

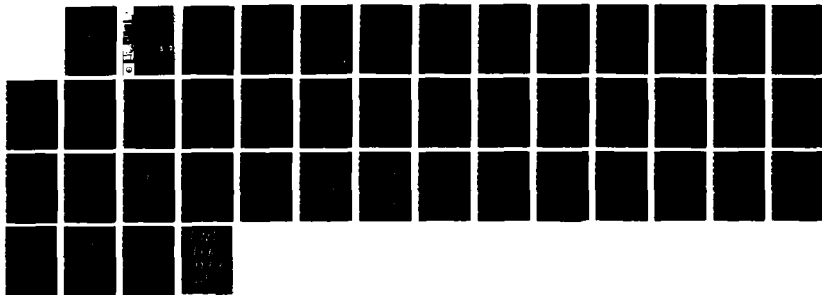
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DREDGING OPERATIONS TECHNICAL SUPPORT PROGRAM

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WAVE TRANSMISSION CHARACTERISTICS OF VARIOUS FLOATING AND BOTTOM-FIXED RUBBER-TIRE BREAKWATERS IN SHALLOW WATER

Experimental Model Investigation

by

Dennis G. Markle, Mary A. Cialone

Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631



September 1987

Final Report

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Prepared for DEPARTMENT OF THE ARMY
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US Army Engineer Waterways Experiment Station
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110-1101 519

REPORT DOCUMENTATION PAGE				Form Approved OMB No 0704-0188 Exp Date Jun 30, 1986	
1a REPORT SECURITY CLASSIFICATION Unclassified			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
4 PERFORMING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper CERC-87-8			7a NAME OF MONITORING ORGANIZATION USAEWES Environmental Laboratory		
6a NAME OF PERFORMING ORGANIZATION USAEWES, Coastal Engineering Research Center		6b OFFICE SYMBOL (if applicable)	7b ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631		
6c ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631		8a NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers		8b OFFICE SYMBOL (if applicable)	
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
11 TITLE (Include Security Classification) Wave Transmission Characteristics of Various Floating and Bottom-Fixed, Rubber-Tire Breakwaters in Shallow Water; Experimental Model Investigation		10 SOURCE OF FUNDING NUMBERS			
12 PERSONAL AUTHOR(S) Markle, Dennis G.; Cialone, Mary A.		PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
13a TYPE OF REPORT Final report	13b TIME COVERED FROM _____ TO _____	14 DATE OF REPORT (Year, Month, Day) September 1987		15 PAGE COUNT 44	
16 SUPPLEMENTARY NOTATION Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Bottom fixed, Model tests, Wave transmission		
			Breakwaters, Rubber tire		
			Floating, Water waves		
19 ABSTRACT (Continue on reverse if necessary and identify by block number) A two-dimensional experimental model investigation was conducted at a scale of 1:4, model:prototype, to determine and compare the wave transmission characteristics of various floating and bottom-fixed, rubber-tire breakwater concepts when placed over or on a mild bottom slope in shallow water and exposed to nonbreaking and breaking waves. Wave transmission characteristics of each concept as it corresponds to incident wave height, wave period, water depth, wave steepness, relative wave height, and relative depth are presented in both graphical and tabular form. The concepts are ranked from best to worst relative to the wave protection they appear to provide in a shallow-water wave environment.					
20 DISTRIBUTION AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a NAME OF RESPONSIBLE INDIVIDUAL			22b TELEPHONE (Include Area Code)		22c OFFICE SYMBOL

PREFACE

The model investigation reported herein was requested and funded through the Environmental Resources Division, Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). The EL point of contact was Mr. H. H. Allen. Funds were provided through the Dredging Operations Technical Support (DOTS) Program which is sponsored by the Office, Chief of Engineers, US Army, through the Dredging Division of the Water Resources Support Center (WRSC-D), Fort Belvoir, Va. Dr. R. M. Engler was the DOTS Program Manager. Technical Monitor was Mr. D. Mathis, WRSC.

Model tests were conducted at the WES Coastal Engineering Research Center (CERC), under the general supervision of Mr. C. E. Chatham, Chief, Dynamics Division, and Mr. D. D. Davidson, Chief, Wave Research Branch. Tests were conducted by Mrs. M. A. Cialone, Civil Engineer, and Mr. C. Lewis, Civil Engineering Technician, under the supervision of Mr. D. G. Markle, Research Hydraulic Engineer. This report was prepared by Mr. Markle and Mrs. Cialone. This report was edited by Mrs. J. W. Leach, WES Information Technology Laboratory.

Chief of CERC during publication of this report was Dr. J. R. Houston; Assistant Chief was Mr. C. C. Calhoun, Jr. Chief of EL was Dr. John Harrison.

Commander and Director of WES during publication of this report was COL Dwayne G. Lee, CE. Technical Director was Dr. Robert W. Whalin.



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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI
(metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
miles (US statute)	1.609344	kilometres
pounds (force)	4.448222	newtons
inches	2.54	centimetres
degrees (angle)	0.01745329	radians

WAVE TRANSMISSION CHARACTERISTICS OF VARIOUS FLOATING AND
BOTTOM-FIXED, RUBBER-TIRE BREAKWATERS IN SHALLOW WATER

Experimental Model Investigation

PART I: INTRODUCTION

Background

1. The US Army Engineer (USAE) Waterways Experiment Station (WES) has been investigating ways to creatively dispose of dredged material in an environmentally compatible manner for the last 14 or more years through the Dredged Material Research Program (DMRP) and the Environmental Effects of Dredging Programs. The Habitat Development Project of the DMRP demonstrated that beneficial wildlife and fisheries habitat could be created by establishing marsh on dredged material (USAEWES 1978). Marsh has not just been used for development of habitat. The Coastal Engineering Research Center (CERC) at WES demonstrated that marsh vegetation can be used to stabilize coastal shores (Knutson and Woodhouse 1983). Marsh has historically been developed in areas of low to moderate fetch distances, 1/2 to 5-1/2 miles,* and in protected coves (Knutson and Innskeep 1982). Once established, marsh grass will reduce or prevent shoreline erosion for a long time in certain wave climates and will provide a more cost-effective technique than structural protection. The key to successful marsh development and shore stabilization is to provide enough initial wave protection so that transplanted grass stems become established. The Environmental Laboratory (EL) of WES established marsh grass on dredged material in areas normally considered to have a low probability of success by erecting various breakwater systems, thereby affording wave protection to the vegetation transplanted behind the breakwaters (Allen et al. 1978; Allen and Webb 1983). By successfully establishing the marsh grass, dredged material was cost effectively stabilized, and a beneficial habitat was simultaneously developed. These breakwater systems were successful; however, some were considered too expensive or inadequate for higher wave-energy areas than those

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

in which tests were conducted. Therefore, CERC was asked by EL to investigate expedient and cost-effective rubber-tire breakwater systems that could be used in moderate to high wave-energy areas and, through the use of physical wave model tests, evaluate and compare their performances.

Purpose of Model Study

2. A two-dimensional (2-D) experimental model investigation was conducted to determine and compare wave transmission characteristics of various floating and bottom-fixed, rubber-tire breakwater concepts when placed over or on a mild bottom slope in shallow water and exposed to both nonbreaking and breaking waves.

PART II: THE MODEL

Design of Model

3. Based on the size of available model materials, capabilities of the test facility, and proposed water depths at the sea side of the breakwater concepts, it was determined that 2-D wave transmission tests should be conducted at an undistorted linear scale of 1:4, model to prototype. Based on Froude's model law (Stevens et al. 1942) and the linear scale of 1:4, the following model-to-prototype relations were derived. Dimensions are in terms of length (L)* and time (T).

<u>Characteristic</u>	<u>Dimensions</u>	<u>Model-Prototype Scale Relations</u>
Length	L	$L_r = 1:4$
Area	L^2	$A_r = L_r^2 = 1:16$
Volume	L^3	$V_r = L_r^3 = 1:64$
Time	T	$T_r = L_r^{1/2} = 1:2$

Selection of Test Conditions

4. Prototype water depths of 2.0 and 4.0 ft and a bottom slope of 1V on 55H were selected as representative of the areas where the various breakwater concepts would be used. The water depths were defined as those existing at the most seaward extent of the breakwaters (exclusive of mooring lines) and are referred to later by the term D_1 . Prototype wave periods T of 2.0, 4.0, 6.0, 8.0, and 10.0 sec for prototype wave heights ranging from low amplitude nonbreaking to depth- or steepness-limited breaking waves were selected as representative of the wave conditions that could exist at various prototype sites.

* For convenience, symbols and unusual abbreviations are listed in the Notation (Appendix A).

Test Facility

5. All tests were conducted in a 2-ft-wide by 165-ft-long concrete flume (Figure 1). The flume was equipped with a flap type wave generator capable of producing monochromatic waves of various periods and heights. All model breakwaters were installed on the 1V-on-55H bottom slope. Thus, portions of the 1V-on-55H slope extended seaward and shoreward of the model breakwaters.

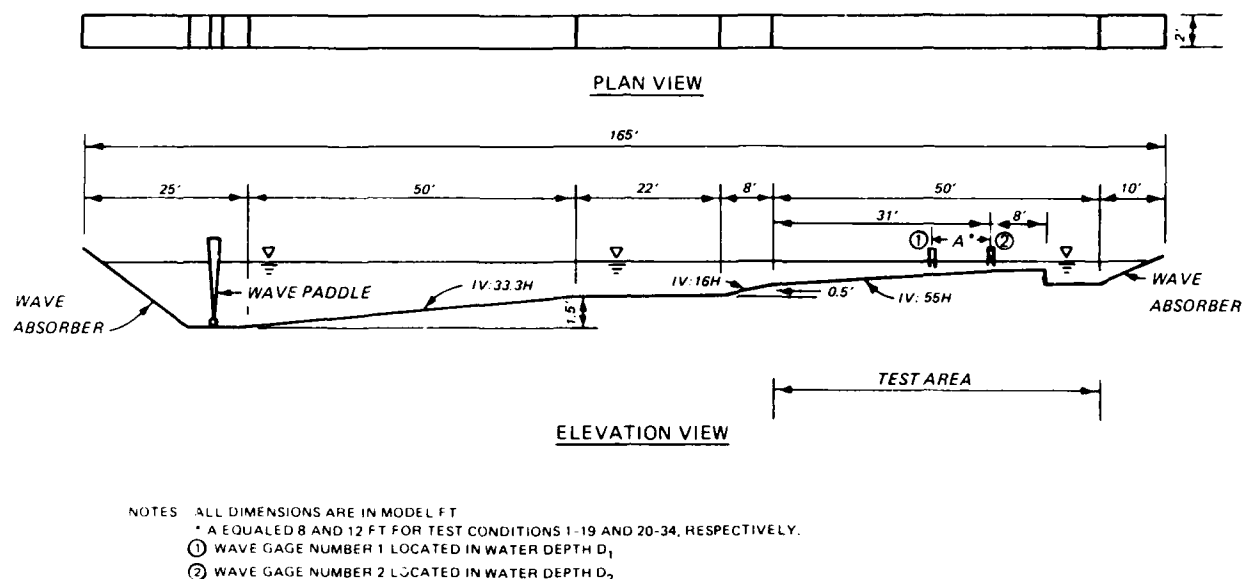


Figure 1. Test facility layout and wave gage locations for testing at prototype water depths D_1 of 2.0 and 4.0 ft

Flume Calibration and Test Procedures

6. Parallel resistance-type gages and strip charts were used to measure and record, respectively, wave heights created in the test flume. The electrical output of these gages was directly proportional to their submergence depth. The wave gages were positioned as shown in Figure 1. During calibration for the 2.0-ft test depth, wave gage 1 was positioned 8.0 ft from the top of the 1V-on-55H slope in the 0.5-ft model water depth which corresponded to a 2.0-ft prototype depth D_1 . Wave gage 2 was positioned at the top of the 1V-on-55H slope in a model water depth of 0.354 ft. This corresponded to a prototype water depth D_2 of 1.416 ft. During calibration for the 4.0-ft test depth, wave gage 1 was positioned 12 ft from the top of the 1V-on-55H

slope in a model water depth of 1.0 ft which corresponded to a 4.0-ft prototype depth D_1 . Wave gage 2 was positioned at the top of the 1V-on-55H slope in a model water depth of 0.781 ft which corresponded to a 3.124-ft prototype depth D_2 . The horizontal distances between the two wave gages corresponded to approximately one-half wave length (defined at wave rod 1) for the maximum wave period tested. These distances were needed to allow time and distance for the wave energy transmitted through and/or over the breakwaters to reform into a wave form that could be measured by the wave gage. The high turbulence that existed immediately shoreward of the breakwaters would not have allowed accurate measurement of the transmitted wave energy. Thus, during calibration, wave gages 1 and 2 defined the incident wave heights H_i and H_{inc} reaching depths D_1 and D_2 , respectively, without a breakwater concept in the flume. During testing, wave gage 1 was removed, and a breakwater concept was installed in the flume; and wave gage 2 was used to measure the transmitted wave heights H_T reaching depth D_2 . Table 1 is a listing of the H_i , H_{inc} , wave steepness H_i/L_1 , relative depth D_1/L_1 , and relative wave height H_i/D_1 test conditions selected for this test series.

PART III: BREAKWATER CONCEPTS AND TEST RESULTS

Description of Breakwater Concepts

7. Two floating and seven bottom-fixed breakwater concepts were tested. All nine concepts used car tires as the primary construction material. All of the model breakwater concepts were constructed using techniques that would reproduce, as closely as possible, the structural characteristics that would be achieved using general prototype construction techniques.

8. Concepts 1, 5, 6, and 7 (Plate 1) were constructed using a scrap tire configuration developed by the Goodyear Tire and Rubber Company. Construction techniques and engineering data on this concept are presented and cited by Hales (1981). The width of each concept was limited to two modules due to the test flume width. Concepts 1 and 7 each were one module long. Concept 1 was free-floating and was restrained by two 10-ft-long (prototype) mooring lines. The mooring lines were attached on the sea side to the center of each module. In many instances, tire breakwaters used in a shallow-water environment will become submerged due to the tires filling with sediment. Concept 7 was fastened to the flume bottom to simulate this submerged condition. Both Concepts 5 and 6 were three modules long. Concept 5 was restrained by two 20-ft-long (prototype) mooring lines attached to the sea-side modules in the same manner as Concept 1. Concept 6 was attached to the flume bottom to simulate a breakwater that was submerged due to siltation.

9. Concept 2 (Plate 2) was taken from the Section 54, low cost shore protection (Office, Chief of Engineers 1981) final report. The prototype concept consisted of driving cylindrical timber piles in a triangular pattern, parallel to the shoreline. Rubber tires were threaded onto the pilings and held in place with either timbers or cable. Plastic pipe and wire were used in the model to simulate pilings and restraining cables, respectively. The plastic pipe was fastened to the flume floor to reproduce rigidity of the driven prototype pilings.

10. Concepts 3, 4, 8, and 9 (Plate 3) consisted of rubber tires threaded on cables that were stretched between cylindrical timber pilings driven in either one or two rows parallel to the shoreline. These concepts were developed and provided by EL. Concept 3 consisted of a single row of tires, two tiers high. The inside rim of the top tier of tires rested on the

cable, while the bottom tier of tires rested on the bottom, and the cable passed through the center of each tire. Concept 4 consisted of two rows of tires, two tiers high. Its construction was identical to Concept 3. Concepts 8 and 9 were each three tiers high but had one and two rows of tires, respectively. Unlike Concepts 3 and 4, the bottom tier of tires on Concepts 8 and 9 rested on the bottom cable; i.e., the bottom cable was raised on the pilings a sufficient distance so that it supported the tires rather than having them supported from the bottom. Thus, all three tiers of tires on Concepts 8 and 9 were supported by the cables. The timber pilings were not reproduced in the model. Small steel rods and/or heavy-gauge wire were placed or stretched across the flume to simulate the cables, and model tires were threaded onto the rods or wire. A sufficient number of tires was used to fill the 2-ft flume width, but they were not compressed between the flume walls. Thus, the model tires were free to move on the rods or wire with the same freedom that they would have on a prototype structure. A short description of each breakwater and its corresponding concept number are given in Table 2.

Test Results

11. Concepts 1-7 were consecutively installed in the flume and exposed to Test Conditions 1-19 (Table 1). The transmitted wave height H_T produced by each test condition was measured at wave gage No. 2 ($D_2 = 1.416$ ft). Concepts 3, 5, 6, 8, and 9 were tested in the same manner using Test Conditions 20-34 (Table 1). The transmitted wave heights were measured at water depth D_2 (3.124 ft). The transmitted wave heights measured for each concept are presented in Table 3 for Test Conditions 1-19 and Table 4 for Test Conditions 20-34.

12. Also presented in Tables 3 and 4 are values of the wave height reduction coefficient C_r , which is a ratio of the transmitted wave height H_T to the incident wave height H_{inc} . Both of these wave heights were measured at the same water depth for the same incident wave condition, but H_T and H_{inc} were measured with and without a breakwater concept in place. Thus, a C_r value of 1.0 indicates that no benefit is being derived by the breakwater for that test condition. A C_r value greater than 1.0 means that the structure actually causes the wave height reaching water depth D_2 to be greater than the wave height that would reach depth D_2 without the structure

in place. This can be explained by the observation that for several of the larger incident wave heights, incident waves were breaking prior to reaching depth D_2 when the breakwater was not in place. When a breakwater concept was placed in the flume, it disrupted the natural wave breaking; and, in some instances, the wave energy lost due to the interference of the breakwater concept was less than the wave energy lost during the undisturbed wave breaking process. Thus, in these instances, more wave energy reached depth D_2 than would have if no breakwater had been in place. For the cases where C_r was less than 1.0, the smaller the C_r value the greater the benefit or wave-energy dissipation derived from the breakwater concept.

13. The values of C_r derived for each test condition and concept combination were plotted against T , H_i , H_i/L_1 , D_1/L_1 , and H_i/D_1 (Plates 4-8 for Test Conditions 1-19 and Plates 9-13 for Test Conditions 20-34, respectively). For the plots of C_r versus T , H_i , D_1/L_1 , and H_i/D_1 , lines were drawn connecting the maximum values of C_r for each concept tested. Since tested values of H_i/L_1 were closely spaced, selected maximum values of C_r were plotted and connected with a smooth curve to define an upper limit envelope of the experimental data. The individual data points lying below the lines or curves on each plot were removed for clarity.

14. Another useful method of comparing wave protection provided by the various concepts was to calculate the ratio of the amount of wave energy that reached depth D_2 in a given period of time with a concept in place to the wave energy that reached the same point in the same interval of time without the concept in place. Through use of Equation 1 (Shore Protection Manual 1977) incident wave energy per wave length per foot of wave crest E can be calculated:

$$E = \frac{\gamma H^2 L}{8} \quad (1)$$

where

γ = specific weight of water in which the breakwater is situated, pcf

H = incident or transmitted wave height, ft

L = wave length at depth where wave height is measured, ft

If it is assumed that each of the incident wave conditions was to occur for 1 hr, the number of waves per hour can be calculated for each incident wave

period/wave height combination. Then Equations 2 and 3 can be used to calculate, for a range of wave heights at a given wave period, the energy per foot of wave crest reaching depth D_2 in a given period of time with E_T and without E_{inc} a breakwater in place, respectively:

$$E_T = \sum_{K=1}^n N \frac{\gamma(H_T)_K^2 L_2}{8} \quad (2)$$

$$E_{inc} = \sum_{K=1}^n N \frac{\gamma(H_{inc})_K^2 L_2}{8} \quad (3)$$

where

n = number of different incident or transmitted wave heights tested at each wave period

N = number of waves per hour reaching depth D_2 for given wave period

H_T = transmitted wave height reaching depth D_2 with breakwater in place, ft

L_2 = wave length of incident or transmitted wave at depth D_2 , ft

H_{inc} = incident wave height reaching depth D_2 without breakwater in place, ft

The ratio of E_T to E_{inc} for a given wave period was referred to as the wave energy reduction coefficient E_r . (It should be remembered that this is an average E_r for a given wave period and does not represent either a minimum or maximum value.) Like C_r , E_r values of 1.0 indicate that the structure is providing no protection; values greater than 1.0 are showing that the structure may actually have a detrimental effect; and values less than 1.0 indicate that the structure does reduce incident wave energy (the smaller the E_r value, the more protection being provided). The E_r values were calculated for tested concepts and test conditions and represented in Table 5 and Plate 14 for Test Conditions 1-19, and Table 6 and Plate 15 for Test Conditions 20-34.

15. In order to compare the energy dissipation produced by the various concepts, the average wave energy reduction coefficient $\bar{E}_r$ defined by Equation 4, was calculated:

$$\bar{E}_r = \frac{\sum_{K=1}^m (E_r)_m}{m} \quad (4)$$

where m = number of wave periods tested on each breakwater concept. Thus, $\bar{E}_r$ represents an overall average measure of the energy dissipation exhibited by each concept for the full range of test conditions. The $\bar{E}_r$ values for the concepts exposed to Tests Conditions 1-19 and 20-34 are presented in Tables 5 and 6, respectively.

PART IV: CONCLUSIONS

16. Based on the test conditions and results reported herein, it was found that the concepts tested can be ranked from best to worst, in regard to their overall ability to dissipate incident wave energy, as follows:

- a. For concepts positioned on or over a 1V-on-55H (mild) bottom slope with their sea side in a 2.0-ft water depth and exposed to incident wave heights ranging from 0.5 to 1.8 ft for wave periods of 2.0, 4.0, 6.0, 8.0, and 10.0 sec:

- (Best) 1. Concept 4, two rows of tires on cables, two tiers high.
2. Concept 6, three bottom-fixed Goodyear modules.
3. Concept 3, one row of tires on cables, two tiers high.
4. Concept 5, three floating Goodyear modules.
5. Concept 7, one bottom-fixed Goodyear module.
6. Concept 2, tires on wooden pilings.
7. No breakwater.

- (Worst) 8. Concept 1, one floating Goodyear module.

- b. For concepts positioned on or over a 1V-on-55H (mild) bottom slope with their sea side in a 4.0-ft water depth and exposed to incident wave heights ranging from 1.0 to 3.0 ft for wave periods of 2.0, 4.0, 6.0, 8.0, and 10.0* sec:

- (Best) 1. Concept 9, two rows of tires on cables, three tiers high.
2. Concept 8, one row of tires on cables, three tiers high.
3. Concept 3, one row of tires on cables, two tiers high.
4. Concept 5, three floating Goodyear modules.
5. Concept 6, three bottom-fixed Goodyear modules.

- (Worst) 6. No breakwater.

* Maximum wave height for 10.0-sec wave period at 4.0-ft depth was limited by test facility capabilities to 1.8 ft.

PART V: DISCUSSION

17. With the need to determine and compare wave-attenuating characteristics of several floating and bottom-fixed, rubber-tire breakwater concepts in a relatively short period of time with limited funding, the decision was made to use a 2-D physical model as opposed to a three-dimensional (3-D) physical model. The 2-D model was able to address wave shoaling and wave transmission and overtopping for incident waves that approach at a 90-deg angle to the structures. The alongshore length of structure reproduced in the 2-D model was limited by flume width and model scale. Unlike a 3-D model, the 2-D model could not address alongshore structure length and structure placement relative to the shoreline required to optimize wave protection for a range of incident wave directions. Other variables not addressed in the model study that need to be considered during selection, design, and construction of any concept addressed herein are wave refraction over more complex bottom bathymetry, wave diffraction around the structure, the ability of the concept to structurally withstand combined wave-, wind-, debris-, and current-induced forces, and effects of local wave- and current-induced scour on the structural stability. Another consideration is structural rigidity of a bottom-fixed structure. In the model tests it was assumed that the prototype timber piles would be rigid and any support cables would be drawn tight and thus be relatively inflexible under load. Any large degree of flexibility of these components on the prototype structures will result in transmitted wave heights that exceed those measured in the 2-D model for the concepts and incident wave conditions reported herein.

18. Selection of the best concept for a particular prototype application should begin with a good understanding of the local wave and bottom bathymetry conditions. Where local conditions are similar to the model test conditions, data presented herein can be used to select the concept which will provide the best wave protection. Once a concept has been selected, considerations and decisions will have to be made concerning the items discussed above. This decisionmaking process can be aided by the use of both numerical and physical models that have been fitted to exact site-specific conditions. Through the analysis of local conditions and the selected concept, these models can provide guidance on length and positioning of a structure needed to minimize wave transmission and effects of wave diffraction and refraction

(thus maximizing wave protection provided by a structure). These models also can provide information on wave and current loading, possible local scour problems, and effects of various degrees of structural flexibility.

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Table 1

Test Conditions

Test Condition	Wave Period T, sec	Incident Wave		Incident Wave		Wave Steepness		Relative Depth		Relative Wave Height	
		Height H_i at Depth D_1 ft*	H_i at Depth D_1 ft*	Height H_{inc} at Depth D_2 ft*	H_i/L_1 ** at Depth D_1	D_1/L_1 at Depth D_1	H_i/D_1 at Depth D_1				
$D_1 = 2.0$ ft and $D_2 = 1.416$ ft											
1	2.0	0.50	0.36	0.36	0.034	0.139	0.25				
2	2.0	0.75	0.64	0.64	0.052	0.139	0.38				
3	2.0	1.00	0.78	0.78	0.069	0.139	0.50				
4	2.0	1.25	0.74	0.74	0.087	0.139	0.63				
5	4.0	0.50	0.52	0.52	0.016	0.064	0.25				
6	4.0	1.00	1.30	1.30	0.032	0.064	0.50				
7	4.0	1.70	0.81	0.81	0.054	0.064	0.85				
8	6.0	0.50	0.65	0.65	0.011	0.042	0.25				
9	6.0	1.00	0.91	0.91	0.021	0.042	0.50				
10	6.0	1.50	0.74	0.74	0.032	0.042	0.75				
11	6.0	1.80	0.71	0.71	0.038	0.042	0.90				
12	8.0	0.50	0.69	0.69	0.008	0.031	0.25				
13	8.0	1.00	0.89	0.89	0.016	0.031	0.50				
14	8.0	1.50	1.02	1.02	0.024	0.031	0.75				
15	8.0	1.70	0.96	0.96	0.027	0.031	0.85				
16	10.0	0.50	0.58	0.58	0.006	0.025	0.25				
17	10.0	1.00	1.28	1.28	0.013	0.025	0.50				
18	10.0	1.50	0.97	0.97	0.019	0.025	0.75				
19	10.0	1.80	0.88	0.88	0.023	0.025	0.90				

(Continued)

* Measured without a breakwater in place.

** L_1 is the wave length of incident wave H_1 in water depth D_1 .

Table 1 (Concluded)

Test Condition	Wave Period T, sec	Incident Wave		Incident Wave		Wave Steepness		Relative Depth		Relative Wave Height	
		Height H_1 at Depth D_1 ft*	Height H_{inc} at Depth D_2 ft*	Height H_1/L_1^{**} at Depth D_1	Height H_1/D_1 at Depth D_1	Depth D_1	Depth D_1	Depth D_1	Depth D_1		
$D_1 = 4.0$ ft and $D_2 = 3.124$ ft											
20	2.0	1.00	0.88	0.055	0.221	0.25					
21	2.0	1.50	1.49	0.083	0.221	0.38					
22	2.0	1.85	1.47	0.102	0.221	0.46					
23	4.0	1.00	1.21	0.023	0.093	0.25					
24	4.0	2.00	2.11	0.046	0.093	0.50					
25	4.0	3.00	2.14	0.070	0.093	0.75					
26	6.0	1.00	1.24	0.015	0.060	0.25					
27	6.0	2.00	2.19	0.030	0.060	0.50					
28	6.0	3.00	1.51	0.045	0.060	0.75					
29	8.0	1.00	1.33	0.011	0.045	0.25					
30	8.0	2.00	2.46	0.022	0.045	0.50					
31	8.0	3.00	1.84	0.033	0.045	0.75					
32	10.0	1.00	1.71	0.009	0.036	0.25					
33	10.0	1.50	2.66	0.013	0.036	0.38					
34†	10.0	1.80	2.33	0.016	0.036	0.45					

† Limited by test facility wave generator capabilities.

Table 2
Breakwater Concepts

<u>Concept</u>	<u>Description</u>
1	One floating Goodyear module
2	Tires on wooden pilings
3	One row of tires on cables, two tiers high
4	Two rows on tires on cables, two tiers high
5	Three floating Goodyear modules
6	Three bottom-fixed Goodyear modules
7	One bottom-fixed Goodyear module
8	One row of tires on cables, three tiers high
9	Two rows of tires on cables, three tiers high

Table 3

Transmitted Wave Heights H_T and Wave Height Reduction Coefficients C_r

for Concepts Tested in 2.0-ft Water Depth

Test Condition**	$H_T:C_r$ * for Indicated Concept						
	1	2	3	4	5	6	7
1	0.29:0.81	0.37:1.03	0.17:0.47	0.09:0.25	0.09:0.25	0.07:0.19	0.28:0.78
2	0.42:0.66	0.58:0.91	0.23:0.36	0.12:0.19	0.16:0.25	0.11:0.17	0.44:0.69
3	0.51:0.65	0.64:0.82	0.26:0.33	0.15:0.19	0.20:0.26	0.16:0.21	0.67:0.86
4	0.59:0.80	0.72:0.97	0.33:0.45	0.16:0.22	0.23:0.31	0.18:0.24	0.56:0.76
5	0.53:1.02	0.51:0.98	0.20:0.38	0.11:0.21	0.26:0.50	0.21:0.40	0.42:0.81
6	1.14:0.88	0.79:0.61	0.35:0.27	0.23:0.18	0.40:0.31	0.27:0.21	0.77:0.59
7	1.04:1.28	0.72:0.89	0.50:0.62	0.35:0.43	0.46:0.57	0.38:0.47	0.80:0.99
8	0.62:0.95	0.46:0.71	0.24:0.37	0.15:0.23	0.34:0.52	0.24:0.37	0.38:0.58
9	1.17:1.29	0.90:0.99	0.37:0.41	0.26:0.29	0.58:0.64	0.36:0.40	0.76:0.84
10	1.08:1.46	0.77:1.04	0.46:0.62	0.31:0.42	0.67:0.91	0.55:0.74	0.65:0.88
11	1.02:1.44	0.74:1.04	0.50:0.70	0.30:0.42	0.65:0.92	0.57:0.80	0.69:0.97
12	0.46:0.67	0.41:0.59	0.19:0.28	0.16:0.28	0.29:0.42	0.22:0.32	0.32:0.46
13	1.13:1.27	0.80:0.90	0.34:0.38	0.24:0.27	0.49:0.55	0.32:0.36	0.80:0.90
14	1.00:0.98	0.82:0.80	0.43:0.42	0.28:0.27	0.53:0.52	0.44:0.43	0.75:0.74
15	0.87:0.91	0.86:0.90	0.48:0.50	0.28:0.29	0.58:0.60	0.47:0.49	0.80:0.83
16	0.61:1.05	0.45:0.78	0.29:0.50	0.15:0.26	0.31:0.53	0.16:0.28	0.38:0.66
17	1.08:0.84	0.97:0.76	0.30:0.23	0.32:0.25	0.54:0.42	0.37:0.29	0.93:0.73
18	1.22:1.26	0.81:0.84	0.63:0.65	0.40:0.41	0.60:0.62	0.46:0.47	0.74:0.76
19	1.21:1.38	0.85:0.97	0.73:0.83	0.37:0.42	0.63:0.72	0.46:0.52	0.73:0.83

* Wave height reduction coefficient is ratio of transmitted wave height H_T (in feet) to incident wave height H_{inc} ; i.e., $C_r = H_T/H_{inc}$.

** Refer to Table 1.

Table 4

Transmitted Wave Heights H_T and Wave Height Reduction Coefficients C_r
for Concepts Tested in 4.0-ft Water Depth

Test Condition**	$H_T:C_r^*$ for Indicated Concept				
	3	5	6	8	9
20	0.58:0.66	0.36:0.41	0.84:0.95	0.31:0.35	0.11:0.13
21	1.02:0.68	0.51:0.34	1.10:0.74	0.63:0.42	0.19:0.13
22	1.02:0.69	0.60:0.41	1.25:0.85	0.72:0.49	-- --
23	0.51:0.42	0.65:0.54	0.99:0.82	0.53:0.44	0.32:0.26
24	1.07:0.51	1.10:0.52	1.63:0.77	0.80:0.38	0.41:0.19
25	1.69:0.79	1.03:0.48	1.66:0.78	1.36:0.64	0.48:0.22
26	0.74:0.60	0.94:0.76	0.76:0.61	0.53:0.43	0.44:0.35
27	1.61:0.74	1.77:0.81	1.78:0.82	1.07:0.49	0.77:0.35
28	1.75:1.16	1.46:0.97	1.59:1.05	1.69:1.12	0.96:0.64
29	0.68:0.51	1.01:0.76	1.11:0.83	0.79:0.59	0.36:0.27
30	1.56:0.63	1.80:0.73	1.60:0.65	1.68:0.68	0.53:0.22
31	2.28:1.24	2.28:1.24	1.63:0.89	1.88:1.02	1.04:0.57
32	0.75:0.42	1.27:0.74	1.42:0.83	0.55:0.32	0.37:0.22
33	1.14:0.43	1.86:0.70	1.74:0.65	0.77:0.29	0.50:0.19
34	1.31:0.56	2.16:0.93	1.54:0.66	0.78:0.33	0.58:0.25

* Wave height reduction coefficient is ratio of transmitted wave height H_T (in feet) to incident wave height H_{inc} ; i.e., $C_r = H_T/H_{inc}$.

** Refer to Table 1.

Table 5

Energy Reduction Coefficients E_r and Average Energy Reduction Coefficient $\bar{E}_r$
for Concepts Tested in 2.0-ft Water Depth

Test Conditions**	E_r^* for Indicated Concept						
	1	2	3	4	5	6	7
1-4	0.51	0.83	0.15	0.04	0.07	0.04	0.61
5-7	1.01	0.54	0.16	0.07	0.17	0.10	0.54
8-11	1.72	0.93	0.29	0.12	0.57	0.35	0.70
12-15	1.01	0.69	0.18	0.07	0.29	0.18	0.60
16-19	1.22	0.68	0.30	0.11	0.31	0.16	0.57
For all test conditions $\bar{E}_r =$	1.09	0.73	0.22	0.08	0.28	0.17	0.60

* E_r = ratio of wave energy per foot of wave crest reaching depth D_2 with a breakwater in place to the wave energy reaching depth D_2 without a breakwater in place.

** Refer to Table 1.

Table 6

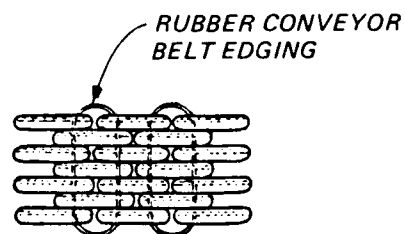
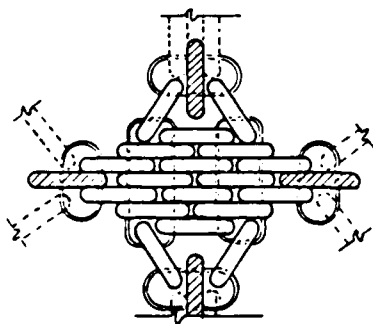
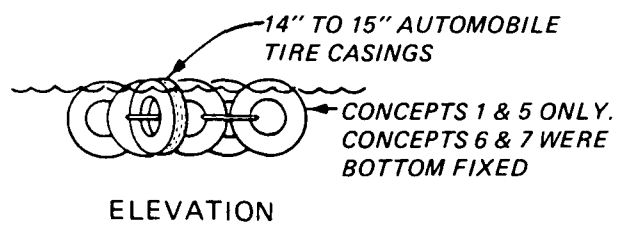
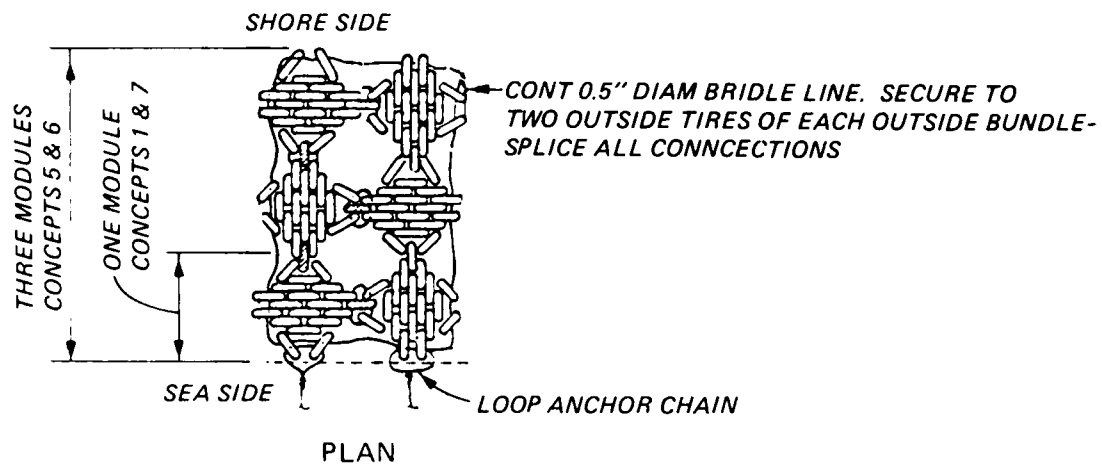
Energy Reduction Coefficients E_r and Average Energy Reduction Coefficient $\bar{E}_r$

for Concepts Tested in 4.0-ft Water Depth

Test Conditions**	E_r^* for Indicated Concept				
	3	5	6	8	9
20-22	0.47	0.15	0.67	0.10	0.02
23-25	0.41	0.26	0.61	0.26	0.05
26-28	0.72	0.71	0.73	0.50	0.20
29-31	0.72	0.84	0.58	0.63	0.13
32-34	0.23	0.64	0.48	0.10	0.05
For all test conditions $\bar{E}_r =$	0.51	0.52	0.61	0.32	0.09

* E_r = ratio of wave energy per foot of wave crest reaching depth D_2 with a breakwater in place to the wave energy reaching depth D_2 without a breakwater in place.

** Refer to Table 1.



NOTE EACH TIRE FILLED WITH 0.5 LB
POLYURETHANE FOAM. TIRES SHOWN
CROSS-HATCHED INTERCONNECT MODULES.

CONCEPTS 1, 5, 6, AND 7
GOODYEAR MODULES

SHORE SIDE

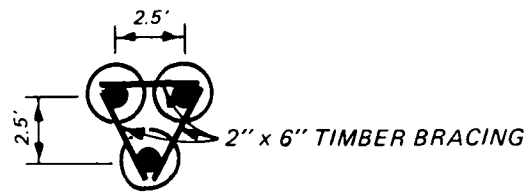
DETAIL "Z"

DETAIL "Y"



SEA SIDE

PLAN



DETAIL "Y"

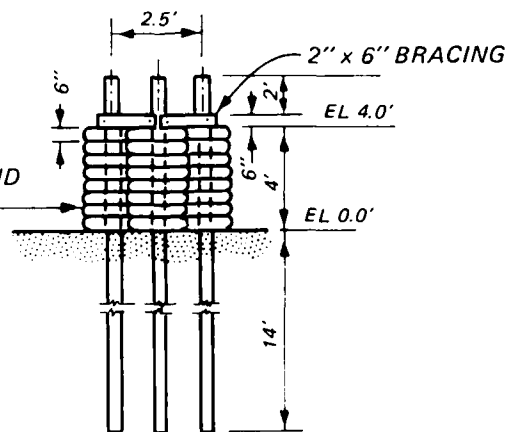
CLASS 5 RESIDENTIAL PILE

WIRE ROPE CLIP

5/8" GALV. CABLE

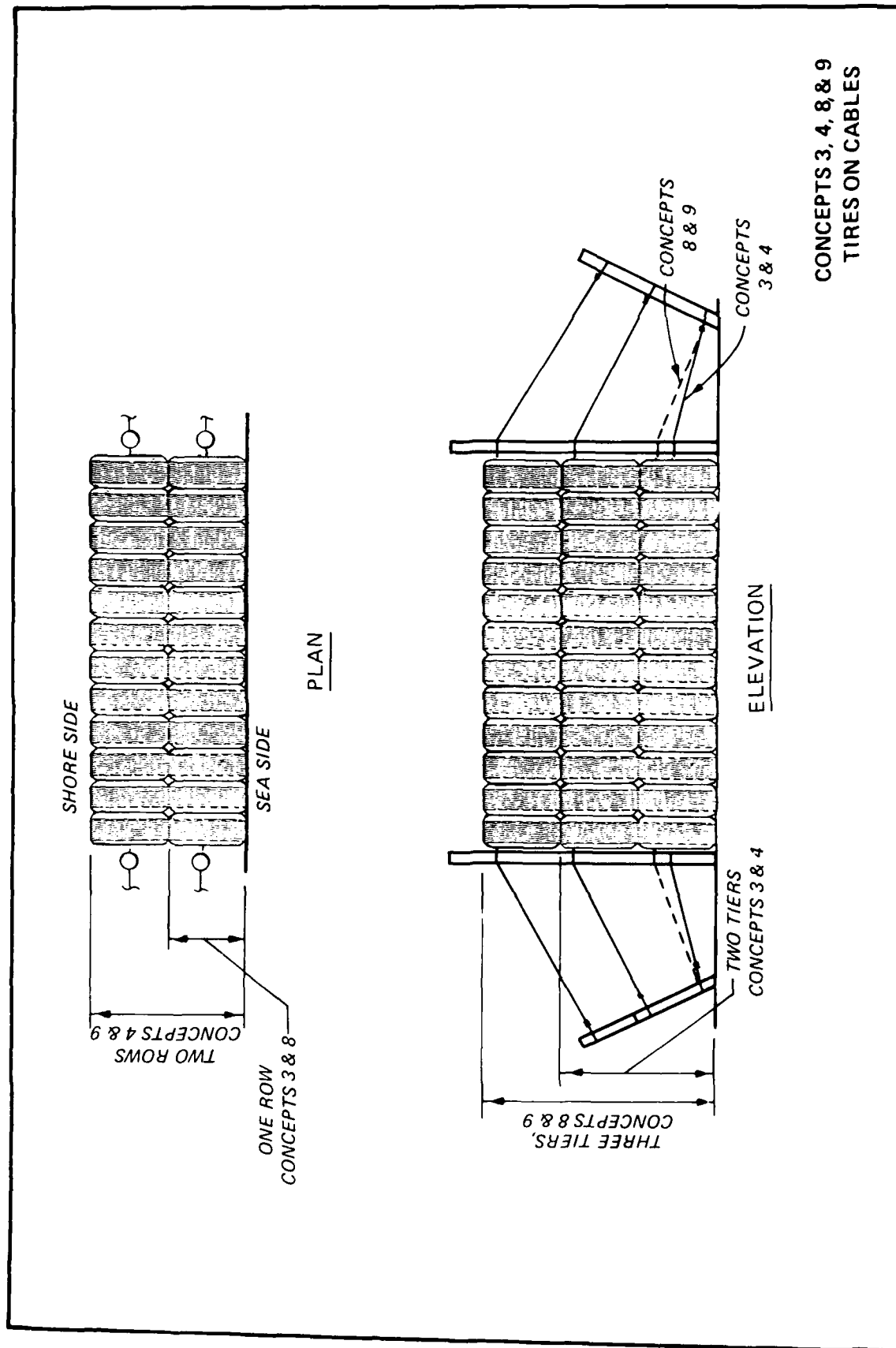
DETAIL "Z"

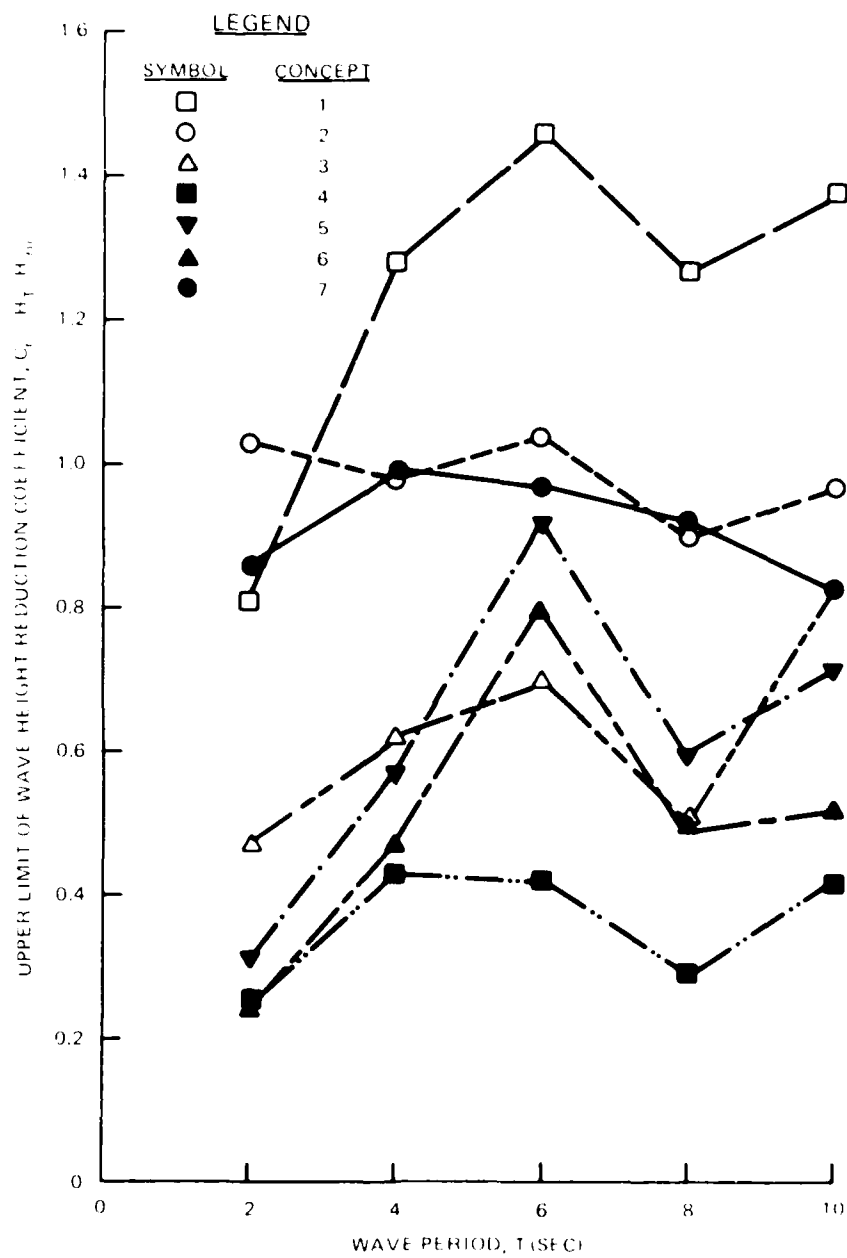
RUBBER TIRES
STACKED FROM GROUND
TO BRACING



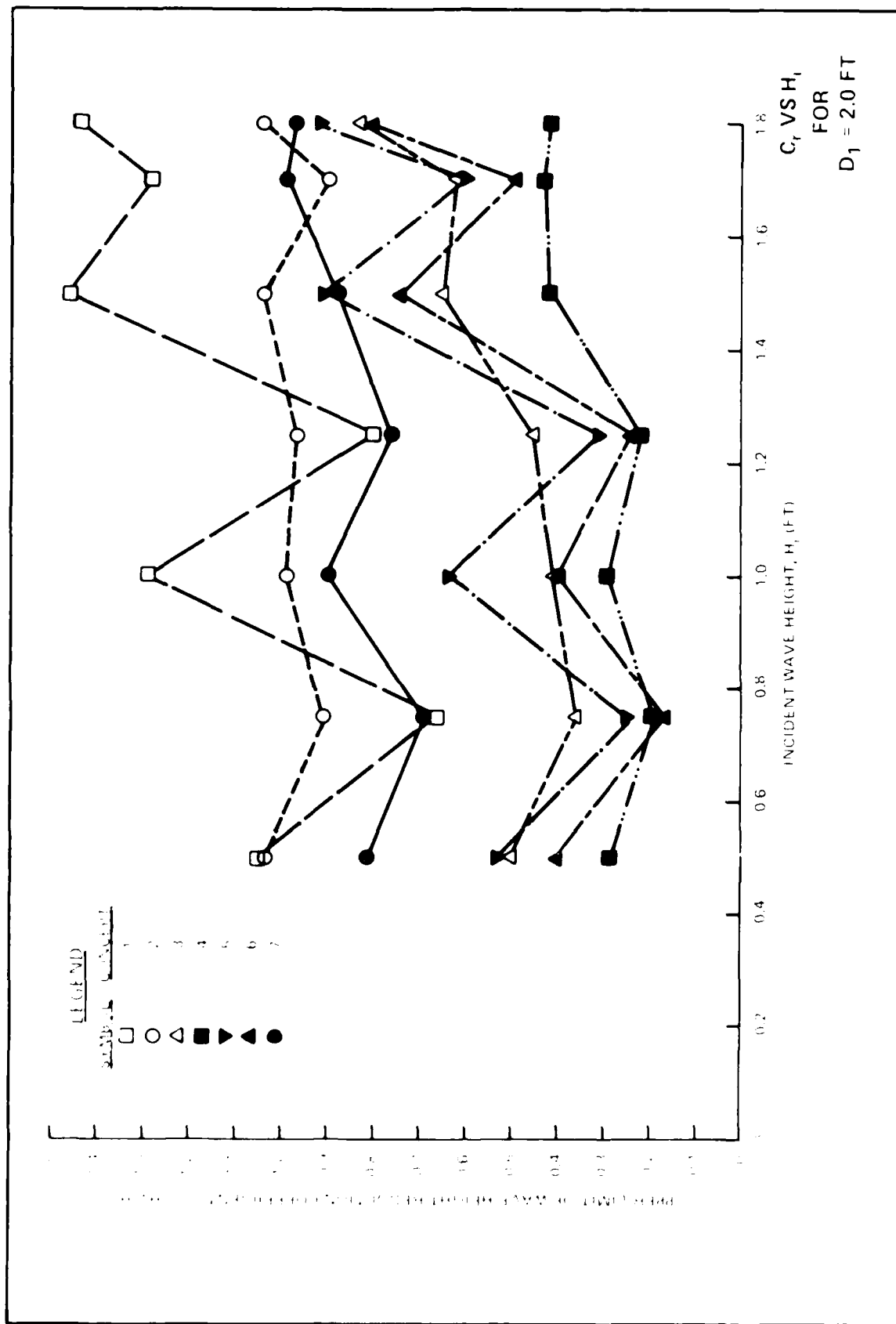
SEA-SIDE ELEVATION

CONCEPT 2
TIRES ON
WOODEN PILINGS





C_r VS T
FOR
 $D_1 = 2.0$ FT



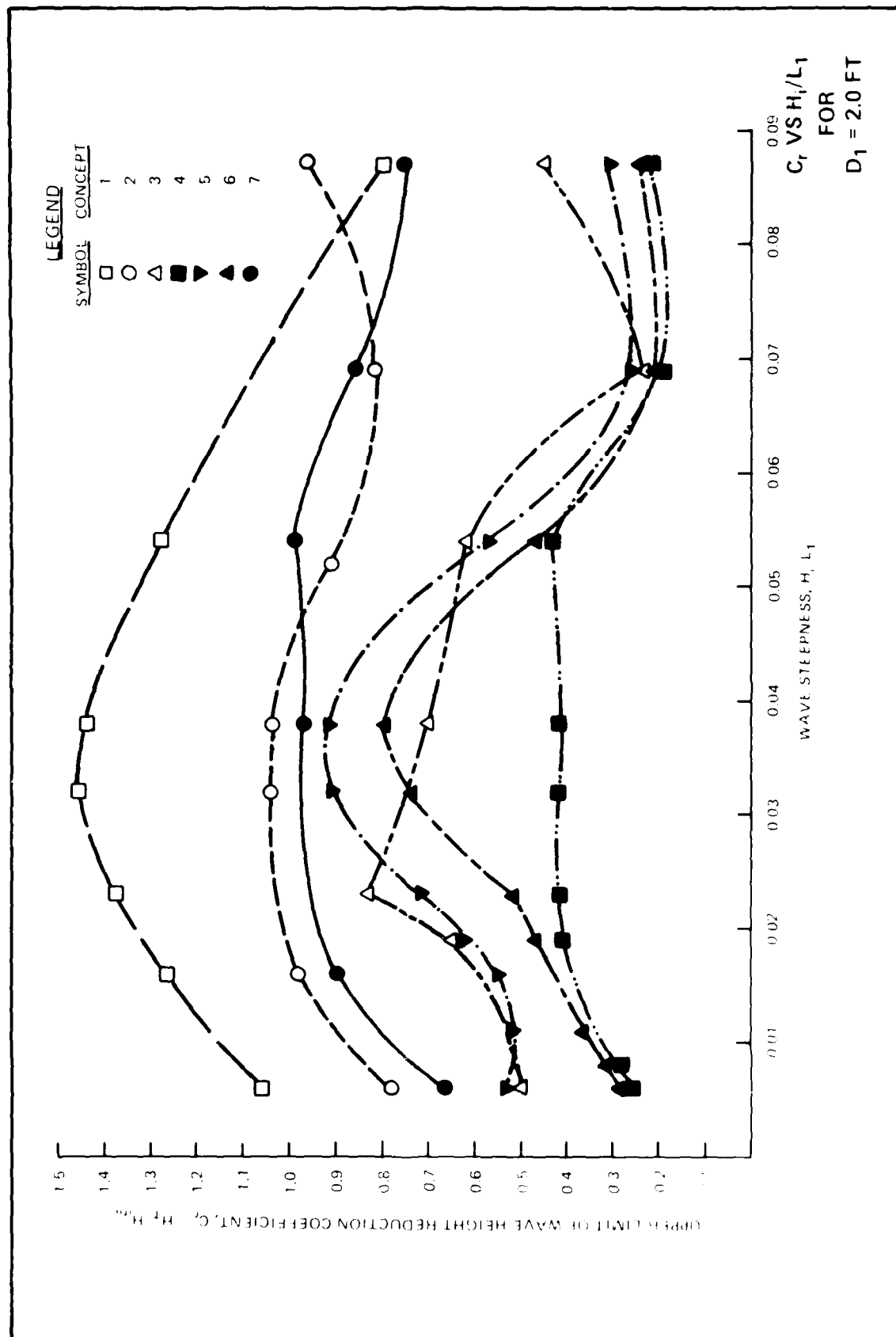
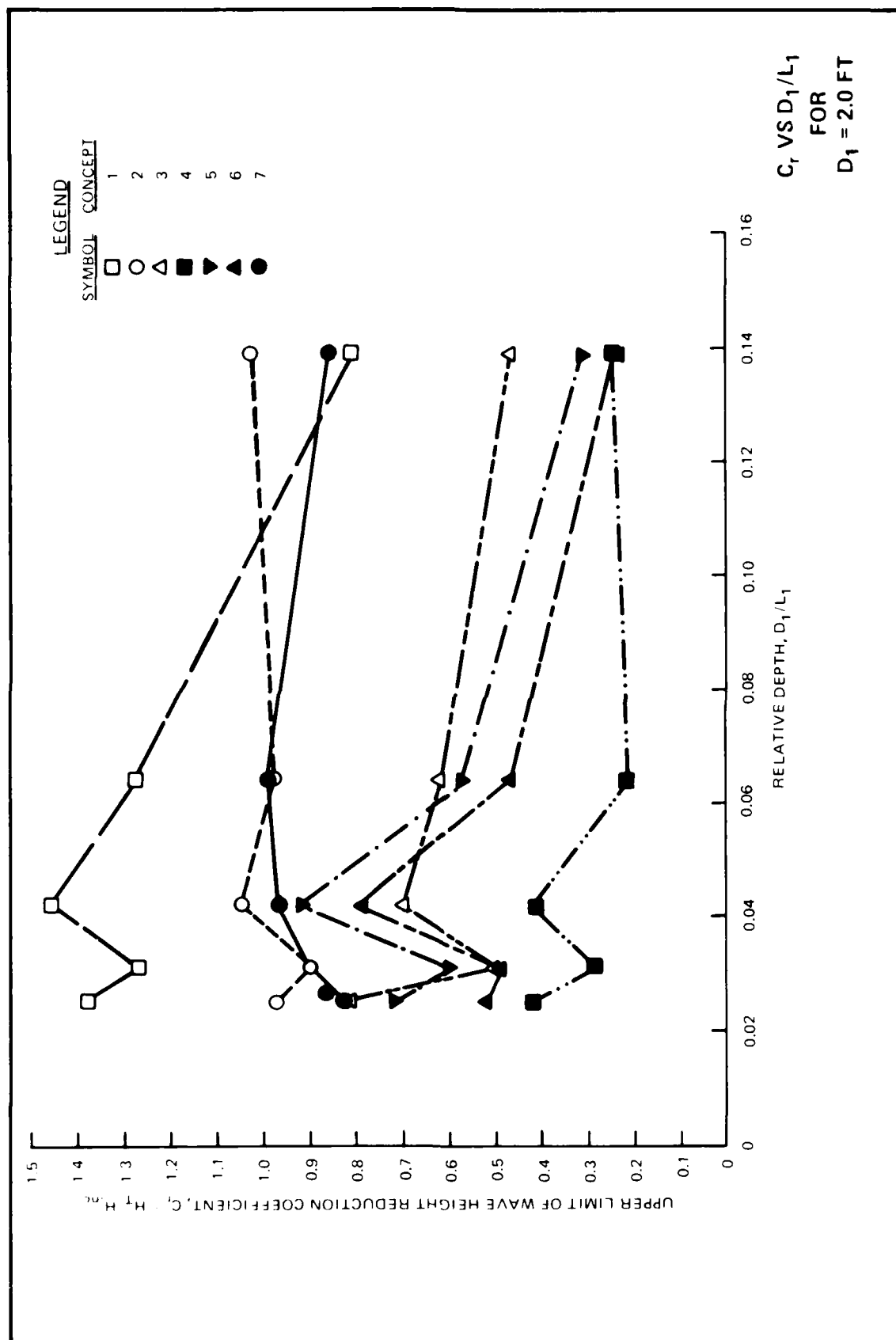


PLATE 6



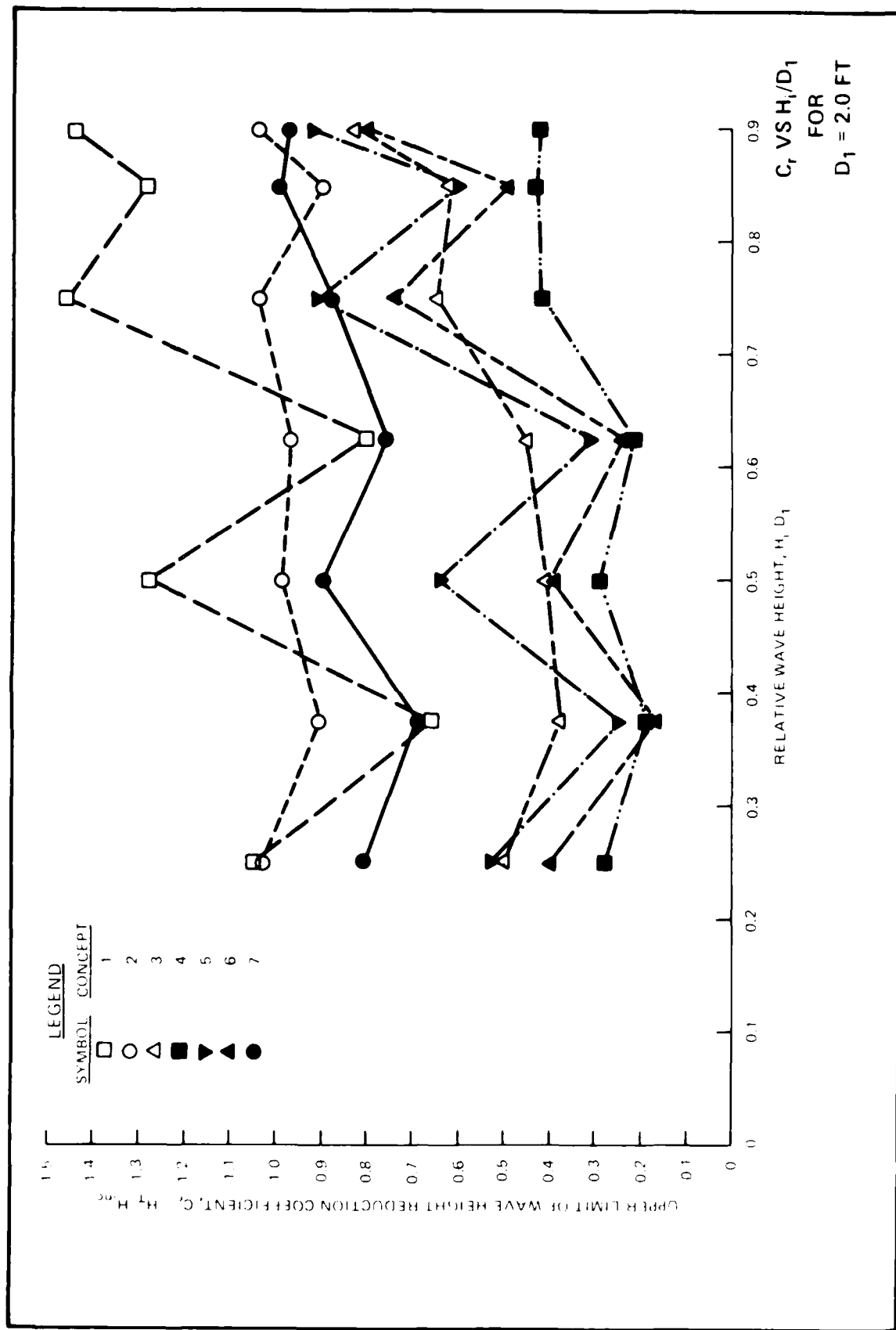
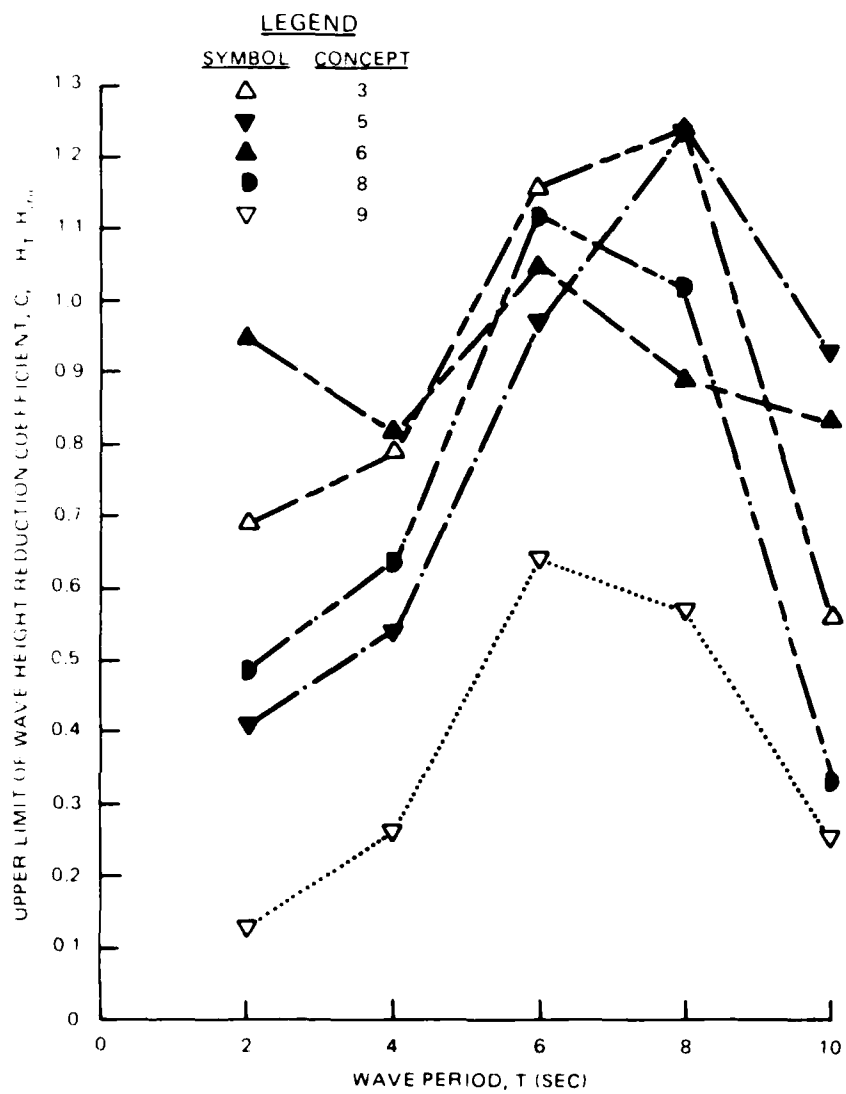
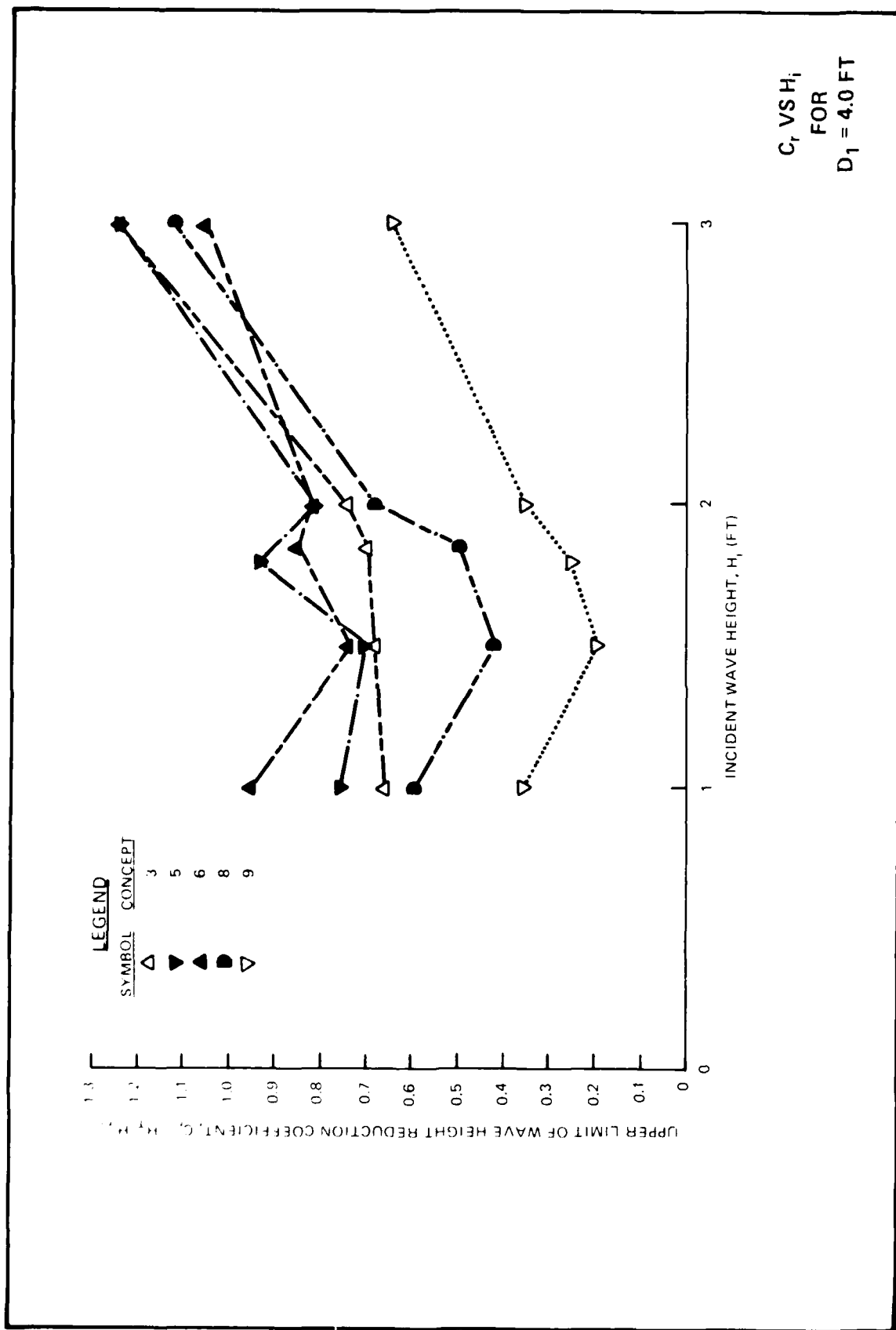


PLATE 8



C_r VS T
FOR
 $D_1 = 4.0$ FT



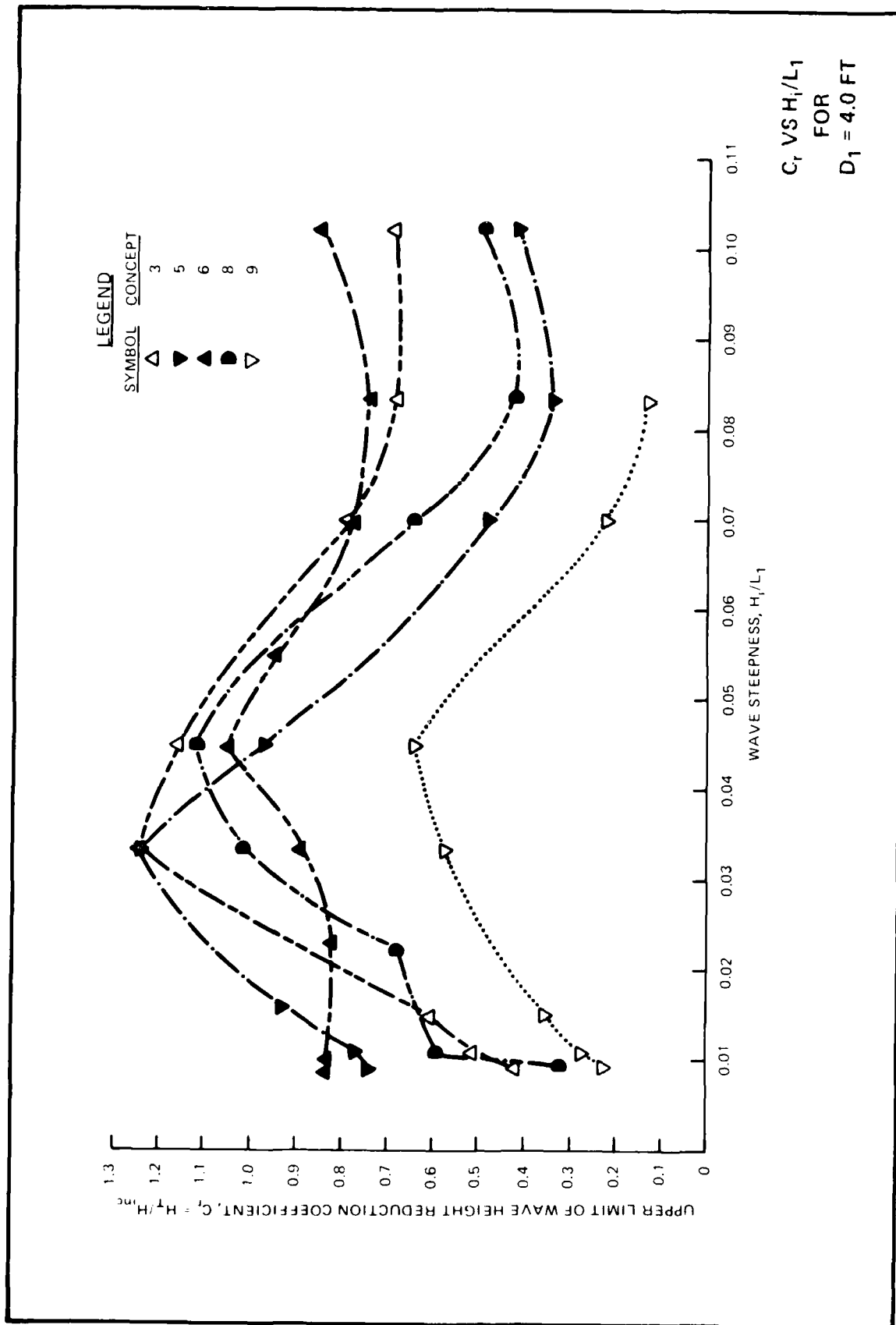
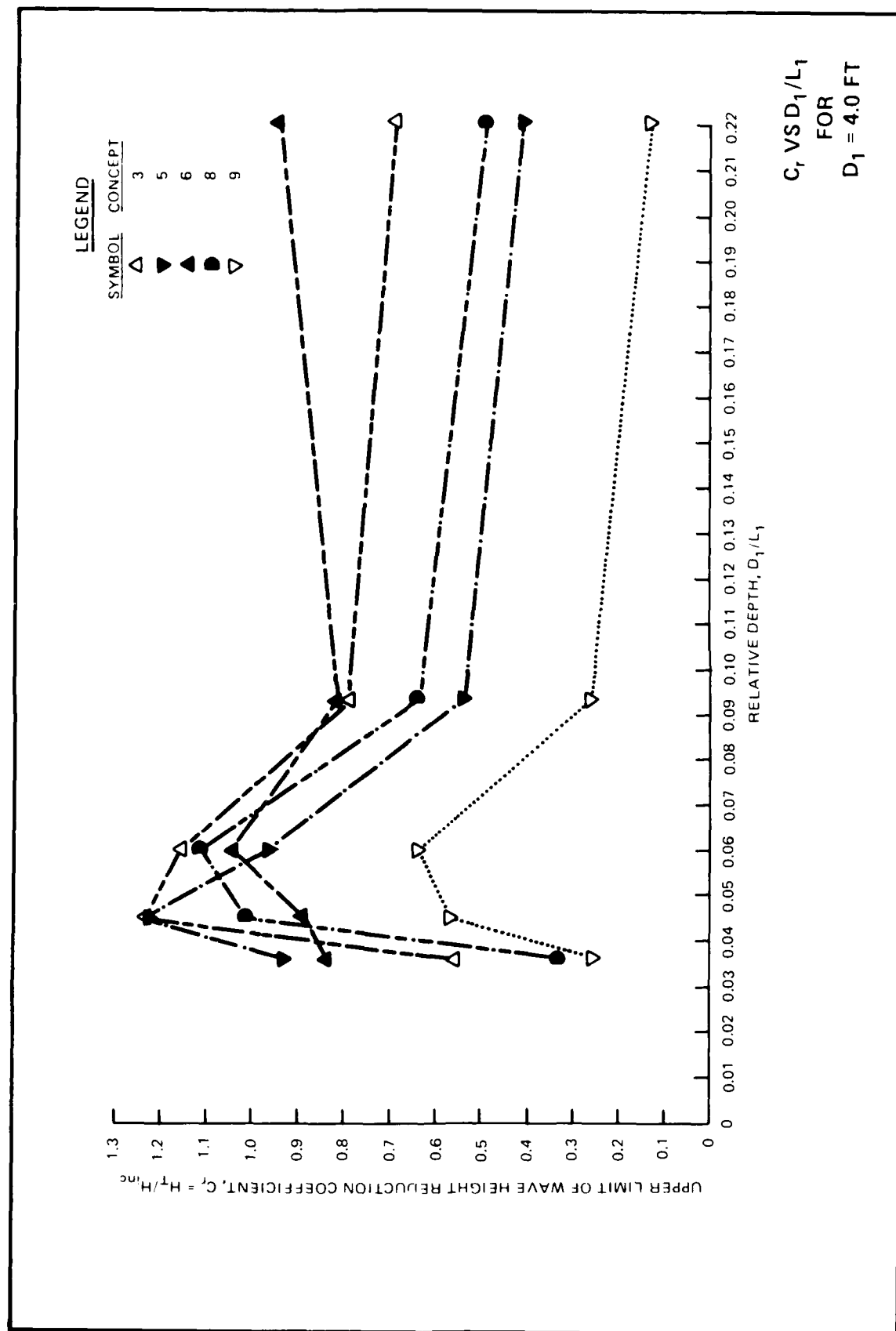
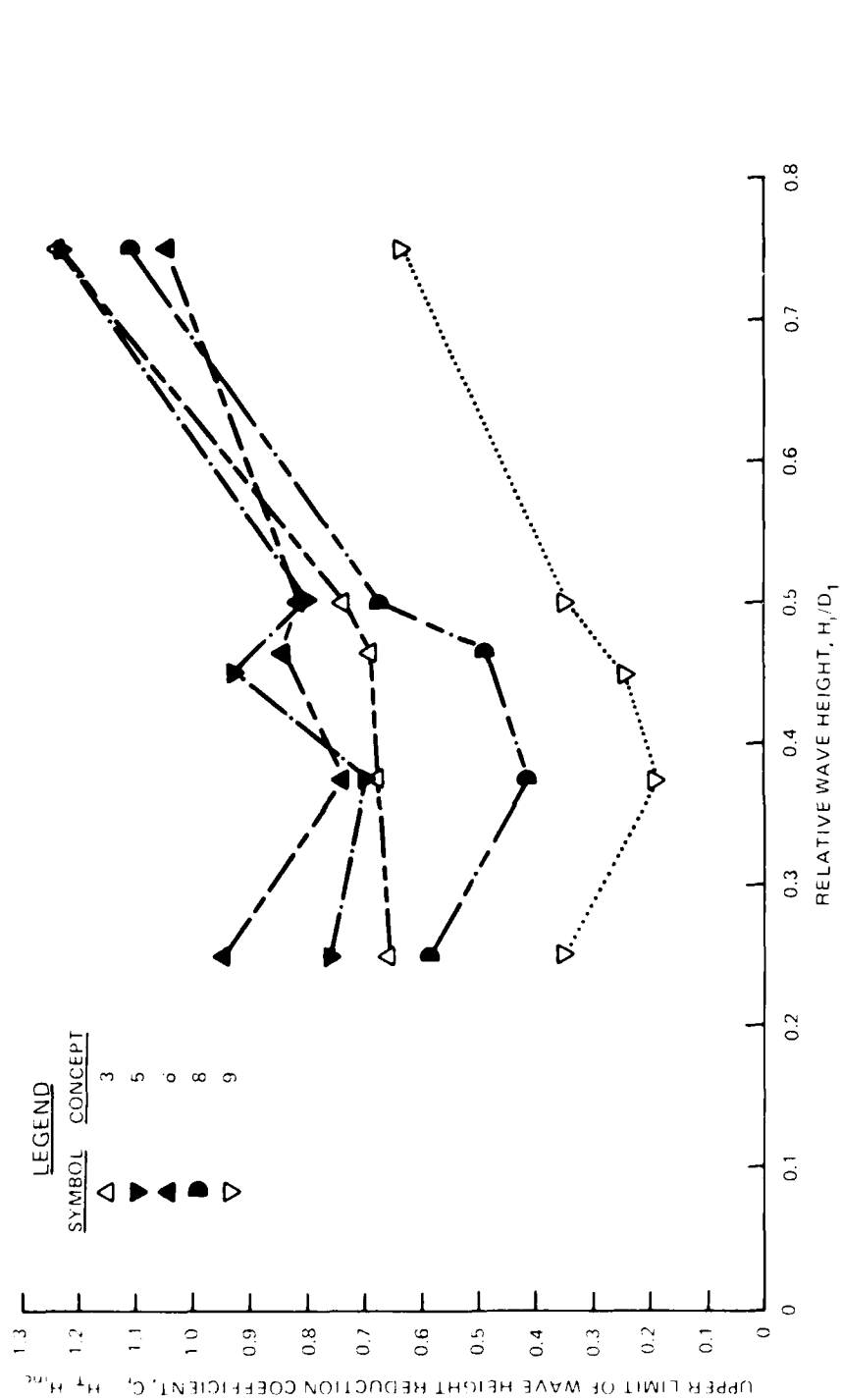
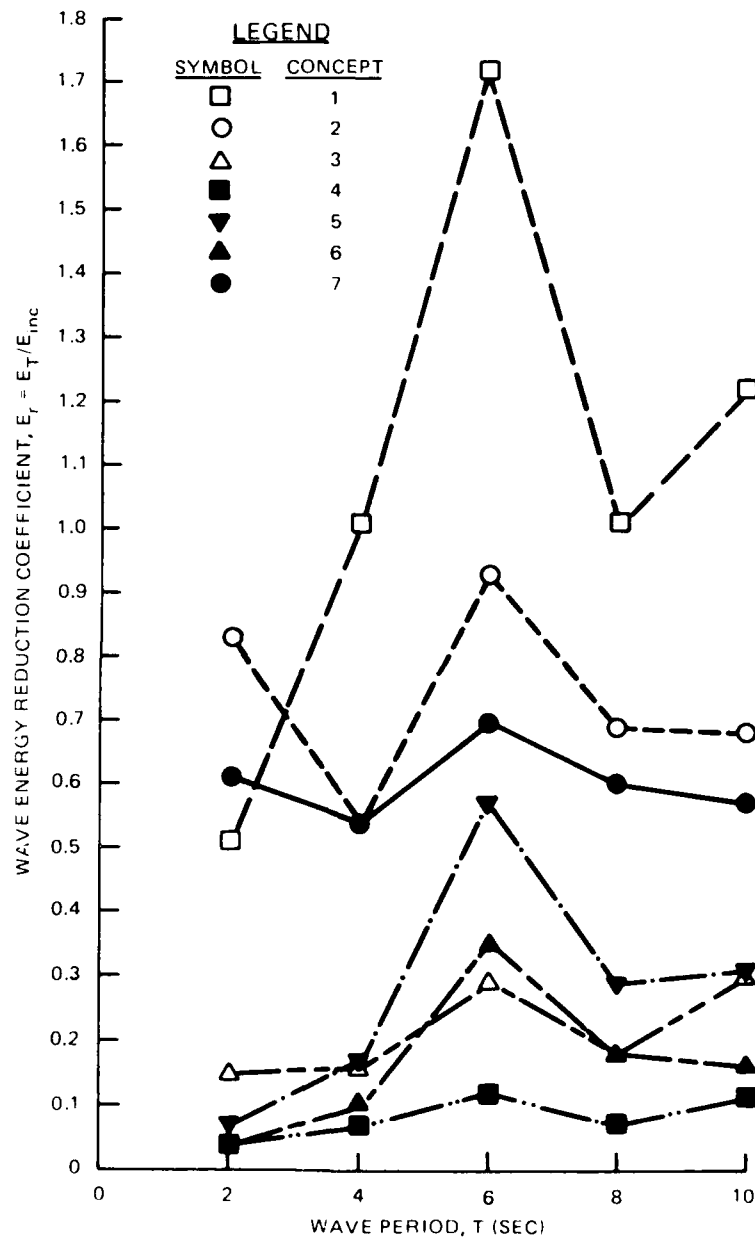


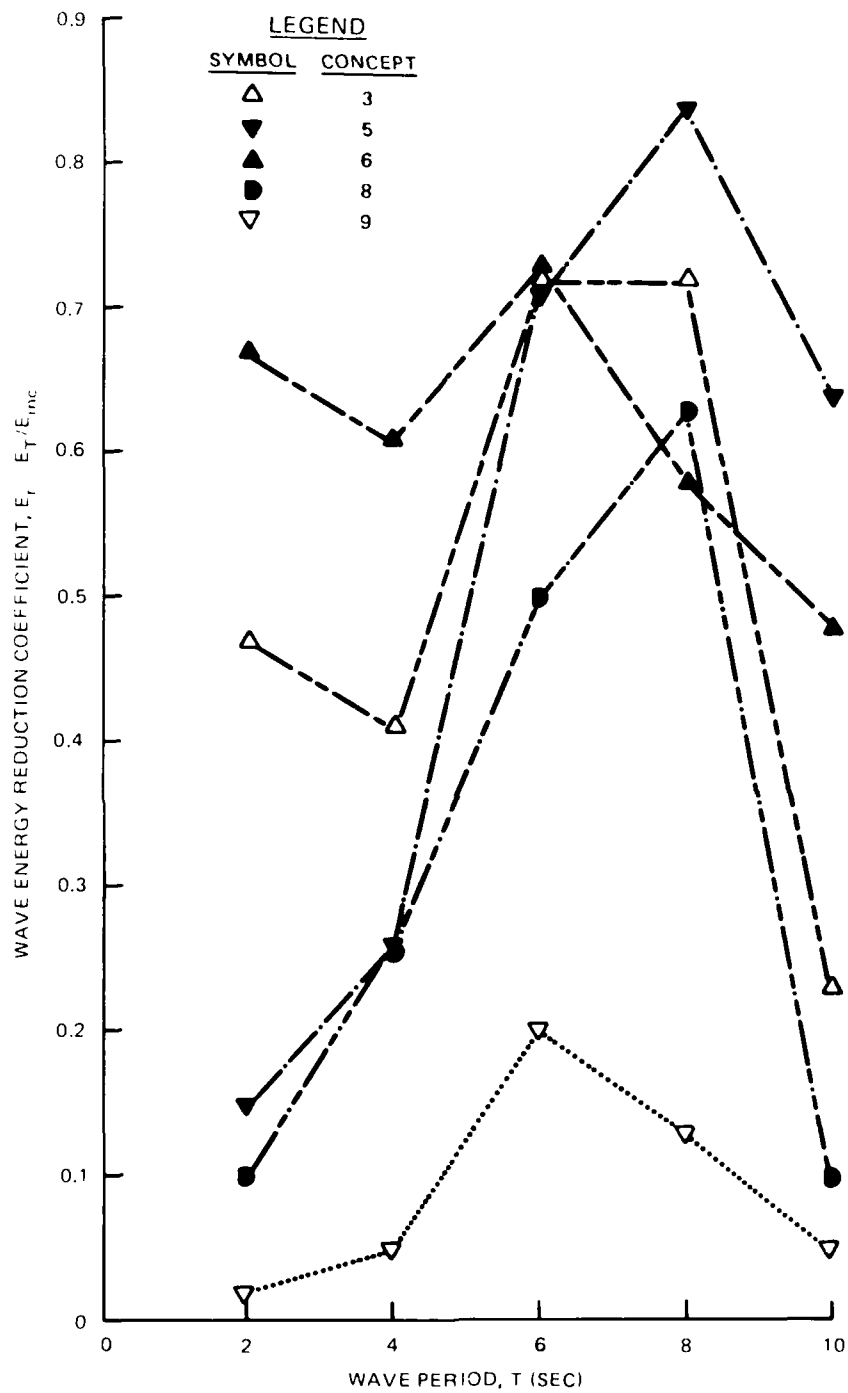
PLATE 12







E_r VS T
FOR
 $D_1 = 2.0$ FT



E_r VS T
FOR
 $D_1 = 4.0$ FT

APPENDIX A: NOTATION

A	Area
C_r	Wave height reduction coefficient = H_T/H_{inc}
D	Water depth, ft
D/L	Relative depth
E	Wave energy, ft-lb/ft
E_r	Wave energy reduction coefficient = E_T/E_{inc}
$\bar{E}_r$	Average wave energy reduction coefficient for a range of wave periods and wave heights
E_T or E_{inc}	Total wave energy per foot of wave crest reaching a location in a given period of time, ft-lb/ft
H	Wave height, ft
L	Length, wave length, ft
m	Number of wave periods
T	Time, wave period, sec
γ	Specific weight, pcf

Subscripts

i	Refers to incident condition at depth D_1 with no breakwater concept in place
inc	Refers to incident condition at depth D_2 with no breakwater concept in place
r	Refers to the ratio of two quantities
T	Refers to transmitted condition at depth D_2 with breakwater concept in place
1-2	Refers to locations at depths D_1 and D_2 , respectively

END

FEB.

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