

## CHAPTER 68

### FLOATING BREAKWATERS

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#### ABSTRACT

The general objective of this investigation is to determine the wave damping characteristics of model floating breakwaters designed to reduce incident wave heights by processes of wave reflection, wave interference, forced instability of incident waves and turbulence action. Of most interest is the attempt to determine the method and the extent to which the requirement of large mass may be usefully replaced by large moment of inertia of mass in the development of floating breakwaters. Experiments are conducted in a two-dimensional wave channel. Reflection coefficients, transmission coefficients, breakwater motions and mooring forces are determined by experiments. It is found that the range of effectiveness in wave attenuation of floating breakwaters depends on several factors including breakwater design, incident wave properties, depth of water and the motion characteristics of the structures. It is remarkable that the 'A' Frame Breakwater exemplifies that the range of effectiveness of a floating breakwater can be increased by a large increase of its radius of gyration involving only a slight increase of its mass. The mooring forces are of reasonable magnitude. Experimental measurements and observations indicate that the 'A' Frame Breakwater

is stable throughout the range of model tests.

#### INTRODUCTION

Floating breakwaters offer numerous advantages as compared to fixed structures such as the rubble-mound and caisson breakwaters in certain engineering applications involving the provisions of temporary harbours for seasonal or transient marine activities, the development of marinas for recreational purposes, and in the protection of reclaimed lands. Marinas built in certain inland bodies of water may require breakwaters which can be installed during the summer months but are removed during the winter months due to ice formation. The important features of floating breakwaters include mobility, short erection time, freedom from silting, scour and foundation problems, and comparatively small initial and maintenance costs, especially for deep water locations. The development of floating breakwaters by investigators has been influenced by certain features including large masses and hence long natural periods of oscillation, small amplitudes of oscillations of massive structures subjected to waves of small periodicities and large damping. A summary of previous investigations on transportable breakwaters is given by Bulson (1). Results of laboratory tests on floating rigid breakwaters can be found in Marks (2), Homma et al (3) and Kato et al (4).

#### Description of Floating Breakwaters

Fig. (1) shows the basic unit of the 'A' Frame breakwater developed by the Department of Public Works of Canada, and Figs. (2a) and (2b) show variations of the basic unit. The 'A' Frame consists

essentially of a central rigid curtain of wood, and two aluminum cylinders symmetrically located and rigidly connected to the curtain at intervals. The mass radius of gyration of the structure about a lateral axis through its centre of gravity (axis parallel to wave crest) may be varied by altering the cylinder spacing. The lower cylinders in Figs. (2a) and (2b) are 50% porous. In Fig. (2a) the upper and lower cylinders are connected by a series of chains. In Fig. (2b) the cylinders are welded. The 'A' Frame Breakwaters are shown in Plate (1). The Pontoon, Fig. (3) is a massive unit of rectangular cross-section. The Double Module breakwater shown in Fig (4) consists essentially of two massive units of Prismatic cross-sections. The depths of submergence of the Double Module and Pontoon depend on their masses. The properties of the breakwaters are shown in Tables 1 and 2.

Dimensional Considerations

The physical factors which influence the transmission coefficient, reflection coefficient and the horizontal components of the mooring forces of the 'A' Frame breakwater are considered. The analysis refers to the 'A' Frame shown in Fig. (1).

The transmission coefficient  $H_t/H_1$  is expressed as

$$K_t = H_t/H_1 = f (H_1, L, L_1, h_1, h_3, d, \gamma_b, \gamma_w, \gamma_s) \dots (1a)$$

Hence 
$$K_t = f_1 \left( \frac{H_1}{L}, \frac{L}{L_1}, \frac{h_1}{L}, \frac{d}{L}, \frac{h_3}{L}, \frac{\gamma_w}{\gamma_b}, \frac{\gamma_s}{\gamma_w} \right) \dots (1b)$$

The condition for no wave breaking over the structure is expressed as

$$h_3 > \Delta h + \left| \eta_t + \eta_r \right|_{\max} \dots (2)$$

$d_2/d_1$	Wt. lbs.	Radius of Gyration $K_2$ ft.	Metacentric height GM ft.	Natural Period of Heaving $T_h$ Secs.	Natural Period of Rolling $T_r$ Secs.	$T_h/T_r$
PONTON						
0.45	45	.475	1.023	.52	.52	1.0
.58	58	.47	0.814	0.591	0.579	1.022
0.92	92	0.468	0.556	0.744	0.696	1.068
DOUBLE MODULE						
.32	19.6	.539	1.6	.441	.472	.935
.44	27.0	.53	1.182	.518	.540	.96
.48	29.4	.528	1.073	.542	.565	.96

TABLE I Properties of Pontoon and Double Module

Half-Cylinder Spacing $L_1$ (ft.)	Wt. of Breakwater $W_1$ (lbs.)	Radius of Gyration $K_2$ (ft.)	Meta-centric Height GM (ft.)	Angle of Heel (degree)	Natural Period of Rolling Motion $T_r$ (sec.)
1.17	16.4	1.01	2.92	2.5	0.655
			1.87	5.0	0.82
1.92	17.08	1.58	7.65	1.5	0.63
			5.06	3.0	0.778
1.41	16.64	1.19			
0.54	15.9	0.53			
$h_1 = 1.17$ ft.					

TABLE (2) Properties of the 'A' Frame Breakwater

where  $\eta_i$  and  $\eta_r$  are the instantaneous elevations of the incident and reflected waves, respectively above still water level and  $\Delta h$  is the rise in still water level given to first order approximation

by

$$\Delta h = \frac{H_i^2}{L} \text{ Coth } Kd$$

For a given breakwater system  $\frac{\gamma_w}{\gamma_b}$  and  $\frac{\delta_s}{\gamma_w}$  are constant, and if the condition expressed in Eq. (2) obtains, expression (1b) can be simplified

by combining  $h_i/L$  and  $d/L$  to give

$$K_T = f_2 \left( \frac{H_i}{L}, \frac{L}{L_i}, \frac{h_i}{d} \right) \quad \dots (3)$$

Since  $\frac{T_n}{T} = f_0 \left( \frac{L}{L_i} \right),$

$$K_T = f_3 \left( \frac{H_i}{L}, \frac{T_n}{T}, \frac{h_i}{d} \right) \quad \dots (4)$$

For deep water waves ( $d \geq L/2$ ) and for values of  $h_i \approx L/2,$

$$\begin{aligned} K_T &= f_4 \left( \frac{H_i}{L}, \frac{L}{L_i} \right) \\ &= f_5 \left( \frac{H_i}{L}, \frac{T_n}{T} \right) \end{aligned} \quad \dots (5)$$

Similarly the reflection coefficient  $\frac{H_r}{H_i}$  is expressed as

$$K_r = H_r/H_i = f_6 \left( \frac{H_i}{L}, \frac{L}{L_i}, \frac{h_i}{d} \right) \quad \dots (6)$$

and may be simplified to give

$$\begin{aligned}
 K_r &= f_7 \left( \frac{H_i}{L}, \frac{L}{L_1} \right) \\
 &= f_8 \left( \frac{H_i}{L}, \frac{T_n}{T} \right) \quad \dots (7)
 \end{aligned}$$

The horizontal component of the mooring force is expressed as

$$F = \phi (H_i, H_r, L, L_1, h_1, d, \gamma_w, \gamma_b, \gamma_s) \quad \dots (8a)$$

Hence 
$$\frac{F \cdot h_1}{\gamma_w H_i^2 L} = \phi_1 \left( \frac{H_i}{L}, \frac{H_r}{H_i}, \frac{L}{L_1}, \frac{\gamma_w}{\gamma_b}, \frac{\gamma_s}{\gamma_w}, \frac{h_1}{d} \right) \quad \dots (8b)$$

For deep water waves and for values of  $h_1 \approx L/2$

$$\frac{F \cdot h_1}{\gamma_w H_i^2 L} = \phi_2 \left( \frac{H_i}{L}, \frac{H_r}{H_i}, L/L_1 \right) \quad \dots (9)$$

The left hand term of expression (9) is termed the mooring force function and its denominator is proportional to the wave energy per unit width per wave length of the incident waves. The wave energy dissipated  $\left(\frac{H_d}{H_i}\right)^2$  by wave breaking and other sources may be obtained from the equation of conservation of energy,

$$\begin{aligned}
 \left(\frac{H_d}{H_i}\right)^2 &= 1 - \left(\frac{H_T}{H_i}\right)^2 - \left(\frac{H_r}{H_i}\right)^2 \\
 &= f_9 \left( \frac{H_i}{L}, L/L_1, \frac{h_1}{d} \right) \quad \dots (10)
 \end{aligned}$$

Experiments

The experiments were performed in a two-dimensional wave channel 100 ft. long x 2 ft. wide x 4' deep. Near one end of the channel is located a hinged type wave maker with suitable adjustments for varying its pitch. An efficient, mildly sloping, low reflection beach is located

at the end of the channel distant from the wave maker. A filter located about 15 ft. from the wave generator is required to smooth the waves by reducing the irregularities which may arise due to the motion of the wave paddle. The available space for experiment is about 65 ft. between the filter and the beach.

Two wave probes containing the active electrical elements through which the wave profiles are measured are mounted on carriages, one of which can roll along two rails fixed on the top of the channel. Outputs from the electrode system are fed through a bridge circuit into a Sanborn D.C. Amplifier Recorder where the wave profiles are recorded.

The mooring cable of the breakwater is a 1/16 inch diameter steel cable which passes under a fixed frictionless pulley and is attached to a calibrated linear compression spring connected to a rack which can actuate a spur gear controlling the slider of the potentiometer in a bridge circuit. The motion of the breakwater causes a displacement of the slider from its null position and the resulting voltage changes are recorded by a Sanborn Recorder. A schematic representation of the experimental set up is shown in Fig. (5). Plate (2) shows the force meter and Plate (3) shows a sample record of the transmitted waves and mooring forces.

### Procedure

The wave length of the incident waves was computed from the relationship

$$L = \frac{gT^2}{2\pi} \tanh kd \quad \dots (11)$$

The metacentric height ( $\overline{GM}$ ) of the 'A' Frame breakwater was determined by experiment in still water. The natural period of rolling is obtained from the expression

$$T_n = \frac{2 \pi K_2}{\sqrt{g (\overline{GM})}} \quad \dots (12)$$

where  $T_n$  = natural period of rolling in still water

$K_2$  = radius of gyration of breakwater

$g$  = acceleration due to gravity

The incident and reflected wave heights were obtained from the measured wave height envelop of the wave form seaward of the breakwater.

That is,

$$H_i = \frac{|n_i + n_r|_{\max} + |n_i + n_r|_{\min}}{2}$$

$$H_t = \frac{|n_i + n_r|_{\max} - |n_i + n_r|_{\min}}{2} \quad \dots (13)$$

Due to wave breaking, the incident wave heights given by expression (13) sometimes differed from those obtained by measurement without the breakwater in the wave channel. The latter values were used in the evaluation of the reflection and transmission coefficients and mooring forces.

Scales

The model waves and breakwaters were designed in accordance with Froude's principle. The scales were. 'A' Frame, 1:11; Double Module, 1:12; and Pontoon, 1:14. The breakwaters were 23½ inches wide.

## RESULTS AND DISCUSSION

Double Module and Pontoon

Both breakwaters depend mainly on the criterion of large mass for their effectiveness. The double module possesses the additional feature of large radius of gyration for a given mass as compared to the pontoon. The wave damping characteristics of the module and pontoon are shown in Figs. (6) and (7) respectively. Harmonic components in the response characteristics and interference effects seem to increase the wave energy transmission at certain frequencies. These breakwaters may be useful in practical applications where breakwaters may also serve as floating piers.

'A' Frame BreakwaterEffect of Wave Steepness

Fig. (8) and (9) show the effects of wave steepness on transmission coefficients as a function of the ratio of wave length to cylinder spacing,  $L/L_1$ . Fig. (10) and (11) concern the reflection coefficients. A simple relationship does not seem to relate either  $K_t$  or  $K_r$  and  $L/L_1$ , as a function  $H_1/L$ . But generally steep waves appear to experience greater attenuation than those of smaller steepnesses. Figs. (9) and (11) show the influence of frequency, as expressed in  $L/L_1$ , on  $K_t$  and  $K_r$ .

Depths of Vertical Curtain

The 'A' Frame breakwaters in this series have equal masses and approximately equal radii of gyration. Fig. (12) shows that the

effect of the depths of the vertical curtain is slight for deep water waves, provided  $\frac{h_1}{d}$  is about 0.25. The influence of depths would be significant for shallow water waves.

Effect of Moment of Inertia

Fig. (13) and (14) show plots of  $K_T$  against  $L/d$  for various values of  $L_1/d$  and for two different depths of water. The ratio  $L_1/d$ , kept constant for each of the curves, specifies the spacing of the cylinders and the radius of gyration of the structure as shown in Table 2. The similarity of trends of the behaviour of the 'A' Frame breakwater for different depths of water is evident. Minimum  $K_T$  seems to exist at certain values of  $L/d$  and increases with increasing values of  $L_1/d$ . If a value of  $K_T = 50\%$  is arbitrarily defined as cut-off of wave transmission, the range of effectiveness of the 'A' Frame is increased by a factor of about 1.7 for a threefold increase of the radius of gyration. It is of interest that the masses of the breakwaters differ by only about 7%.

Fig. (15) shows the wave attenuation characteristics of the "4" Cylinder 'A' Frames. Better efficiency is achieved by the welded cylinders. Wave generation by the lower cylinders of the chain-connected unit impairs its performance.

Energy Balance

Fig. (16) shows an energy balance curve, Eq. (10). The figure shows the importance of energy dissipation through the various sources including wave breaking and damping as compared to the

reflected wave energy.

#### Mooring Forces

Figs. (17), (18) and (19) show plots of  $\frac{F_{H1}}{\gamma_w H_1^2 L}$  against  $L/L_1$  for different 'A' Frame breakwaters. The influence of water depth on peak mooring forces is shown in Figs (19). Fig (20) concerns the forces involved in mooring the double module. A typical frequency distribution of the mooring forces of an 'A' Frame breakwater is shown in Fig.(21). From a design standpoint, the peak forces are of most interest, but the average horizontal force component, which refers here to the mode of a force record of at least seventy cycles of loading, is important from considerations of the fatigue characteristics of the mooring rope. The plots of Figs.(17) to (20) show definite trends. The scatter in the results may be partly attributed to the influence of wave steepness, relative depth of water and the response characteristics of the moored breakwaters to the wave forces.

#### Effect of Elasticity of Mooring Line

Table (3) shows the effect of the elasticity of the mooring line on both the coefficient of transmission and the mooring forces. Springs of different spring constants were incorporated in the mooring lines as shown in columns (4) and (5). Larger mooring forces are obtained in the system with a stiffer spring. The transmission coefficients vary only slightly except in the welded 'A' Frame, probably caused by wave generation and interference effects on the harbour side of the breakwater.

TABLE (3) Effect of Elasticity of Mooring Cable on Mooring Forces

'A' FRAME $L_1 \approx 1.17^k$									
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Wave length $L$ (ft.)	Wave Height $H_L$ (ft.)	$L/L_1$	$F_1$ (lbs.) $K_1=21.5$ lbs /in.	$F_2$ (lbs.) $K_2=57$ lbs /in.	$(K_1)_2$	$(K_1)_2$	$F_2 / F_1$	$\frac{(K_1)_2}{(K_1)_1}$	$\frac{F_1 h_1}{\gamma H_1^2 L}$
6.5	.39	5.55	10.4	11.6	.77	.77	1.08	1	0.093
6.5	.43	5.55	11.7	14.9	.77	.77	1.27	1	0.0855
6.5	.54	5.55	14.3	17.0	.71	.73	1.19	1.03	0.067
5.1	.40	4.36	10.40	13.2	57	.625	1.27	1.1	0.113
'A' CYLINDER WELDED 'A' FRAME $L_1 = 1.41^k$									
6.5	.40	4.6	13	14.4	.58	.68	1.11	1.17	0.106
5.1	.38	3.62	11	12.1	.41	.475	1.1	1.16	0.127

LEGEND

$(K_1)_1$  = Transmission Coefficient, Mooring Condition, Column (4)

$(K_1)_2$  = Transmission Coefficient Mooring Condition, Column (5)

$F_1, F_2$  = Total force on mooring cable

$F_1^H$  = Horizontal force on cable per ft. width of breakerwater.

Observations and Measurements of Motions: 'A' Frame

The effects of resonance were neither apparent from the force records, measurements of motions nor from observations of the motions of the 'A' Frame breakwater.

Fig. (22) shows a plot of the maximum displacement,  $X_m/H_i$ , in sway motion against the maximum displacement in heave motion,  $F_m/H_i$ , of the centre of mass of the 'A' Frame. The trends of the relationship between  $X_m/H_i$  and  $F_m/H_i$  depends on  $L/L_1$  but no simple description is evident.

For short incident waves regular pulsating motions of the breakwater were observed. The breakwater would oscillate for a short time, then halt and again commence its oscillations. The angles of heel and the mooring forces during these oscillations were small. Since the metacentric height is found to depend on the angle of heel, it seems difficult to define a unique natural period of oscillation. The influence of added mass, added moment of inertia and damping increases the complexity of the problem.

Conclusions

1. The damping of water waves by the Double Module and Pontoon Breakwaters depends largely on the criteria of large mass. They may be useful in situations where transportable breakwaters may be required to serve as floating piers.
2. The 'A' Frame breakwater exemplifies that an effective floating breakwater system can be developed in which large moment of inertia of mass is the dominant factor rather than the mass.

The reduction of wave heights is effected through the processes of wave reflection, dissipation and wave interference.

3. The reflection and transmission coefficient of the breakwater system are influenced by incident wave steepness, but no simple relationships are apparent.
4. For deep water waves the effect of the depth of the vertical curtain on transmission coefficient is small provided  $h_1/d$  is about 0.25.
5. A definite trend is indicated by the plot of the horizontal force function  $\frac{F \cdot h_1}{\rho_w H_1^2 L}$  against  $L/L_1$ . The scatter in the result may be due partly to the influence of reflection coefficient, wave steepness and the response characteristics of the breakwater.
6. The peak forces are about 1.5 to 2 times the average forces.

NOMENCLATURE

d	Depth of water
F	Horizontal component of mooring force per foot width of breakwater
$h_1$	Draft of 'A' Frame Breakwater
$h_3$	Height of vertical curtain above still water level
$H_i$	Incident wave height
$H_d$	Dissipate wave height
$H_t$	Transmitted wave height
$H_r$	Reflected wave height
K	Wave number, $\frac{2\pi}{L}$
$K_1, K_3$	Spring constants
$K_2$	Radius of gyration
$K_r$	Reflection coefficient
$K_t$	Transmission coefficient
L	Wave length
$L_1$	Distance of cylinder from vertical curtain
$L_2$	Distance between cylinder centres
T	Period of incident waves
$T_n$	Natural period of oscillation of breakwater
$X_m$	Maximum displacement in sway-motion
$Z_m$	Maximum displacement in heaving motion

- $\gamma_b$  Unit weight of breakwater
- $\gamma_s$  Submerged unit of weight structure
- $\gamma_w$  Unit weight of water

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- (3) Hom-ma, M., Horikawa, K and Mochizuki, H, *"An Experimental Study on Floating Breakwater"*, Coastal Engineering in Japan, Vol. 7, 1964 pp 85 - 94
- (4) Kato, J., Hagino, S. and Uekita, Y., *"Damping Effect of Floating Breakwater to which Anti-Rolling System is Applied"*, Proceedings of the Tenth Conference on Coastal Engineering, Vol. 2, Japan, Sept. 1966, pp 1068 - 1078



PLATE (1)  
'A' FRAME BREAKWATER



PLATE (2)  
MOORING FORCE METER

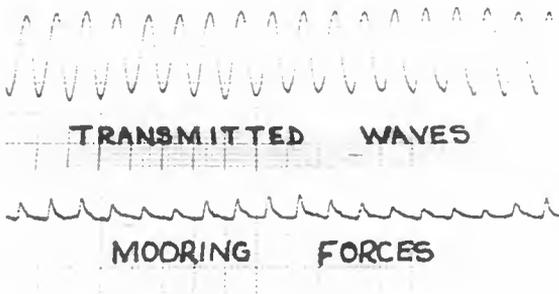


PLATE (3)  
SAMPLE RECORD

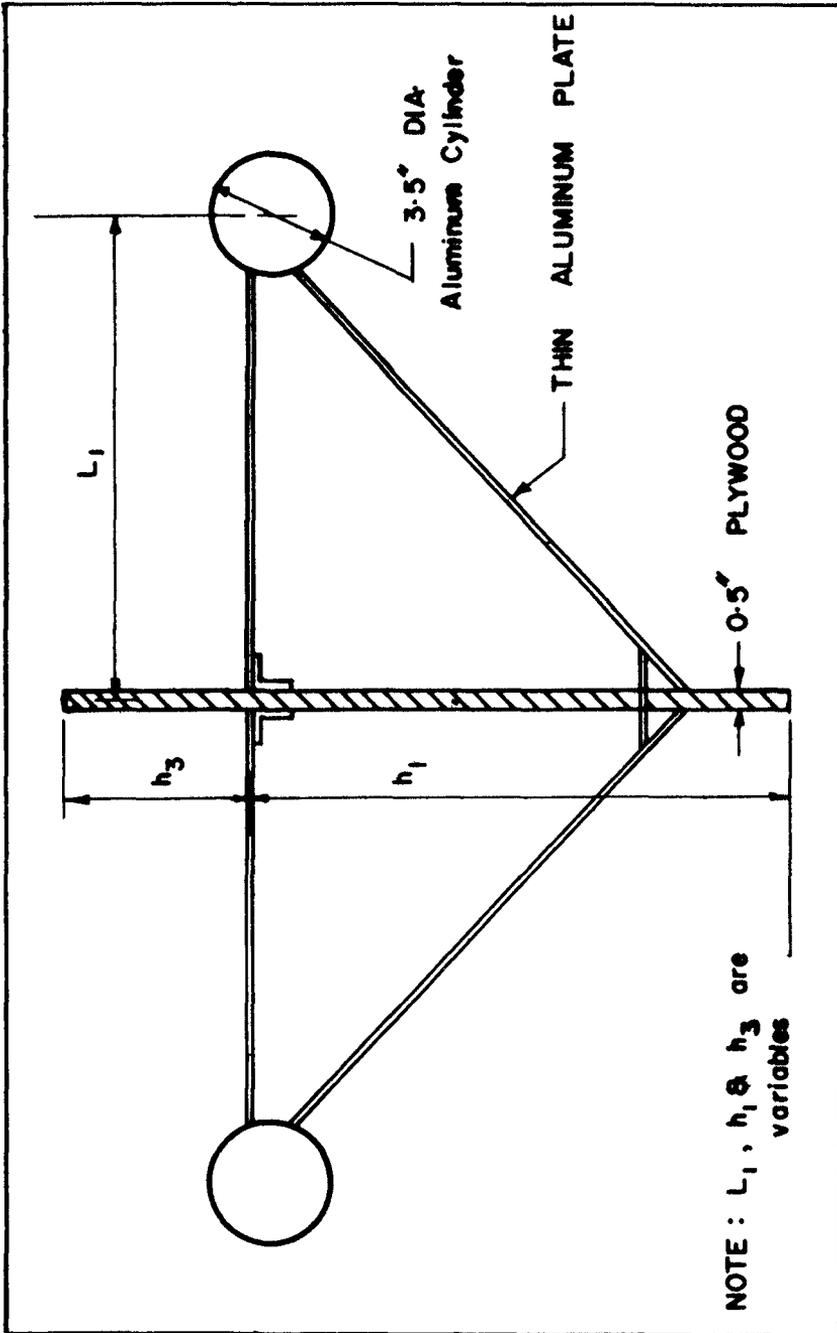
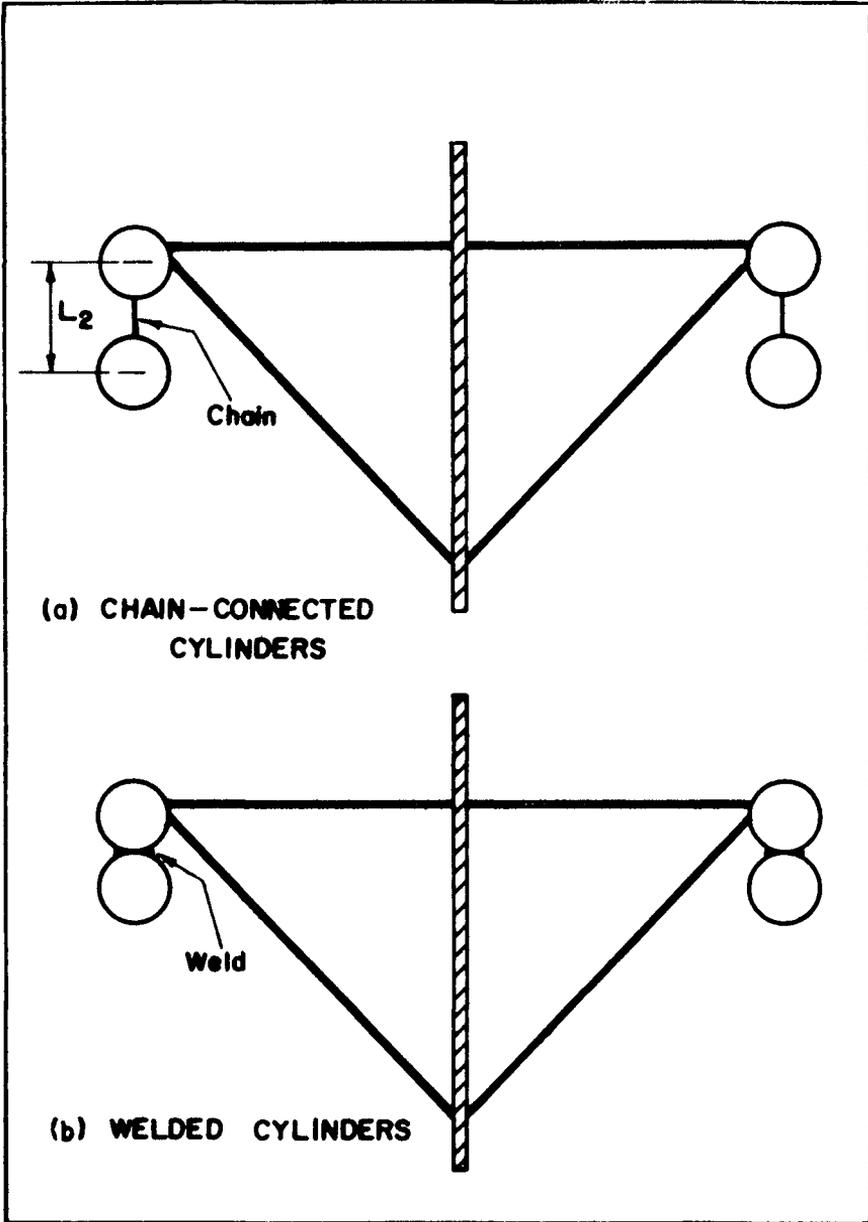
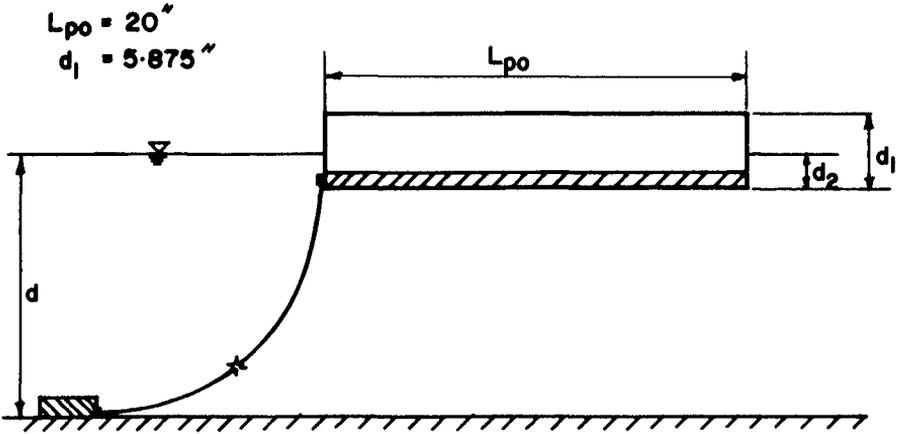


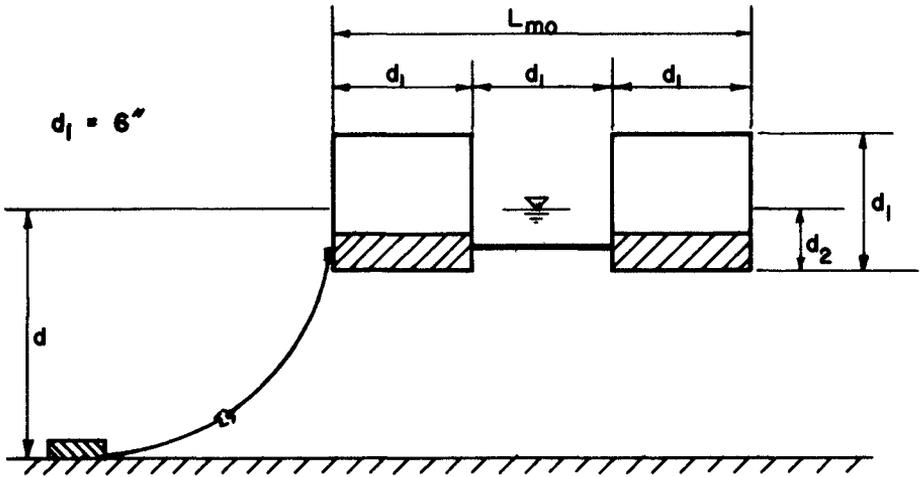
FIG.(1) 'A' FRAME BREAKWATER



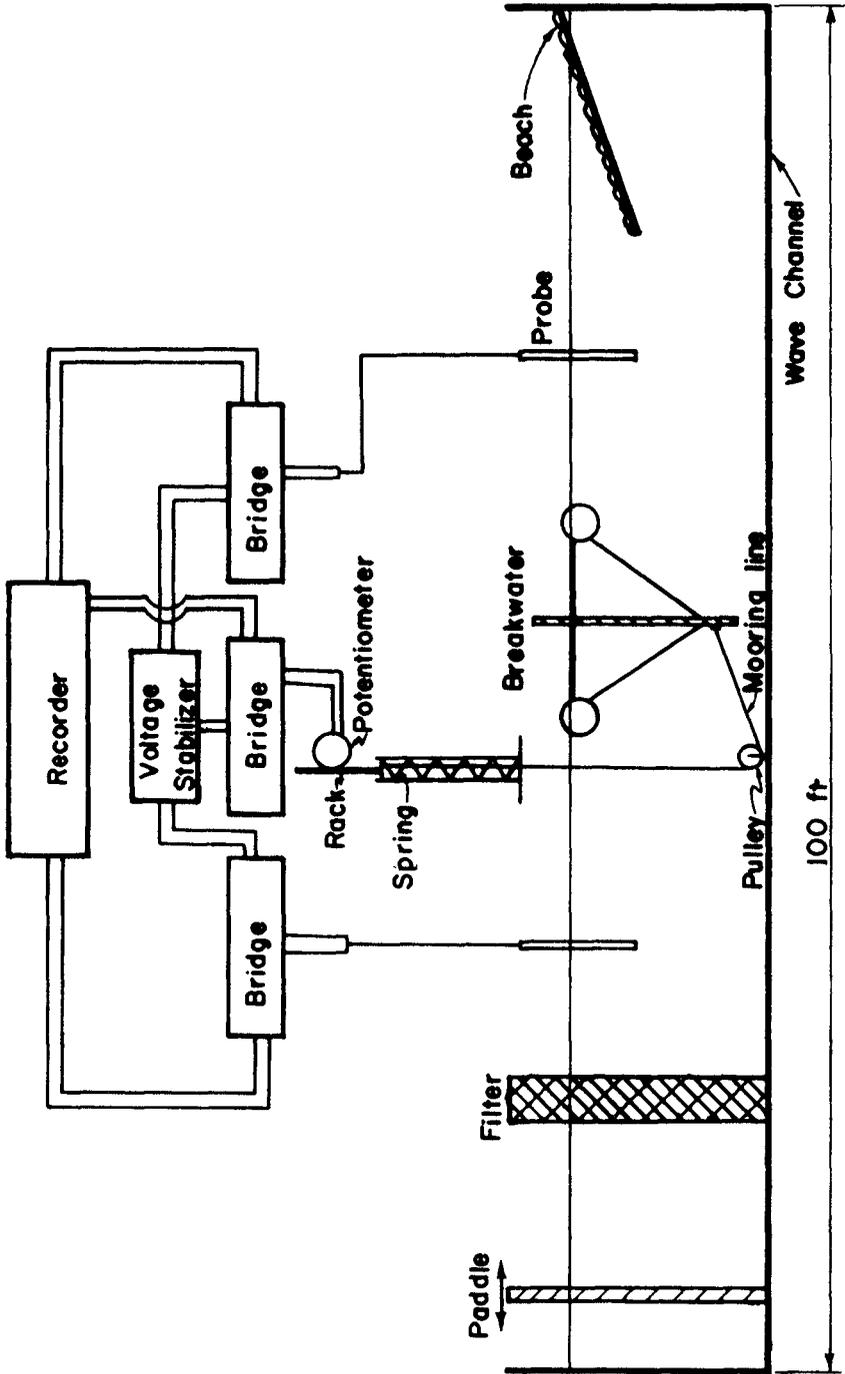
FIG(2) "4" CYLINDER 'A' FRAME "



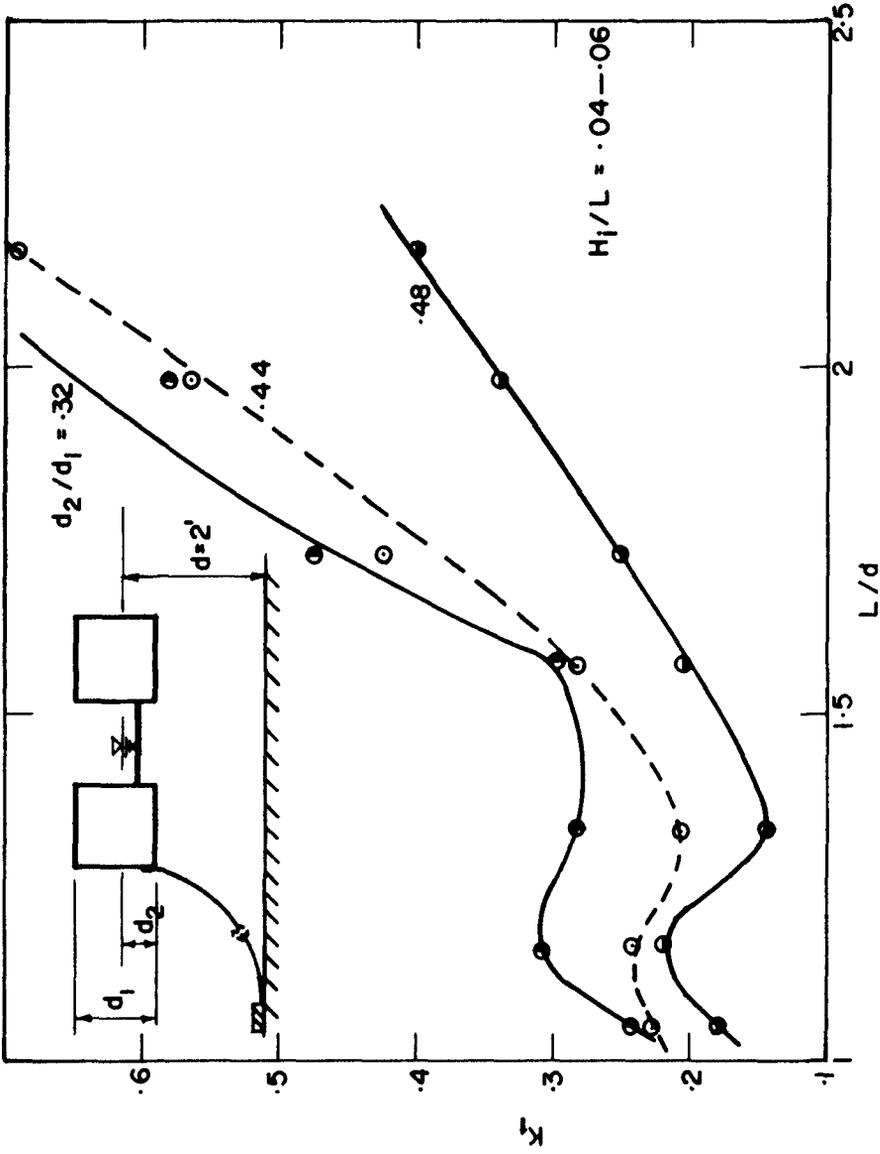
FIG(3) PONTOON BREAKWATER



FIG(4) DOUBLE MODULE BREAKWATER



FIG(5) FUNCTIONAL ARRANGEMENT OF EQUIPMENT



FIG( 6 ) DOUBLE MODULE : WAVE DAMPING CHARACTERISTICS

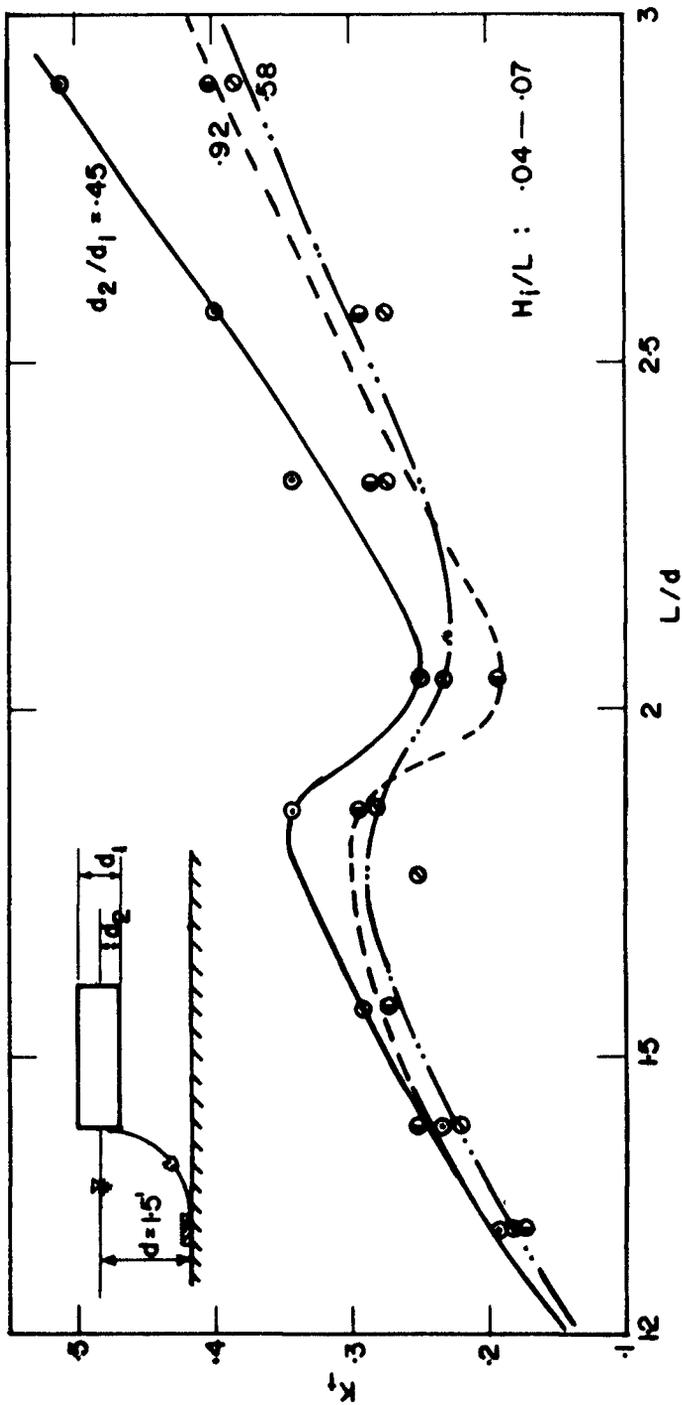
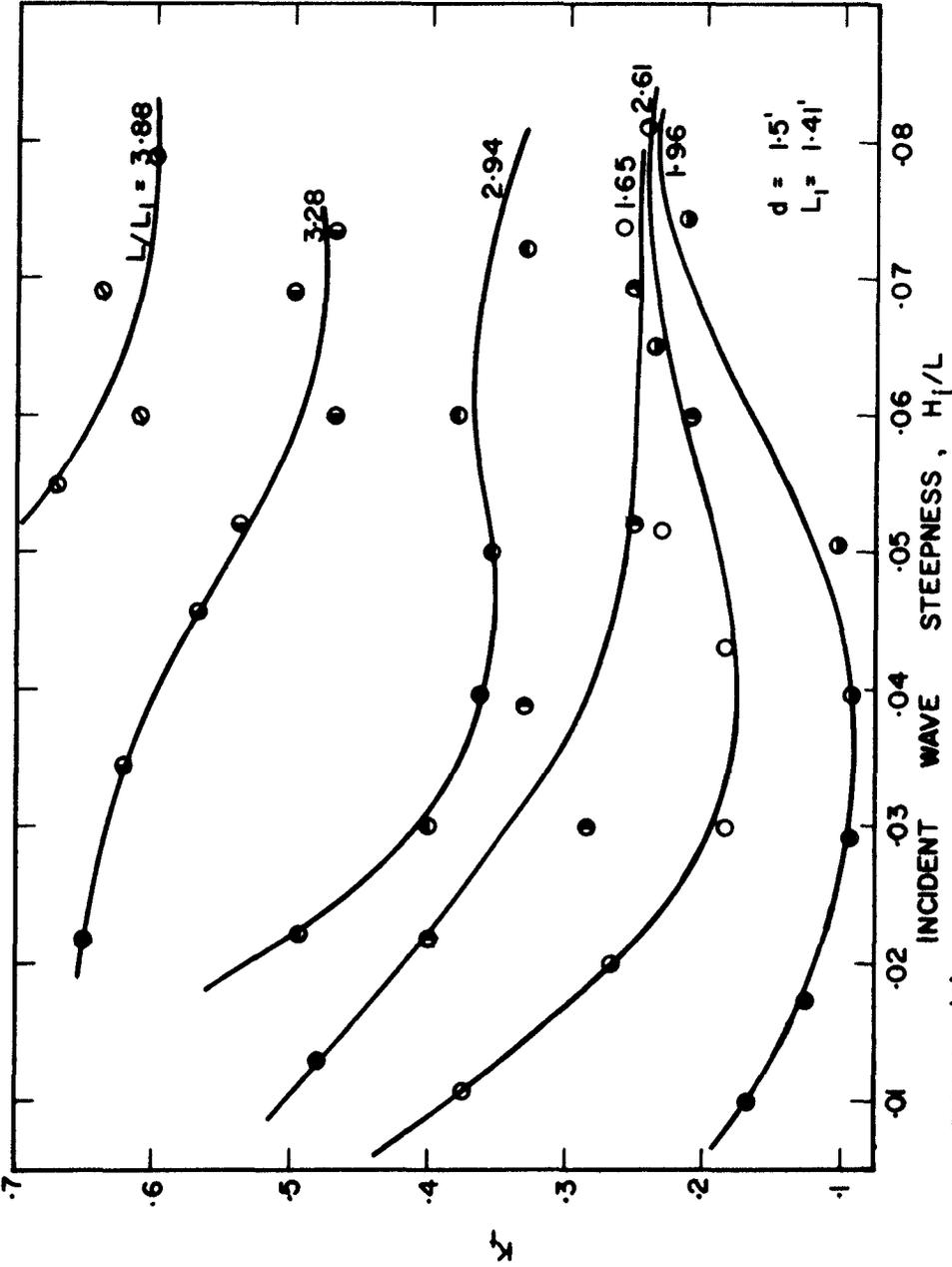
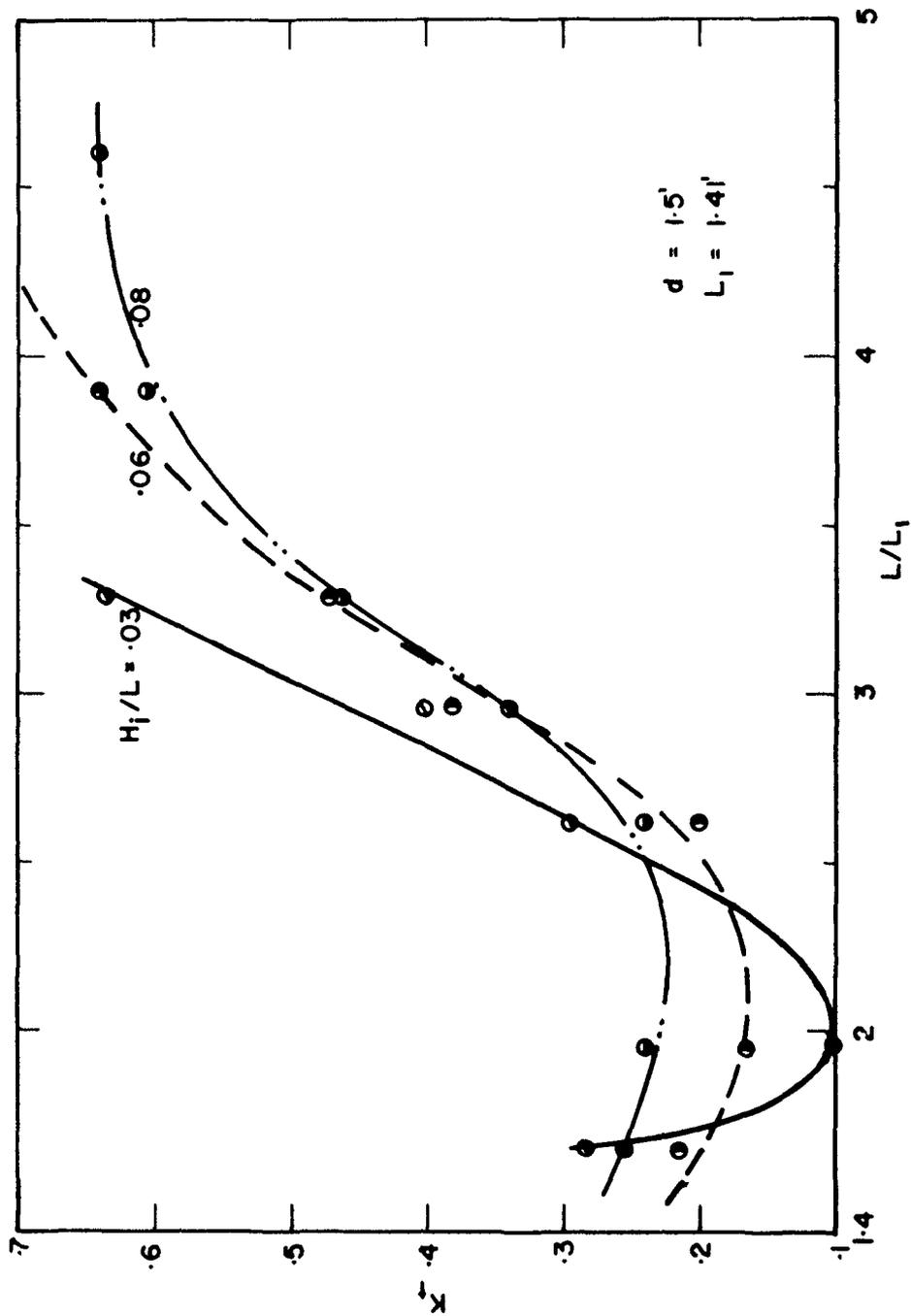


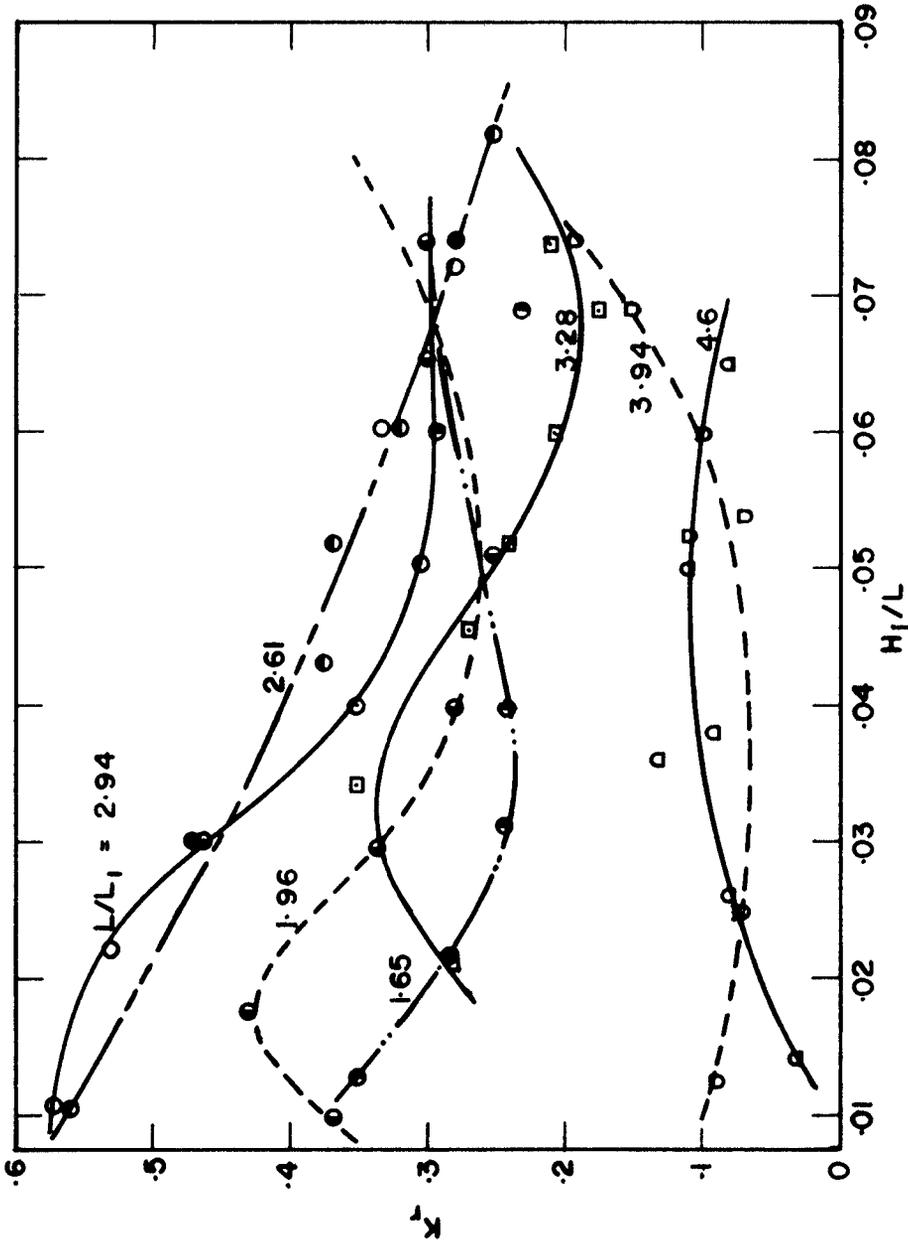
FIG.(7) PONTOON BREAKWATER : WAVE DAMPING CHARACTERISTICS



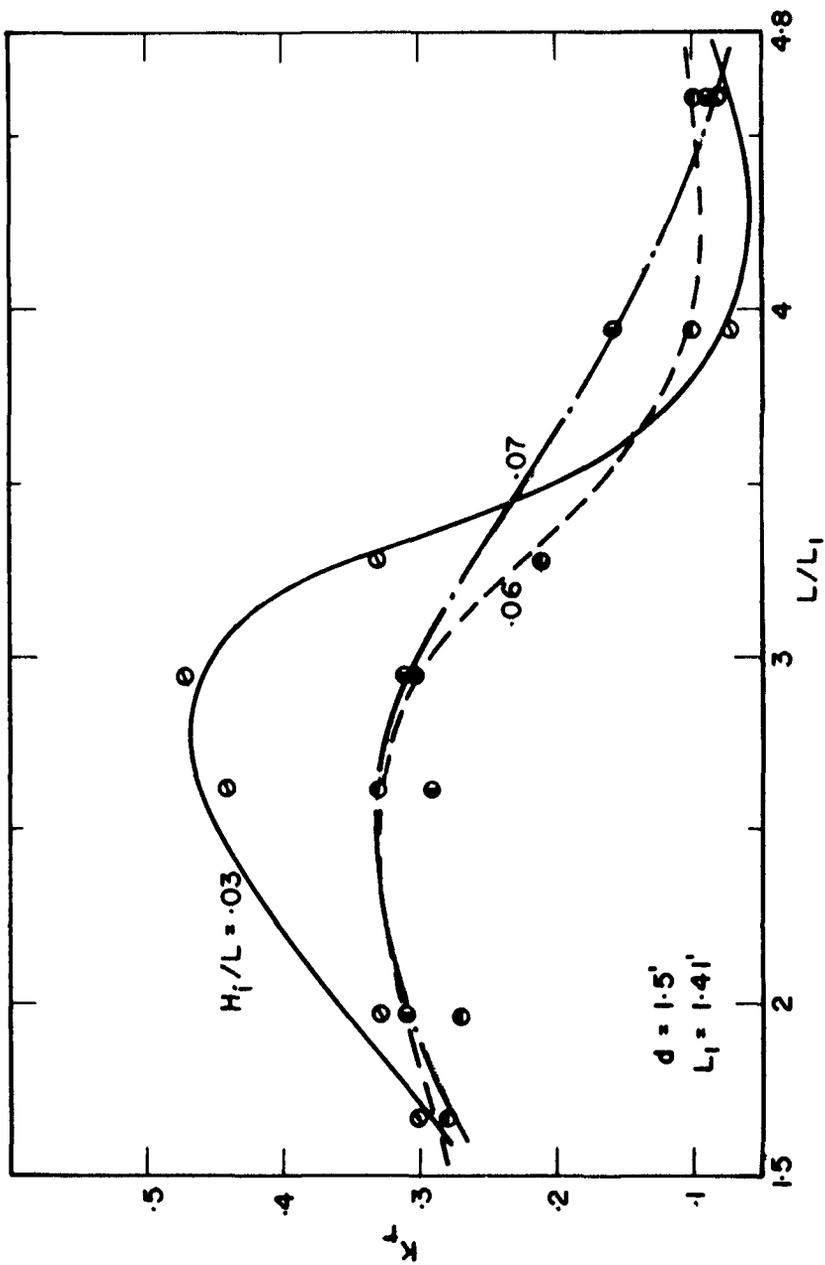
FIG(8) 'A' FRAME BREAKWATER : EFFECT OF WAVE STEEPNESS



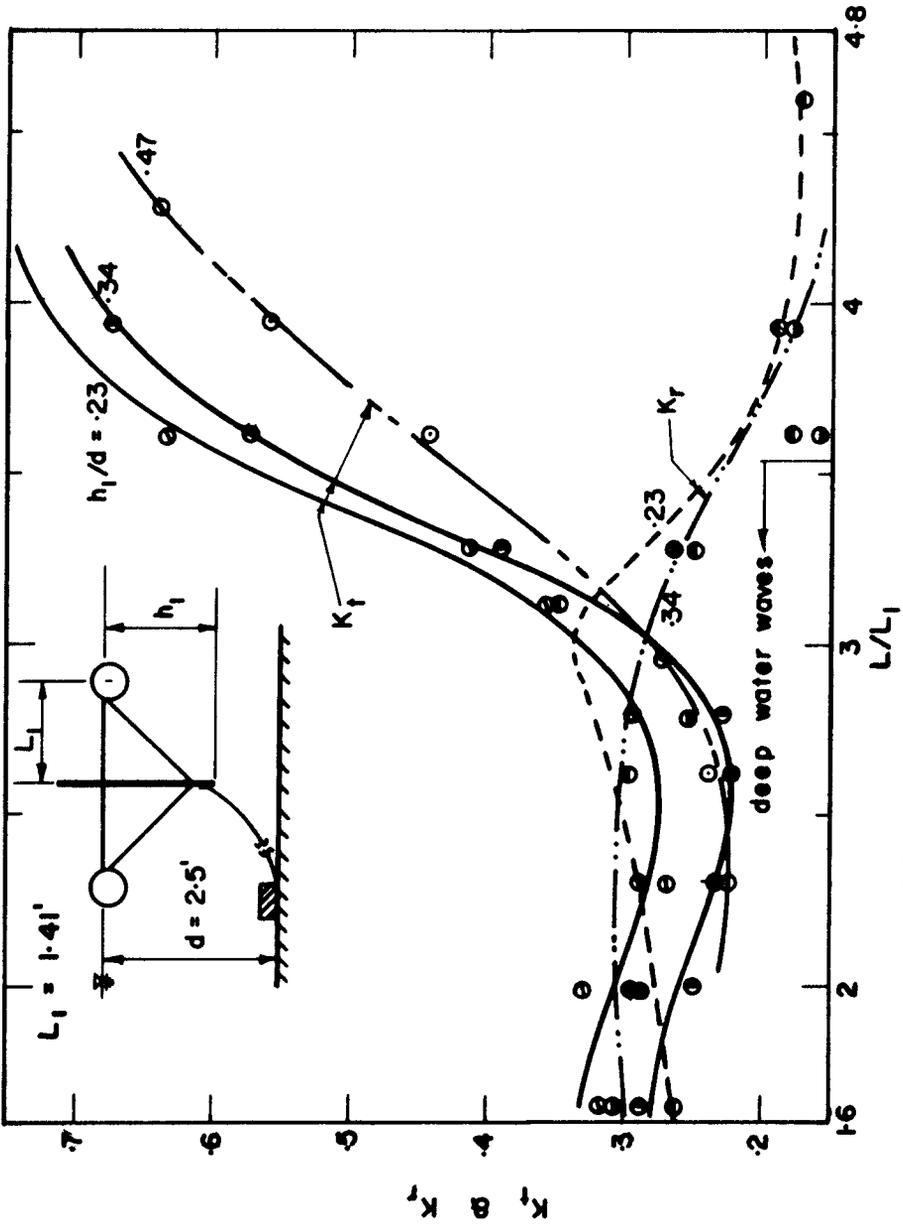
FIG(9) 'A' FRAME : INFLUENCE OF FREQUENCY



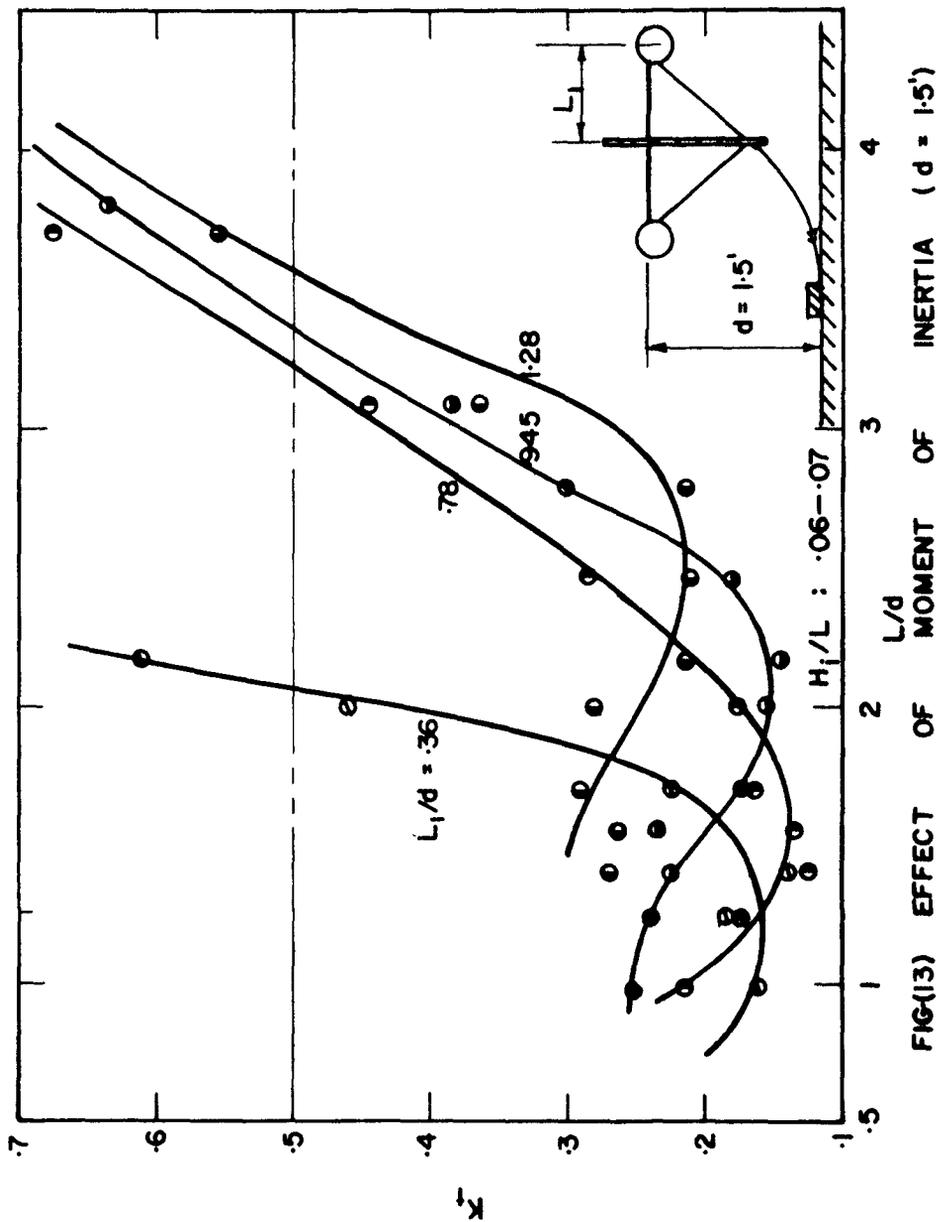
FIG(10) REFLECTION COEFFICIENT : EFFECT OF WAVE STEEPNESS



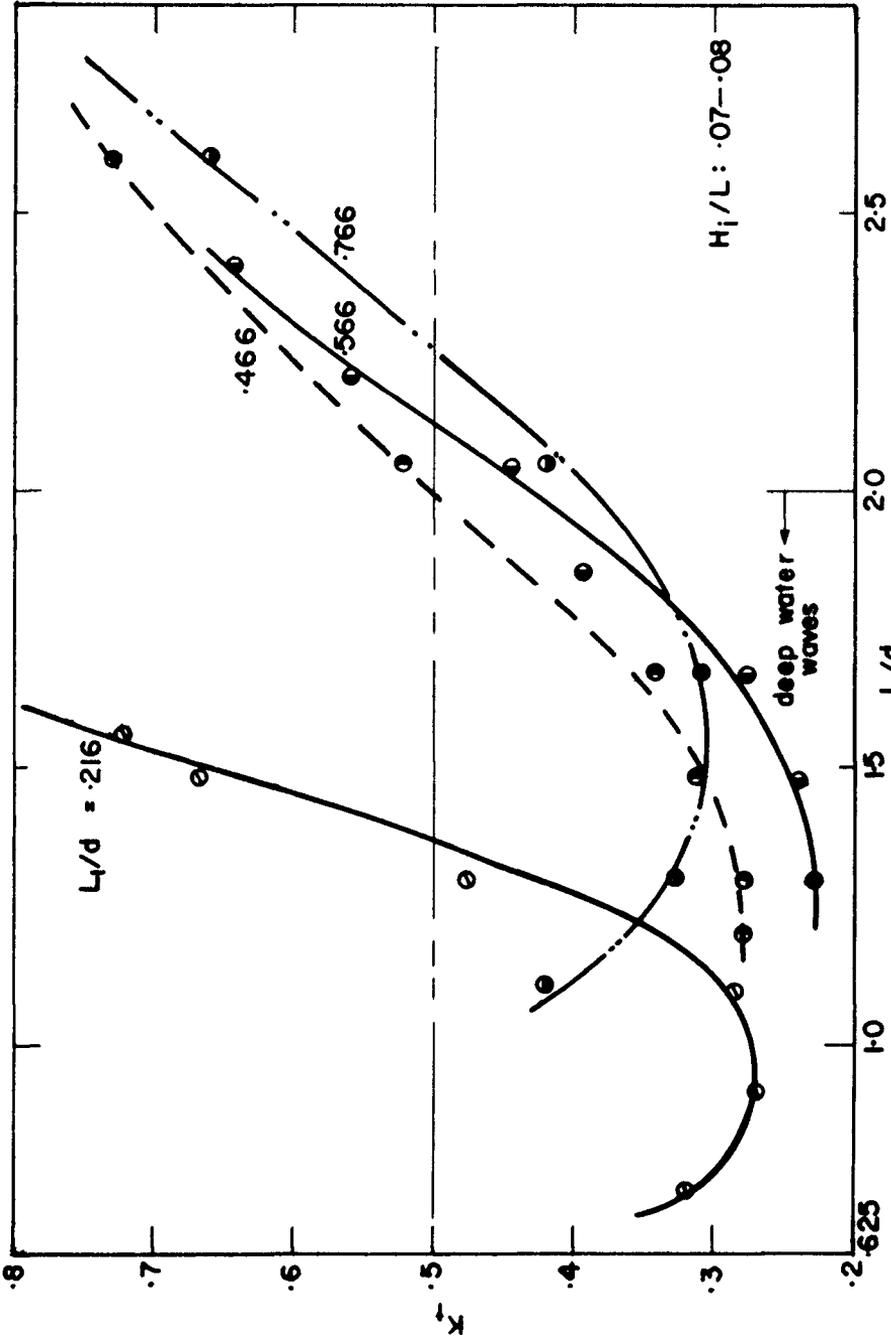
FIG(11) REFLECTION COEFFICIENT : EFFECT OF FREQUENCY



FIG(12) EFFECT OF DEPTH OF VERTICAL CURTAIN

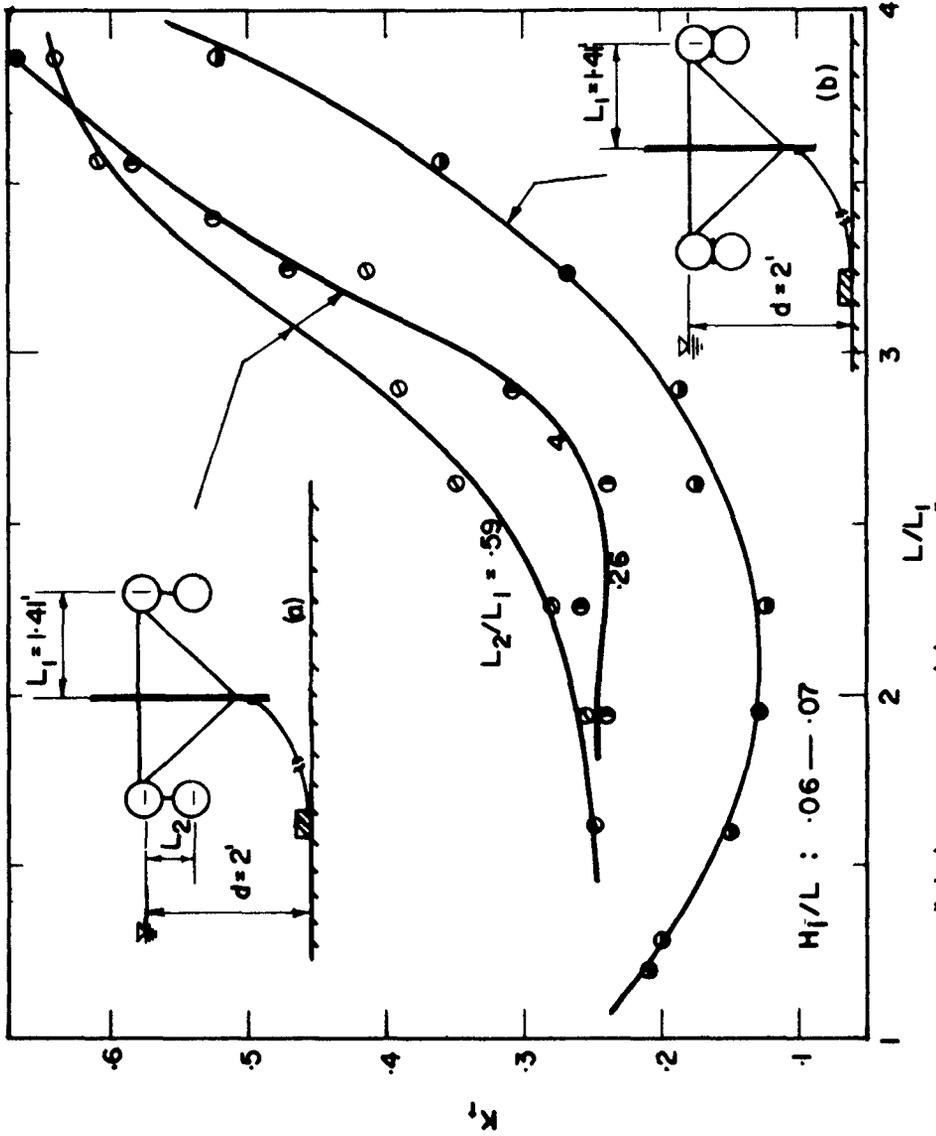


FIG(13) EFFECT OF MOMENT OF INERTIA ( $d = 1.5'$ )

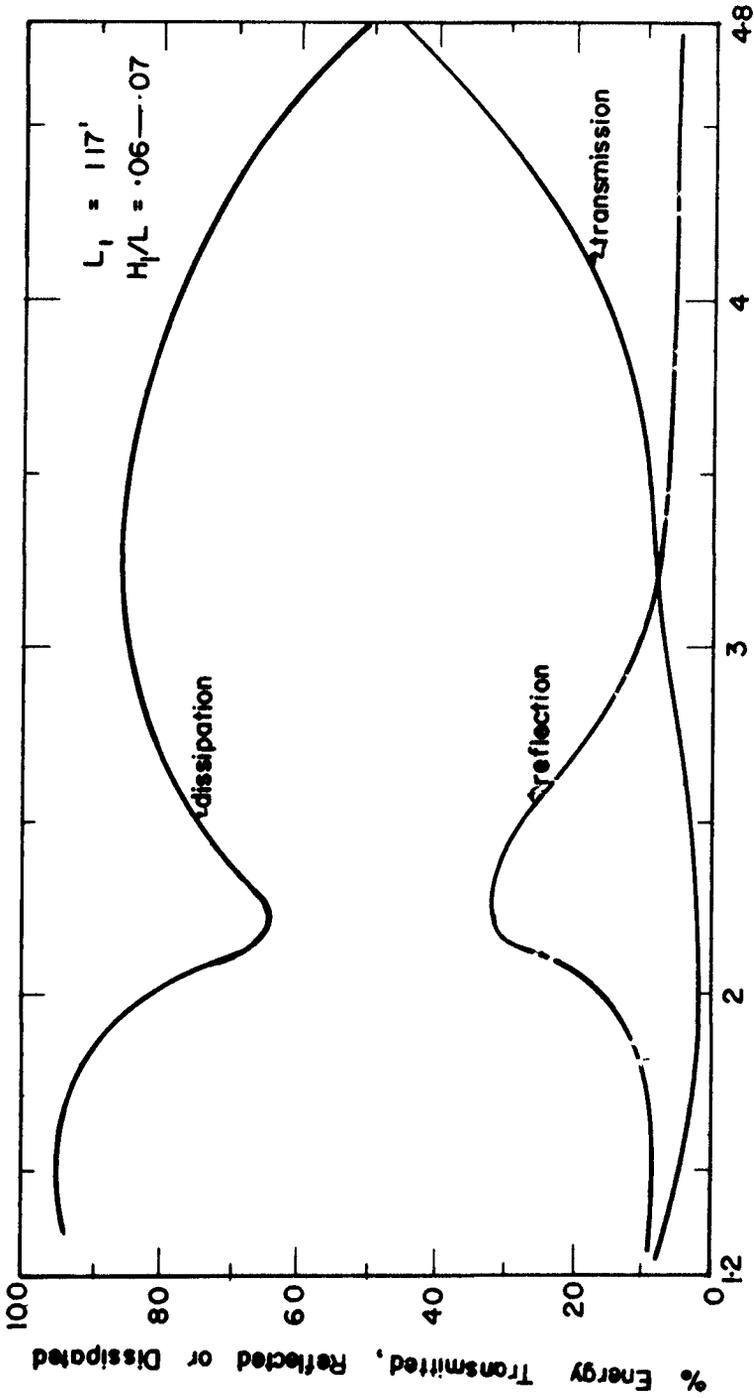


FIG(14) EFFECT OF MOMENT OF INERTIA ( $d = 2.5$ )

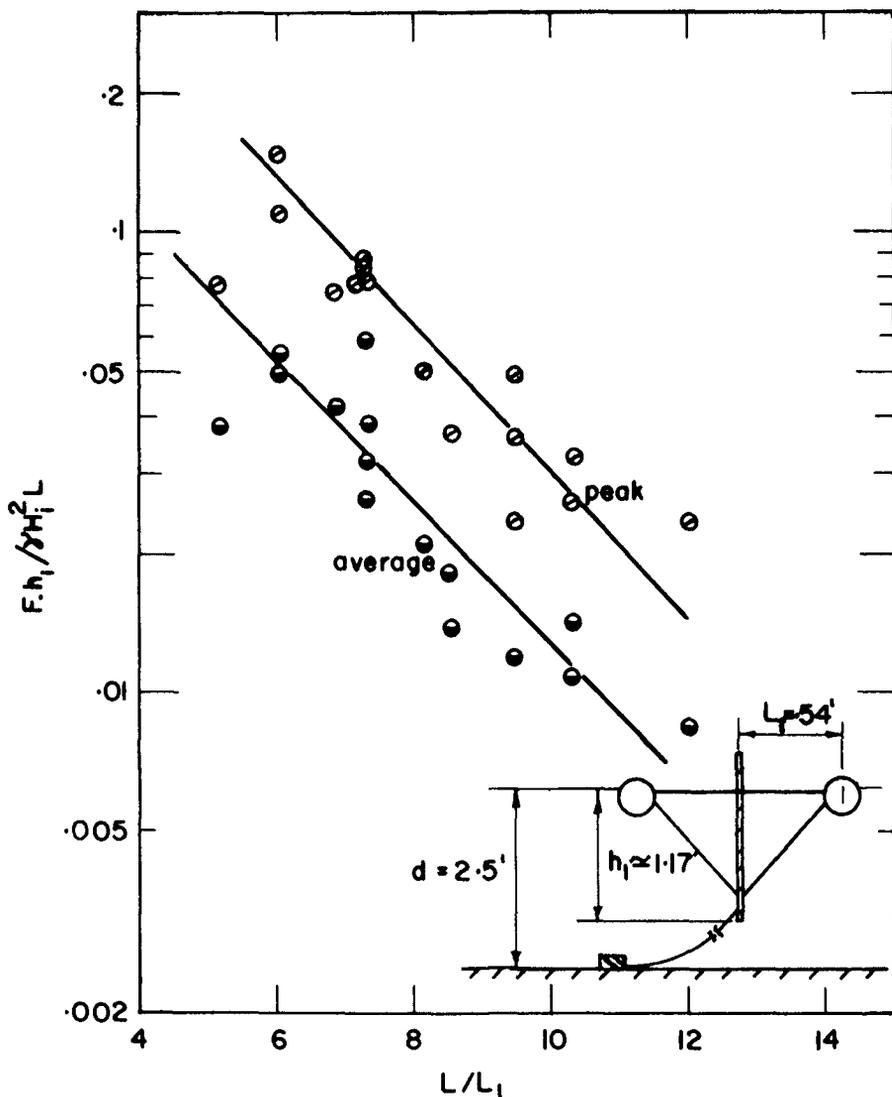
$H_1/L : .07-.08$



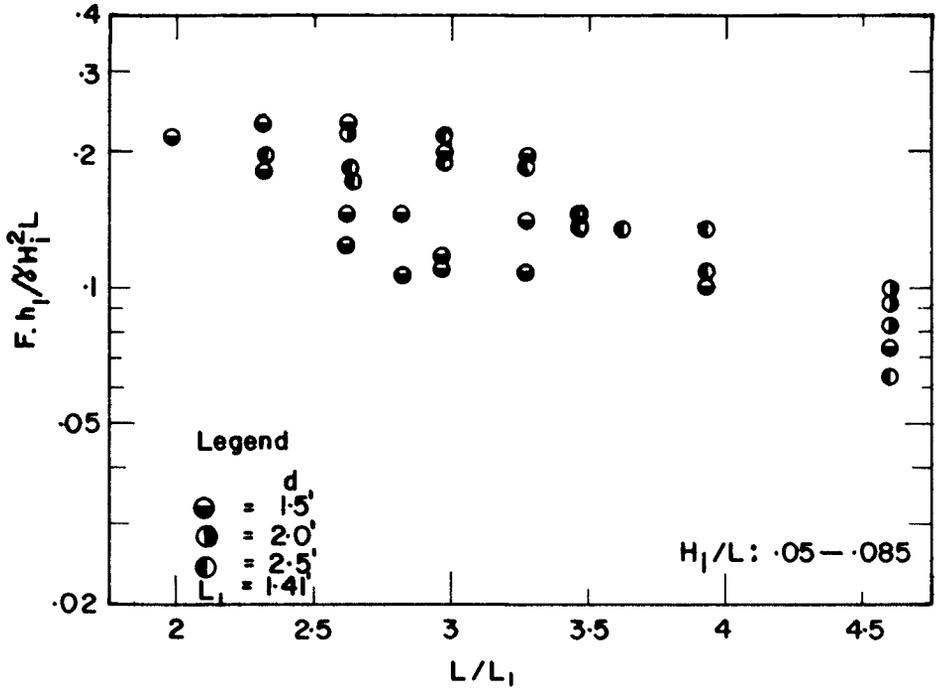
FIG(15) " '4' CYLINDER 'A' FRAME": WAVE DAMPING CHARACTERISTICS



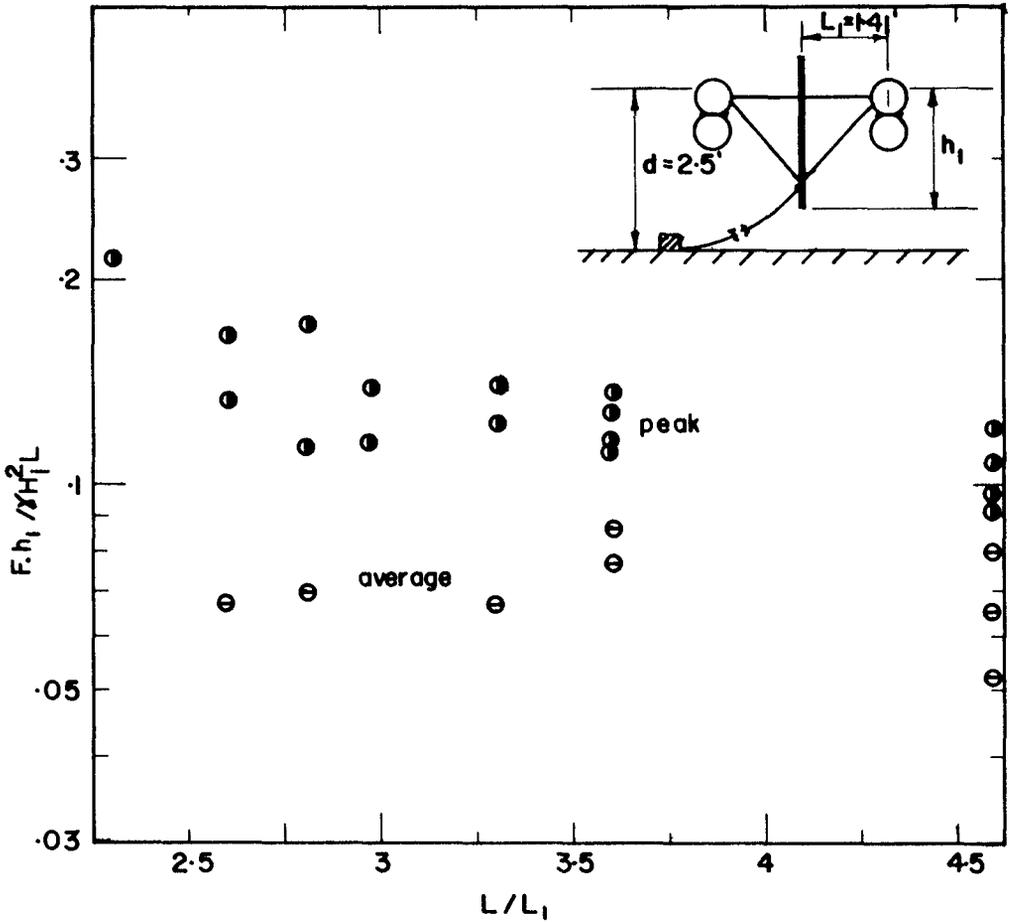
FIG(16) ENERGY BALANCE



FIG(17) 'A' FRAME : PEAK & AVERAGE  
MOORING FORCES



FIG(18) EFFECT OF DEPTH OF WATER ON PEAK MOORING FORCES



FIG(19) "4" CYLINDER "A" FRAME " MOORING FORCES

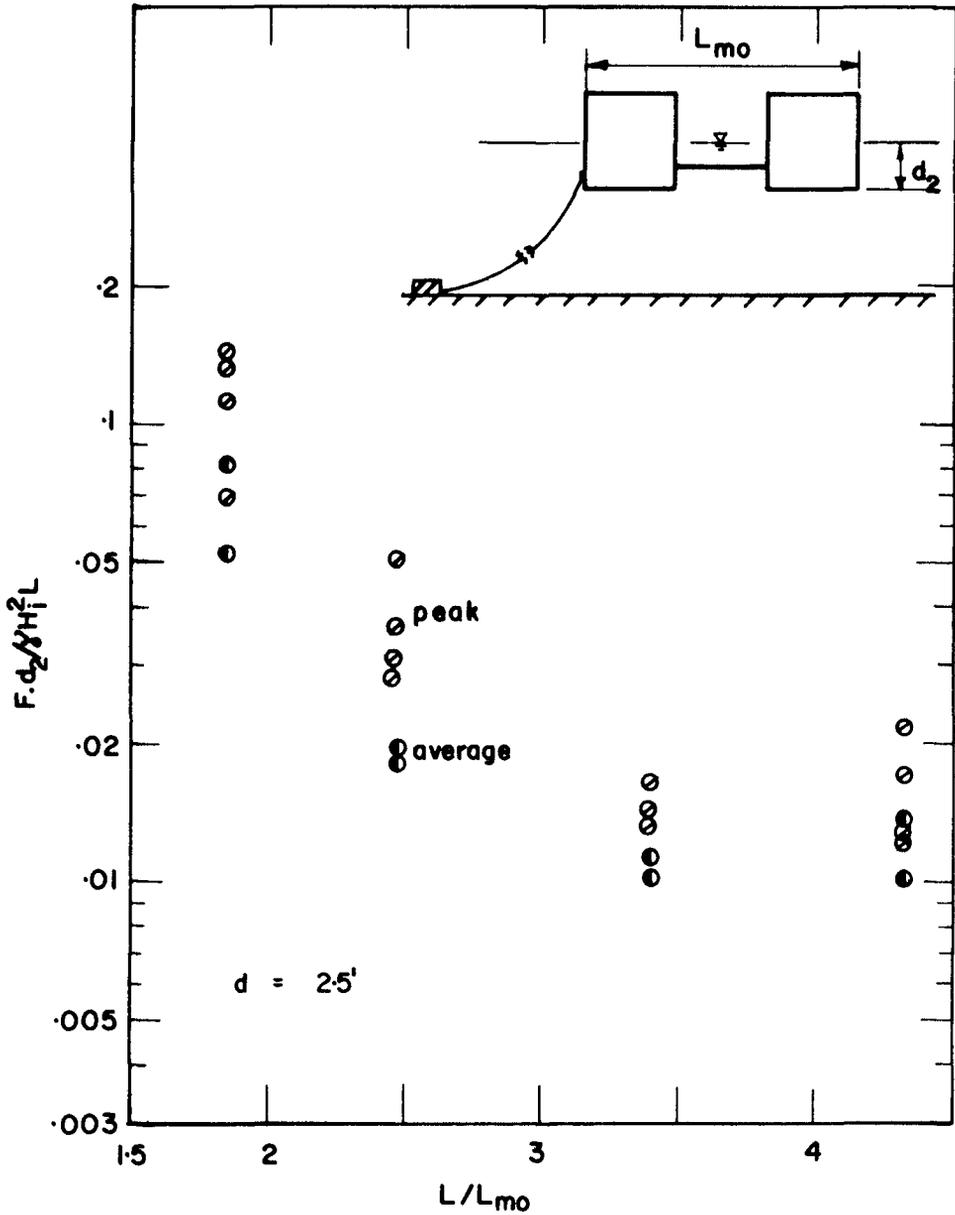


FIG-(20) DOUBLE MODULE : PEAK & AVERAGE MOORING FORCES

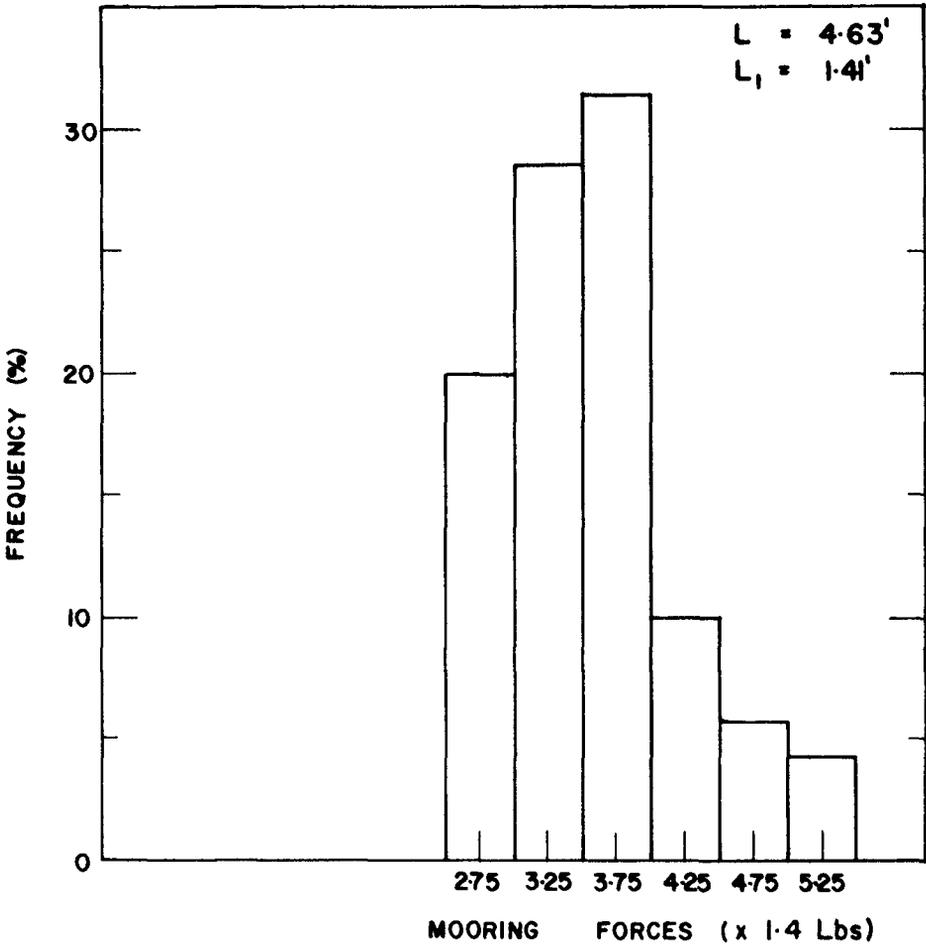
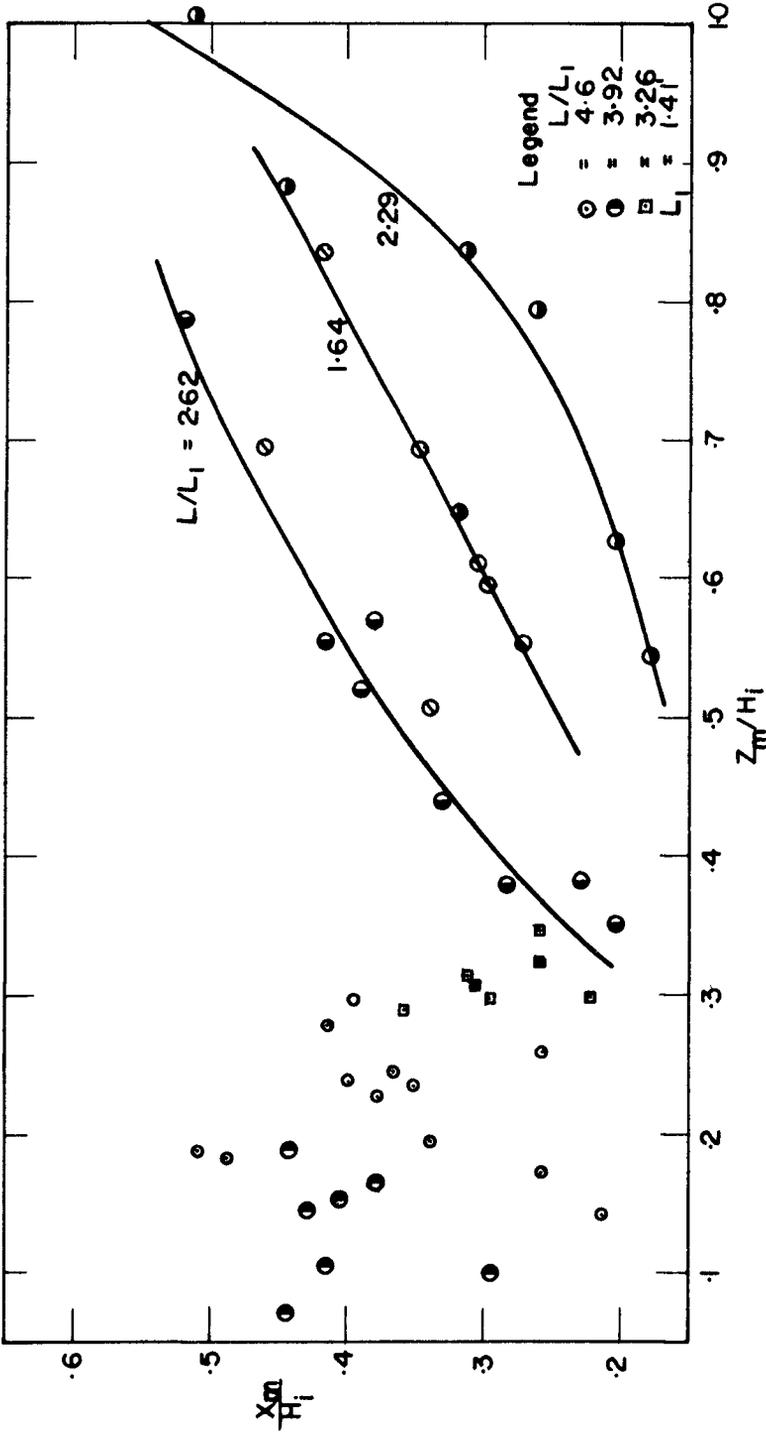


FIG-(21) 'A' FRAME : TYPICAL FREQUENCY DISTRIBUTION OF MOORING FORCES



FIG(22) HEAVING & SWAYING MOTIONS OF AN 'A' FRAME BREAKWATER