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SCALE EFFECTS IN SEAWORTHINESS

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by

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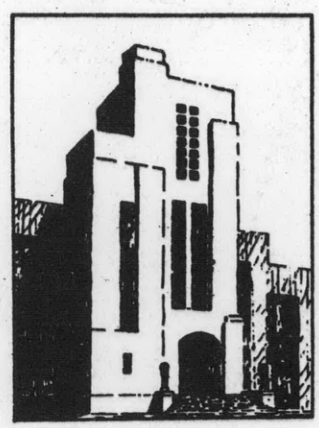
M. D. Bledsoe
and
G. P. Stefun



Prepared for the
American Towing Tank Conference
Eleventh General Meeting

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NOTATION

$_a$	Added model resistance coefficient referred to the nominal wave height (h)
$_t$	Total model resistance coefficient referred to the nominal wave height (h)
$_s$	Total model resistance coefficient in still water
	Froude number
$_o$	Still water Froude number
	Nominal wave height trough to crest
$_m$	Measured wave height, trough to crest
	Length of model
$_a$	Added model resistance in waves of height h
$_s$	Total model resistance in still water
$_t$	Total model resistance referred to the nominal wave height (h)
$R_t)_m$	Measured total model resistance in waves of height h_m
	Nominal wetted surface of model
	Model speed
$_o$	Amplitude of heave referred to the nominal wave height (h)
$z_o)_m$	Measured amplitude of heave in waves of height h_m
$_m$	Measured heave lag referred to pitch in waves of height h_m
$_o$	Dimensionless amplitude of heave
ϑ	Maximum wave slope referred to the nominal wave height (h)
ϑ_m	Maximum wave slope computed from the measured wave height (h_m)
λ	Wave length
ρ	Density of water in tank
Ψ_o	Dimensionless amplitude of pitch
ψ_o	Amplitude of pitch referred to the nominal wave height (h)
$(\psi_o)_m$	Measured amplitude of pitch in waves of height h_m

ABSTRACT

In this paper the effect of model size on the seaworthiness characteristics of a parent form of a fast cargo vessel is investigated. Five and ten-ft models of the Series 60, 0.60 block coefficient were tested in waves of constant height and constant slope. Resistance, amplitudes of pitch and heave, speeds and phase lags were measured in the Froude number range of 0 to 0.30. The results are presented in dimensionless form for purposes of comparison. The tests were performed in waves defined by the wave length to model length ratio (1.00, 1.25, 1.50), by the wave length to wave height ratio (30) and by the model length to wave height ratio (48). Performances of a self-propelled and a towed model are also compared.

It is found that within the accuracy of the experiments, and considering only realistic wave and speed conditions, no practically important scaling effects exist for the form and sizes investigated. It is also shown that self-propulsion and towing tests result in the same motion under the above mentioned specifying conditions.

INTRODUCTION

In this chapter three subjects are discussed. First, the relation of the work to other projects is described, then its aim and possible significance are outlined, and, finally, various approaches and basic principles are mentione

The tests and analyses presented in this paper were performed during a period of approximately one year in the 140-ft and 1800-ft wave basins at the David Taylor Model Basin. Some of the work was connected with the activities of the Series 60 Task Group of the Seaworthiness Panel of the Society of Naval Architects and Marine Engineers.[1*] Other parts were performed in connection with the International Comparison Tests organized by the International Towing Tank Conference. The results reported here were or are being used also to study non-linear effects, to investigate the influence of a bulb on the motion in waves[2], to establish correlation between self-propulsion and towing in waves, to compare computed and measured added resistances, to study the location of the pitching axis[3], etc. Military and commercial interest in fast cargo ships increased considerably in the past year and the coincidence of our research on Series 60 forms with this interest greatly facilitated the performance of our work which in turn served immediate defense purposes.

The purpose of the present paper is to study scale effects in seaworthiness experiments. By scale effect we mean the following. Using two geometrically and dynamically similar models of different sizes and assuming the validity of the Froude scaling law, compare in non-dimensional form the pertinent seaworthiness parameters. If these non-dimensional values agree within the experimental error, then the tests show no scale effects. If the size of the model influences the dimensionless results then we speak of scale effects, i.e. the Froude scaling law does not apply. Accepting the above definition of scale

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*References are listed on page 14 of this report.

effect, the following two questions are identical: will the Froude scaling law apply, or are there any scale effects in seaworthiness experiments. The problem might be of some importance since full scale behavior can be predicted from model tests only if the scaling law is established. If two different size models do not show scale effect, the full scale behavior might still be uncertain, since it is possible that the scaling law applies only in a limited size range. On the other hand, if model experiments show scale effects then the presently used prediction techniques for full scale behavior are in serious doubt. An associated question is the selection of the model size for wave studies. Small models are easy to handle, less expensive, require smaller facilities, etc. Large models have the advantage of simpler instrumentation. Self-propulsion units, gyroscopes, etc. do not have to be miniaturized for large models. The fact is that if testing techniques of various towing tanks are compared, the effect of various model sizes might confuse the comparison, unless the question of scale effect is satisfactorily settled.

After establishing a definition of the problem and outlining its significance, a method of approach can be designed to find the answer. It is required to test different size models in conditions satisfying the Froude scaling law. Unfortunately, different size models generally are not tested with the same testing techniques, therefore the separation of scale effects from effects introduced by the different testing techniques complicates matters. In the research reported in this paper a 5-ft model was tested with a gravity type dynamometer, and a 10-ft model with an oscillating tow force (hanging weight technique). The dynamic properties of these systems are similar but not identical. Therefore, the 10-ft model was also tested with an entirely different technique, i.e. self-propulsion. Motion results obtained with the 10-ft model, first towed then self-propelled showed no significant differences, therefore a comparison between the motion of the 5 and 10-ft models might be considered to be meaningful.

A comparison study requires that the experimental errors be smaller than the differences which are attributed to scale effects. The accuracy obtainable in seaworthiness experiments varies with the test conditions selected. For instance in waves shorter than the length of the model, the motion as well as speed reduction results are not as reliable as in longer waves. For comparison purposes, therefore, the test conditions should be selected so that the results are reliable and the quantities to be compared should be easily measurable.

DESCRIPTION OF TESTS

The work was performed on two models of the Series 60 parent form, 0.60 block coefficient. The 5-ft model was tested in the 140-ft basin using a gravity type dynamometer and a pneumatic type wave generator. The tests were performed in still water and in waves of lengths, 3.75, 5, 6.25 and 7.5 ft. The first series of tests used a constant wave height (1.25 in) the second series a constant wave length to wave height ratio of 30. The model speed was varied from 0 to 2.4 kts.

The 10-ft model was tested with self-propulsion and also with a towing arrangement which allowed the model freedom in surge. The wave lengths were 7.5, 10, 12.5 and 15 ft. Two wave height conditions were used; a constant height of 2.5 in and a constant wave length to wave height ratio of 30. The model speed varied from 0 to 3.6 kts.

Tests were also performed with a 20-ft self-propelled model of the same parent form. Analysis of these tests has not sufficiently progressed to permit a detailed discussion of the results in this paper, therefore, only a few qualitative comments will be made regarding these tests.

The non-dimensional test conditions, applicable to all models are as follows:

1. Wave length to model length ratio: λ/L = 0.75, 1.00, 1.25 and 1.50.

2. Model length to wave height ratio: 48, also wave length to wave height ratio: 30.

3. Froude number: 0 to 0.30.

Tables I, II and III facilitate the conversion of the test conditions from the dimensionless to the dimensional form.

TABLE I
TABLE OF WAVE LENGTHS (FT)

Length of Model (ft)	Wave length - model length ratio (λ/L)			
	0.75	1.00	1.25	1.50
5	3.75	5.00	6.25	7.50
10	7.50	10.00	12.50	15.00
20	15.00	20.00	25.00	30.00

TABLE II
TABLE OF WAVE HEIGHTS (IN)

Wave Length (ft)	Wave length - wave height ratio (λ/h)				
	30	36	48	60	72
3.75	1.50*	1.25*	.94	.75	.62
5.00	2.00*	1.67	1.25*	1.00	.83
6.25	2.50*	2.08	1.56	1.25*	1.04
7.50	3.00*	2.50*	1.88	1.50	1.25*
10.00	4.00*	3.33	2.50*	2.00	1.67
12.50	5.00*	4.17	3.12	2.50*	2.08
15.00	6.00*	5.00*	3.75	3.00	2.50*
20.00	8.00*	6.67	5.00*	4.00	3.33
25.00	10.00*	8.33	6.25	5.00*	4.17
30.00	12.00*	10.00	7.50	6.00	5.00*

*These were the actual test conditions.

TABLE III
TABLE OF MODEL SPEEDS (KTS)

Froude Number	Length of Model (ft) 5	10	20
0	0	0	0
.05	.375	.530	.750
.10	.750	1.061	1.501
.15	1.125	1.592	2.251
.20	1.501	2.122	3.001
.25	1.876	2.653	3.762
.30	2.251	3.183	4.502

The longitudinal radius of gyration was 25 percent of the length for both the 5 and 10-ft models. The weight of the 5-ft model in test condition was 33.27 lb, that of the 10-ft model 266 lb, and of the 20-ft model 2130 lb.

The 5-ft wood model had a varnished surface, the 10-ft model was made of plastic reinforced with fiberglass and its surface was painted. The 20-ft model was made of wax. No turbulence stimulation was used on any of the models.

The motion of the models was photographed with a 35mm movie camera, the 10-ft model was also equipped with a pitch gyroscope and the 20-ft model with bow and stern accelerometers, with a heave potentiometer and with a gyroscope.

The waves were measured with a stationary, capacitance-type wave height recorder during the tests with the 5-ft model and traveling wave probes were used for the 10 and 20-ft model tests. Photograph 1 shows the 5-ft model in the 140-ft basin. The model is free to pitch and heave; its surging motion is coupled with the dynamic effect of the towing system, i.e. with the elastic effect of the towline and with the inertia effect of the tow weight and pulleys. The model is completely covered except for a lucite collar around the tow post. In the 30:1 wave length to wave height ratio condition the original collar did not succeed in completely eliminating the adverse effects of splash and the model shipped some water. To alleviate this condition the fore part of the collar was built up. The increased height of the collar is shown in the photograph. It was also noticed in these severe conditions that the ends of the V arm were hitting the bow and the stern. In bow up condition the model was climbing on a crest, its resistance increased (surging force directed to the stern) and the tow force stayed approximately constant. As a result of the force acting on the towline and of the increased drag acting on the model, the tow post and the rigidly attached V arm rotated around the pivot point. The combination of this rotation and the bow up condition resulted sometimes in a contact between the model and the V arm. The pivot axis was located at the LCG in the waterplane.

Photograph 2 shows the 10-ft fiberglass model with the self-propulsion unit and gyroscope. The lead weights were permanently fixed, after the desired radius of gyration was established. The driving motor was a 1/20 HP, DC motor, the RPM of which was regulated by a variable resistance in series with the armature. The RPM was measured with a slotted disc, magnet, and pulse counter combination. Photograph 3 shows a self-propulsion test with the 10-ft model in the large wave basin. The tow arm, pivoted at the waterline at the LCG, was attached to a pantograph which guides the model and at the same time allowed it to heave. The upper end of the pantograph was attached to a V arm, the ends of which were fixed to a cable loop. The loop allowed the model to surge. The stern and bow targets facilitated the pitch readings and the LCG target facilitate the heave readings from the movies. The reference boards, rigidly attached to the carriage, were used to determine the model's vertical and longitudinal location at every instant. Combining the longitudinal location of the model with the wave record and with the pitching and heaving motions, the phase angles could be determined. The towed tests were performed by removing the propeller and by balancing the resistance of the model by a hanging weight attached to the forward pulley.

In case of large surging motion the tow weight's contribution to the inertia forces of the model might be significant. Since the mass of the system in the longitudinal direction is the sum of the masses of the model and the tow weight and of the added mass, the surging motion might be influenced by the tow weight. It was found that the model's own inertia force plus that of the added mass were much larger than the inertia effect of the tow weight because of the relatively small resistance, small surging amplitudes and small frequencies. It is believed that the self-propelled and the towed tests gave for all practical purposes the same motions because of the negligible effect of the inertia of the tow weight and of the propeller. It was observed with the 10 as well as with the 20-ft models that even in conditions resulting in periodic propeller emergence the surge was insignificant and hardly measurable.

Photograph 4 shows preliminary testing of the 10-ft model in the 140-ft basin. The picture shows clearly the pantograph arrangement. During these preliminary tests the cable loop and the supporting structure were used in an up-side-down position. The screw-eyes on the cover plate served two useful purposes. The longitudinal radius of gyration was determined by the conventional bifilar method as well as with the spring method introduced by Professor M. Abkowitz of MIT.* Both these methods required the screw-eyes. During the tests, ropes connected the screw-eyes with the carriage to prevent the model from running away and damaging the pulley system.

Photograph 5 shows the test set-up for the 20-ft self-propelled model. The pantograph and cable-pulley system was the same as for the 10-ft model. In addition to this a bow guide was used, the lower end of which was pivoted on the cover plate and the upper end was allowed to slide on horizontal tracks. The self-propulsion unit was a $\frac{1}{2}$ HP, DC motor.

*A dynamic analysis of the "spring method" performed by one of these writers showed the method to be superior to the bifilar technique in accuracy, speed and especially in sensitivity to instrumentation errors. The method consists of suspending the model from two vertical springs and measuring the frequency of linear and angular oscillatory motion of the system.

ANALYSIS OF TEST RESULTS

RESISTANCE

The measured resistance values were analysed making the assumption that the resistance in waves can be written as the sum of the still water resistance and the added resistance resulting from wave action,

$$R_t = R_s + R_a \tag{1}$$

Here R_t is the total resistance in waves at a given speed,
R_s is the still water resistance at the same speed, and
R_a is the added resistance resulting from wave action.

The tow forces measured in the wave tests were first corrected for tare, and then the total measured resistance $(R_t)_m$ was recorded for each run. Since the same blower RPM and valve frequency of the wavemaker do not always result in the same wave heights, the measured resistances were corrected to the nominal wave height by the formula

$$R_a = \left[(R_t)_m - R_s\right]\left(\frac{h}{h_m}\right)^2 \tag{2}$$

where R_a is the added resistance corresponding to the nominal wave height,
$(R_t)_m$ is the total resistance measured in waves of height h_m, and
R_s is the still-water resistance corresponding to the speed at which the wave test was performed.

Using the $(R_t)_m$ values from the tests and the corresponding still-water resistances, the added resistances (R_a) were computed from Equation (2). Then using Equation (1), the total resistances (R_t) were obtained. The total model resistance coefficient in waves was computed by

$$C_t = \frac{R_t}{\rho/2\, V^2 S} \tag{3}$$

or, after substitution, by

$$C_t = \frac{R_s\left(h_m^2 - h^2\right) + (R_t)_m h^2}{\rho/2\, V^2 S\, h_m^2} \tag{4}$$

The added resistance coefficients were also computed using

$$C_a = \frac{R_a}{\rho/2\, V^2 S} \tag{5}$$

or, after substitution, by

$$C_a = \frac{[(R_t)_m - R_s]\, h^2}{\rho/2\, V^2 S\, h_m^2} \tag{6}$$

It is noted that the conventional total still-water resistance coefficient, defined by

$$C_s = \frac{R_s}{\rho/2\, V^2 S} \tag{7}$$

is in complete agreement with Equation (1), i.e.:

$$C_t = C_s + C_a \tag{8}$$

MOTIONS

The experimentally obtained heave and pitch amplitudes, $(z_o)_m$ and $(\psi_o)_m$ formed the basis of the motion analysis. The dimensionless heave and pitch amplitudes were computed by the following equations:

dimensionless heave amplitude: $$\zeta_o = \frac{2\,(z_o)_m}{h_m} \tag{9}$$

dimensionless pitch amplitude: $$\Psi_o = \frac{(\psi_o)_m}{\vartheta_m} \tag{10}$$

where $\vartheta_m = \frac{\pi h_m}{\lambda}$ is the maximum wave slope corresponding to the measured wave height (h_m) and wave length (λ).

The advantage of computing and presenting the dimensionless values is twofold. First, only through the use of dimensionless values can the results of different size models be compared. Secondly, any inaccuracy in the height of the produced waves is eliminated this way.

The heave and pitch amplitudes corresponding to the nominal wave height (h) can be obtained from

$$z_o = \frac{h}{2}\,\zeta_o \tag{11}$$

and

$$\psi_o = \vartheta\,\Psi_o \tag{12}$$

where $\vartheta = \frac{\pi h}{\lambda}$.

The lag of heave referred to pitch (δ_m) was also obtained from the experiments. No wave height correction was applied to the measured δ_m values, because of the experimental difficulty in determining phase lags in general and because of the uncertainty of the theory involved.

PRESENTATION OF RESULTS

The results are presented in two groups. First, the constant wave height test results (Figures 1 - 8), then the constant wave slope test results (Figures 9 - 16) are given. In both groups the first five figures show resistances which are followed by motion results. The resistance results are presented in the form of total resistances, speed reduction curves and resistance coefficients, the motion results show pitch and heave amplitudes and phase lags. Speed reduction curves comparing the behavior of towed and self-propelled models (Figures 17 and 18) conclude the data presentation. A detailed discussion of the curves is given below.

The resistance curves of the 5 and 10-ft models are shown in Figures 1 and 2. The curves represent constant wave height tests, h = 1.25 in for the 5-ft model and h = 2.50 in for the 10-ft model. The model length to wave height ratio is 48 for both models. The resistance curves were obtained by the analysis described in the previous section, i.e. all values were corrected to the nominal wave height.

Comparison between the 5 and 10-ft model resistances can be made by either plotting speed reduction curves or by computing resistance coefficients. Both methods have advantages and disadvantages. Speed reduction curves based on constant tow force are sometimes difficult to interpret for full scale application; resistance coefficients are sometimes of little significance for wave tests. This last statement becomes clear if one considers the case of zero speed of advance but finite resistance; which situation occurs often in wave tests. The speed reduction curves (Figure 3) were obtained from Figures 1 and 2 by reading off the speeds corresponding to such tow forces which give the same still water Froude numbers for the two models. For instance the tow force giving 0.280 still water Froude number for the 5-ft model is .29 lb and for the 10-ft model is 2.25 lb. The same tow force is needed for F = .228 for the 5-ft and F = .220 for the 10-ft model in $\lambda/L = 1.0$.

The added (C_a) and total (C_t) resistance coefficients are plotted against the Froude number in Figures 4 and 5 for $\lambda/L = 1, 1.25, 1.50$; $L/h = 48$.

The phase lag of heave referred to pitch (δ_m), the dimensionless pitch (Ψ_3) and dimensionless heave (ζ_0) amplitudes are plotted against the Froude number for wave length = model length and wave height = 1/48 x model length in Figure 6 for both models. It is noted that all motion results contain points obtained with the towed 5 and 10-ft models and with the 10-ft self-propelled model. (Resistance curves and the derived quantities of course refer to the towed 5 and 10-ft models only.) Figures 7 and 8 show motion results for $\lambda/L = 1.25$ and 1.50; $L/h = 48$.

Figures 9 and 10 show the resistance curves of the models in $\lambda/h = 30$ waves, Figure 11 compares speed reductions, Figures 12 and 13 give the added and the total resistance coefficients for $\lambda/h = 30$. Figures 14, 15 and 16 compare the motion characteristics in $\lambda/h = 30$ and $\lambda/L = 1, 1.25, 1.50$ waves.

All the basic curves show experimental points (after correction to the nominal wave height). Figures 1, 2, 9 and 10 show the basic resistance curves, Figures 3, 4, 5, 11, 12, 13, 17 and 18 give derived quantities. Points on the speed reduction curves were obtained from the faired resistance curves. Points shown on the resistance coefficient curves were computed using the points on the basic resistance curves.

The motion curves are all basic, since they show experimental points. Various fairing processes might furnish figures in which magnification factors are plotted versus the tuning factor. It was felt, however, that such presentations would add little to the solution of the problem at hand. It is realized that the points shown do not determine the curves uniquely and therefore no importance should be attached to their shape.

Figures 17 and 18 do not compare different size models, but rather the important effects of testing techniques and are included for the sake of completeness, for future reference and because of their general interest and novelty. The curves of Figure 18 do not show experimental points for the following reasons:

(a) it would be difficult to distinguish the points since the curves overlap

(b) these curves do not contribute to scale effect studies.

DISCUSSION OF RESULTS

Seaworthiness tests furnish two kinds of basic information: resistance and motion in waves. Scale effects in seaworthiness, therefore, are to be investigated in relation to resistance and motion. The fact that for certain conditions little or no scale effects on certain quantities are evident does not imply that scale effects are negligible in seaworthiness tests in general.

To arrive at some conclusions regarding the importance of scale effects, practical considerations will guide us. From a practical point of view, motion in a seaway might be considered more important than added resistance, since top speed in waves is generally determined by motion, slamming, shipping green water, etc. Therefore, the reader is advised to put more emphasis on the motion than on resistance correlations. Another practically important point is that some of the graphs show deviations between the 5 and 10-ft model results which are of little significance. For instance, if the 5-ft model pitches 3/4 deg and under identical conditions the 10-ft model pitches only $\frac{1}{2}$ deg, the difference ($\frac{1}{4}$ deg) is 40 percent, as referred to the average pitching angle. A 40 percent deviation means a large scale effect, but the actual pitch angle is too small to be significant from a practical point of view and can not be measured with sufficient accuracy. Small pitch angles and small heave amplitudes are associated with small values of the dimensionless heave and pitch parameters as well as with small wave heights.

The $\lambda/h = 30$ condition corresponds to wave heights of 2, 2.5 and 3 in if $\lambda = 5$, 6.25 and 7.5 ft respectively. The second group of tests ($\lambda/h = 30$) therefore always uses larger wave heights than the first group (h = 1.25 in for the 5-ft model). The wave slope is also higher for the second group (1/30) than for the first group (1/48, 1/60, 1/72). Deviations shown in the curves of the second group, therefore are more pronounced than those of the first group. On the other hand the conditions imposed in the second group might be considered too severe from a practical point of view. For instance if $\lambda/L = 1.5$ and L = 400 ft, the wave length is 600 ft and with $\lambda/h = 30$ the wave height becomes h = 20 ft. In such a seaway the 400-ft cargo ship will not proceed at 30 knots (F = .30). Therefore, the curves and the deviations presented in this report are to be interpreted with considerable caution before final conclusions are reached. It is to be kept in mind that while from a theoretical point of view it is of considerable interest to establish the scale effects for a great variety of test conditions, at the same time it is to be realized that tests at unrealistic speed and wave height combinations are to be eliminated from seaworthiness investigations.

A detailed discussion of the results will be based on the following principles:

1. Small heave (0.1 in) and pitch ($\frac{1}{2}$ deg) amplitudes or deviations are of little practical interest and are approaching the limits of the experimental accuracy.

2. High speed and large wave heights in combination are of no practical significance.

3. Scale effects on the motion are of more practical importance than on the resistance.

The first figure which allows a comparison between the performance of the 5 and 10-ft models is Figure 3. Figures 1 and 2 are not comparable and are included only since they contain the original data from which the speed reduction curves (Figure 3) were obtained. It is an interesting result that the gravity type towing arrangement and the hanging weight towing method give the same speed reduction curves for all practical purposes in h = 1/48 x model length waves. The significance of this agreement is limited, since ships do not operate in a seaway with constant thrust. Elastic and resonance effects of the gravity type dynamometer seem to be of no significance according to these results. The largest deviations (10 percent) occur in short waves and at low thrusts, and these conditions are critical for the test facility since the determination of low model speeds is uncertain. The model generated waves might be superposed on the oncoming waves at such a low speed (0.6 kts for the 5-ft model) therefore the determination of the wave height might not be reliable either.

The total and the added resistance coefficients (Figures 4 and 5) show remarkable agreement except at low speeds for the case in which wave length equals model length. The experimental difficulties mentioned above, of course, apply here too and in addition it should be noted that at low speeds the resistance coefficients approach infinity in wave tests, thus magnifying any errors in the measurements. The resistance coefficients were evaluated only for $\lambda/L = 1$, 1.25 and 1.50 since the shorter wave length tests ($\lambda/L = 0.75$) did not give reliable results, and it was felt that for comparison purposes only well established results should be used. It is noted that the difference between corresponding C_t and C_a values is the still water resistance coefficient. The trends and the relative shapes of the 5 and 10-ft C_t and C_a curves are the same, which shows a fairly constant C_s value for the two models. The C_t curves can be obtained by shifting the corresponding C_a curves vertically up by approximately .005. This is in agreement with the total still water resistance coefficient computed for a 5-ft model from reference 4, at $F = .21$ and it represents an average C_s value in the range of .09 to .24 Froude number.

The agreement between the motions of the 5 and 10-ft models is surprisingly good in $\lambda = L$, and fair in $\lambda = 1.25L$ and $\lambda = 1.5L$ waves. It is, of course, to be realized that the condition shown in Figure 8 corresponds to a maximum slope of 2.50 deg, i.e. the largest pitch angle deviation is 0.4 deg. The largest heave deviation corresponds to 0.12 in (5-ft model scale), therefore, better agreement can be expected only if the experimental techniques are considerably improved. An interesting feature of Figure 8 is a shift of the maximum pitch angle, i.e. the 5-ft model shows a peak at $F = 0.28$ and the 10-ft model at $F = 0.25$. To obtain a realistic picture of this discrepancy, we note that this corresponds to 0.23 kts speed deviation for the 5-ft model, which is very close to the limit of the accuracy of the speed measuring instruments.

The previous discussion dealt with the constant wave height tests, h=1.25 in for the 5-ft and h = 2.5 in for the 10-ft model. In higher waves the agreement between the two models' performance is not completely satisfactory as will be shown below. Figures 9 and 10 can not be compared, since they represent the basic data. Figure 11 shows the speed reduction curves for the two models. The curves at thrusts giving $F_o = .23$ and $F_o = .265$ still water Froude numbers show reasonable agreement. The former indicates less speed reduction for the 5-ft model by approximately 0.15 kts (5-ft scale). With the highest tow force ($F_o = .30$) the 5-ft model loses considerably more speed in waves than the 10-ft model. In this condition the models ship green water and slam. Assuming a 600-ft ship the 5 and 10-ft model predictions in 600-ft long, 20-ft high waves are 15 and 19.5 kts. It might be interesting - at least in principle - that at high thrust the 5 and at low thrust the 10-ft model loses more speed. The curves are given for high still water speeds because at lower F_o values the speed reduction is so serious that the models' forward speed can not be determined with any certainty and accuracy.

The added (Figure 12) and total (Figure 13) resistance coefficients show some deviations, which - as in the case of the less severe wave heights - seem to be large at low speeds. The $C_s \cong .005$ constant shift between the C_t and C_a cruve can be again observed.

A comparison of the motions of the 5-ft with that of the 10-ft model in the severe wave condition shows agreement, except in isolated cases. In showing experimental results the principle was followed that points subject to large expected experimental error were eliminated. It was felt that more certain conclusions, valid in a smaller but well defined range, were more valuable than doubtful conclusions of undefined range. The only serious effect of the model size shows up in the phase lag results in λ = L and λ = 1.5L waves at F = 0.1. The largest deviation occurring in pitch in λ = 1.25L waves at F = 0.1, is less than 1 deg. The largest heave deviation is 0.14 in for the 5-ft model. It might be significant to note that no consistent deviations occur between the two models. The curves shown in Figures 17 and 18 show the practical significance of self-propulsion tests in connection with obtaining speed reduction data. The curves of Figures 17 refer to waves of constant height (12.5 ft for a 600-ft vessel) and show that the speed loss is consistently smaller for constant RPM than for constant thrust. It is well known that as the motion of the ship becomes violent, the captain will reduce the speed voluntarily, therefore, even the constant RPM curves are only of academic interest.

The more severe wave conditions represented by Figure 18 are included for completeness only, since large voluntary speed reductions can be expected in such seas.

Finally, a few remarks might be made in connection with tests performed on a 20-ft model of the same parent form. Agreement between the 5-ft towed, 10-ft towed, 10-ft self-propelled and 20-ft self-propelled models was excellent in the λ = L condition, but at other wave lengths significant deviations were found after preliminary tests and analyses. (The heave and pitch amplitudes of the 20-ft model were consistently lower than those of the 5 and 10-ft models.) Detailed results concerning the 20-ft model, upon establishment of satisfactory techniques, will be published elsewhere. One difficulty encountered during the tests and the analysis was the difference found between the gyroscope, accelerometer and motion picture records. Pitching amplitudes were obtained simultaneously with these instruments and the results compared showed considerable spread. It is felt that averaging processes should not be applied to results of such basically significant tests, therefore the extension of scale effect studies to 20-ft models will have to await the development of a completely reliable experimental technique.

CONCLUSIONS

The authors warn the reader not to arrive at general and unjustifiable conclusions. It is important to realize that the tests were performed with one certain parent form. Therefore, the results are valid, in strict sense only to this form. The results obtained for the conditions of the wave length, wave height and speed described in the report should not be generalized to the ranges not covered in the tests. This paper does not intend to answer the question of whether scale effects in seaworthiness tests in general are significant or negligible. The paper shows results for certain typical conditions for one parent form. The following conclusions, therefore, are valid only in the range of the experiments described in the paper.

A critical analysis of the curves shows that scale effects are negligible for motion studies in wave height equals 1/48th of the model length, and practically negligible in wave height equals 1/30th of the wave length. Speed reduction curves show no scale effects in the milder and some effects in the steeper waves. Resistance coefficients (in waves) show deviations only at low speeds in mild wave conditions, while in steeper waves the resistance coefficients show deviations at all speeds.

Considering the accuracy of the experimental results and the practically significant ship operating ranges only, it can be concluded that at the present time existing experimental techniques do not show significant scale effects.

ACKNOWLEDGMENTS

This paper is the result of the cooperative effort of the members of the Ship Dynamics Branch, David Taylor Model Basin. The experiments were run and the data analyzed under the general supervision of the writers. The special skill and hard work of the co-workers of the authors are gratefully acknowledged. The towing and guidance arrangements for the 10 and 20-ft models were developed and the preliminary design was made by Mr. S. E. Lee. Some of the movie records were read by the personnel of the Reed Research, Inc.

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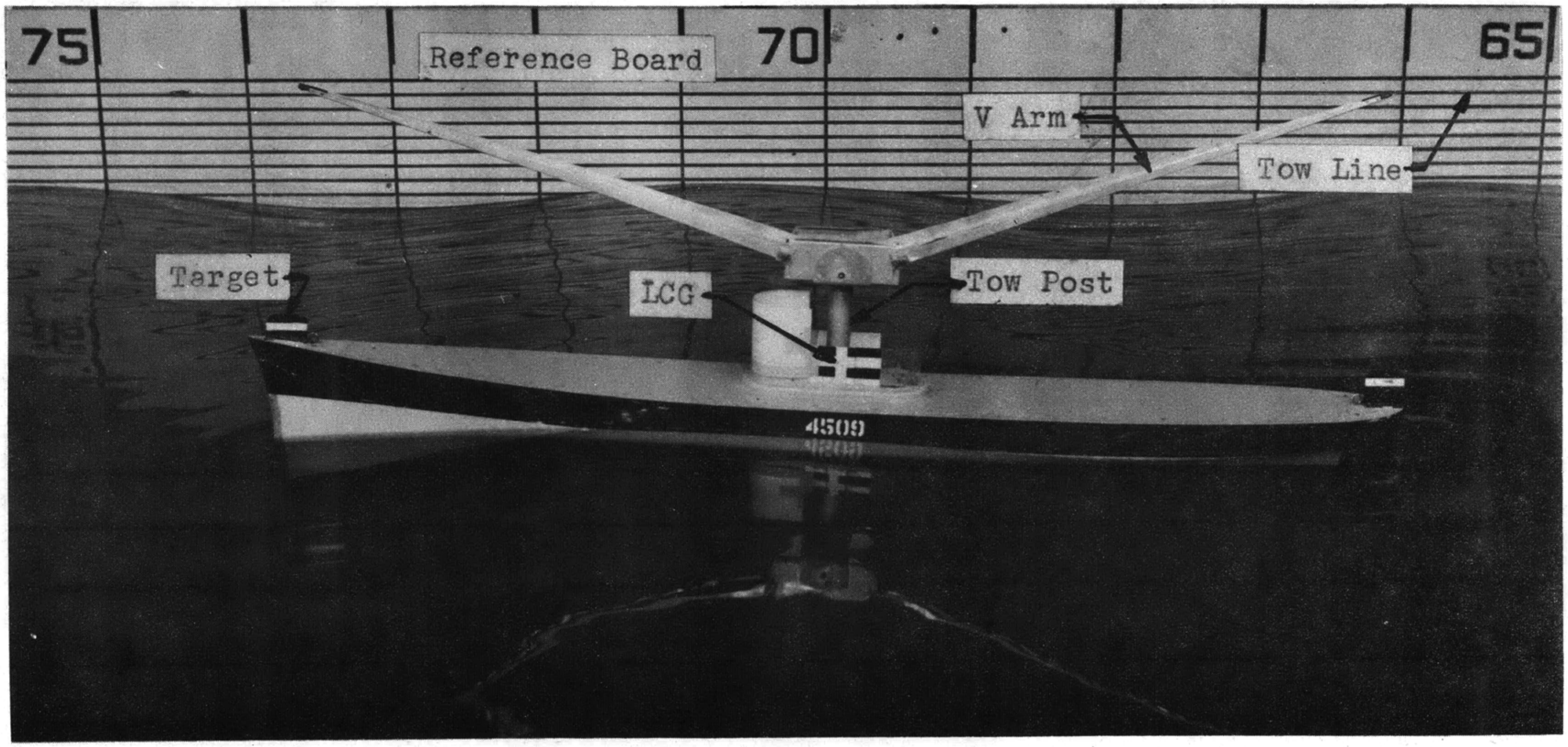
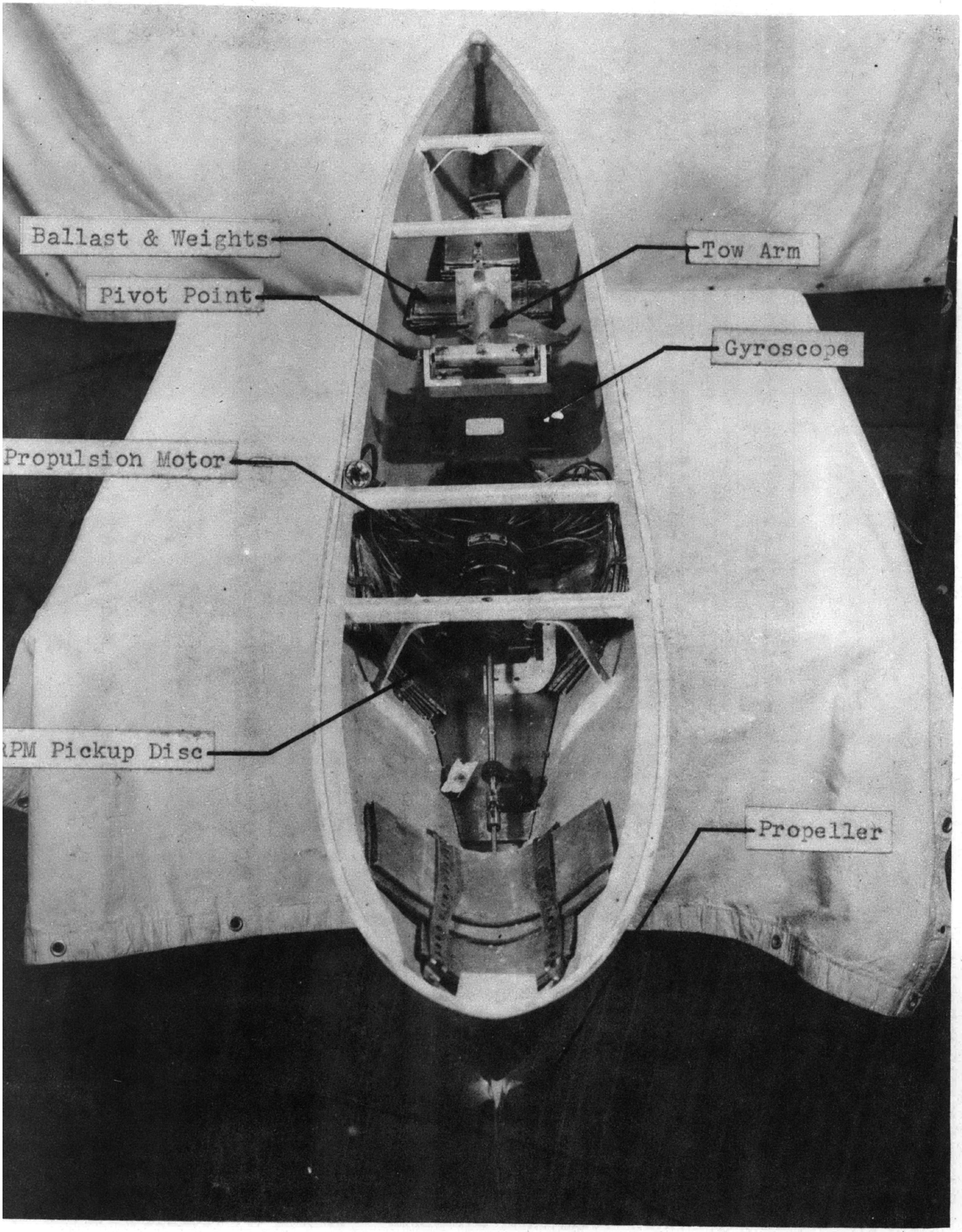
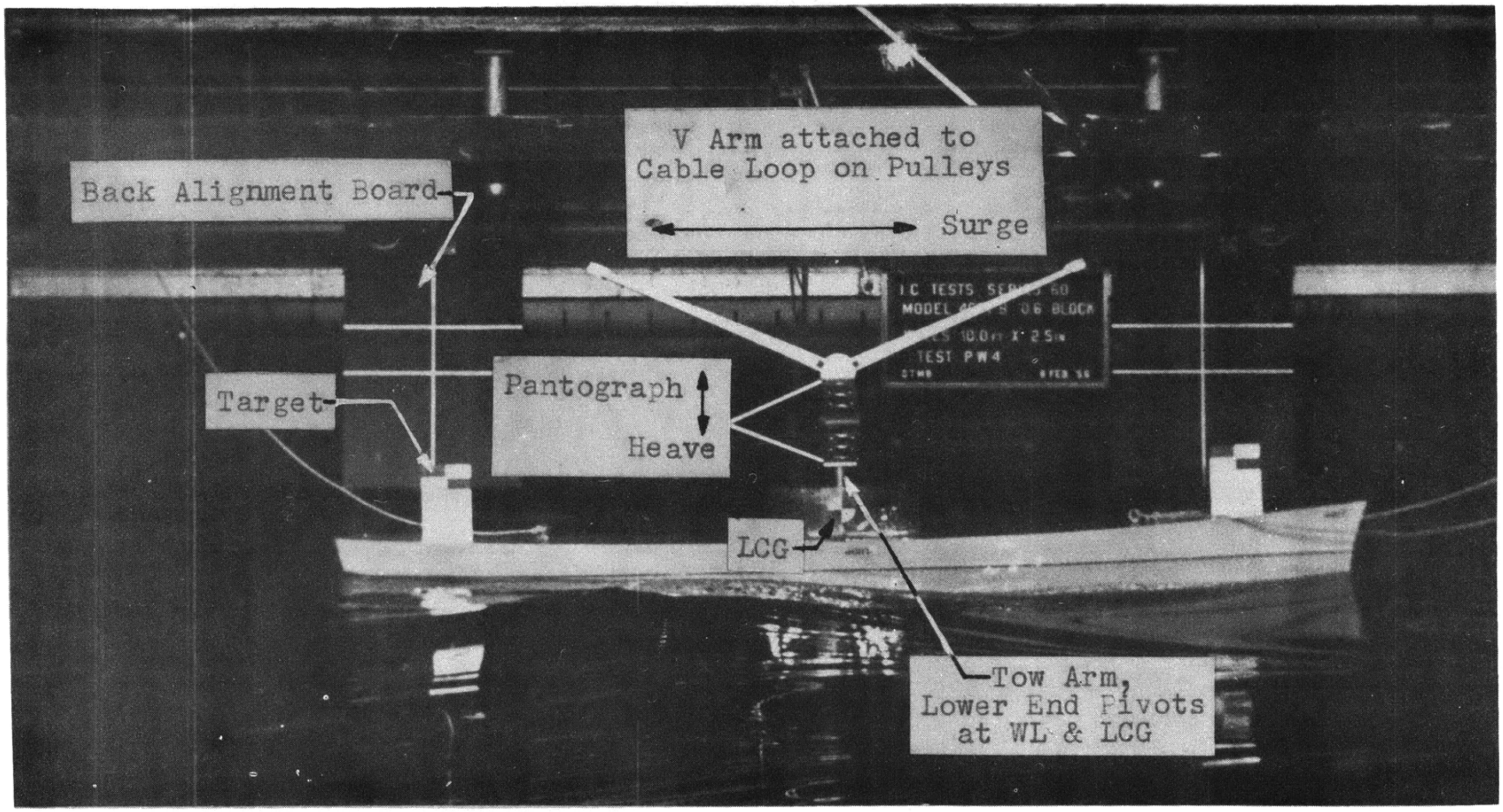


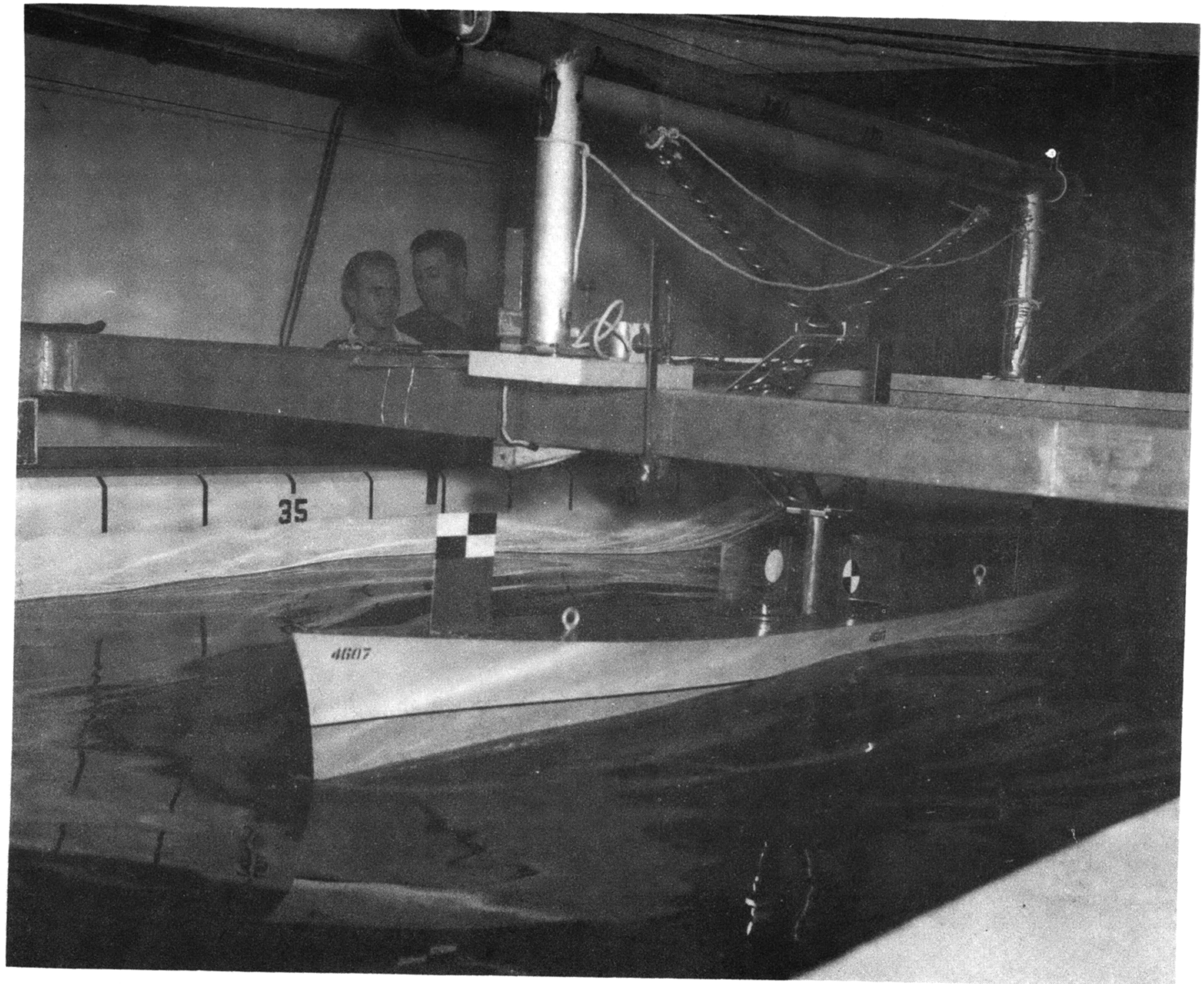
Photograph 1. The 5-ft Model and Towing Arrangement.



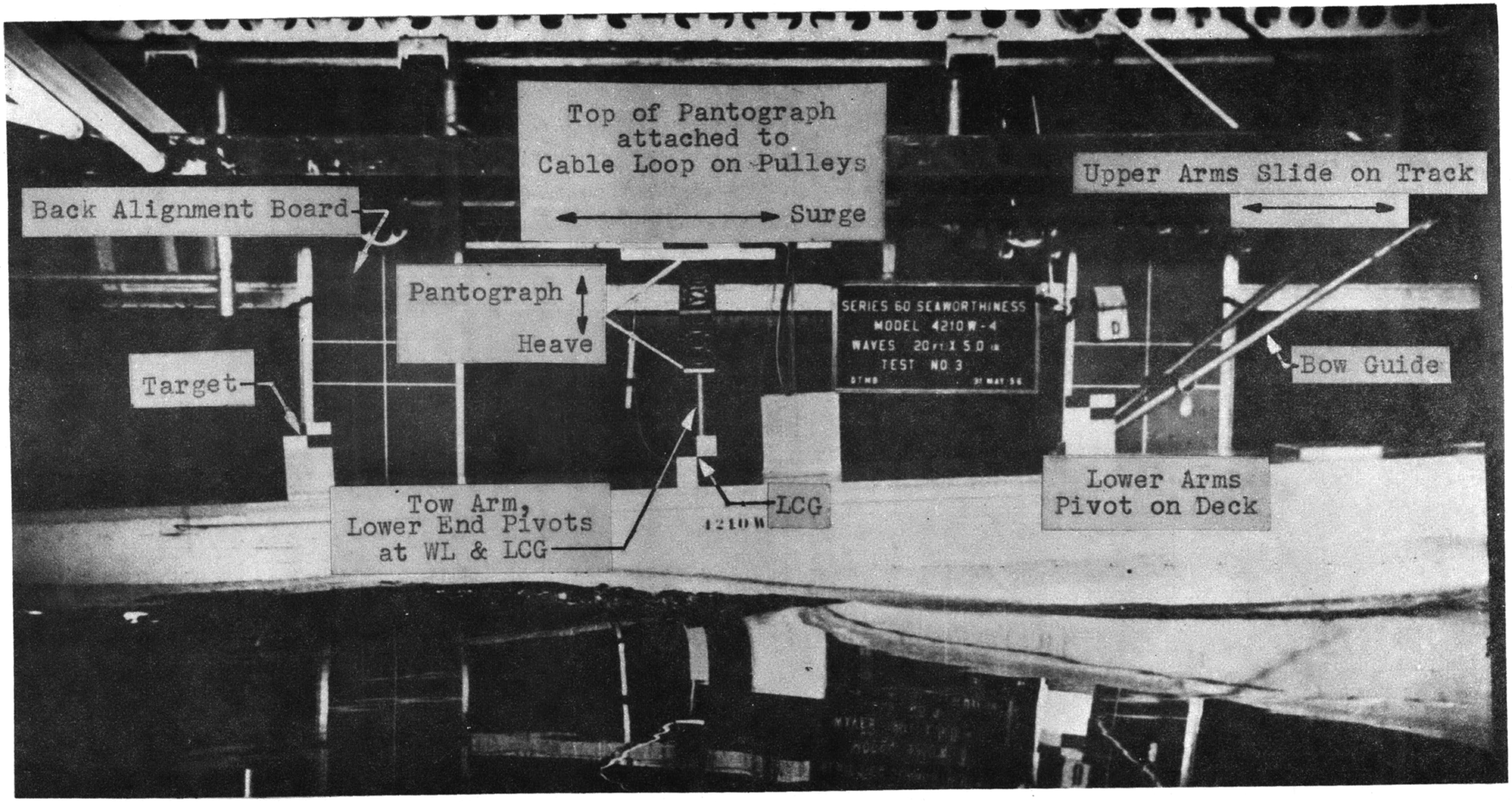
otograph 2. The 10-ft Model and Arrangement of Model Instrumentation.



Photograph 3. The 10-ft Model in the Large Basin.



Photograph 4. The 10-ft Model and Pantograph.



Photograph 5. Testing of the 20-ft Model.

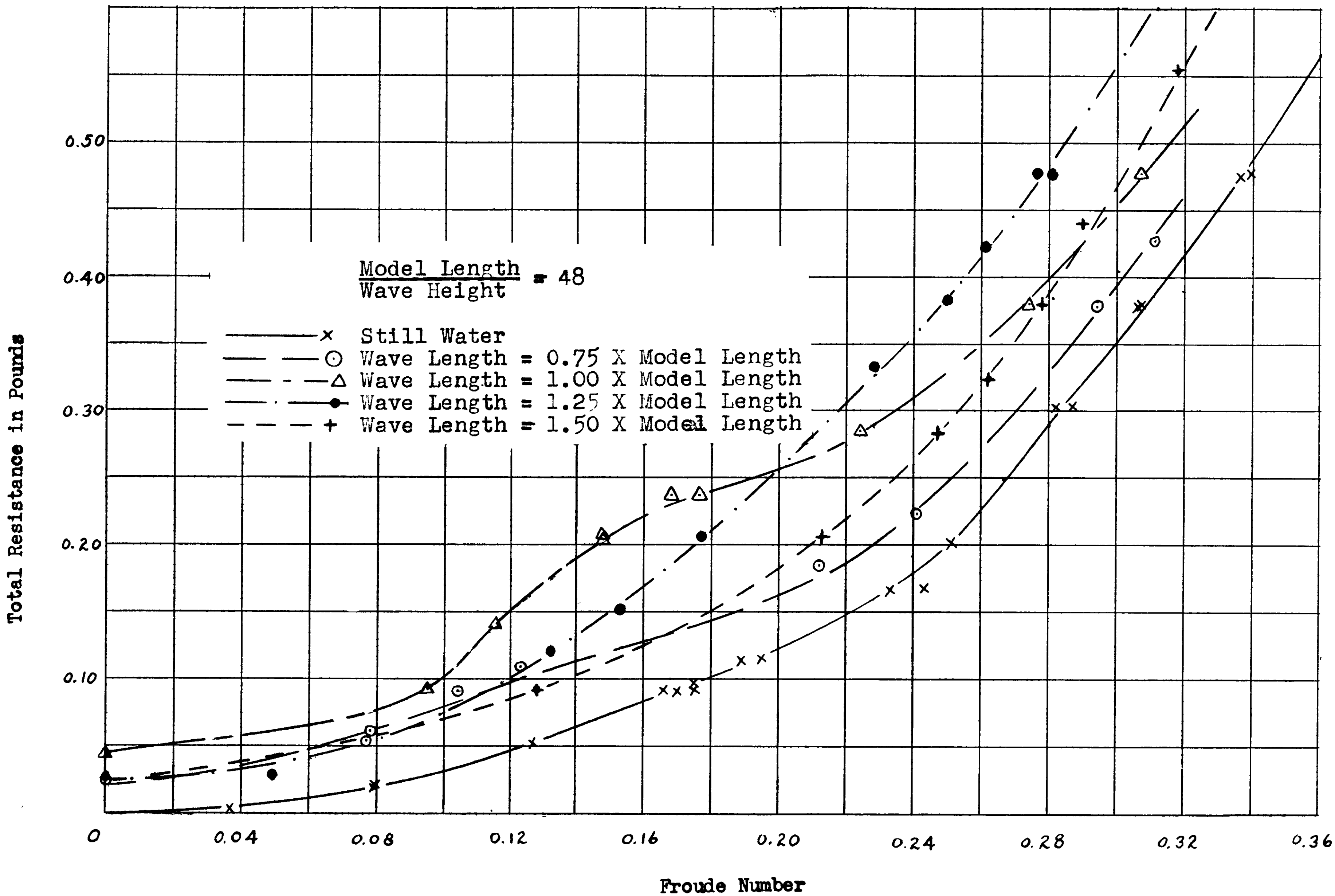


Figure 1 - Model Resistance in Waves of Constant Height- 5-ft Model.

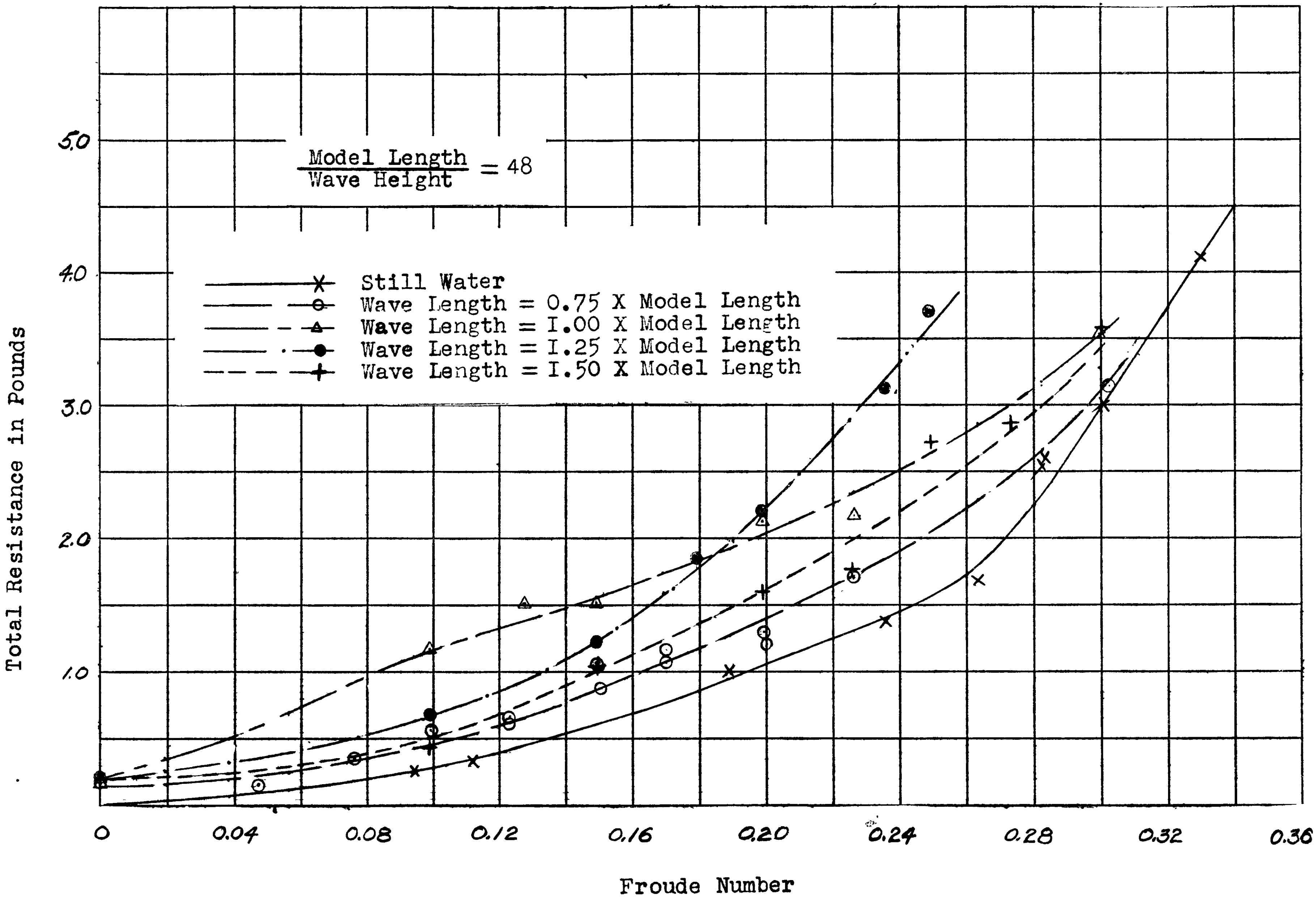


Figure 2 - Model Resistance in Waves of Constant Height-10-ft Model.

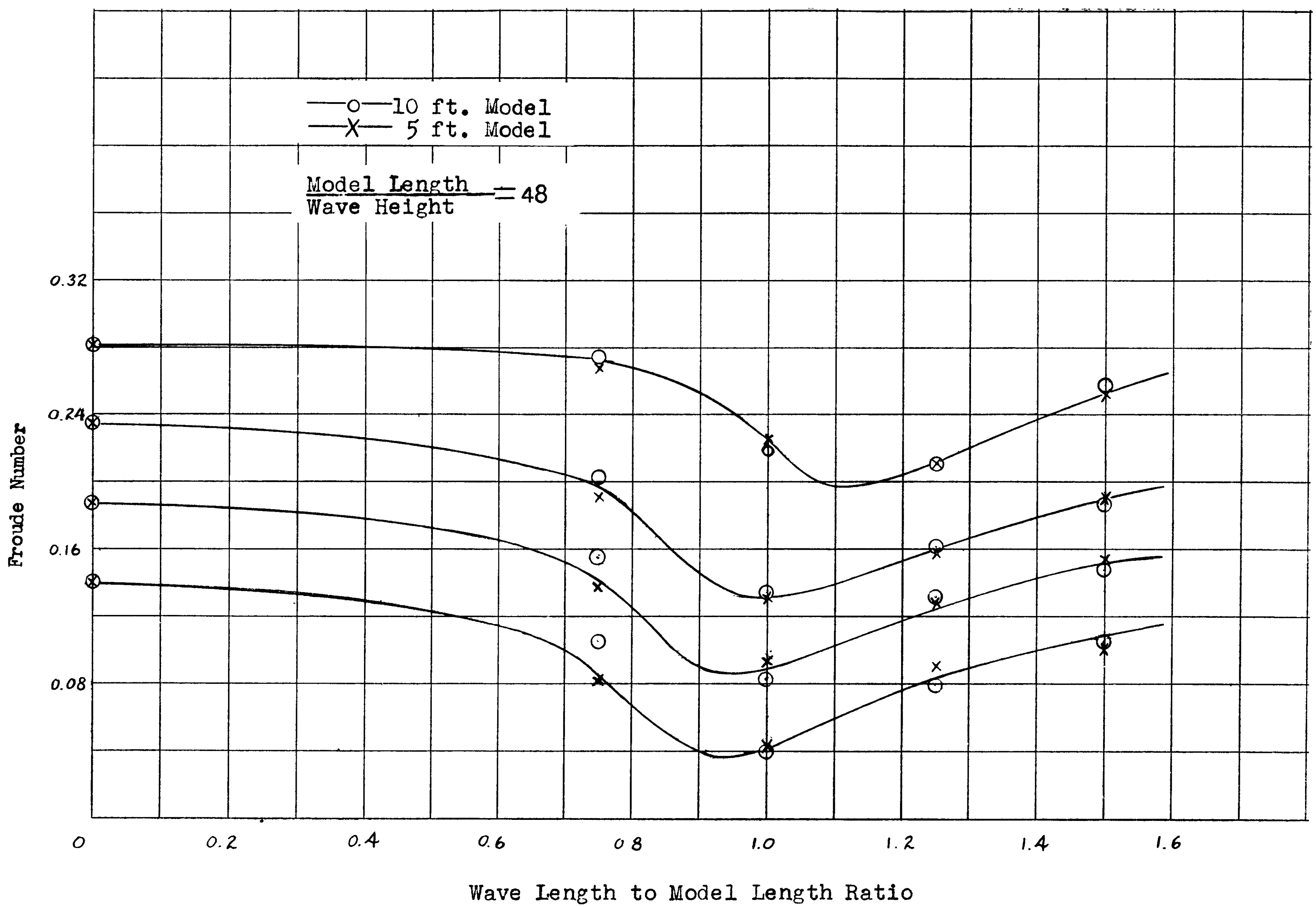


Figure 3 - Speed Reduction in Waves of Constant Height at Constant Tow Force- 5 and 10 -ft Models.

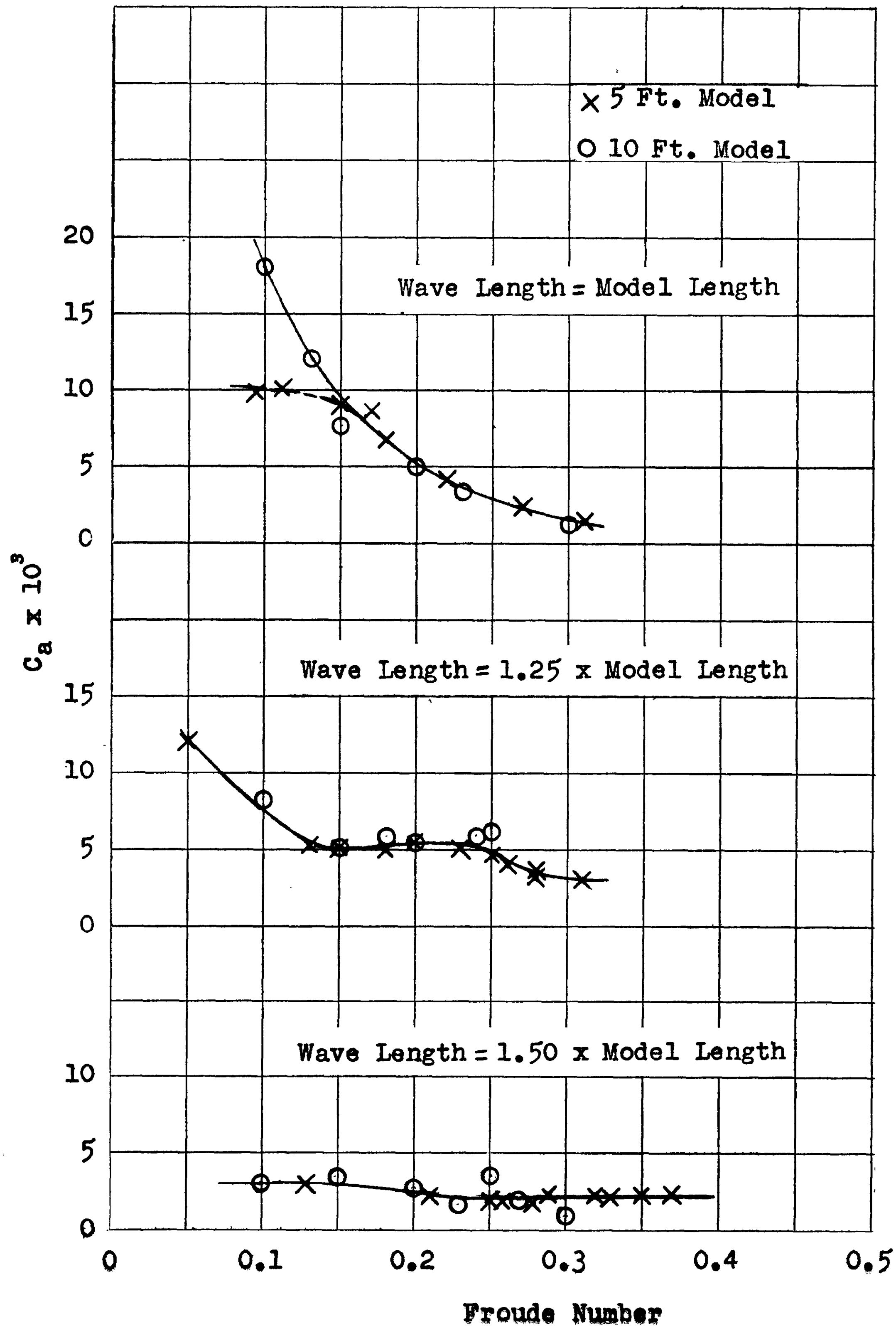


Figure 4. Added Resistance Coefficient in Waves of Constant Height. Wave Height = 1/48 x Model Length.

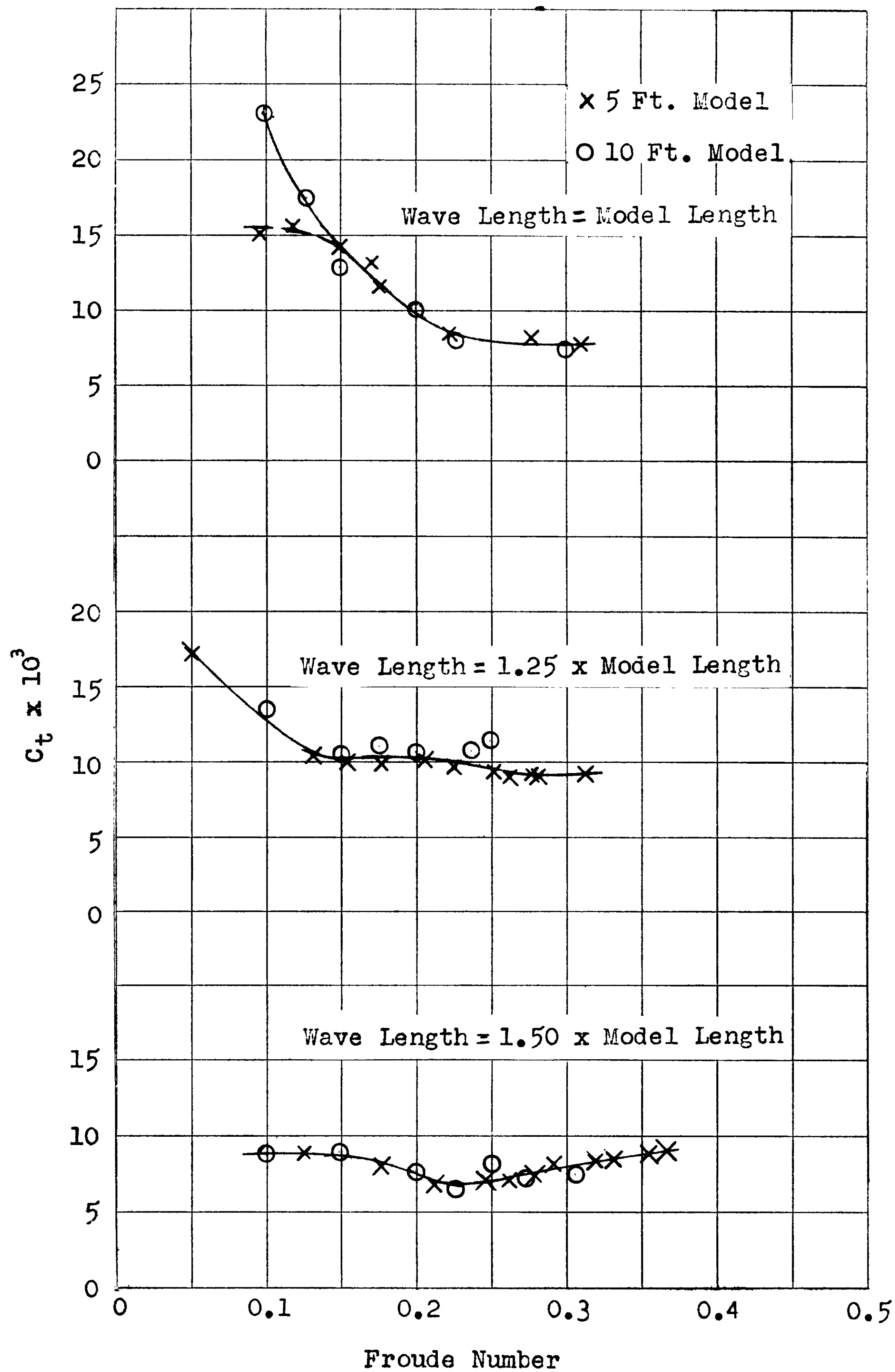


Figure 5. Resistance Coefficient in Waves of Constant Height. Wave Height = 1/48 x Model Length.

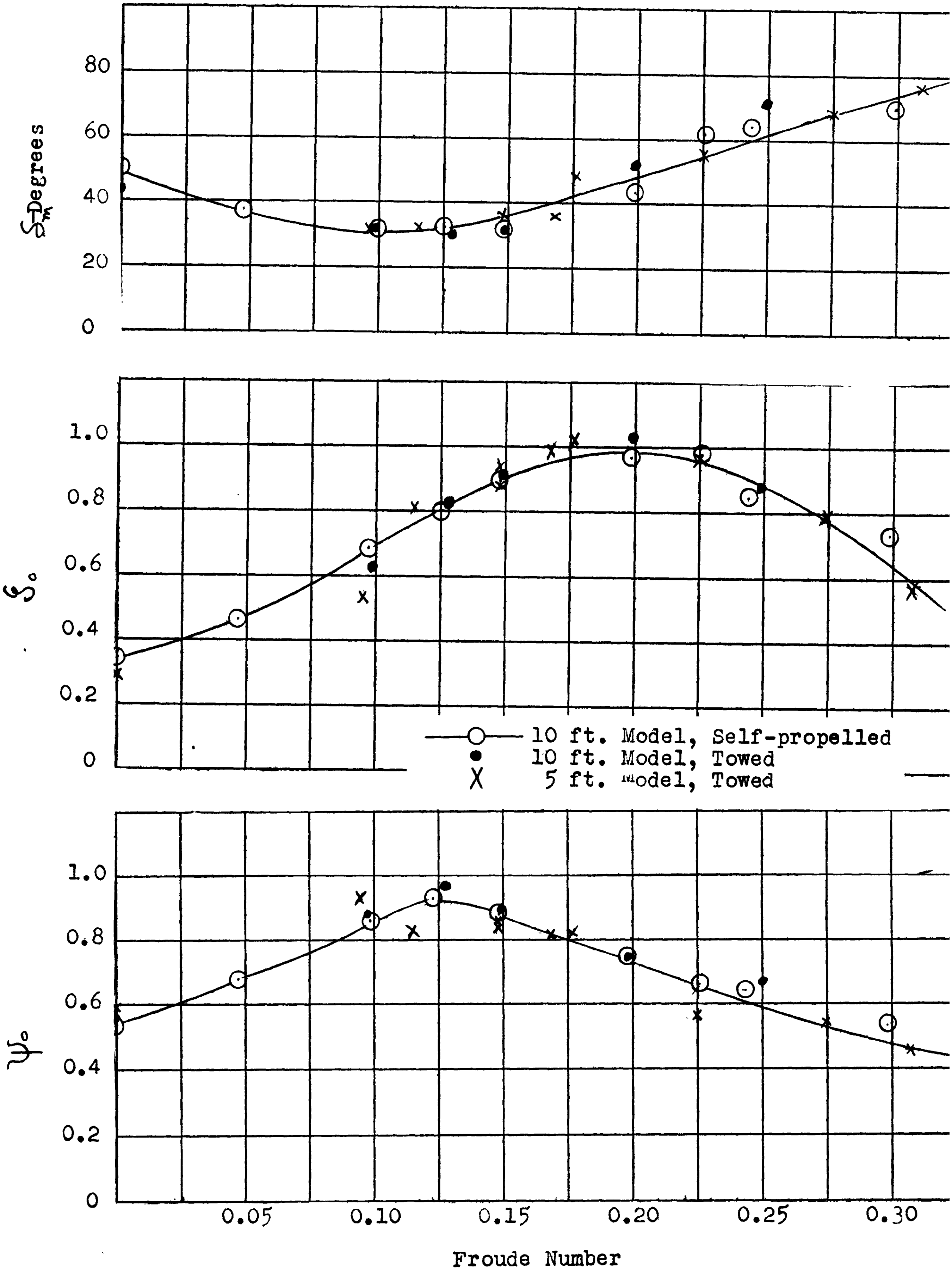


Figure 6- Model Motions in Waves.
Wave Length = Model Length, Wave Height = $\frac{1}{48}$ x Model Length.

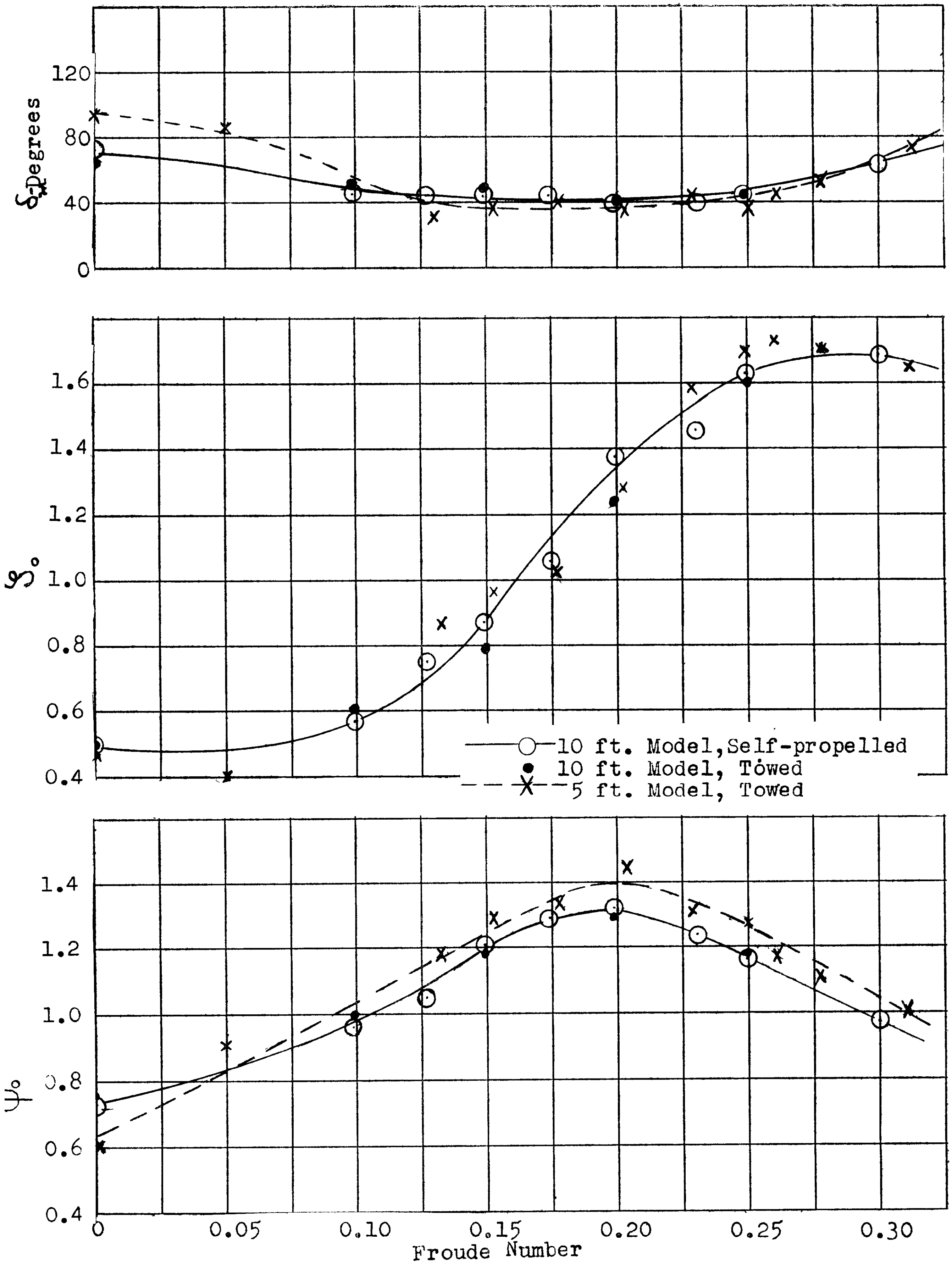


Figure 7 - Model Motions in Waves.
Wave Length = 1.25 x Model Length, Wave Height = $\frac{1}{48}$ x Model Length

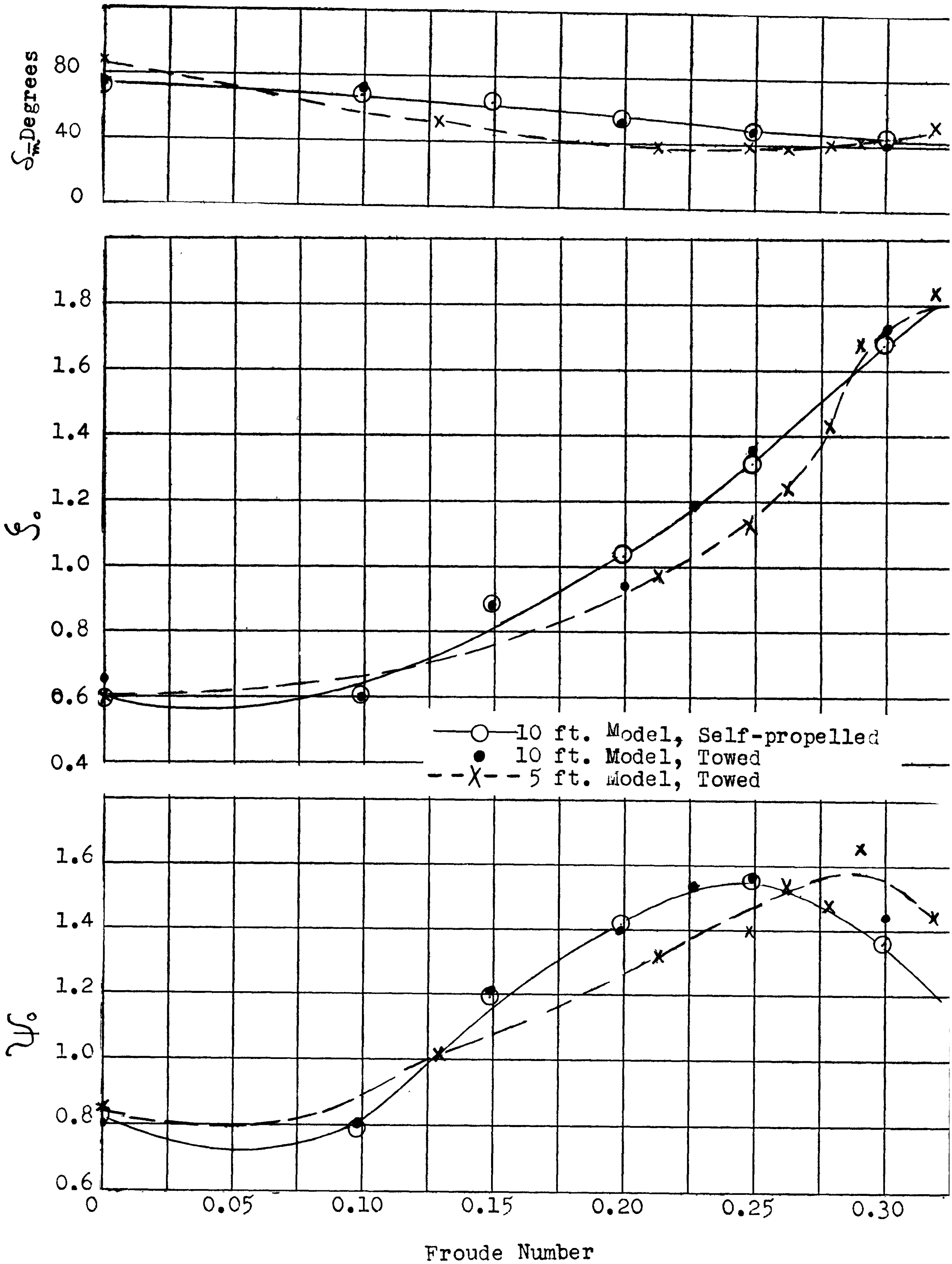


Figure 8 - Model Motions in Waves.
Wave Length = 1.50 x Model Length, Wave Height= $\frac{1}{48}$ x Model Lengt

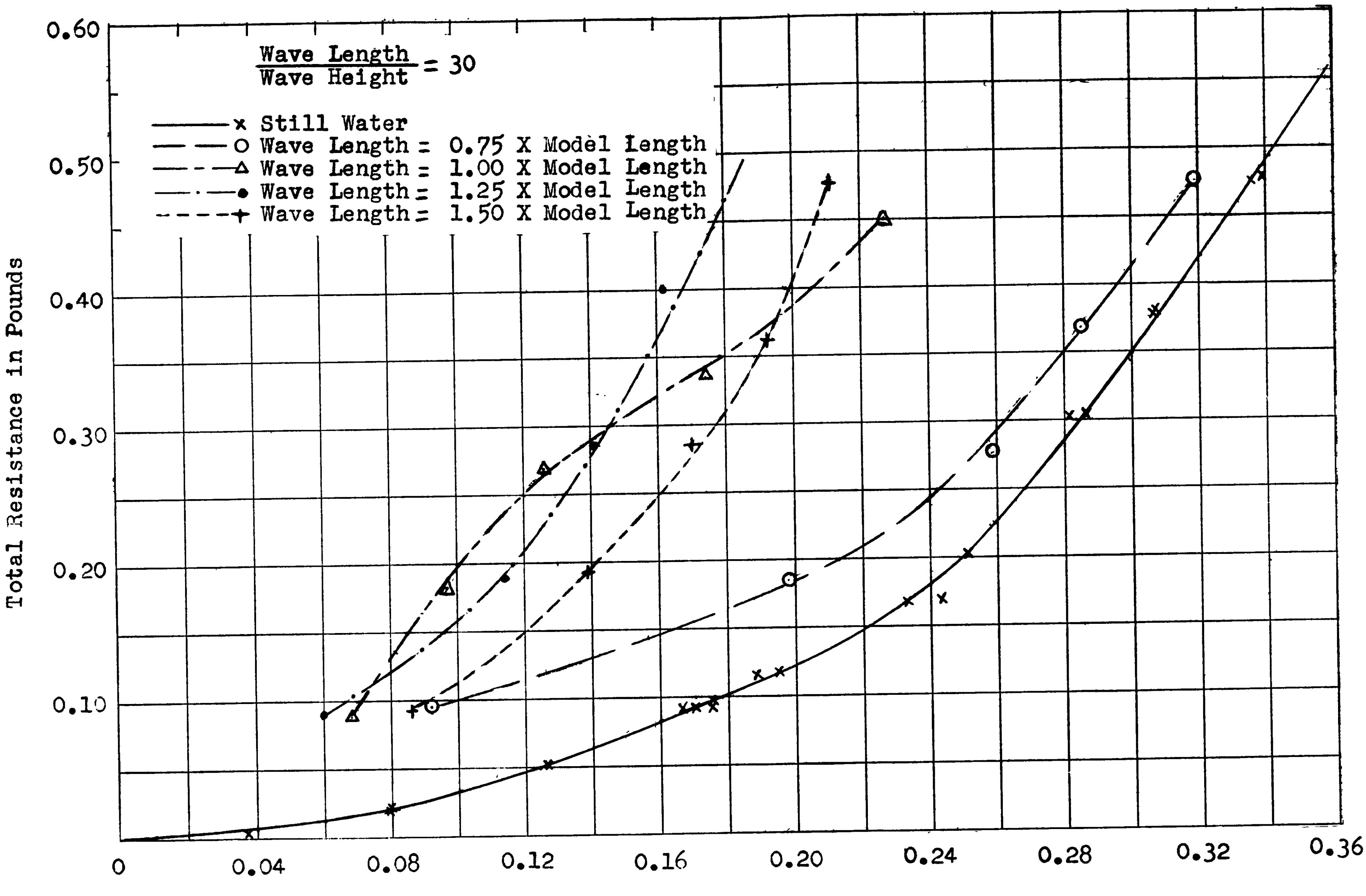


Figure 9 - Model Resistance in Waves of Constant Slope - 5-ft Model.

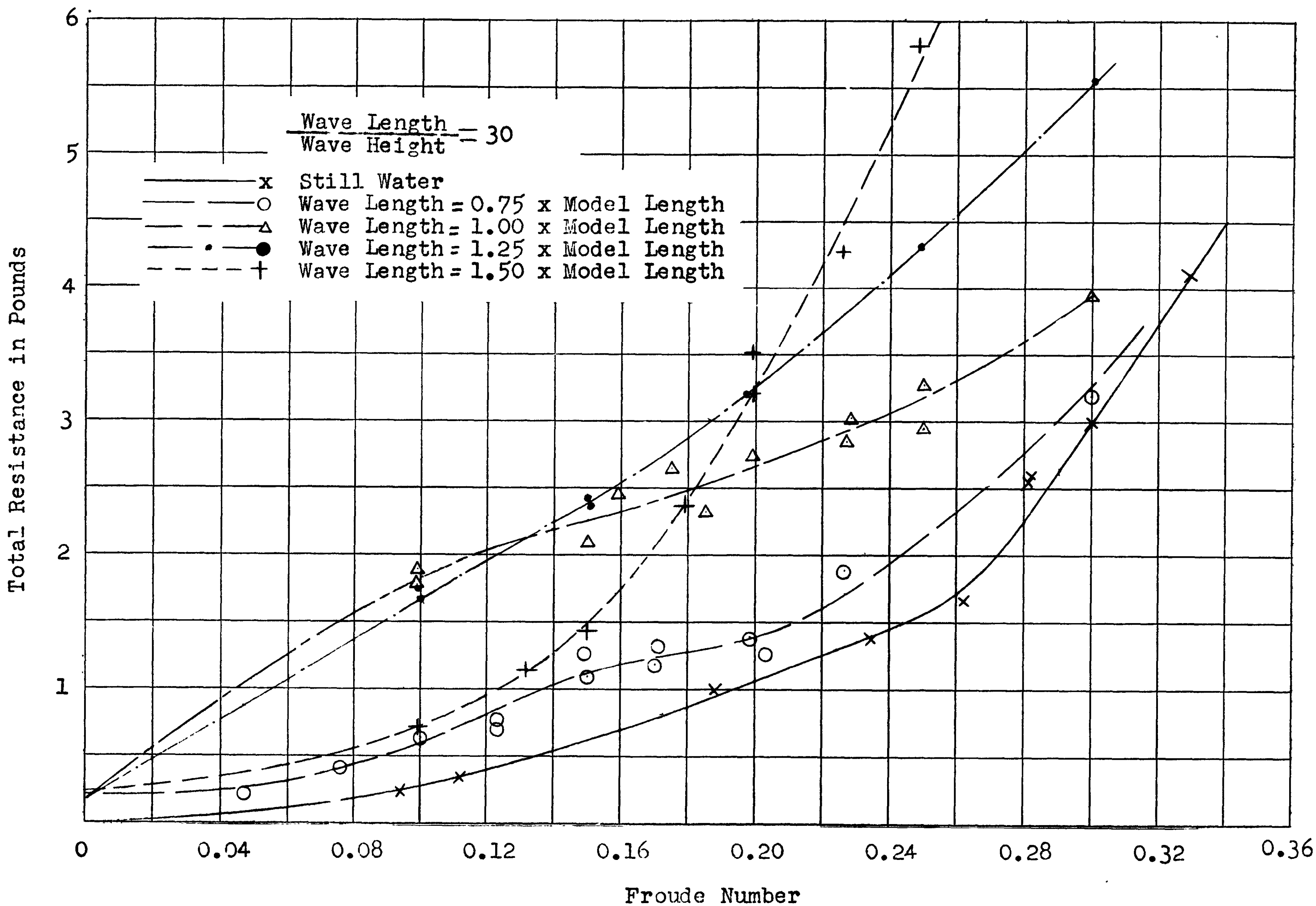


Figure 10- Model Resistance in Waves Of Constant Slope-10 ft. Model

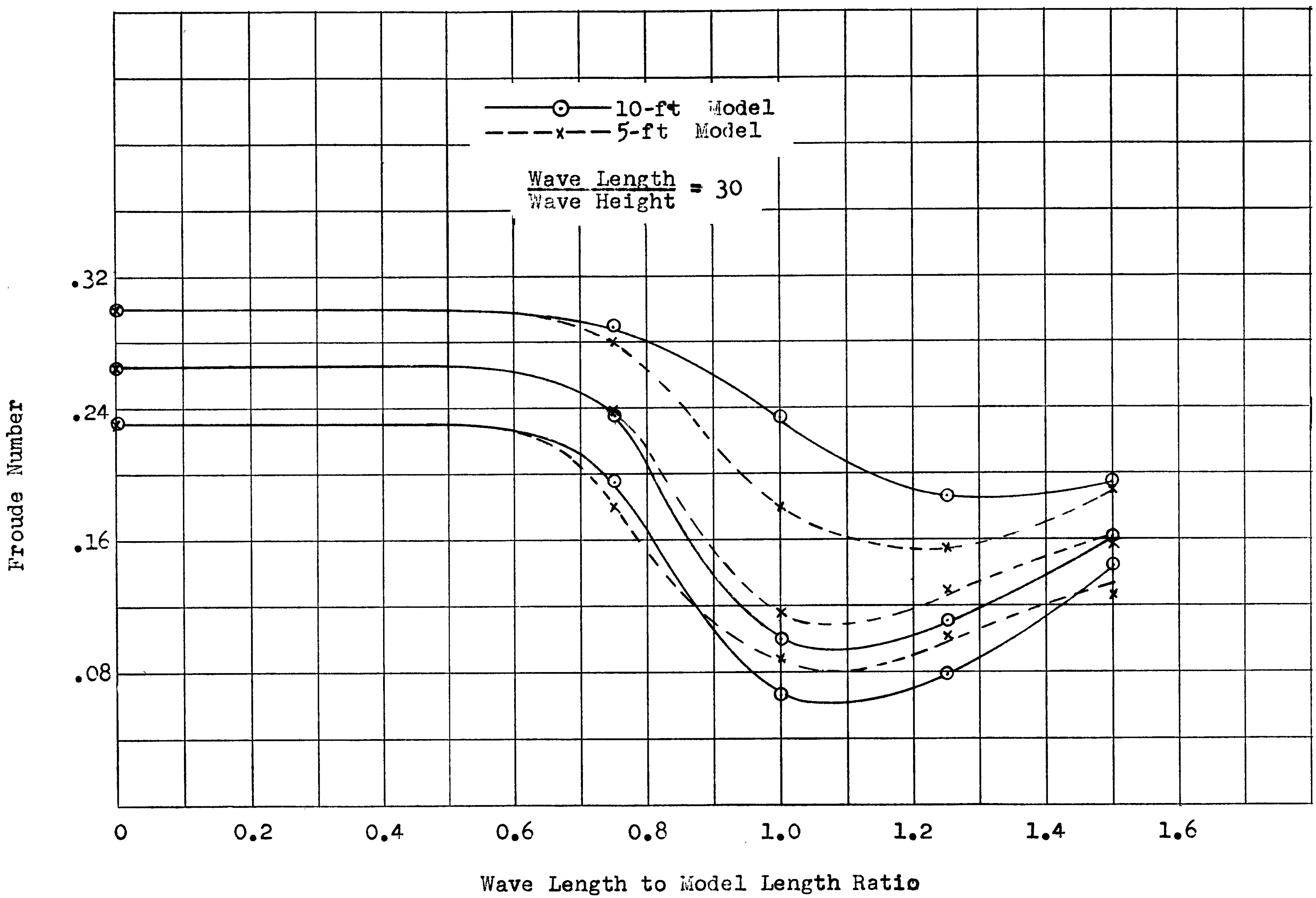


Figure 11 - Speed Reduction in Waves of Constant Slope at Constant Tow Force - 5 and 10-ft Models.

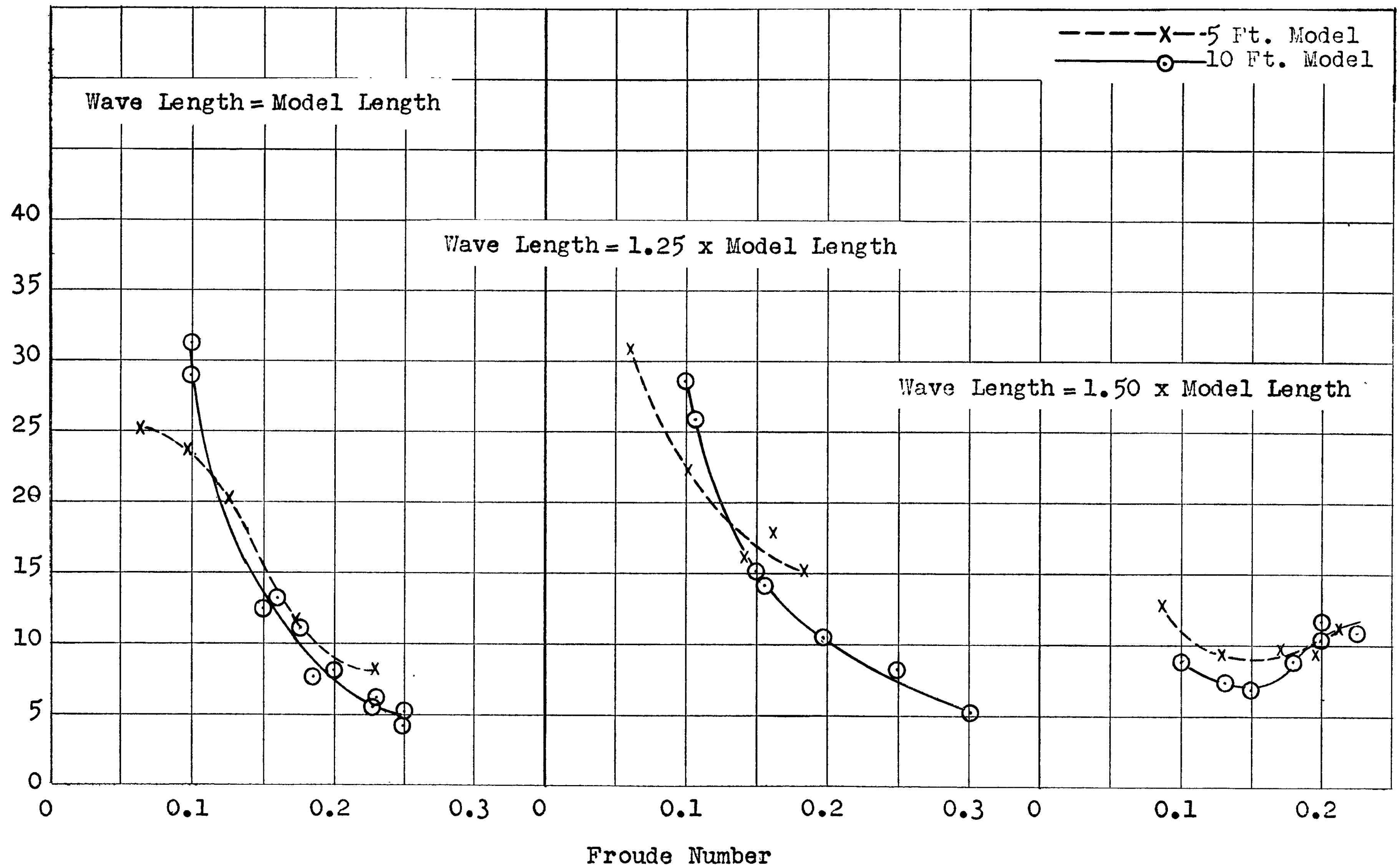


Figure 12. Added Resistance Coefficient in Waves of Constant Slope. Wave Height = 1/30 x Wave Length.

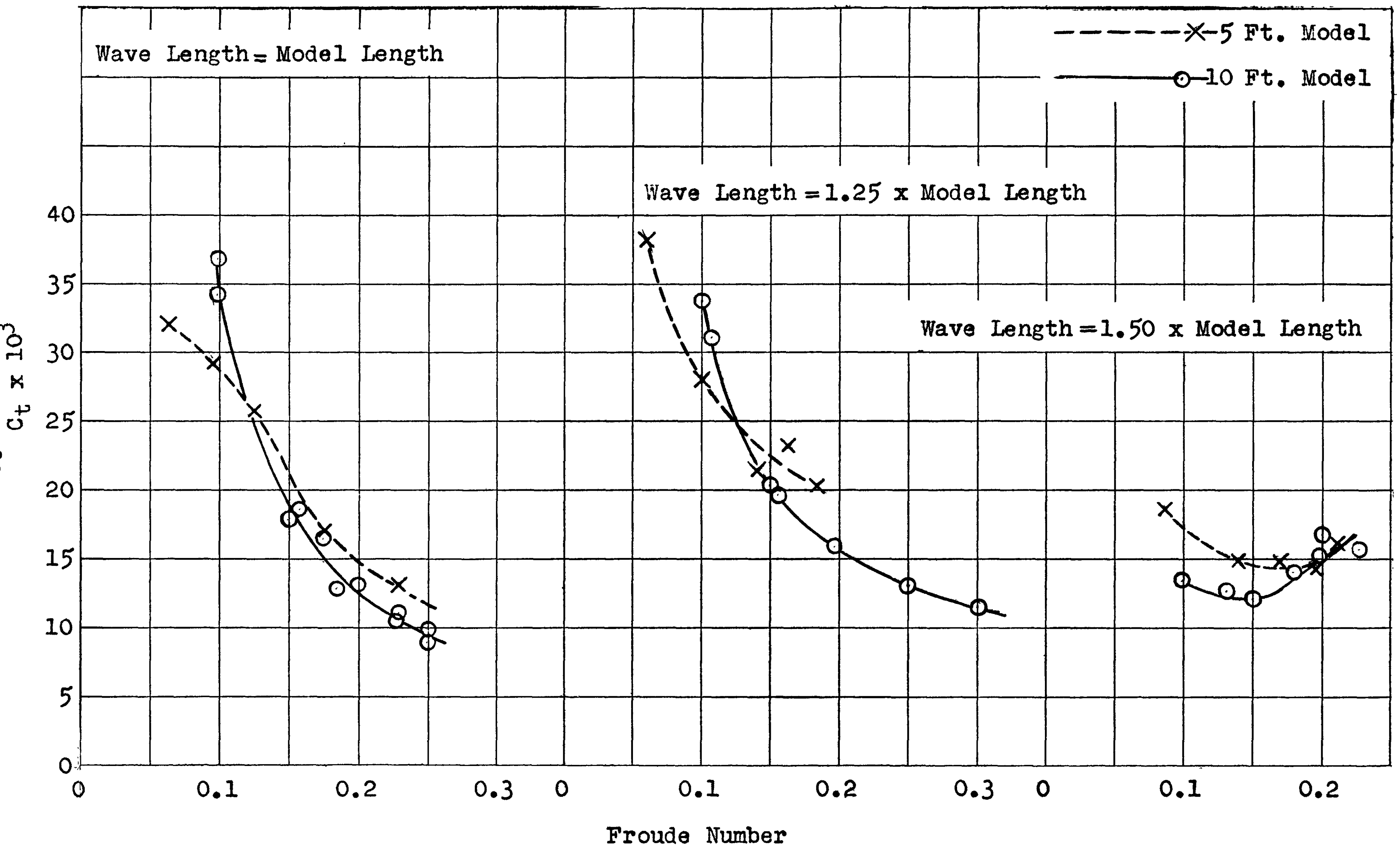


Figure 13. Resistance Coefficient in Waves of Constant Slope. Wave Height = 1/30 x Wave Length.

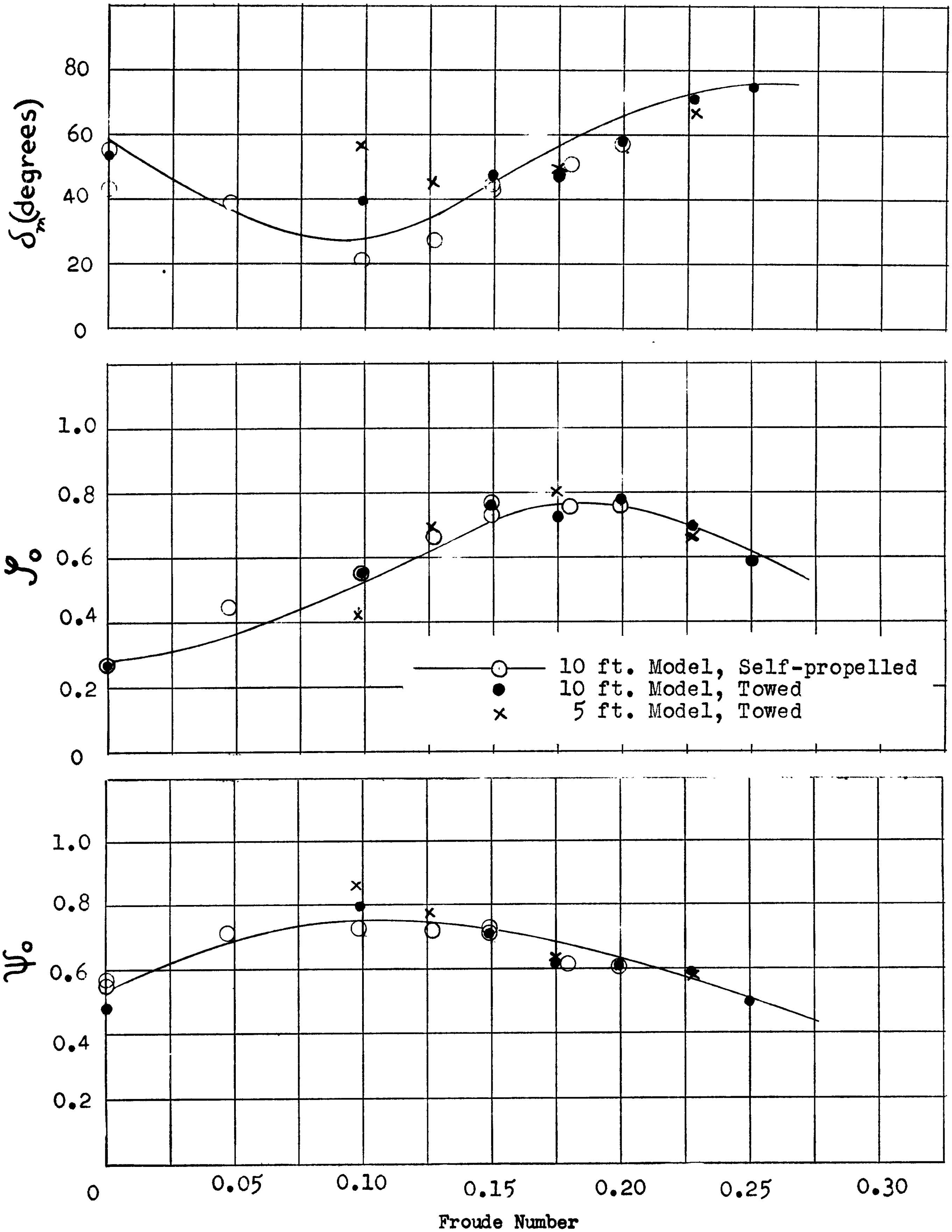


Figure 14. Model Motions in Waves.

Wave Length = Model Length. Wave Height = 1/30 x Wave Length.

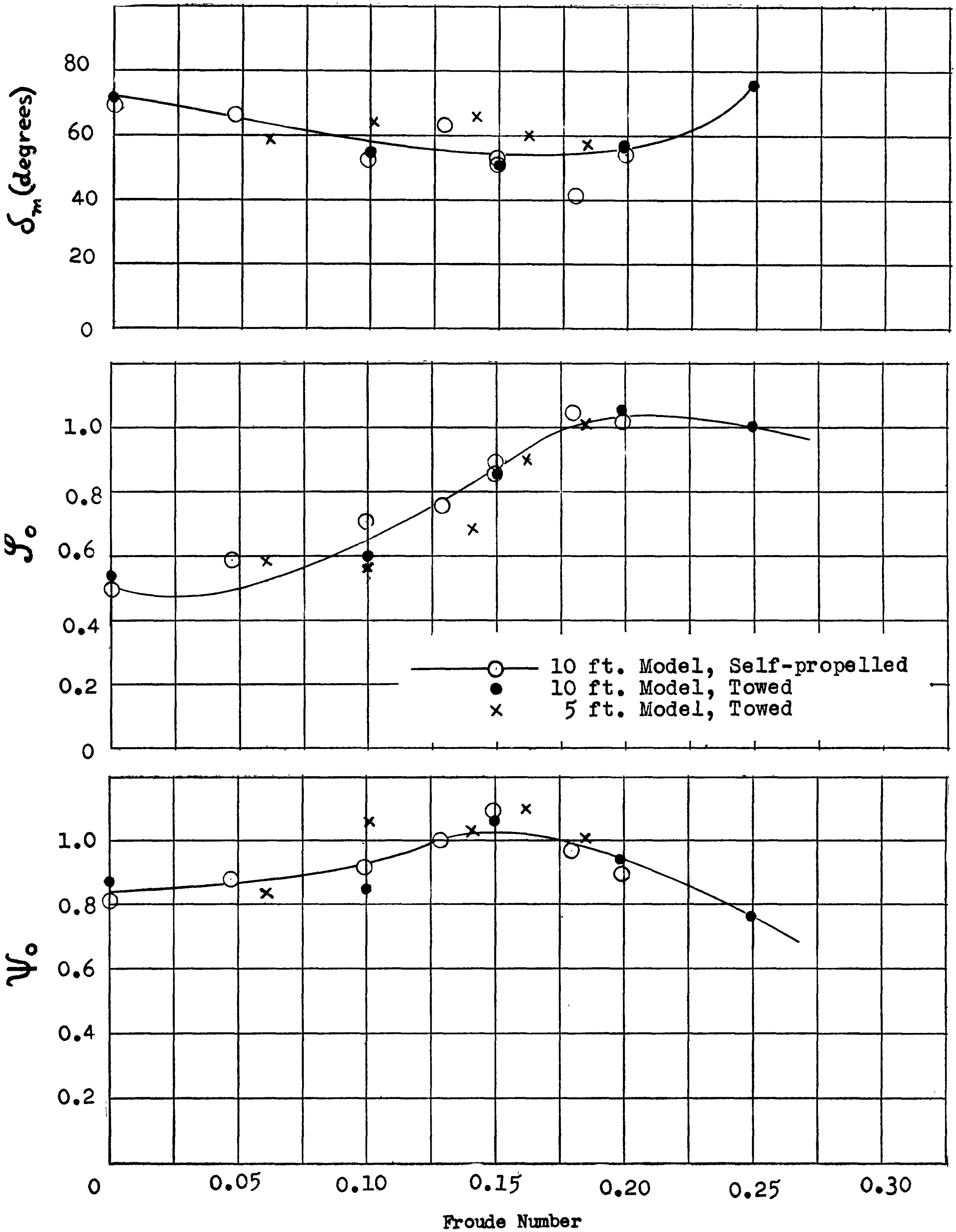


Figure 15. Model Motions in Waves.

Wave Length = 1.25 x Model Length, Wave Height = 1/30 x Wave Length.

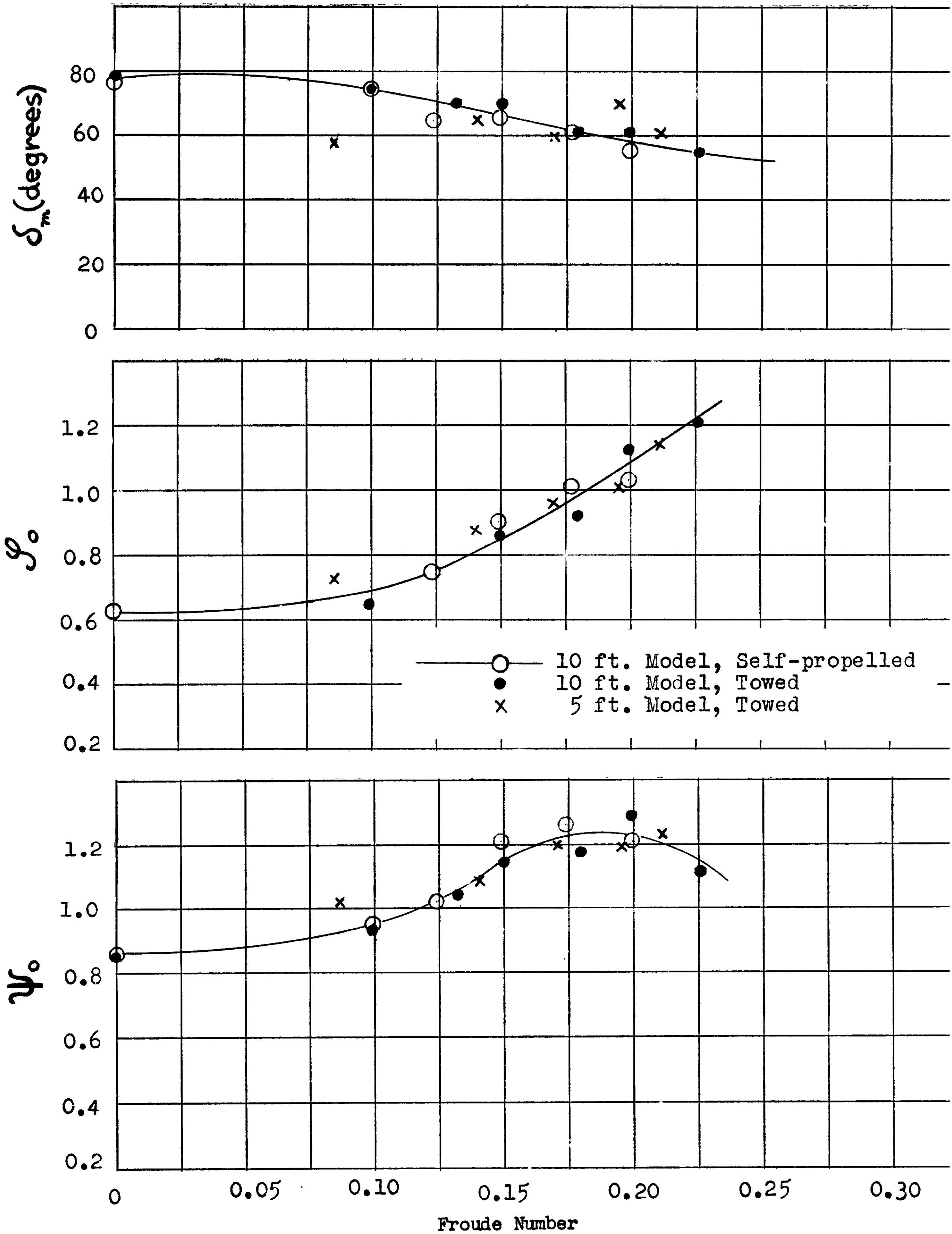


Figure 16. Model Motions in Waves.

Wave Length = 1.50 x Model Length, Wave Height = 1/30 x Wave Length

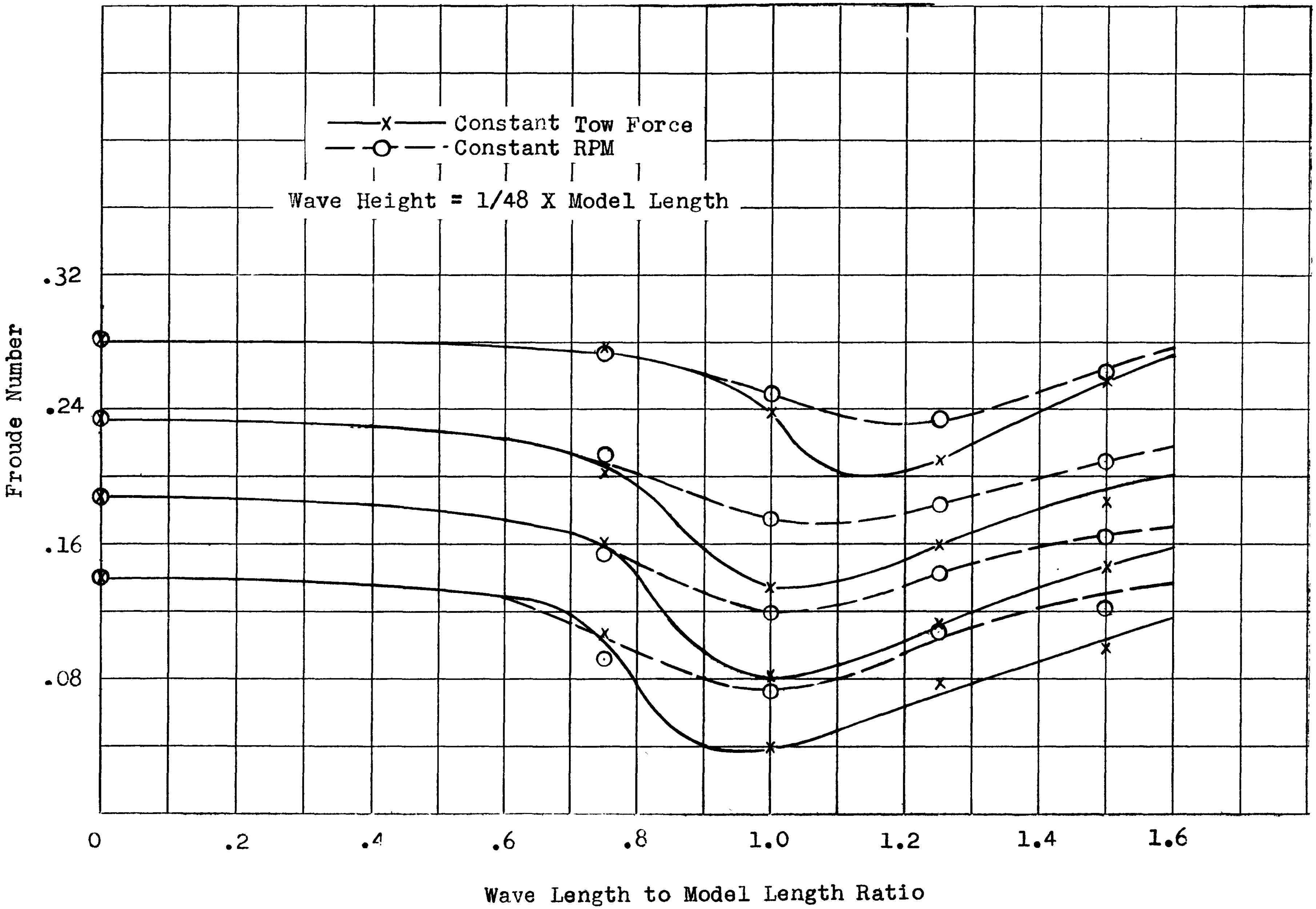


Figure 17

Comparison of Speed Reduction

at Constant Tow Force and Constant RPM in Waves of Constant Height for the 10 ft. Model

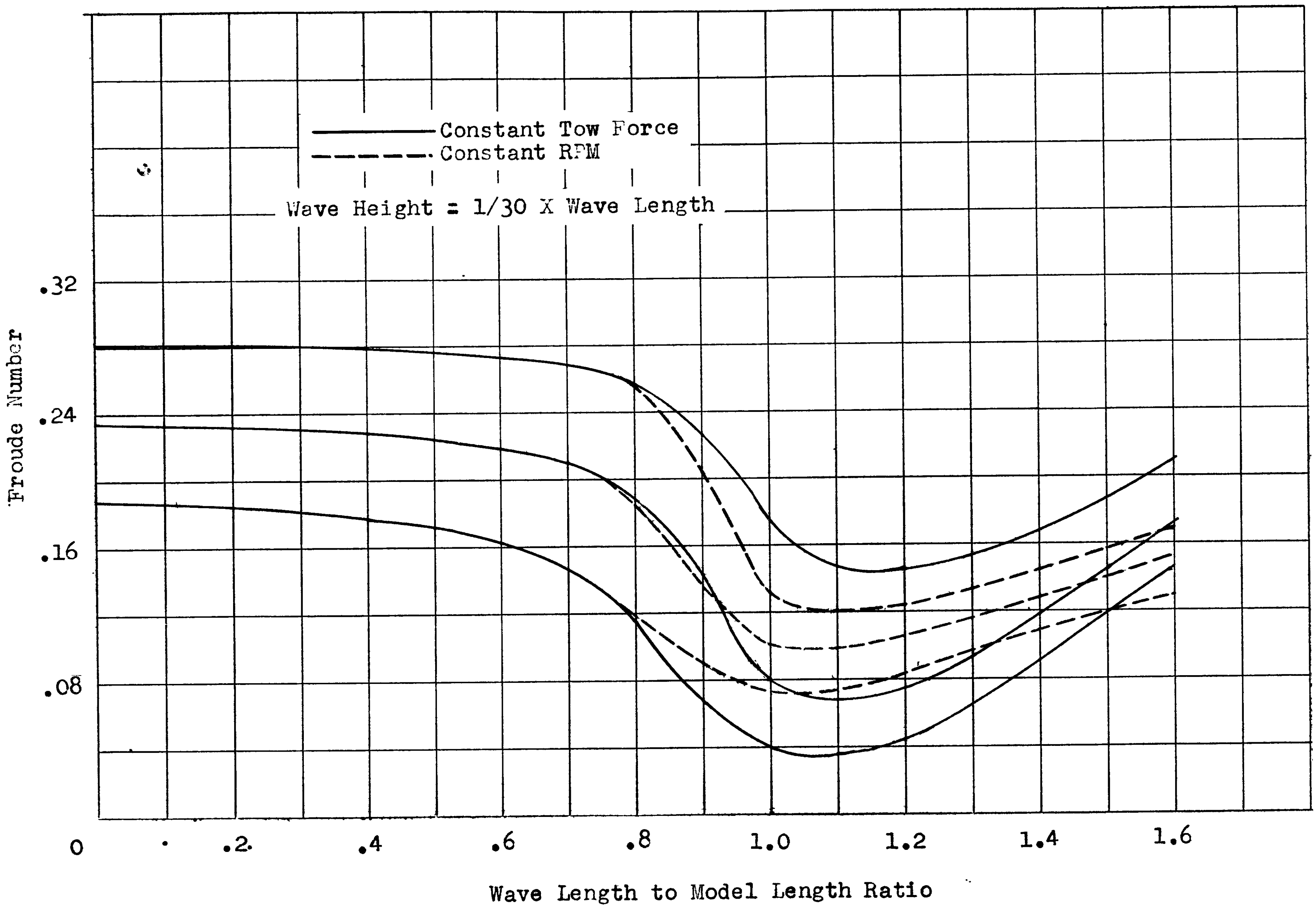


Figure 18

Comparison of Speed Reduction
at Constant Tow Force and Constant RPM in Waves of Constant Slope for the 10 ft. Model

David W. Taylor Model Basin. Rept. 1070.
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It is found that within the accuracy of the experiments, and considering only realistic wave and speed conditions, no practically important scaling effects exist for the form and sizes investigated. It is also shown that self-propulsion and towing tests result in the same motion under the above mentioned specifying conditions.

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