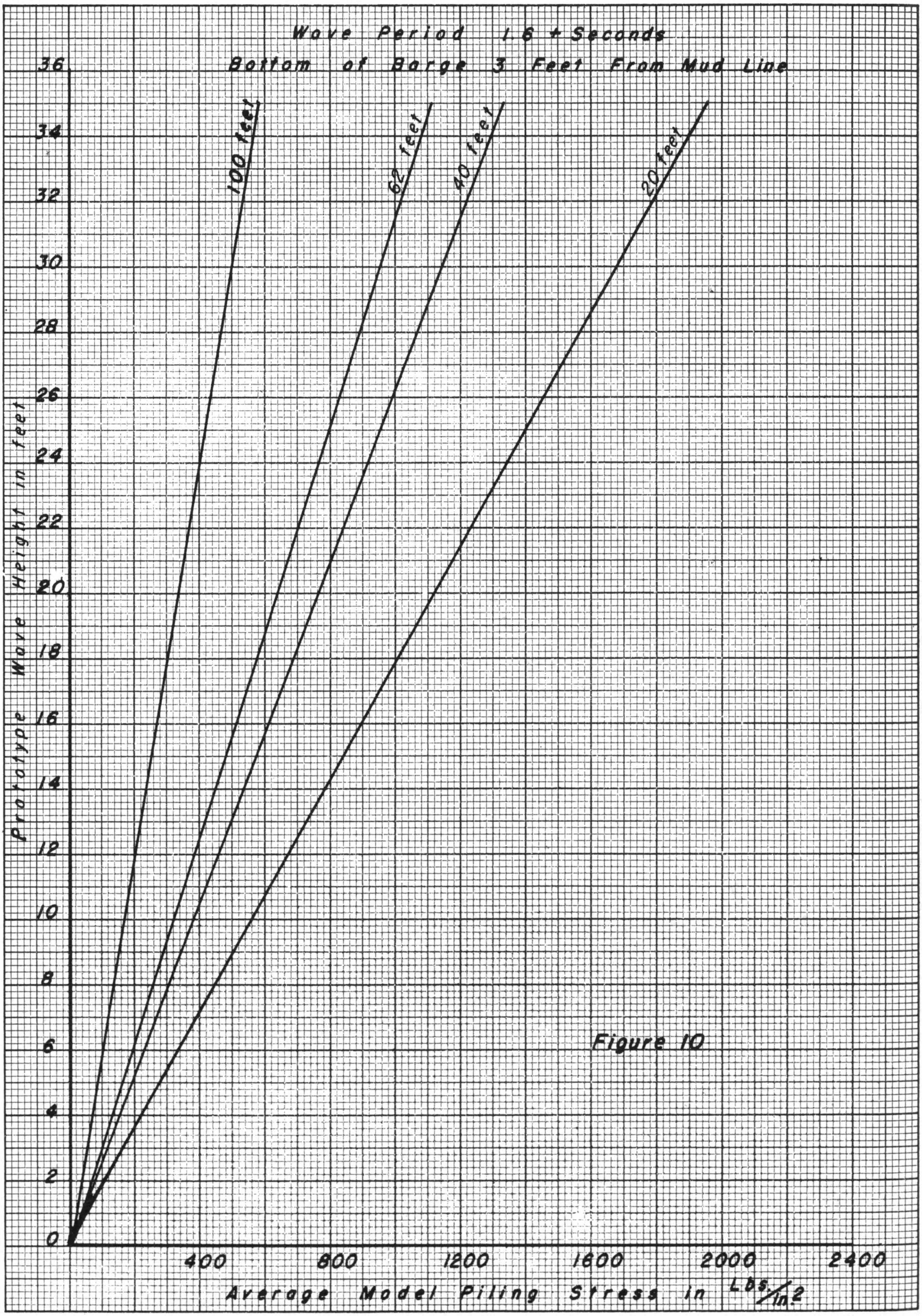
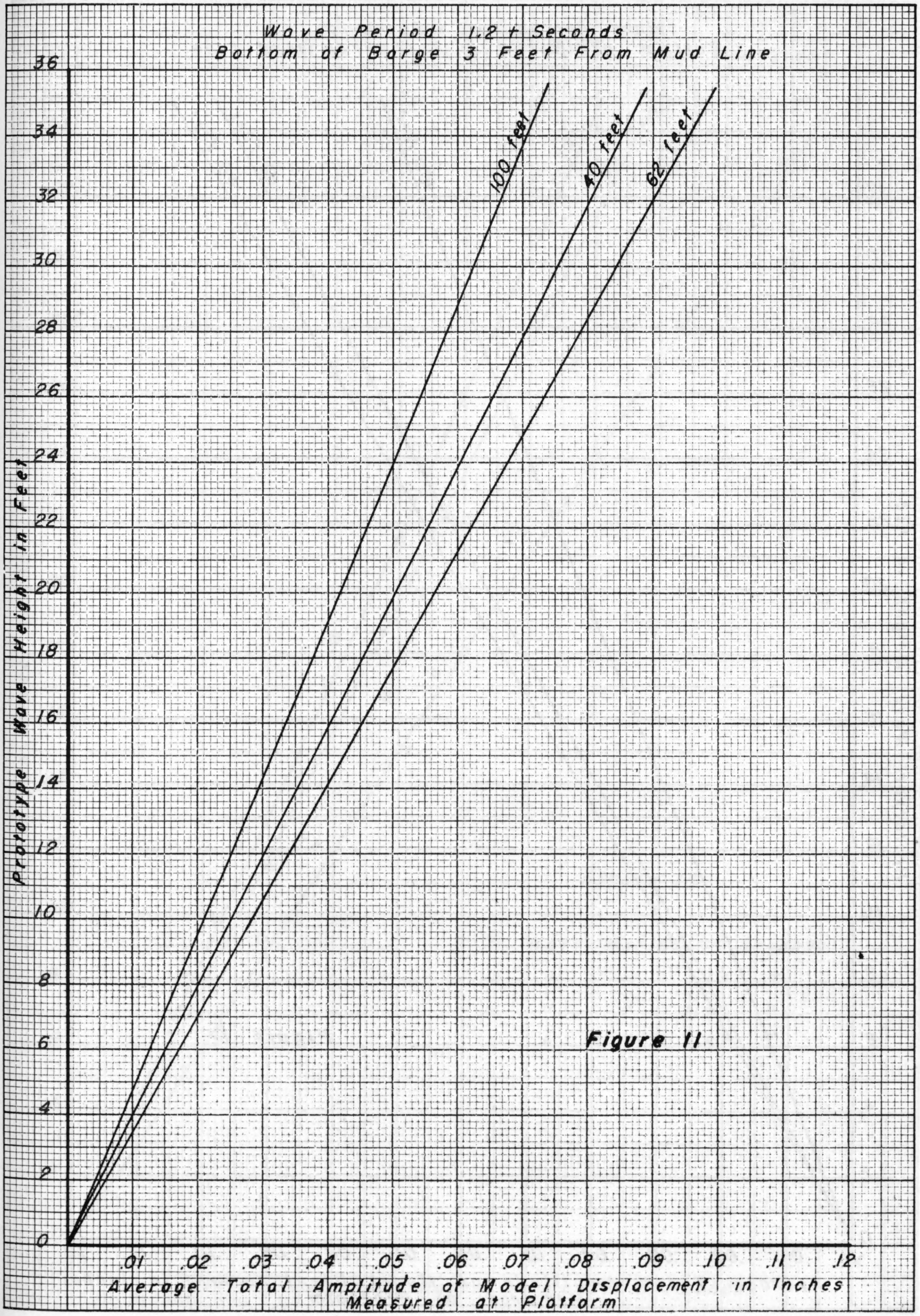
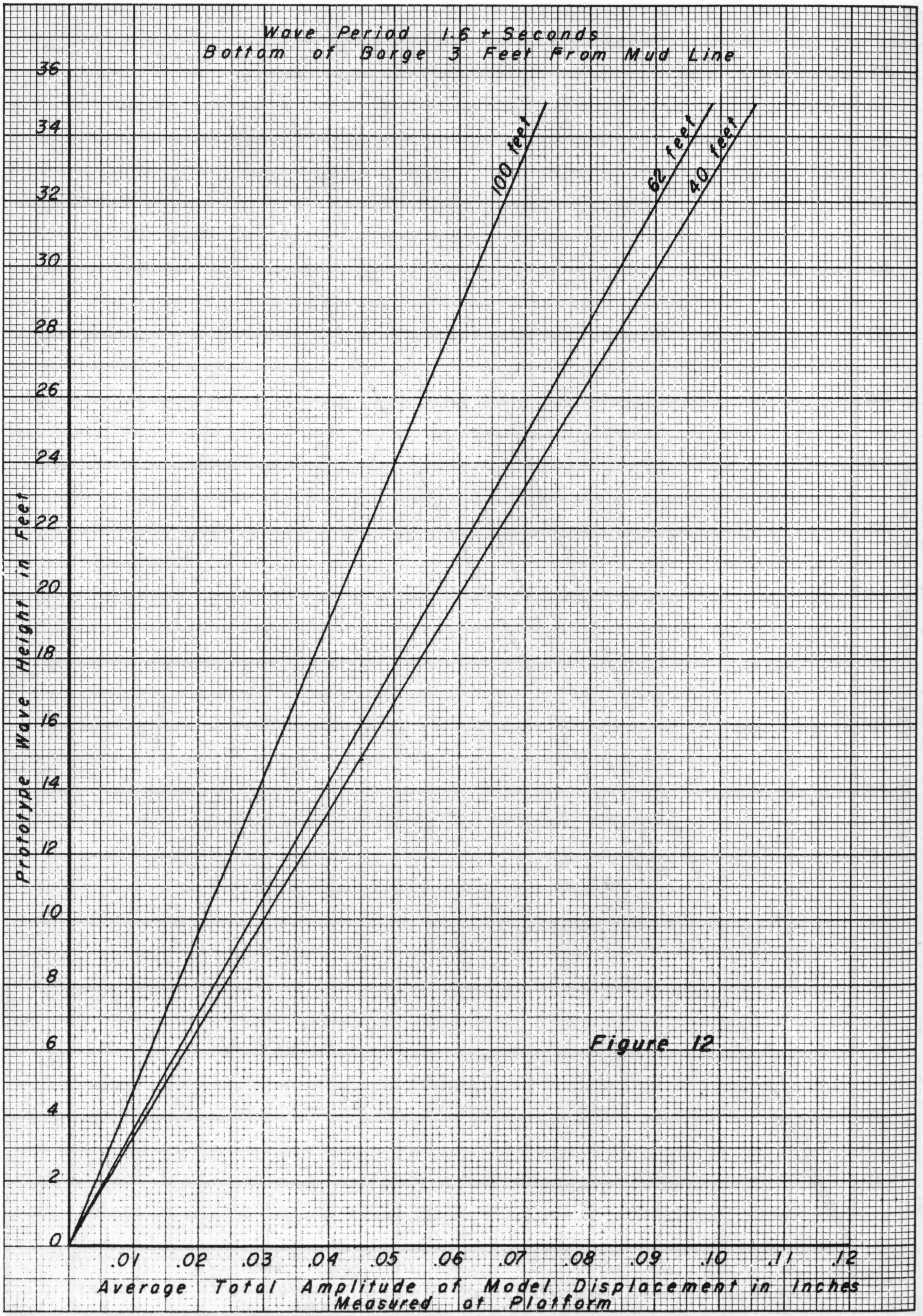

Wave Period 1.6 + Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
62 feet
40 feet
20 feet
Prototype Wave Height in feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
400
800
1200
1600
2000
2400
Average Model Piling Stress in Lbs/In2

Figure 10



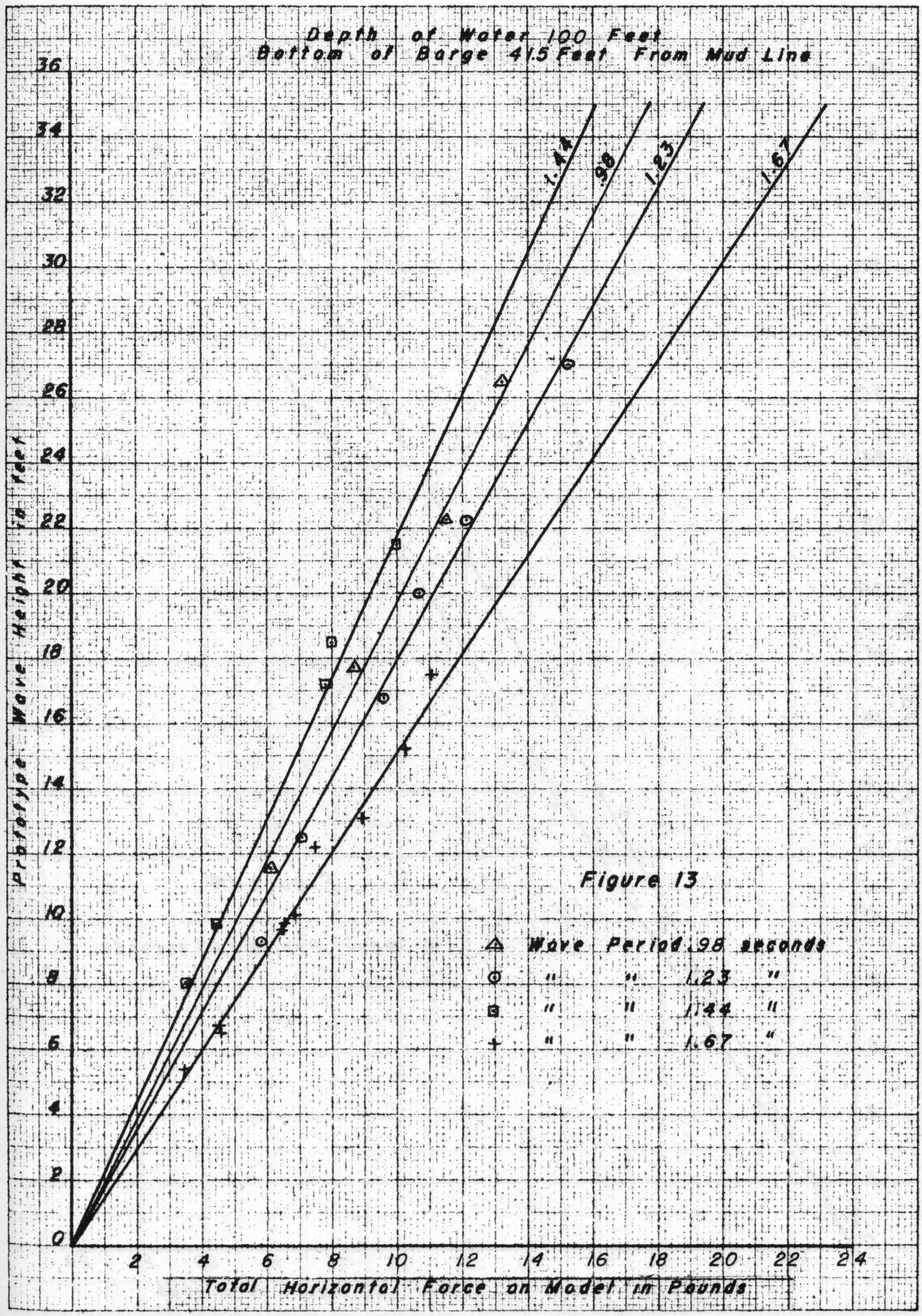
Wave Period 1.2 + Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
40 feet
62 feet
Prototype Wave Height in Feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
Average Total Amplitude of Model Displacement in Inches
Measured at Platform

Figure 11



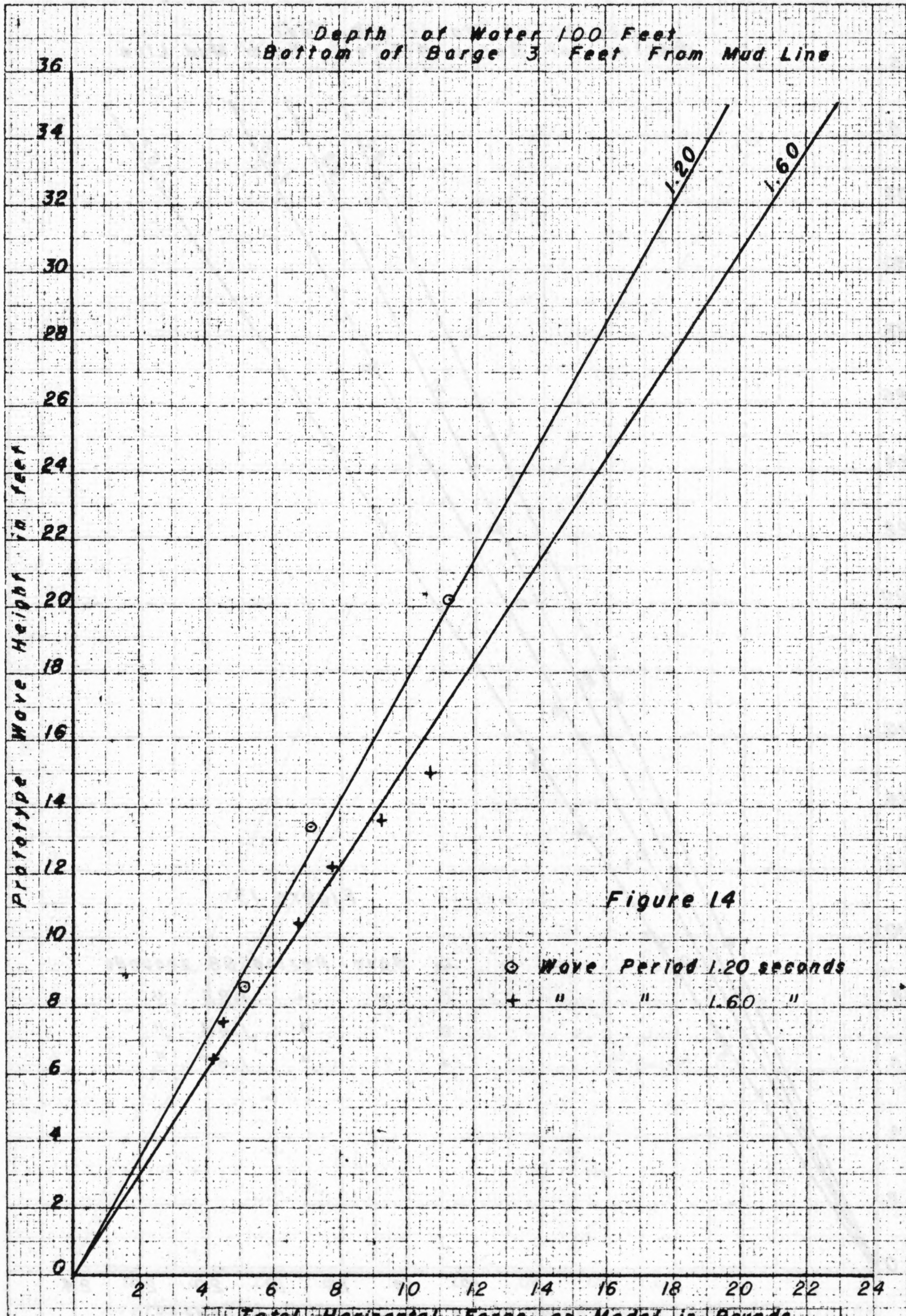
Wave Period 1.6 + Seconds
Bottom of Barge 3 Feet From Mud Line
100 feet
62 feet
40 feet
Prototype Wave Height in Feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
Average Total Amplitude of Model Displacement in Inches Measured at Platform

Figure 12

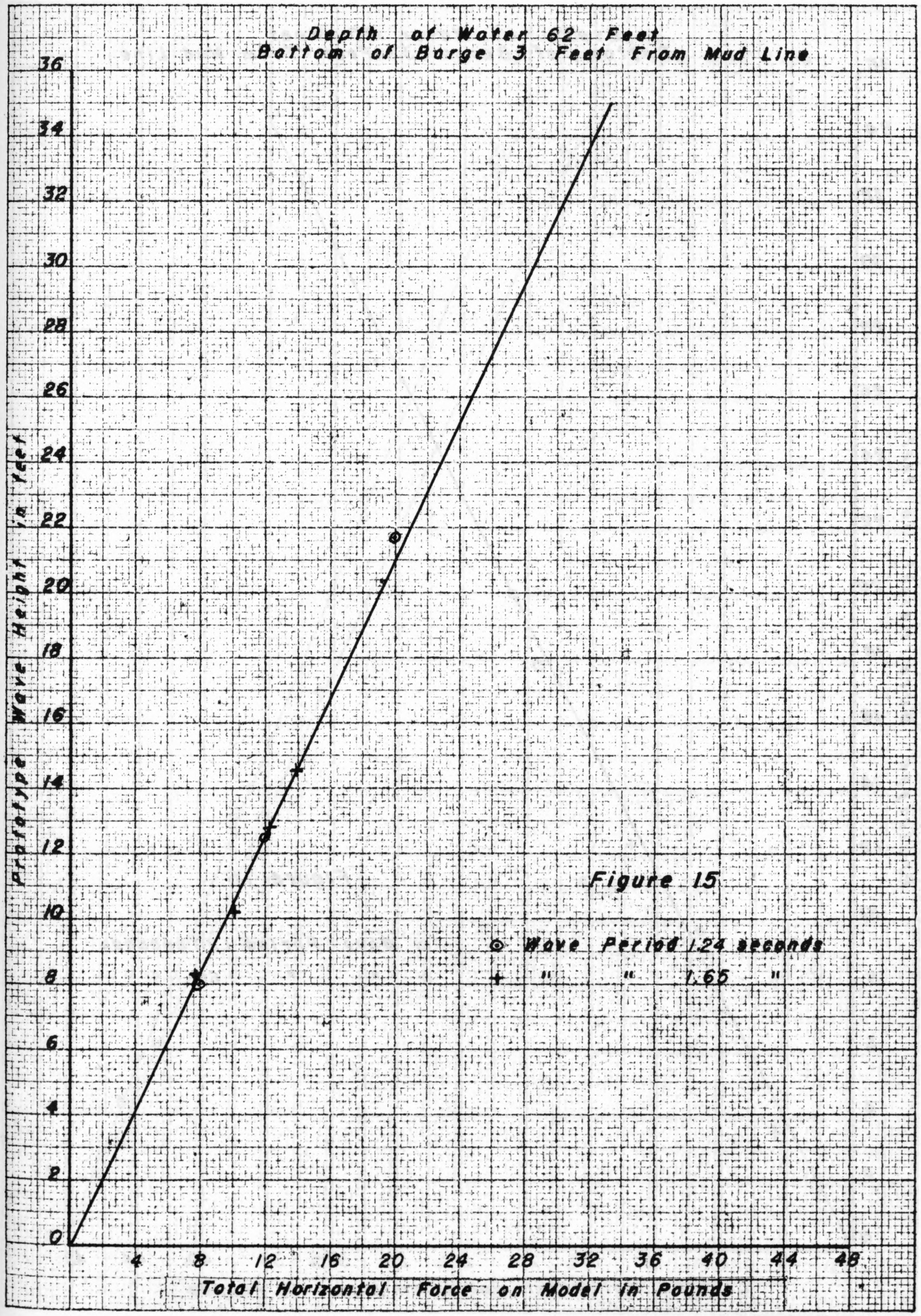


Depth of Water 100 Feet
Bottom of Barge 41.5 Feet From Mud Line
Prototype Wave Height in Feet
Total Horizontal Force on Model in Pounds
1.44
.98
1.23
1.67
Wave Period .98 seconds
" " 1.23 "
" " 1.44 "
" " 1.67 "

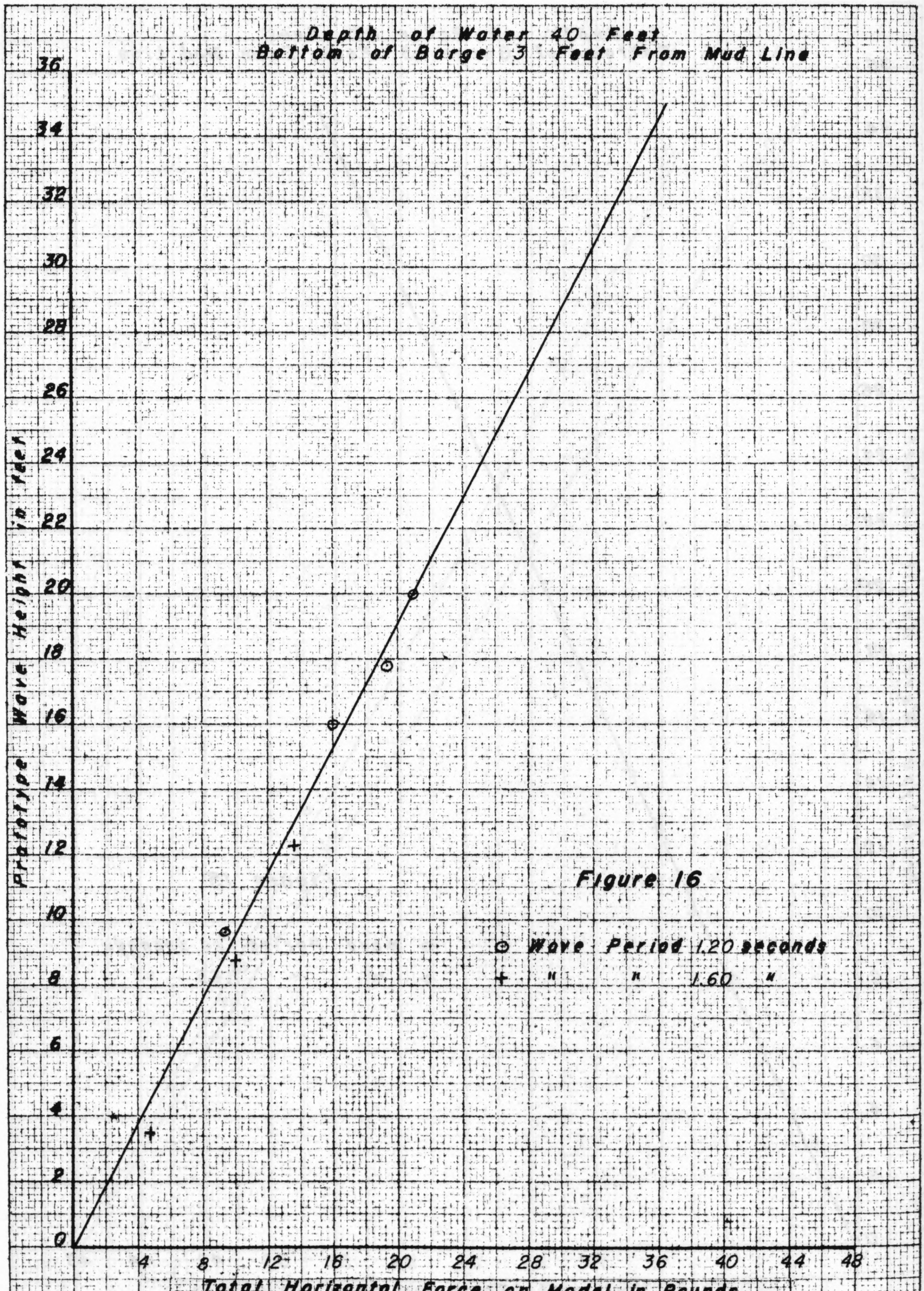
Figure 13



Depth of Water 100 Feet
Bottom of Barge 3 Feet From Mud Line
1.20
1.60
Figure 14
Wave Period 1.20 seconds
" " 1.60 "
Prototype Wave Height in feet
Total Horizontal Force on Model in Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36

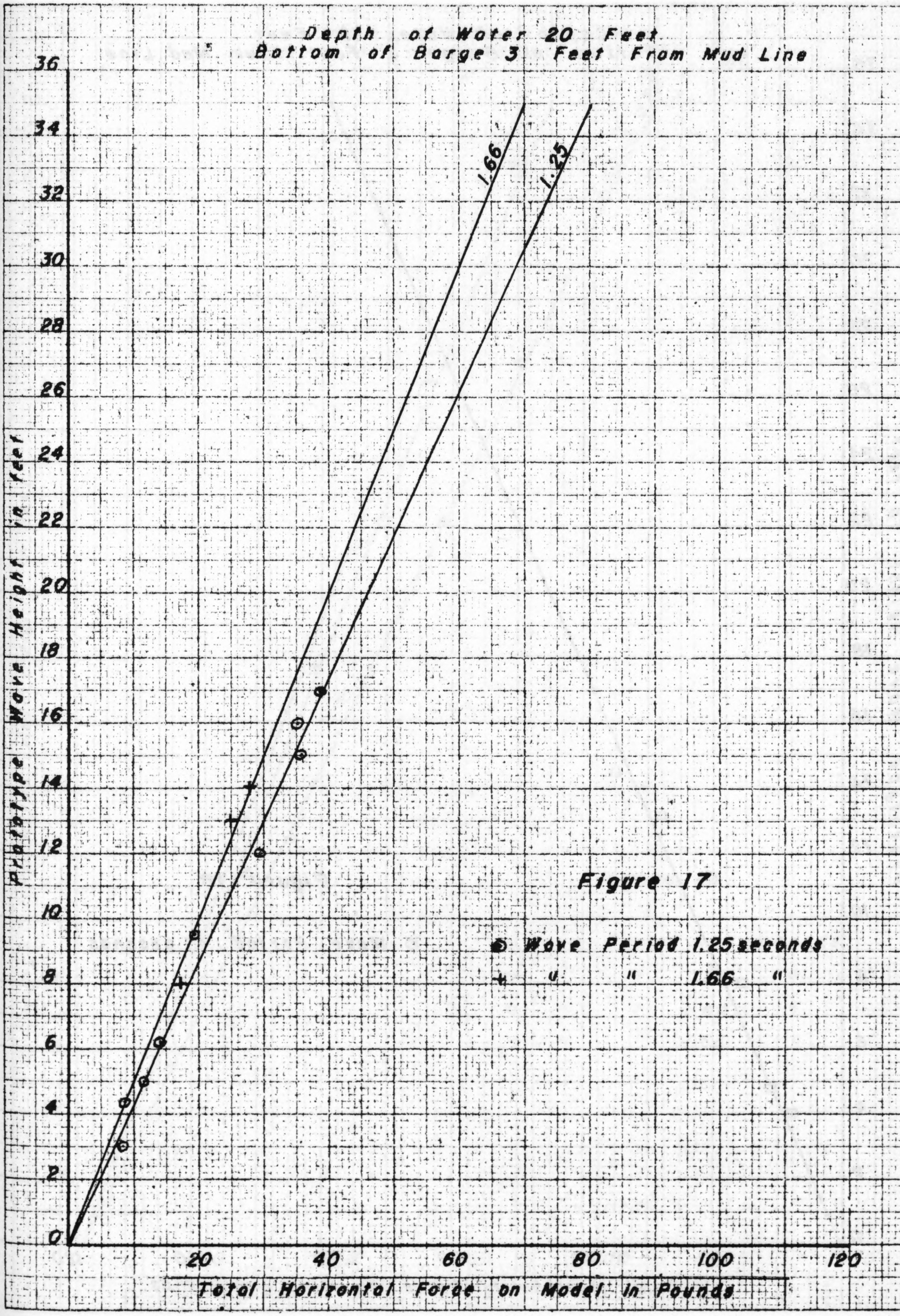


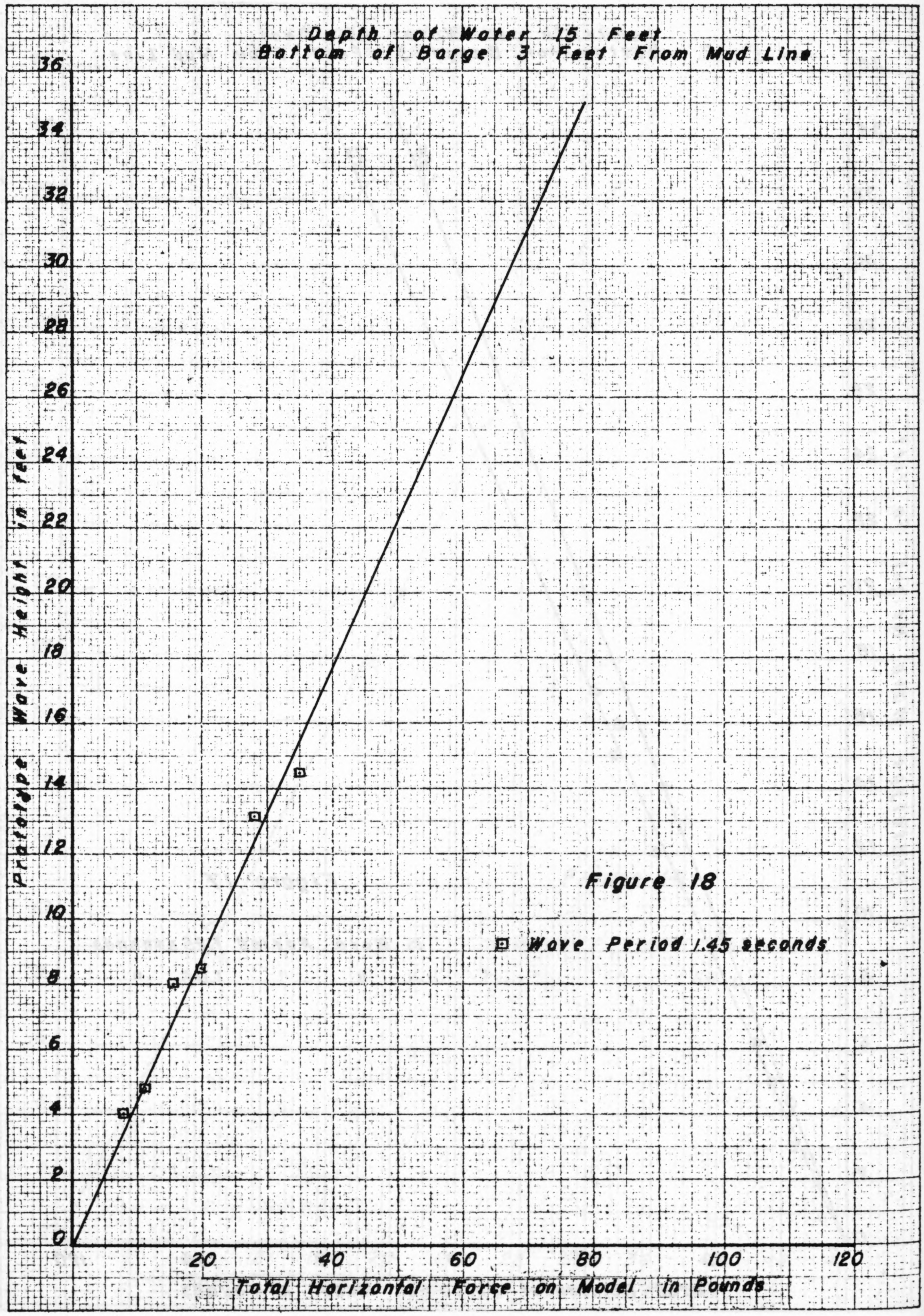
Depth of Water 62 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in Feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Total Horizontal Force on Model in Pounds
4
8
12
16
20
24
28
32
36
40
44
48
Figure 15
Wave Period 1.24 seconds
" " 1.65 "



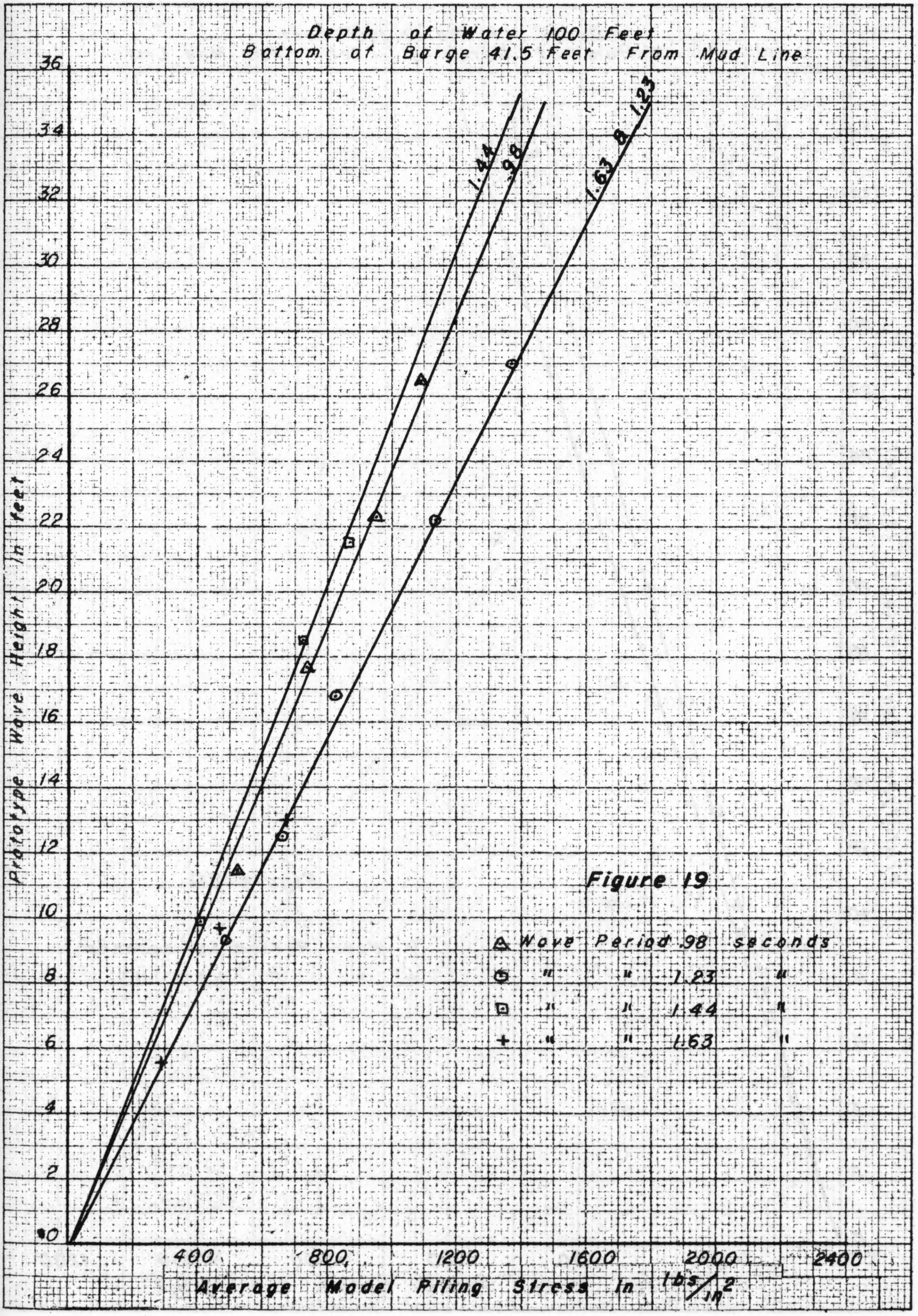
Depth of Water 40 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in Feet
Total Horizontal Force on Model in Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
4
8
12
16
20
24
28
32
36
40
44
48
Wave Period 1.20 seconds
" " 1.60 "

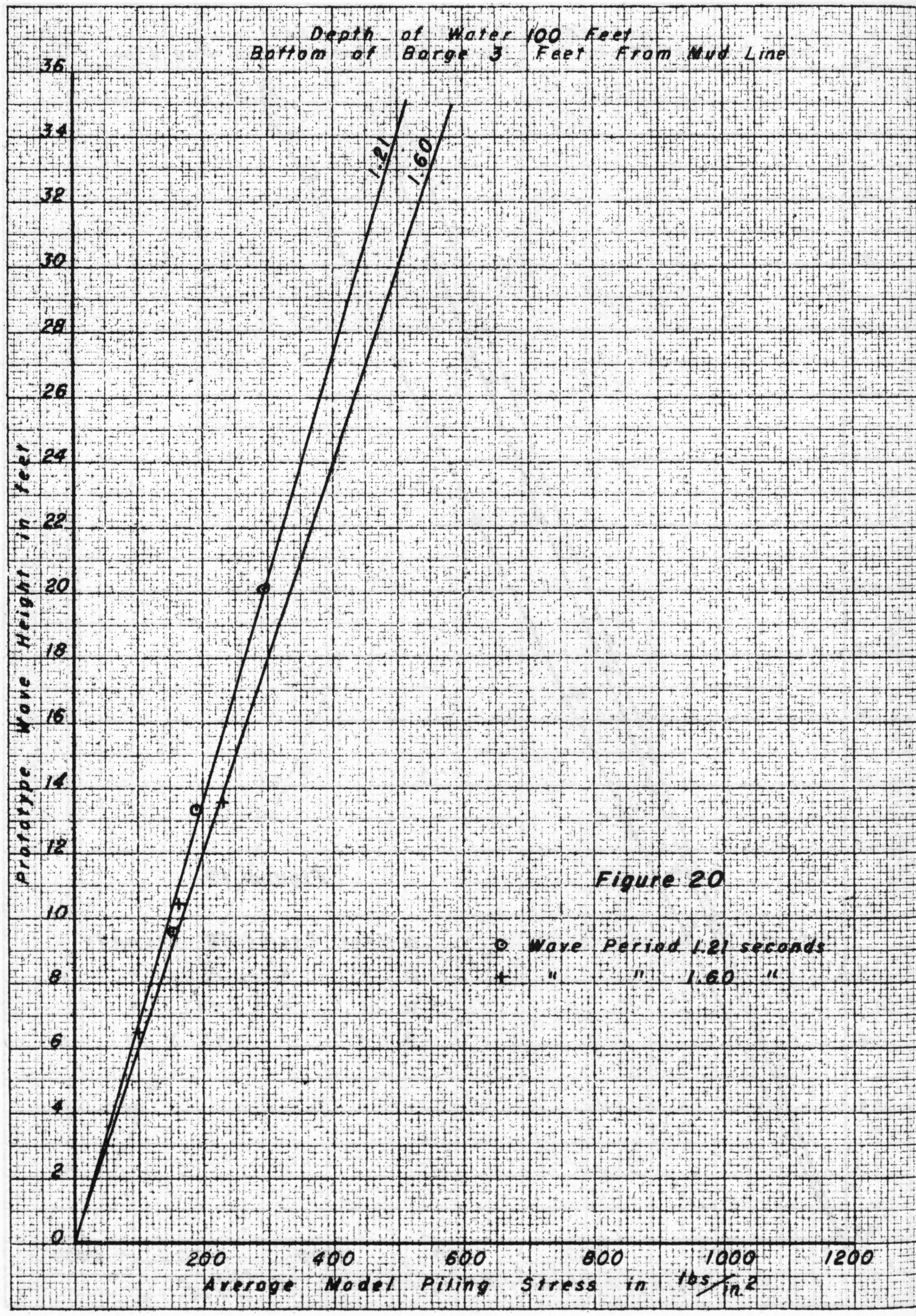
Figure 16


Depth of Water 20 Feet
Bottom of Barge 3 Feet From Mud Line
1.66
1.25
Figure 17
Wave Period 1.25 seconds
" " 1.66 "
Prototype Wave Height in Feet
Total Horizontal Force on Model in Pounds
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
20
40
60
80
100
120



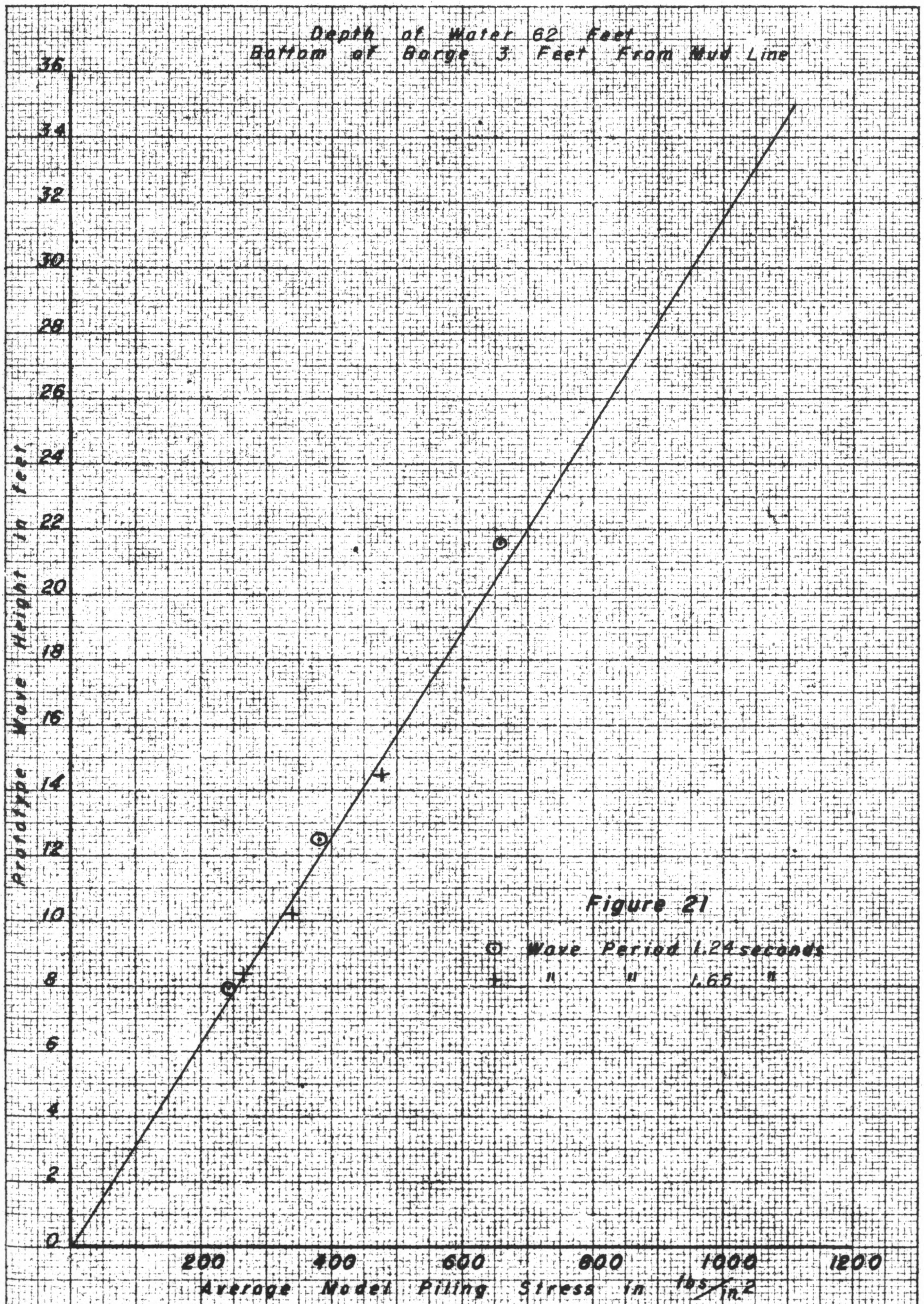
Depth of Water 15 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in Feet
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
20
40
60
80
100
120
Total Horizontal Force on Model in Pounds
Figure 18
Wave Period 1.45 seconds


Depth of Water 100 Feet
Bottom of Barge 41.5 Feet From Mud Line
1.44
.98
1.63 & 1.23
Prototype Wave Height in feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
400
800
1200
1600
2000
2400
Average Model Piling Stress in lbs/in²
Figure 19
Wave Period .98 seconds
" " 1.23 "
" " 1.44 "
" " 1.63 "

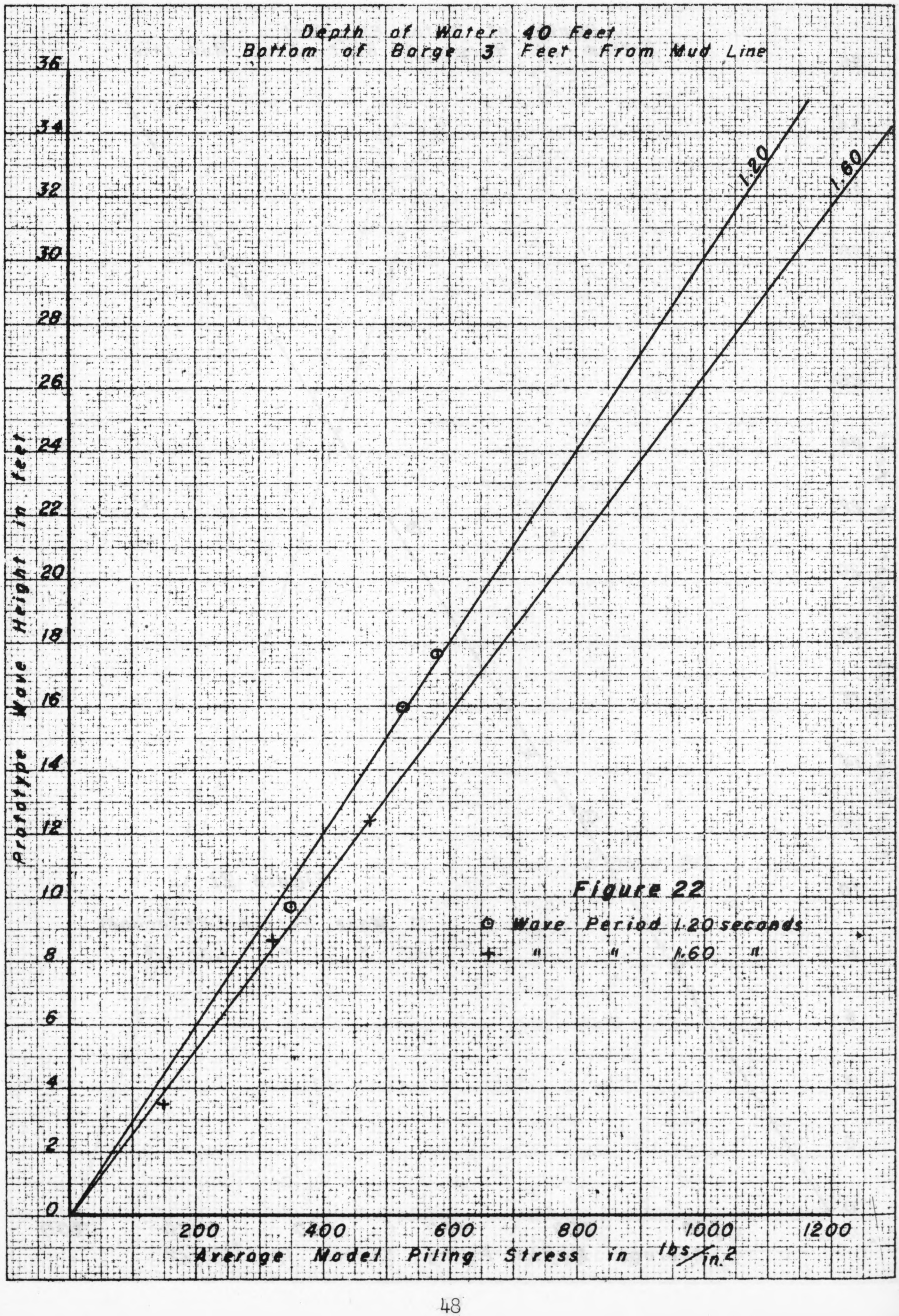


Depth of Water 100 Feet
Bottom of Barge 3 Feet From Mud Line
1.21
1.60
Prototype Wave Height in Feet
Average Model Piling Stress in lbs/in2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
200
400
600
800
1000
1200
Wave Period 1.21 seconds
" " 1.60 "

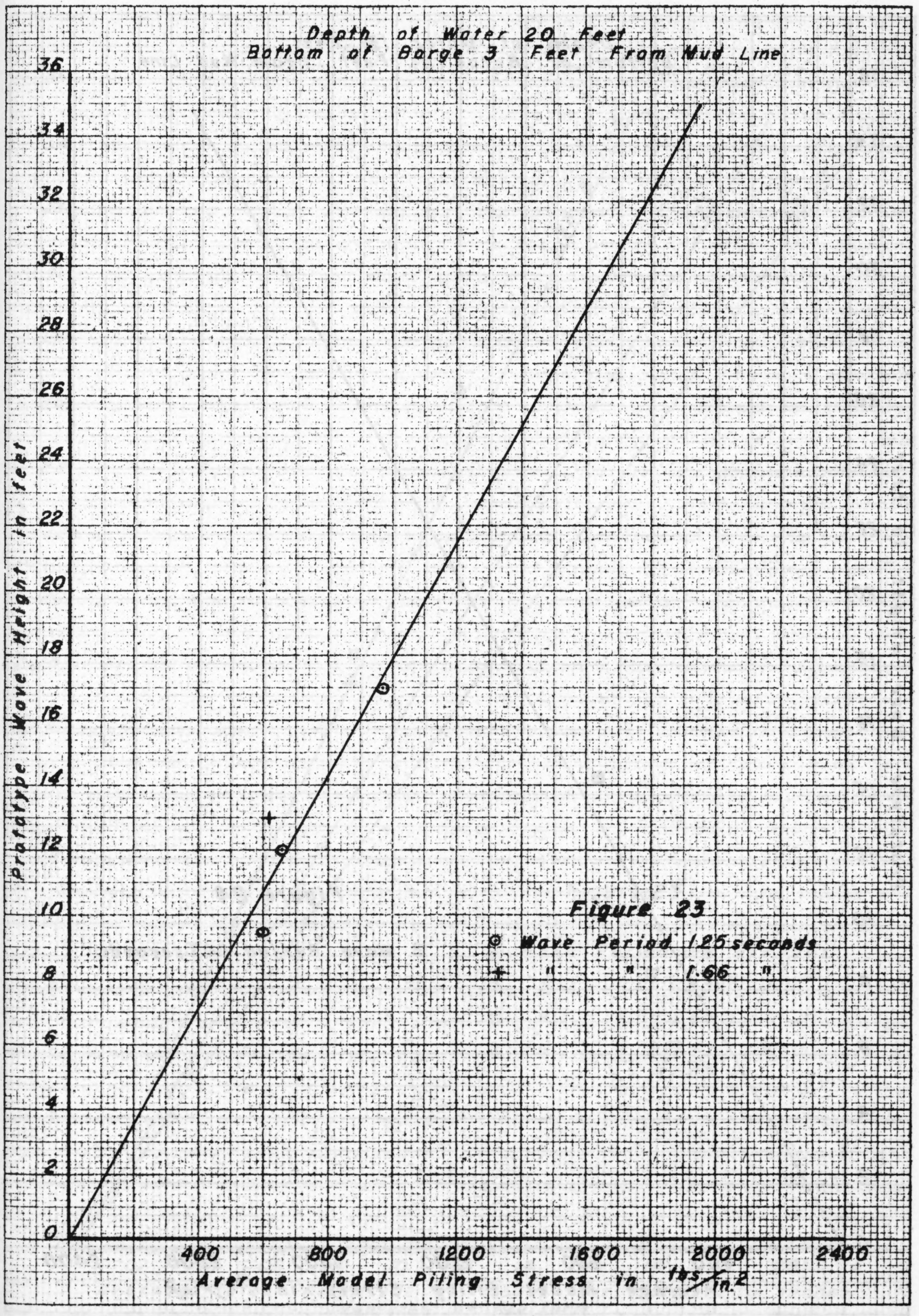
Figure 20



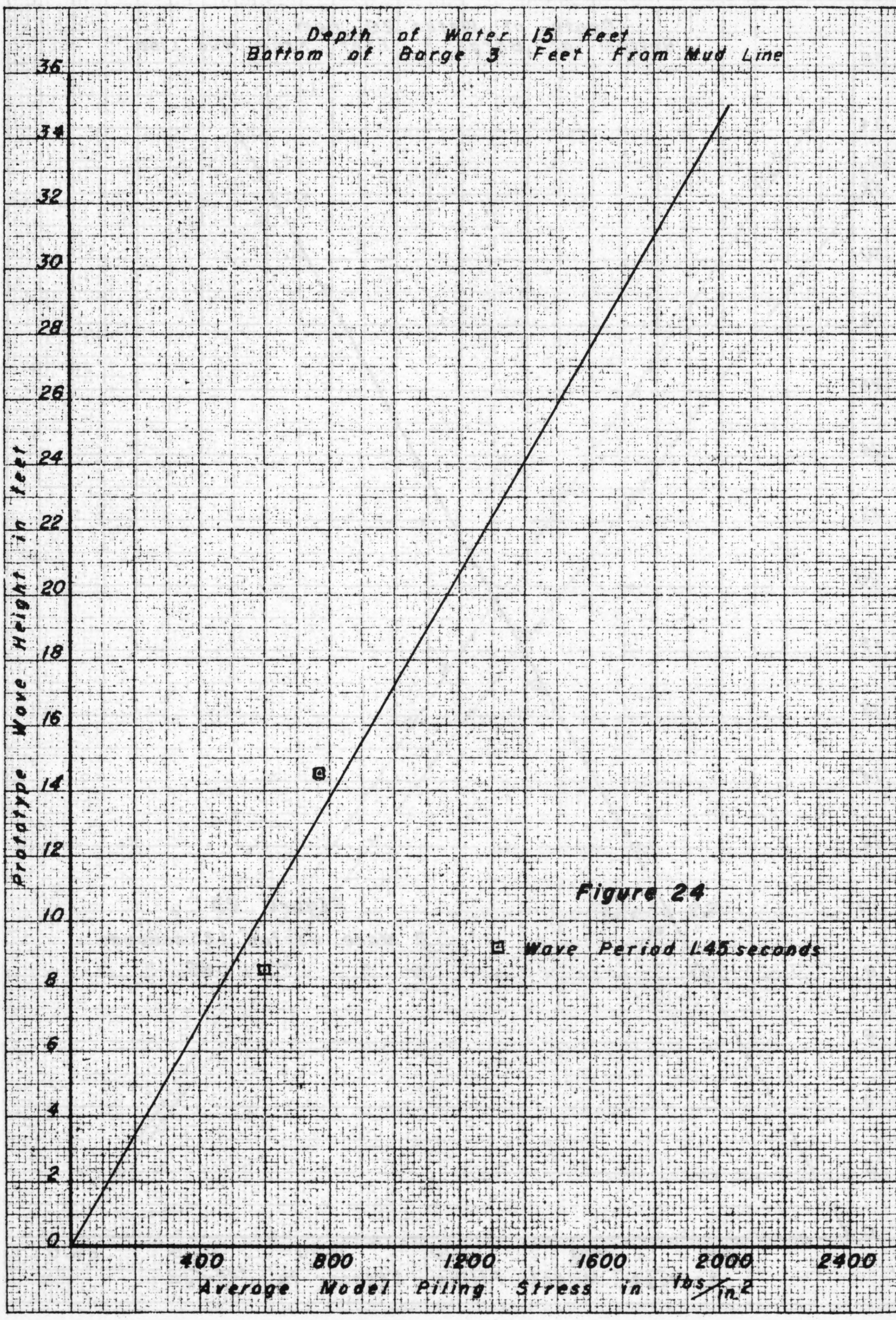
Depth of Water 62 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in Feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
200
400
600
800
1000
1200
Average Model Piling Stress in lbs/in.2
Figure 21
Wave Period 1.24 seconds
" " 1.65 "



Depth of Water 40 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in feet
Average Model Piling Stress in lbs/in.2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
200
400
600
800
1000
1200
1.20
1.60
Figure 22
Wave Period 1.20 seconds
" " 1.60 "

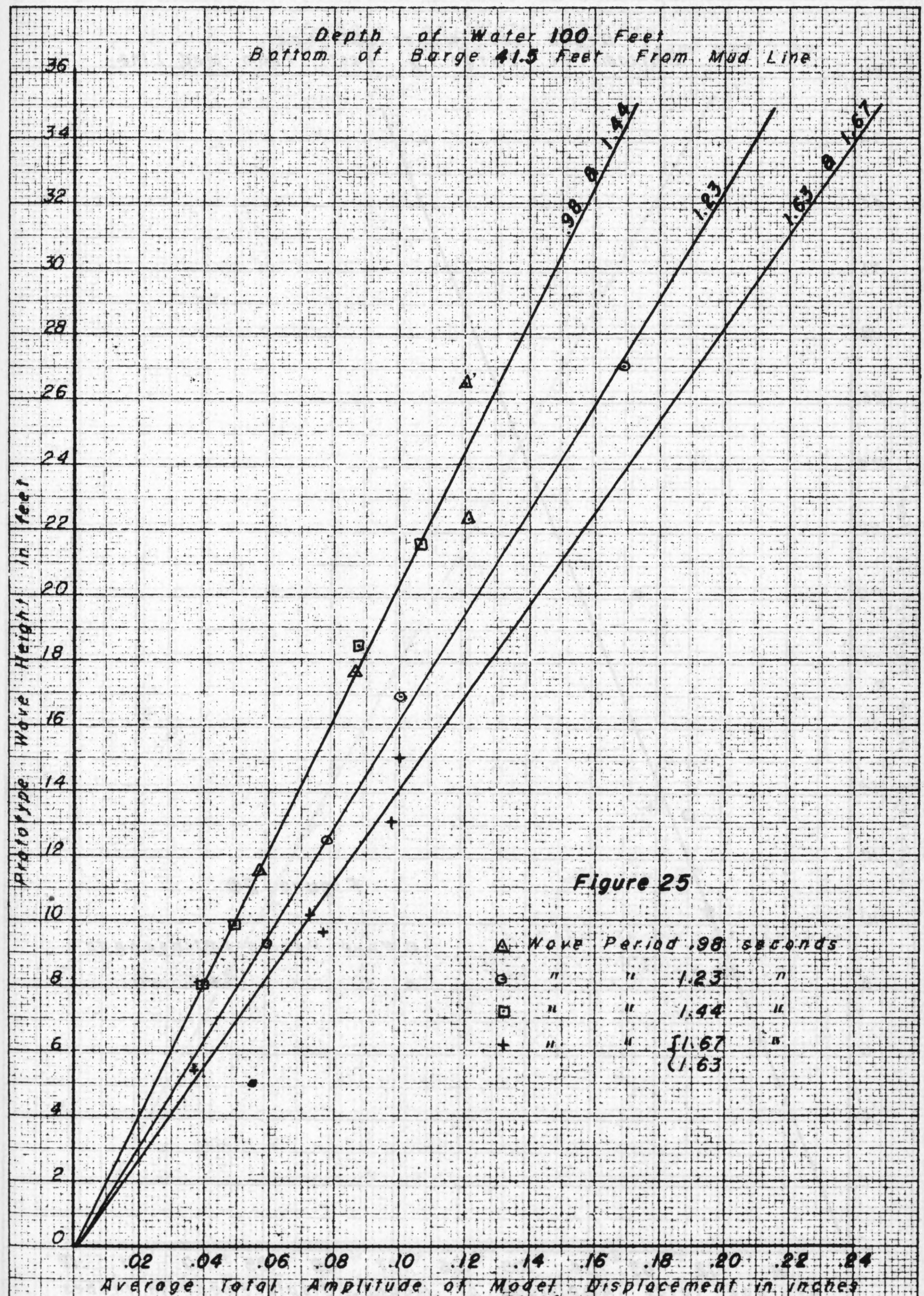


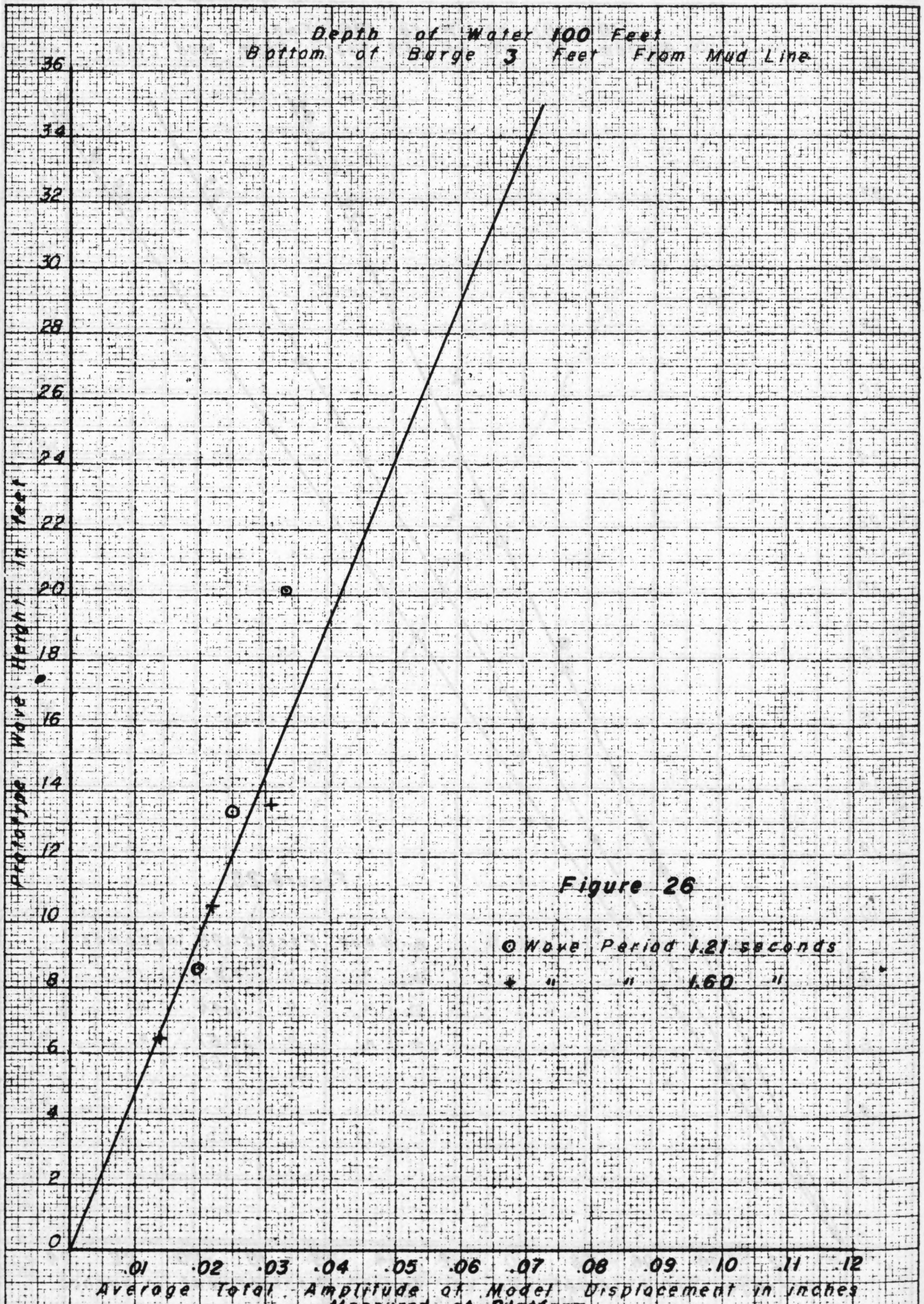
Depth of Water 20 Feet
Bottom of Barge 3 Feet From Mud Line
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Prototype Wave Height in feet
400
800
1200
1600
2000
2400
Average Model Piling Stress in lbs/in.2
Figure 23
⊙ Wave Period 1.25 seconds
+ " " 1.66 "

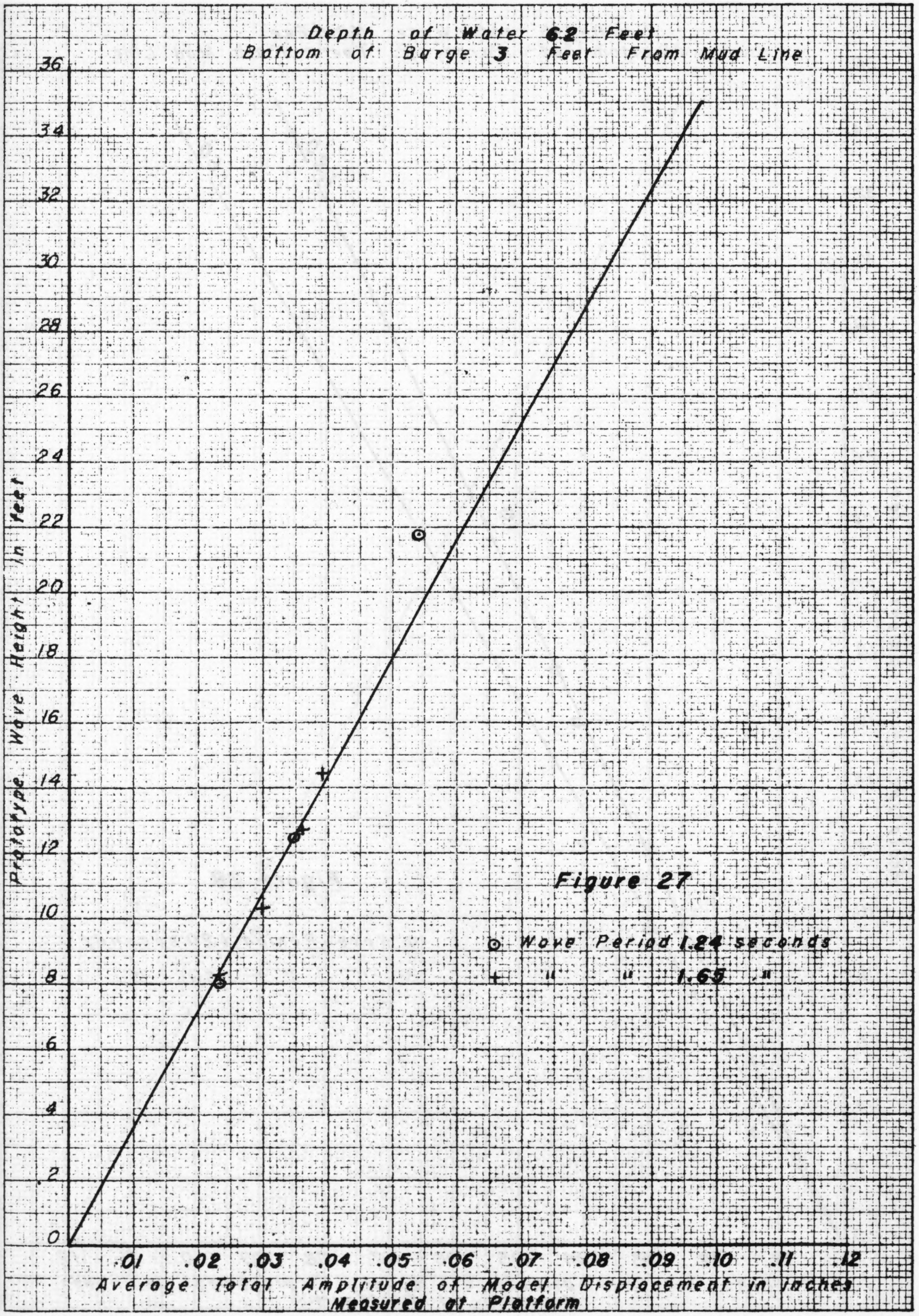


Depth of Water 15 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
400
800
1200
1600
2000
2400
Average Model Piling Stress in lbs/in2
Wave Period 1.45 seconds

Figure 24


Depth of Water 100 Feet
Bottom of Barge 41.5 Feet From Mud Line
.98 & 1.44
1.23
1.63 & 1.67
Prototype Wave Height in feet
Average Total Amplitude of Model Displacement in inches
Measured at Platform
Wave Period .98 seconds
" " 1.23 "
" " 1.44 "
" " {1.67 (1.63 "
Figure 25


Depth of Water 100 Feet
Bottom of Barge 3 Feet From Mud Line
Figure 26
Wave Period 1.21 seconds
" " 1.60 "
Prototype Wave Height in feet
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
.01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12
Average Total Amplitude of Model Displacement in inches
Measured at Platform


Depth of Water 62 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in feet
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
Average Total Amplitude of Model Displacement in inches
Measured at Platform
Figure 27
⊙ Wave Period 1.24 seconds
+ " " 1.65 "

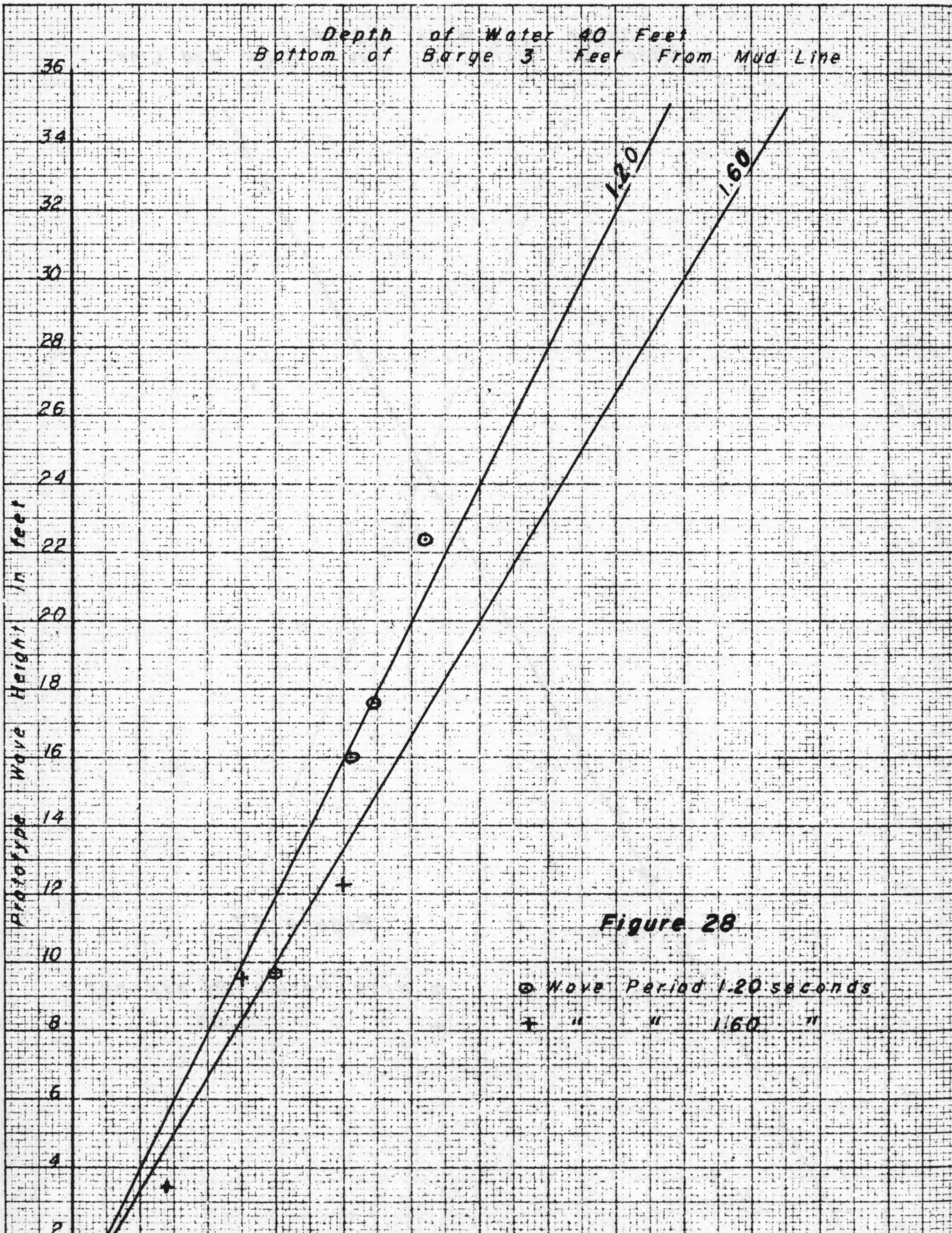
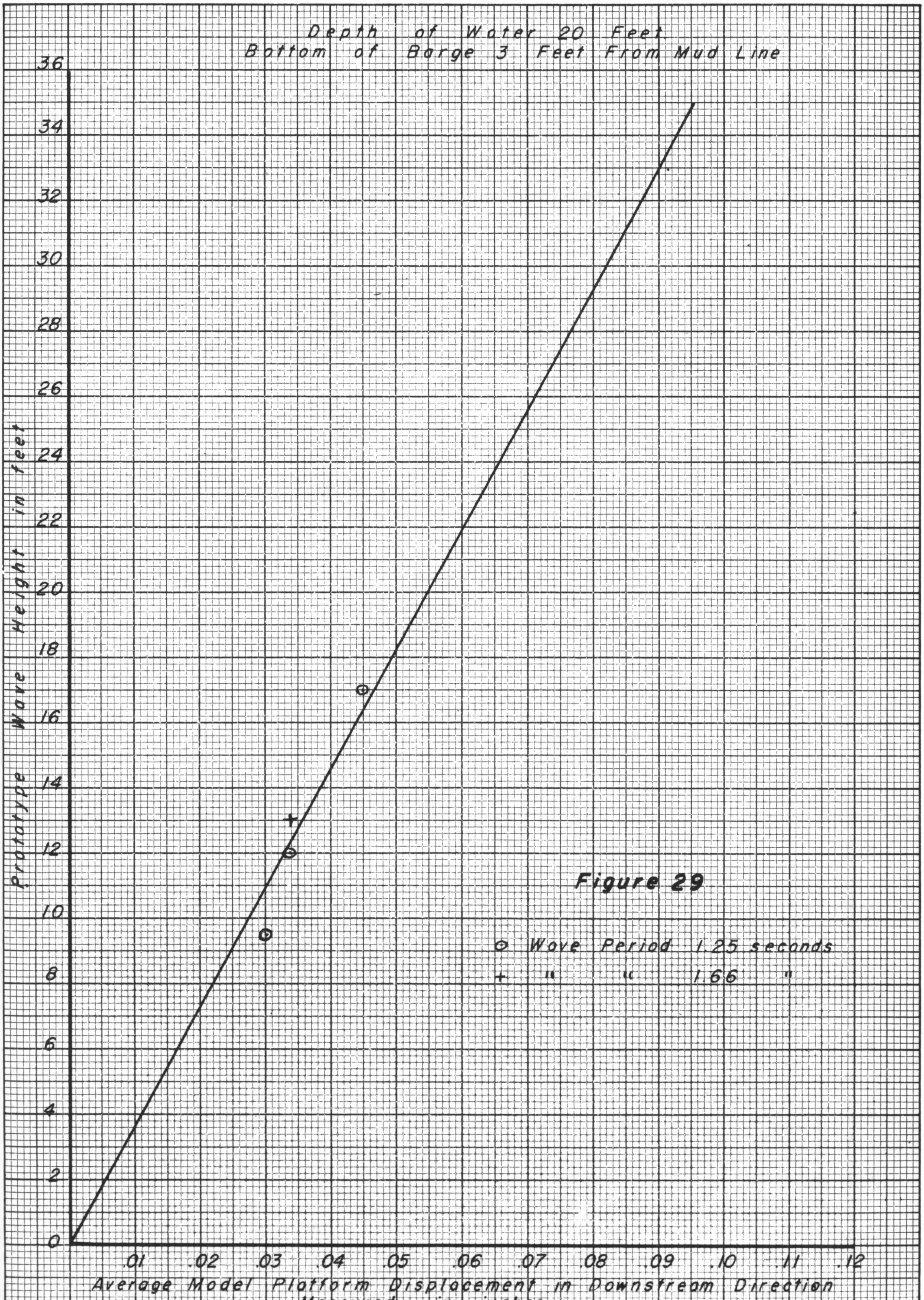
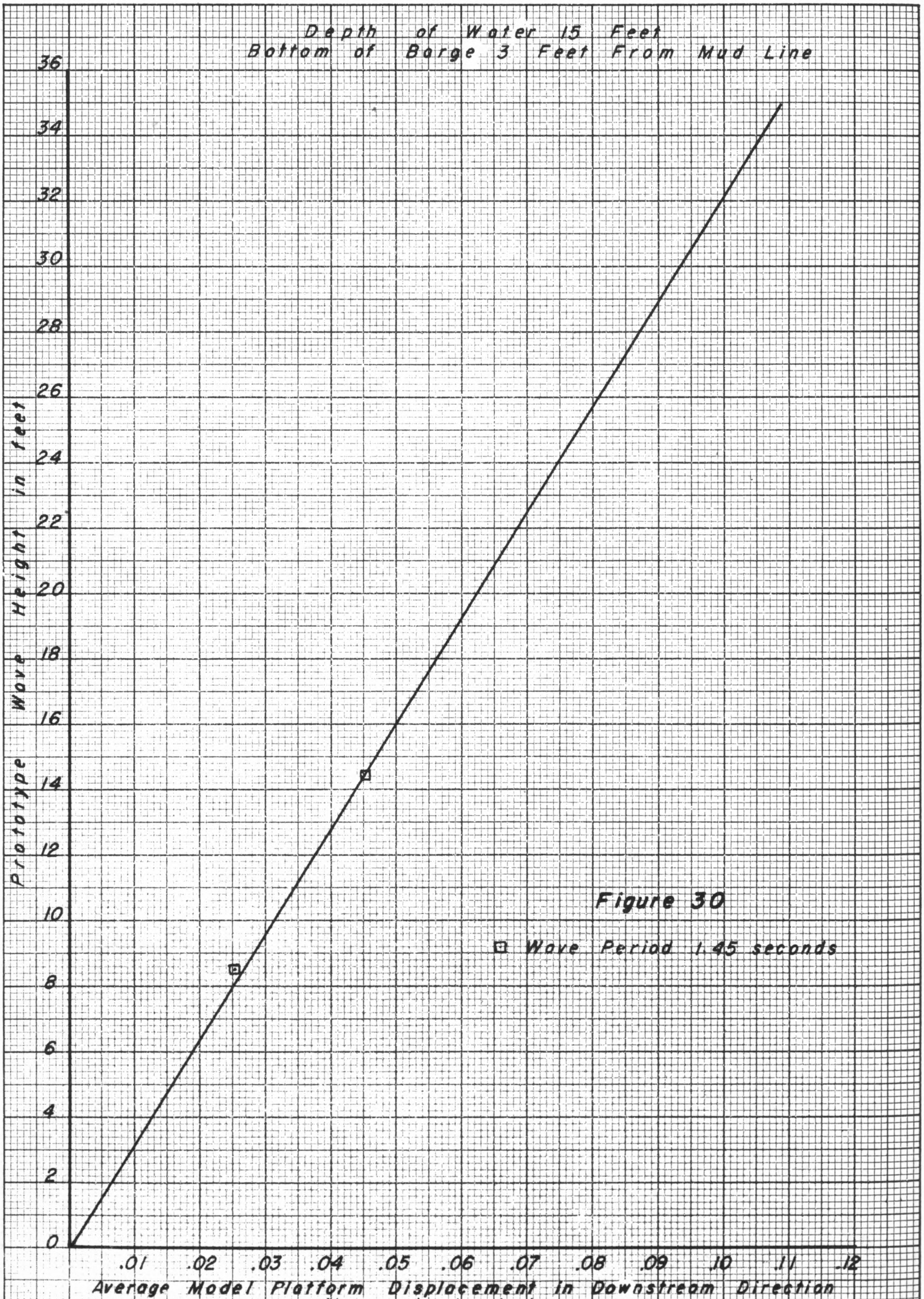

Depth of Water 40 Feet
Bottom of Barge 3 Feet From Mud Line
1.20
1.60
Prototype Wave Height in feet
Average Total Amplitude of Model Displacement in inches
Measured at Platform
Wave Period 1.20 seconds
" " 1.60 "
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12

Figure 28


Depth of Water 20 Feet
Bottom of Barge 3 Feet From Mud Line
Prototype Wave Height in feet
Average Model Platform Displacement in Downstream Direction Measured in inches
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
Figure 29
⊙ Wave Period 1.25 seconds
+ " " 1.66 "


Depth of Water 15 Feet
Bottom of Barge 3 Feet From Mud Line
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Prototype Wave Height in feet
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
Average Model Platform Displacement in Downstream Direction
Measured in inches
Figure 30
Wave Period 1.45 seconds

APPENDIX C

CONVERSION FACTORS

CONVERSION FACTORS

In this appendix, the subscript p denotes prototype quality and the subscript m denotes model quality.

Displacements

For 36 x 3/4-inch piles

$$\Delta = c\ \frac{FL^3}{EI}$$

or

$$\Delta \propto c\ \frac{F}{EL} \quad .$$

Then

$$\frac{\Delta_p}{\Delta_m} = \frac{F_p}{E_p L_p} \cdot \frac{E_m L_m}{F_m} \quad .$$

If

$$\frac{L_p}{L_m} = 50, \quad \frac{F_p}{F_m} = 50^3, \text{ and } \frac{E_m}{E_p} = \frac{1}{3} \quad .$$

then

$$\Delta_p = \frac{50^3}{50 \times 3}\ \Delta_m = 833\ \Delta_m \quad .$$

For 48 x 1-inch piles

$$\Delta_p = 833 \times \frac{13{,}000}{40{,}800}\ \Delta_m = 266\ \Delta_m$$

Piling Stresses

For 36 x 3/4-inch piles

$$f = c\ \frac{FLd/2}{I}$$

or

$$f \propto \frac{F}{L^2}$$

then

$$f_p = \left(\frac{F_p}{F_m}\right)\left(\frac{L_m}{L_p}\right)^2 f_m .$$

If

$$\frac{L_p}{L_m} = 50 \text{ and } \frac{F_p}{F_m} = 50^3 ,$$

$$f_p = 50 f_m.$$

For 48 x 1-inch piles

$$f_p = 50 \times \frac{13,000}{40,800} \times \frac{23.5}{17.63} f_m = 21.2 f_m .$$

Maximum Stress in Piles

The point of measurement of the stress in the model piling was 1.6 inches above the bottom. If the piles are assumed to have equal rigidity at the base and at the lower clamp of the barge, and the distance between these points is d, then there is a point of contra-flexure midway between the base and the clamp, or d/2 from the base.

Therefore $\frac{S_{max}}{S_{meas}} = \frac{d/2}{d/2-1.6}$

or

$$S_{max} = \frac{d}{d-3.2} S_{meas} .$$

Example:

For 100 feet of water, d in model is 12.3 inches.

Therefore $S_{max} = \frac{12.3}{9.1} S_{meas} = 1.36 S_{meas}$.

Thus the maximum stress in the model piling is 1.36 times the measured stress.

Natural Period

For 36 x 3/4-inch piles

$$P_p = \frac{L_p}{L_m} \sqrt{\frac{E_m}{E_p}} \, P_m \, .$$

or

$$P_p = 28.8 \, P_m .$$

$$\left(\text{Natural frequency } T_p = \frac{1}{28.8} T_m\right)$$

For 48 x 1-inch piles

$$P_p = 28.8 \times \sqrt{\frac{13,000}{40,800}} \, P_m = 16.2 \, P_m .$$

$$\left(\text{Natural frequency } T_p = \frac{1}{16.2} T_m\right.$$