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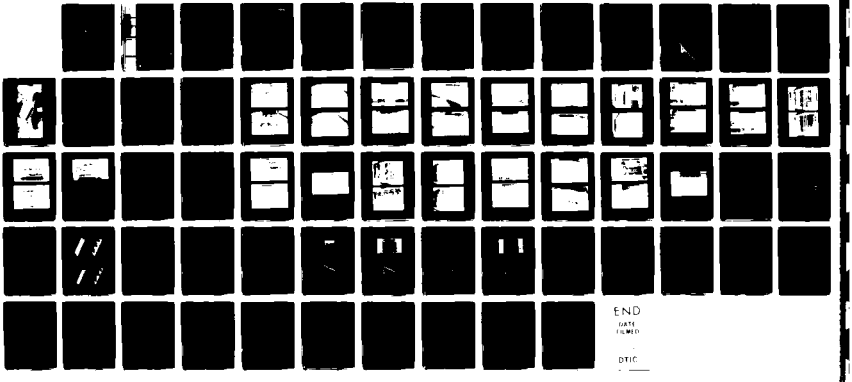

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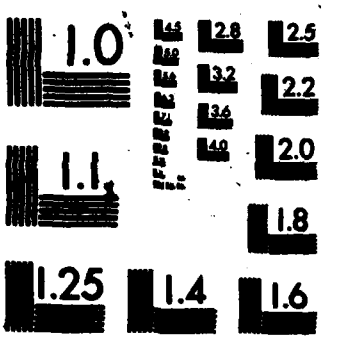

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WAVE STABILITY STUDY OF RIPRAP-FILLED CELLS

Hydraulic Model Investigation

by

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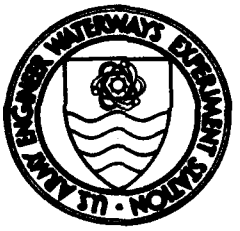

April 1983
Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Both two-dimensional and three-dimensional hydraulic model investigations were conducted to test the stability of a new streambank protection concept when exposed to short-period wave attack. The concept, referred to as "Riprap-Filled Cells," consists of containerizing riprap in various sizes of cells. Based on the 1:4-scale (model:prototype) model tests and results for the "riprap-filled cells" placed on IV-on-2H streambank slopes that are assumed to be stable and impermeable and for angles of wave attack of 90, 60, and 30 deg,

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20. ABSTRACT (Continued).

it is concluded that: (a) one-ft-cube cells (full and half-full of 0.6- to 4.6-lb riprap) are stable (no streambank exposure) for 2.0-sec, 1.0- to 1.75-ft, 4.0-sec, 1.0- to 3.0-ft, and 6.0-sec, 1.0- to 2.5-ft nonbreaking waves; (b) rectangular cells (half-full of 0.6- to 4.6-lb riprap) are stable for nonbreaking wave heights up to and including 1.5 ft for wave periods of 2.0 and 6.0 sec. Wave heights exceeding this produce spot exposures of the streambank; (c) rectangular cells (full of 0.6- to 4.6-lb riprap) are stable for 6.0-sec, nonbreaking waves up to and including 2.0 ft. Wave heights exceeding 2.0 ft produced spot exposures of the streambank; (d) both runup and rundown on all sections tested appear to be functions of wave steepness, relative depth, and angle of wave attack. The angles of wave attack, listed in descending magnitudes of runup and rundown produced, are 60, 90, and 30 deg. One-ft-cube cells, full of riprap, and rectangular cells, half-full of riprap, show trends of decreasing runup and rundown with increasing values of wave steepness and relative depth. Insufficient data are available for these trends to be well defined for the 1-ft-cube cells, half-full of riprap and the rectangular cells, full of riprap.

PREFACE

Authority for the U. S. Army Engineer Waterways Experiment Station (WES) to conduct this study was authorized by Congress through the Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251 (as amended by Public Law 94-587, Sections 155 and 161, October 1976).

The study was conducted by personnel of the Hydraulics Laboratory (HL), WES, under the general direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, Dr. R. W. Whalin, former Chief, and Mr. C. E. Chatham, Jr., Acting Chief of the Wave Dynamics Division; and Mr. D. D. Davidson, Chief of the Wave Research Branch. The tests were carried out by Messrs. C. Lewis and M. S. Taylor and Mrs. B. J. Wright, Engineering Technicians, under the supervision of Mr. D. G. Markle, Research Hydraulic Engineer. This report was prepared by Mr. Markle.

The following WES personnel are acknowledged for their technical assistance and guidance provided during the conduct of the study and the preparation of this report: Mr. J. L. Grace, Jr., Chief of the Hydraulic Structures Division, HL; Mr. E. B. Pickett, HL, Program Manager for the Section 32 Program; Mr. C. L. McAnear, Chief of the Soil Mechanics Division, Geotechnical Laboratory (GL); Mr. N. R. Oswalt, Chief of the Spillways and Channels Branch, HL; Dr. E. M. Perry, Research Civil Engineer, GL; and Mr. S. T. Maynord, Research Hydraulic Engineer, HL.

Commanders and Directors of WES during the conduct of the study and the preparation and publication of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	25.4	millimetres
pounds (force)	4.448222	newtons
pounds (force) per cubic foot	157.087467	newtons per cubic metre

WAVE STABILITY STUDY OF RIPRAP-FILLED CELLS
Hydraulic Model Investigation

PART I: INTRODUCTION

The Problem

1. Availability and ease of construction have made riprap the predominant method used for protecting streambanks from erosive forces. In many instances, the size of riprap needed for stability is not available locally and must be transported to the construction area. Depending on distance, the transporting costs may exceed the benefits derived from the riprap protection. When such a problem arises, alternative methods of bank protection using locally available material must be considered.

Purpose of Model Study

2. Both two-dimensional (2-D) and three-dimensional (3-D) hydraulic model investigations were conducted to test a new streambank protection concept. The concept, referred to as "Riprap-Filled Cells," consists of containerizing the riprap; and the various plans tested will be described in detail in later sections of this report. The idea behind the concept is the ability to use smaller riprap to protect streambank from wave attack that would normally require much larger riprap for stability.

PART II: THE MODEL

Design of Model

3. An undistorted linear scale of 1:4, model to prototype, was selected for both the 2-D and 3-D wave stability models. Scale selection was determined by size of model materials, capabilities of the wave generator, and water depth at the toe of the test sections. Based on Froude's model law* 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).

Characteristics	Dimensions	Model-Prototype Scale Relations
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	$T_r = L_r^{1/2} = 1{:}2$

4. The relationship between the weight of model and prototype riprap was based on the following transference equation:**

$$\frac{(W_r)_m}{(W_r)_p} = \frac{(\gamma_r)_m}{(\gamma_r)_p}\left(\frac{L_m}{L_p}\right)^3\left[\frac{(S_r)_p - 1}{(S_r)_m - 1}\right]^3 \qquad (1)$$

where

subscripts m, p = model and prototype quantities, respectively

W_r = weight of individual stone, lb†

---

* J. C. Stevens et al. 1942. "Hydraulic Models," Manual on Engineering Practice No. 25, American Society of Civil Engineers, New York, N. Y.

** R. Y. Hudson, 1974 (Jan). "Concrete Armor Units for Protection Against Wave Attack," Miscellaneous Paper H-74-2, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

† A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

W_r = specific weight of individual stone, pcf

L_m/L_p = linear scale of model

S_r = specific gravity of an individual stone relative to the water in which it is placed, i.e., $S_r = \gamma_r/\gamma_w$

γ_w = specific weight of water, pcf

Specific weights of the stone and water were assumed to be the same in the model as they are in the prototype, 165 pcf and 62.4 pcf, respectively. Therefore Equation 1 reduces to:

$$\frac{(W_r)_m}{(W_r)_p} = \left(\frac{L_m}{L_p}\right)^3 \qquad (2)$$

Representation of Streambank Slopes

5. The streambank slopes were represented by wooden frameworks which were filled with sand and the sand was overlaid with a sand-cement crust (Figure 1). With the state of the art as it is today, the

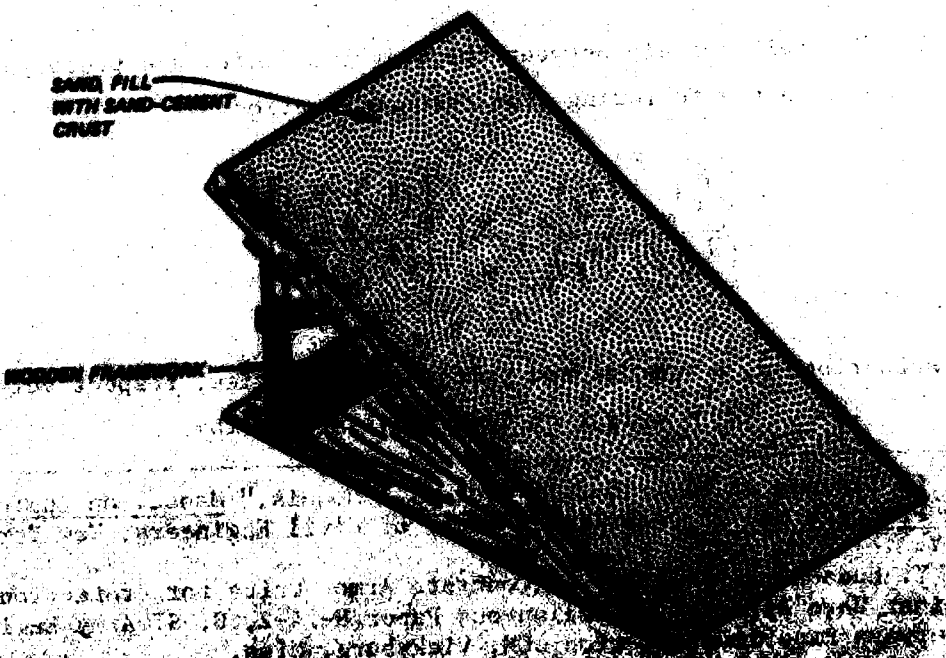


Figure 1.

interaction of waves and streambank soils can only be simulated at a 1:1 scale. Therefore, for these 1:4-scale model tests the streambank stability was not tested and the soil was assumed to be impermeable and stable once the protection was placed on the slope. Only the stability against wave attack of the bank protection concept was tested.

Test Facilities and Equipment

6. All tests were conducted in an L-shaped concrete flume 250 ft long, 50 and 80 ft wide at the top and bottom of the L, respectively, and 4.5 ft deep (Figure 2). The 2-D tests, 90-deg wave attack, and 3-D tests, 60- and 30-deg wave attack, were tested in the flat bottom portion of the flume as indicated in Figures 2 and 3. The photograph was taken from an elevated angle, looking from the wave generator toward the test sections. The flume was equipped with a paddle-type wave generator capable of producing monochromatic waves of various periods and heights. Changes in water-surface elevations, as a function of time (wave heights), were measured by parallel, resistance, electrical wave-height gages and recorded on chart paper by an electrically operated oscillograph. The electrical output of each gage was directly proportional to its submergence depth.

Selection of Test Conditions

7. All tests were conducted for a streambank slope of 1V on 2H. Prototype wave heights ranging from 1.0 to 3.0 ft for wave periods of 2.0, 4.0, and 6.0 sec were chosen as representative of wind- and boat-generated waves. A prototype water depth of 8 ft was modeled for all tests; this water depth ensured that all waves were free of depth limitations and were mostly nonbreaking waves as are found on rivers and streams. All plans were tested for angles of wave attack of 90 deg (2-D model, wave direction 1), 60 deg (3-D model, wave direction 2), and 30 deg (3-D model, wave direction 3).

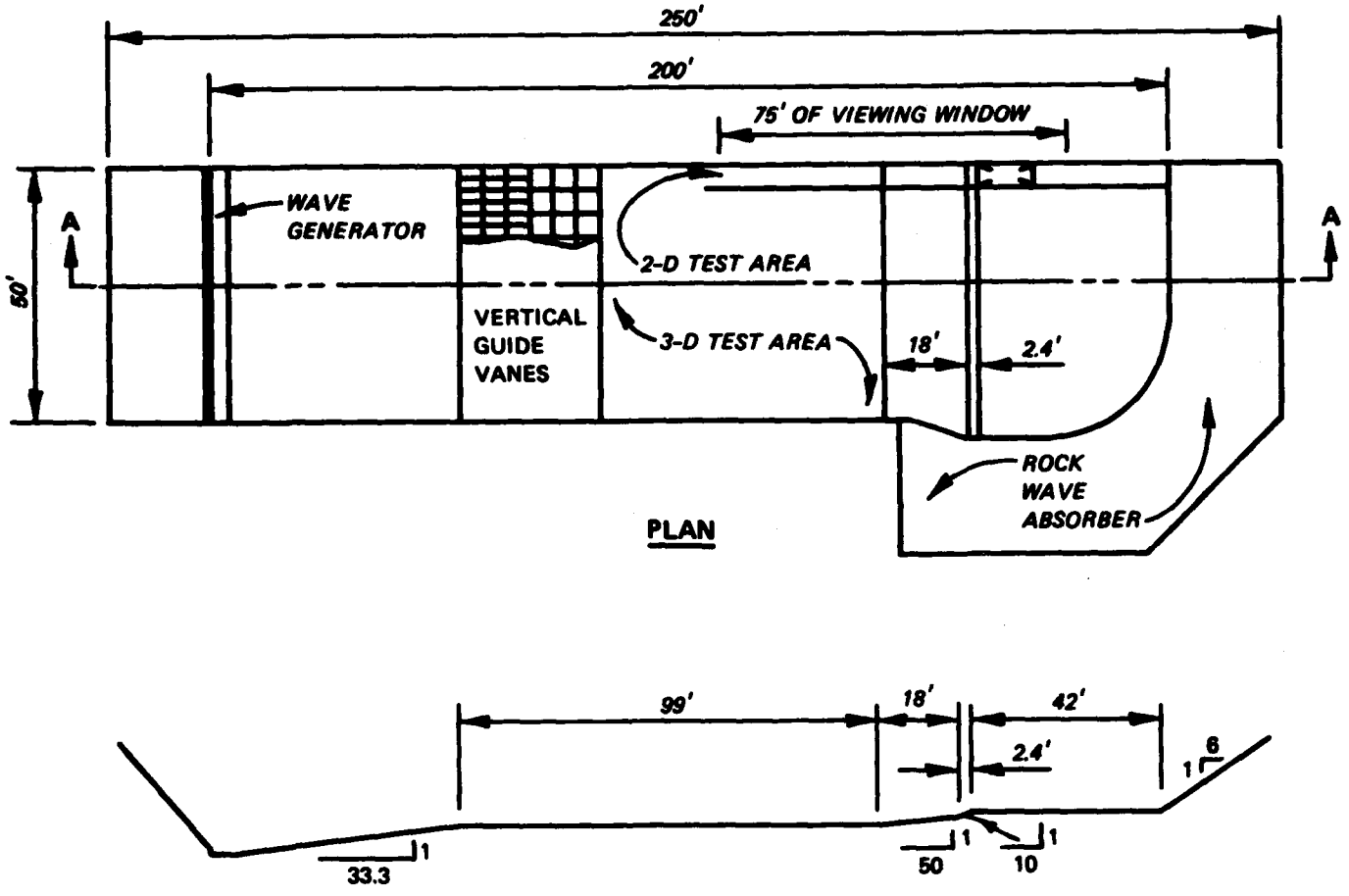


Figure 2. Flume geometry and wave stability testing area

Figure 3. Orientation of test sections in test facility

PART III: TESTS AND RESULTS

Development of Plans

8. Four plans were tested. Plans 1 and 2 (Plates 1 and 2) consisted of 1-ft-cube cells. In Plan 1 the cells were filled with 0.58- to 4.6-lb riprap (Figure 4), whereas in Plan 2 the cells were only half-full of the same size riprap. Plans 3 and 4 (Plates 3 and 4) consisted of 2-ft-high by 4-ft-wide by 1.5-ft-deep rectangular cells. The same size riprap as used in Plans 1 and 2 was used to half-fill and completely fill the cells in Plans 3 and 4, respectively. The riprap-filled cells extended 4.5 ft vertically below the still-water level (swl) on all four plans and extended 6.75 and 7.2 ft vertically above the swl in Plans 1 and 2, and Plans 3 and 4, respectively. Wooden toe strips were used on all four plans, on both the 2-D and 3-D test sections, to hold the cells at the proper elevation on the streambank slopes. Galvanized sheet metal was used to construct the model cells. In the prototype, the cells could be manufactured out of wood, concrete, plastics, etc., depending on available materials and manpower capabilities. The cells could be manufactured in place on the streambank or they could be prefabricated units which could be transported to and set into place on the streambank slopes. The banks would have to be graded to a uniform slope and some means of anchoring the cells would have to be used. Two methods of anchoring, though not model-tested, could be: (a) partial or complete burying of the cells into the bank, or (b) construction of a longitudinal stone dike of large riprap along the toe of the slope and buttressing the base of the cells against it. Any anchoring method used needs to be substantial as the weight of the riprap-filled cells could be quite large and the downslope component of this weight will increase with increasing streambank steepness.

Discussion of Results

9. Plan 1 (Figures 5, 9, and 13) was exposed to 2.0-sec,

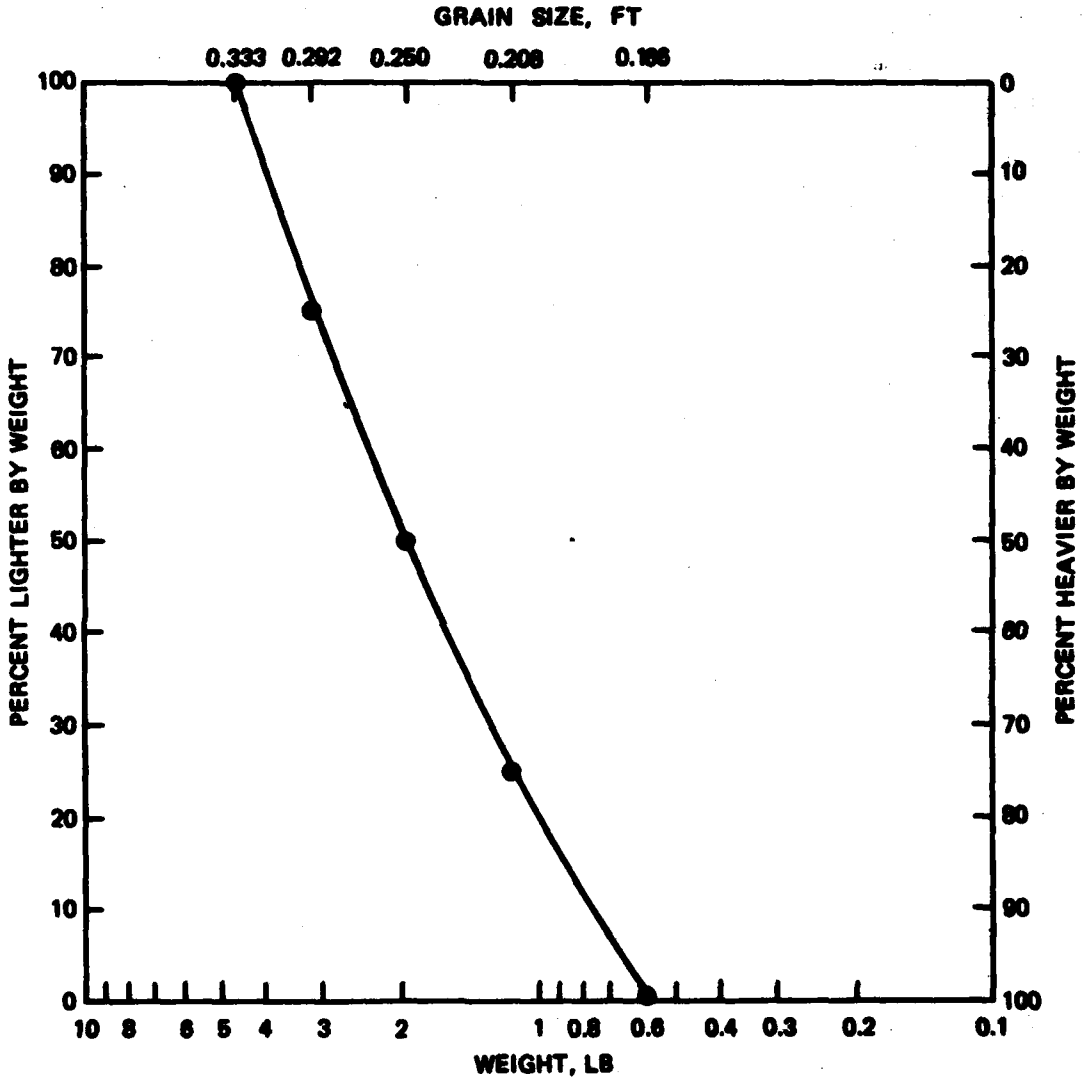


Figure 4. Riprap weight and size gradation, prototype

1.0- to 1.75-ft, 4.0-sec, 1.0- to 3.0-ft, and 6.0-sec, 1.0- to 2.5-ft nonbreaking waves for incident wave angles of 90, 60, and 30 deg. Some partial emptying of the cells occurred in the wave action zone, but none of the cells were emptied enough to cause bank exposure. The volume of riprap removed from the cells varied from one-fourth to two-thirds of the cell volume with the maximum emptying occurring at the swl. The 90- to 60-deg angles of wave attack caused similar damage, whereas the 30-deg angle of wave attack appeared to cause less riprap displacement. The area of cells showing emptying increased with increasing wave height and wave period. The structures were rebuilt after testing each wave period. Figures 6-8, 10-12, and 14-16 show the stabilized conditions of Plan 1 after testing the range of wave heights at each wave period for the three angles of wave attack.

10. Plan 2 (Figures 17, 19, and 21) was exposed to the three angles of wave attack with 2.0-sec, 1.75-ft, 4.0-sec, 3.0-ft, and 6.0-sec, 2.5-ft nonbreaking waves. Some downslope shifting of the riprap in the individual cells occurred, but no emptying of the cells occurred. Reorientation of the riprap in the cells did not result in any bank exposure, but the riprap thickness became very thin toward the upslope side of the cells in the wave action zone. The structures were not rebuilt between testing of subsequent wave conditions and Figures 18, 20, and 22 show the conditions of Plan 2 at the end of testing. Most likely Plan 2 could have withstood higher wave heights, but these were the maximum heights that could be produced for the water depth and wave periods using the available wave generator.

11. Plan 3 (Figures 23, 25, and 28) was exposed to 2.0-sec, 1.0- to 2.0-ft, and 6.0-sec, 1.0- to 3.0-ft nonbreaking waves. Photographs were taken and the structures were rebuilt after testing the range of wave heights at each wave period. For the two wave periods and three angles of wave attack, Plan 3 was stable for wave heights up to and including 1.5 ft. Some reorientation of the riprap occurred in the individual cells but no bank exposure occurred. Wave heights above 1.5 ft caused spot exposure of the streambank. No riprap was displaced out of the cells, but it shifted downslope and forward in the cells causing

Figure 5. Plan 1, before 90-deg wave attack; wave direction 1

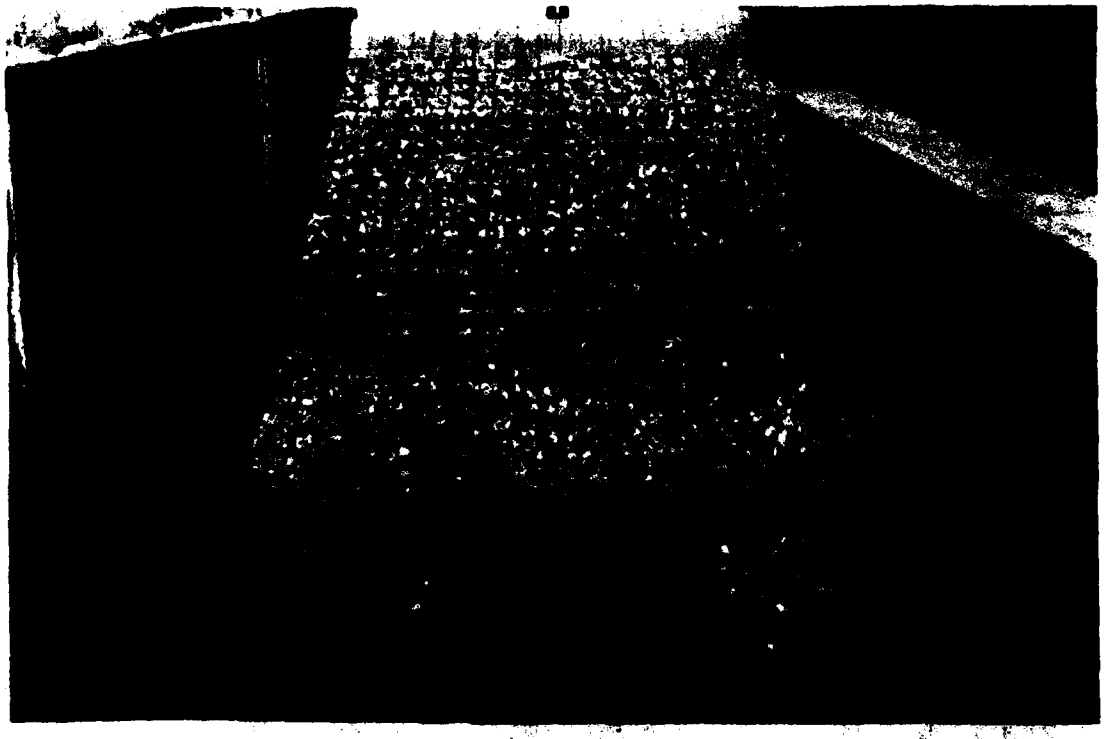


Figure 6. Plan 1, after exposure to 2.0-sec, 1.0- to 1.75-ft nonbreaking waves; wave direction 1

Figure 7. Plan 1, after exposure to 4.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 1

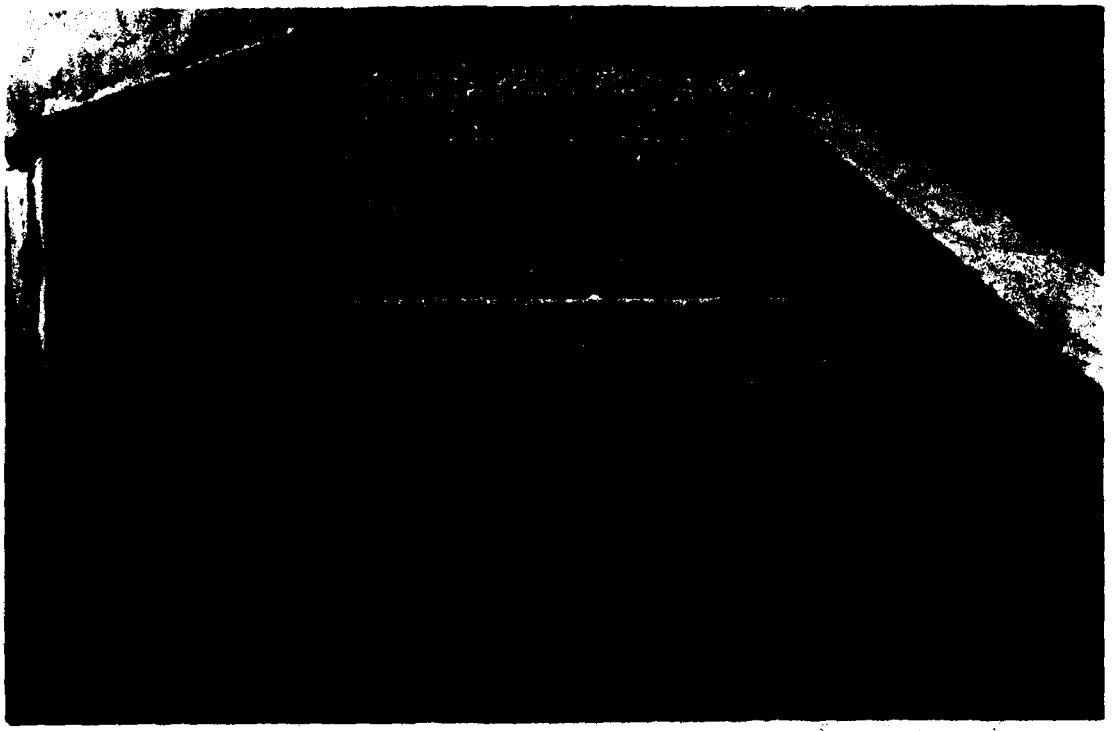


Figure 8. Plan 1, after exposure to 6.0-sec, 1.0- to 2.5-ft nonbreaking waves; wave direction 1

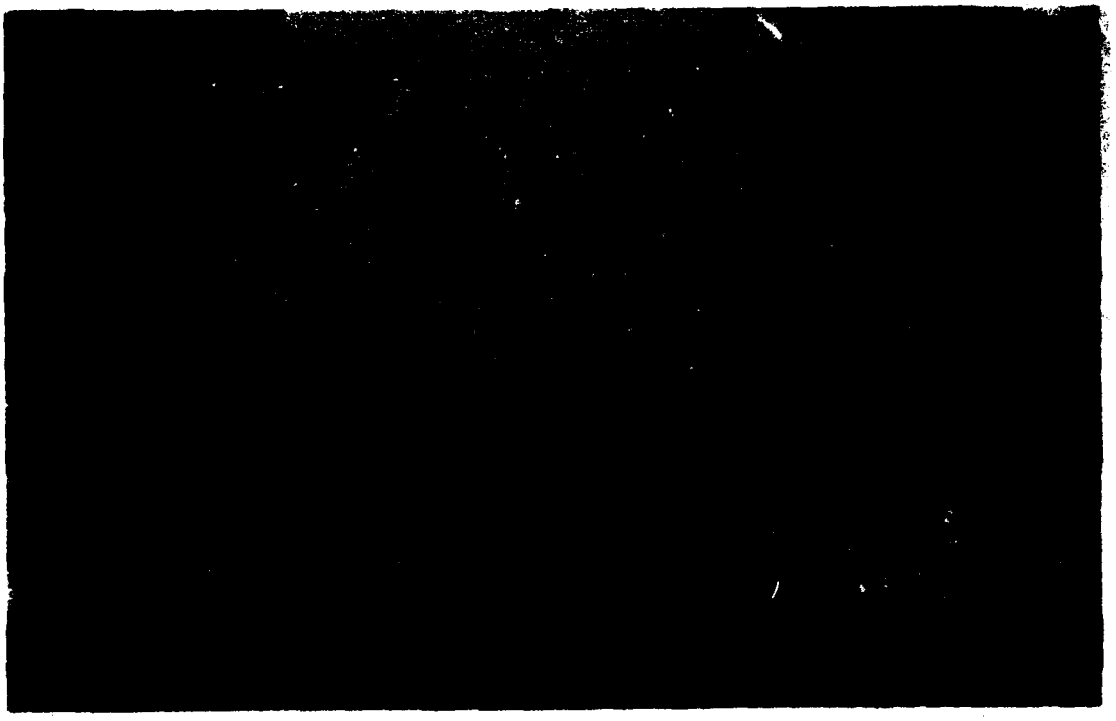


Figure 9. Plan 1, before 60-deg wave attack; wave direction 2

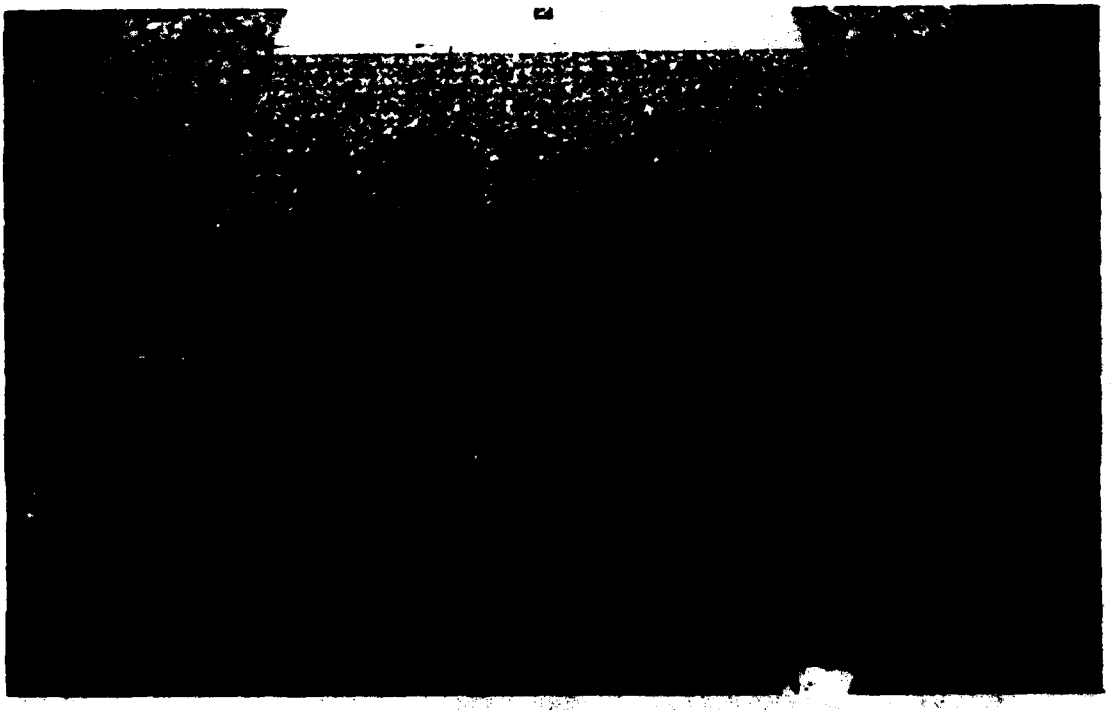


Figure 10. Plan 1, after exposure to 2.0-sec, 1.0- to 1.75-ft nonbreaking waves; wave direction 2

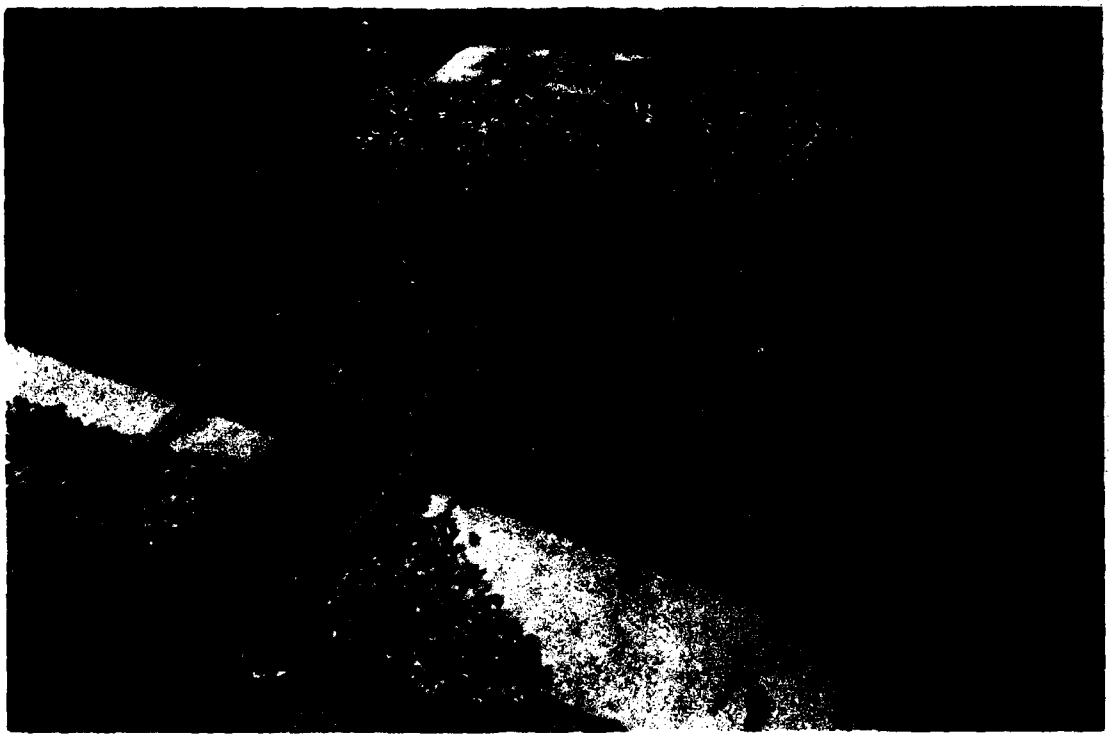


Figure 11. Plan 1, after exposure to 4.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 2

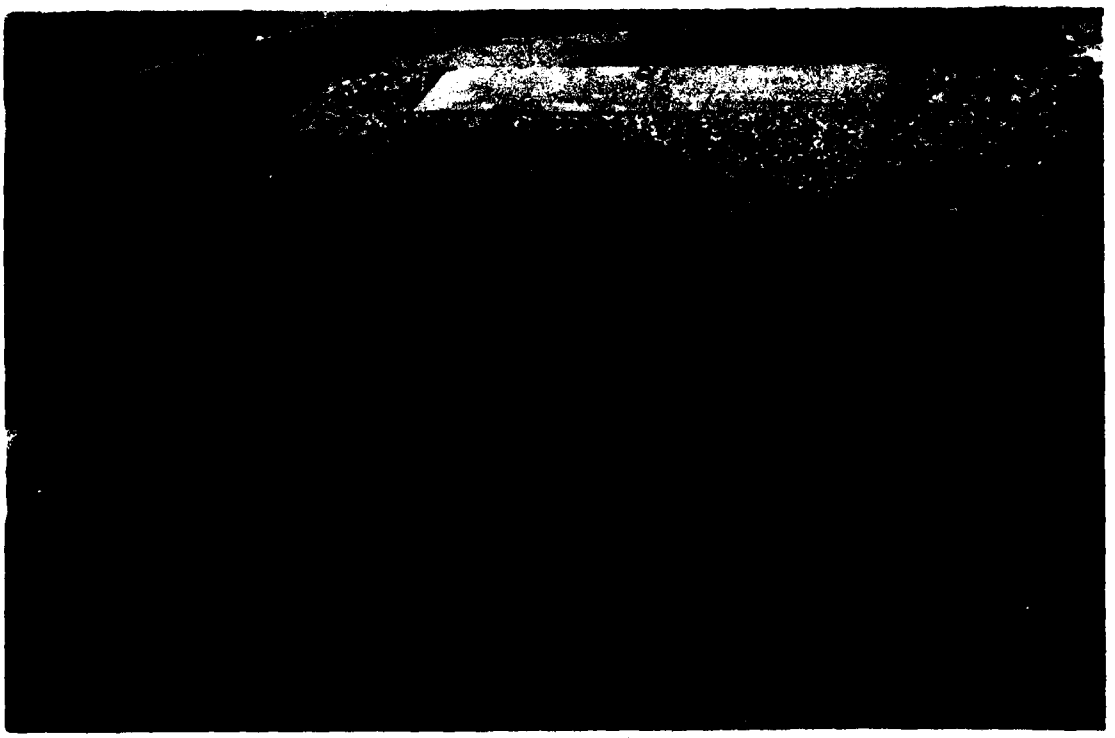


Figure 12. Plan 1, after exposure to 6.0-sec, 1.0- to 2.5-ft nonbreaking waves; wave direction 2

Figure 13. Plan 1, before 30-deg wave attack; wave direction 3

Figure 14. Plan 1, after exposure to 2.0-sec, 1.0- to 1.75-ft nonbreaking waves; wave direction 3

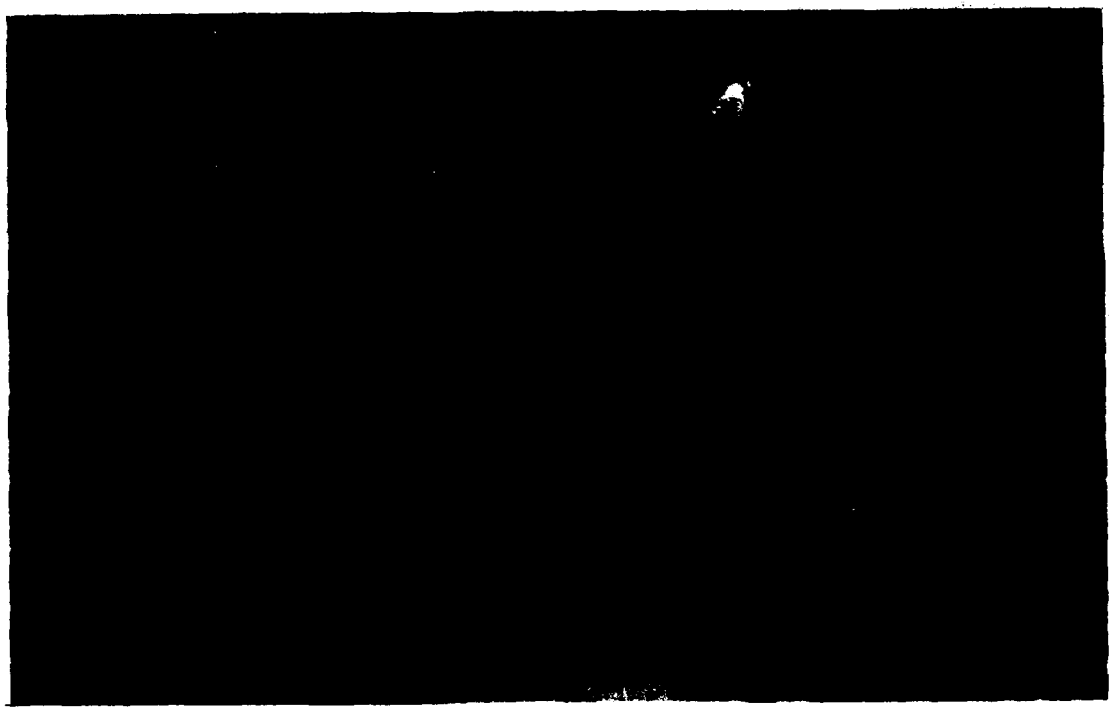


Figure 15. Plan 1, after exposure to 4.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 3

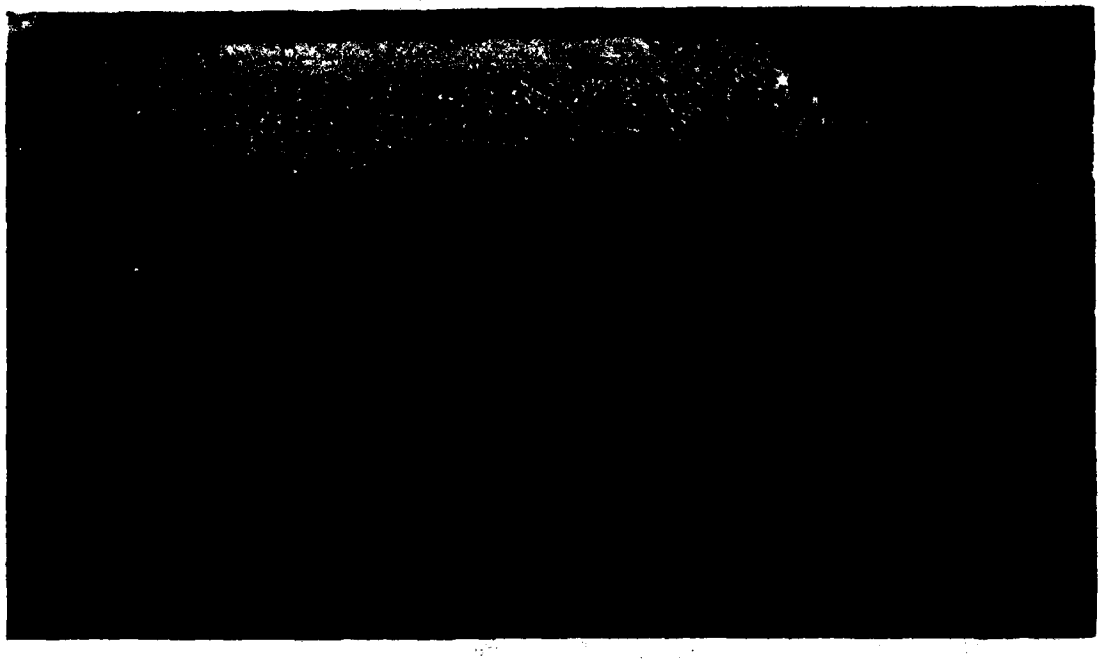


Figure 16. Plan 1, after exposure to 6.0-sec, 1.0- to 2.5-ft nonbreaking waves; wave direction 3

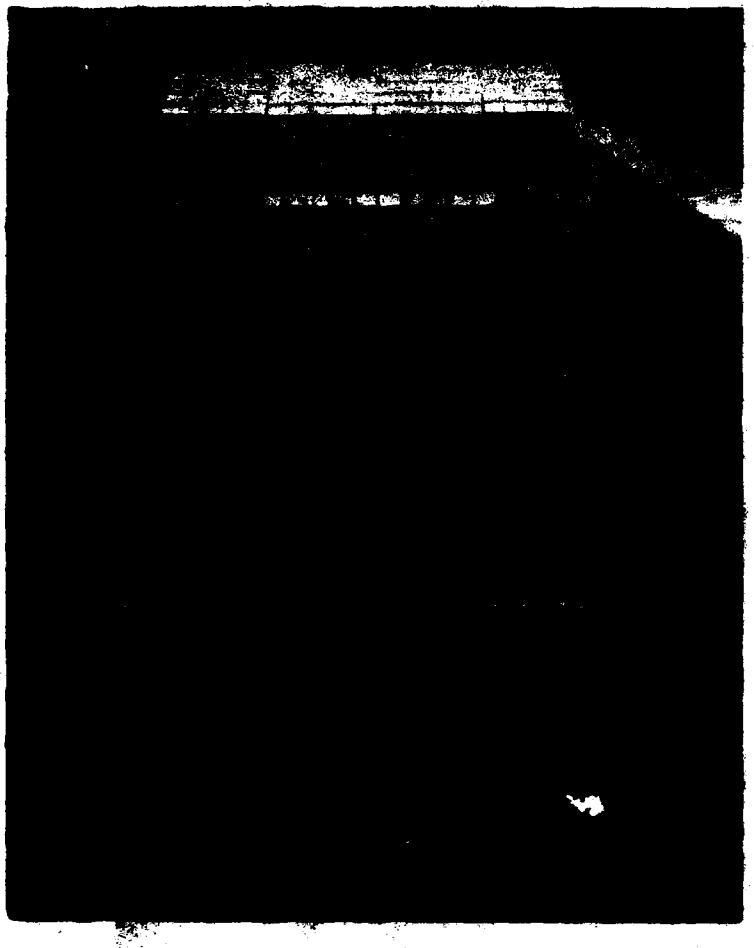


Figure 17. Plan 2, before wave attack from wave direction 1

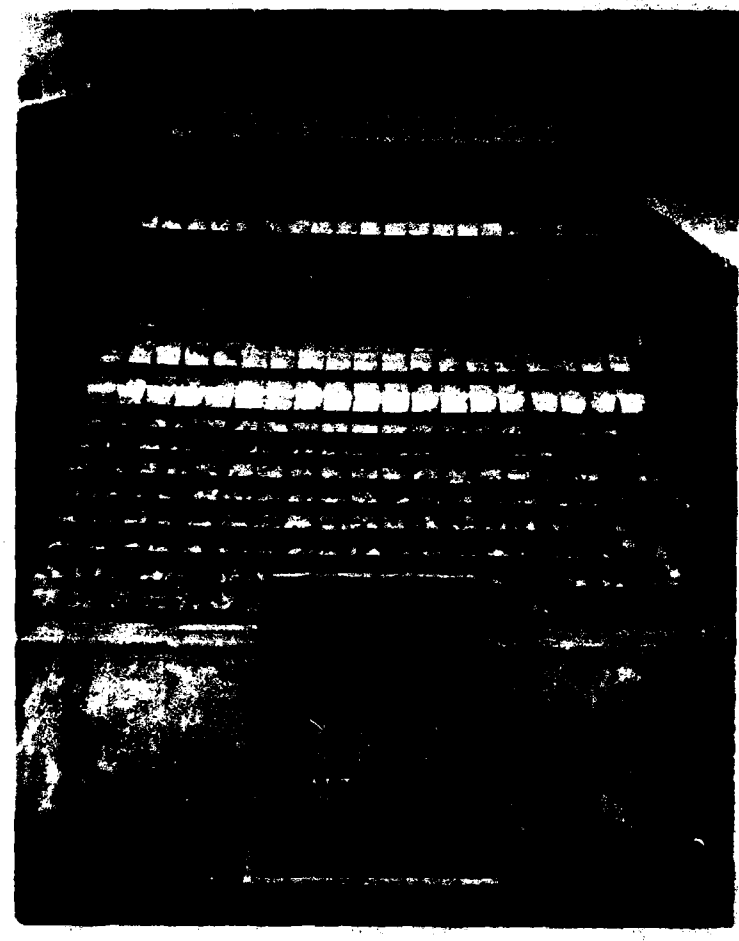


Figure 18. Plan 2, after exposure to 2.0-sec, 1.75-ft, 4.0-sec, 3.0-ft, and 6.0-sec, 2.5-ft nonbreaking waves; wave direction 1

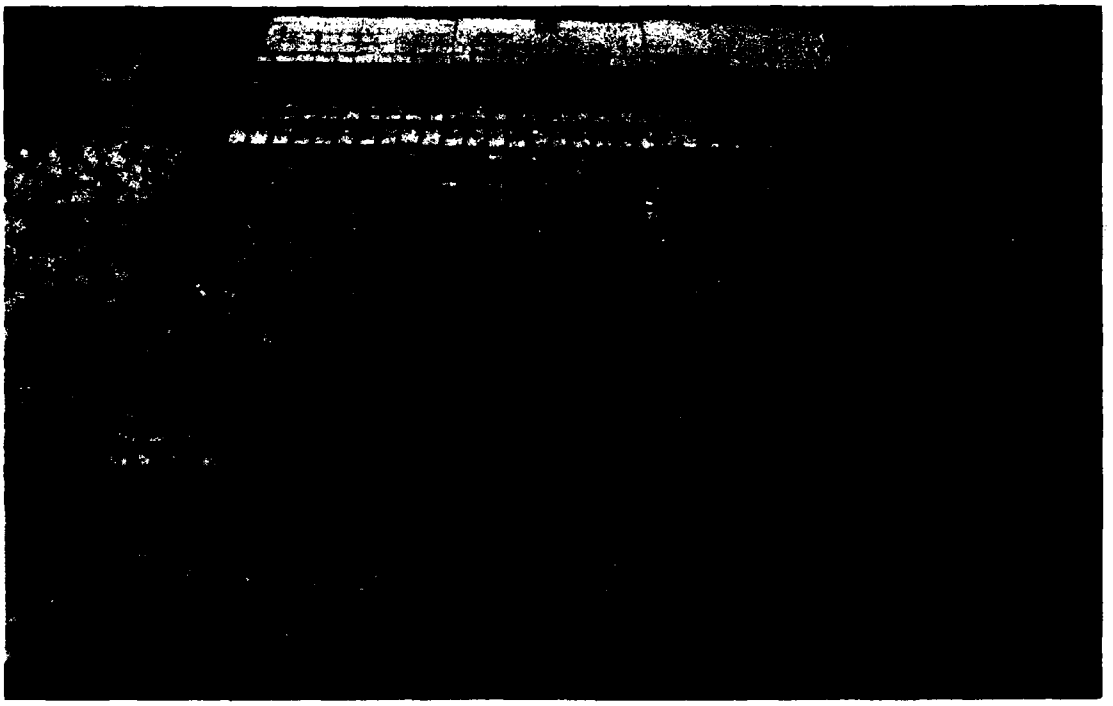


Figure 19. Plan 2, before wave attack from wave direction 2

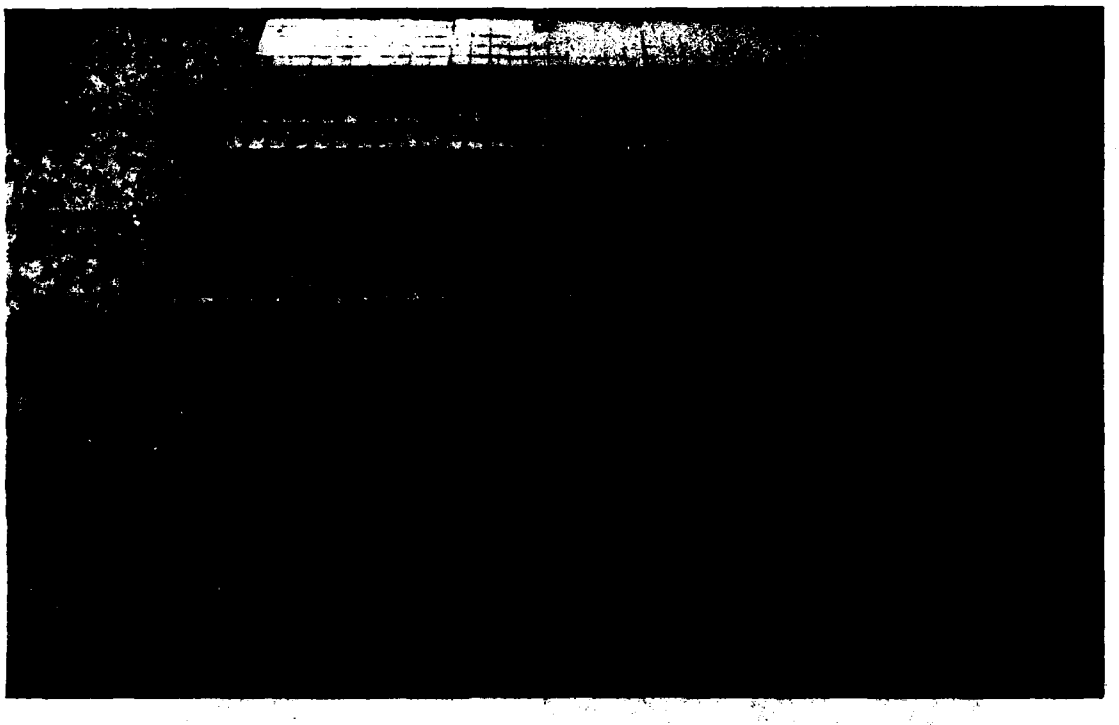


Figure 20. Plan 2, after exposure to 2.0-sec, 1.75-ft, 4.0-sec, 3.0-ft, and 6.0-sec, 2.5-ft nonbreaking waves; wave direction 2

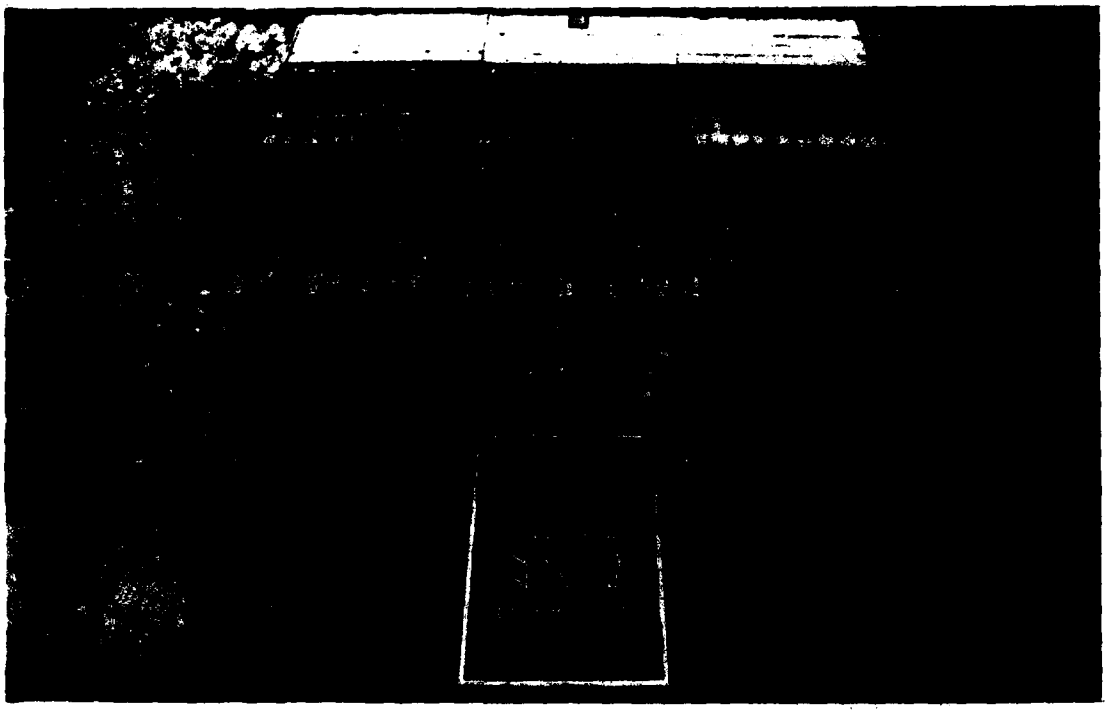


Figure 21. Plan 2, before wave attack from wave direction 3

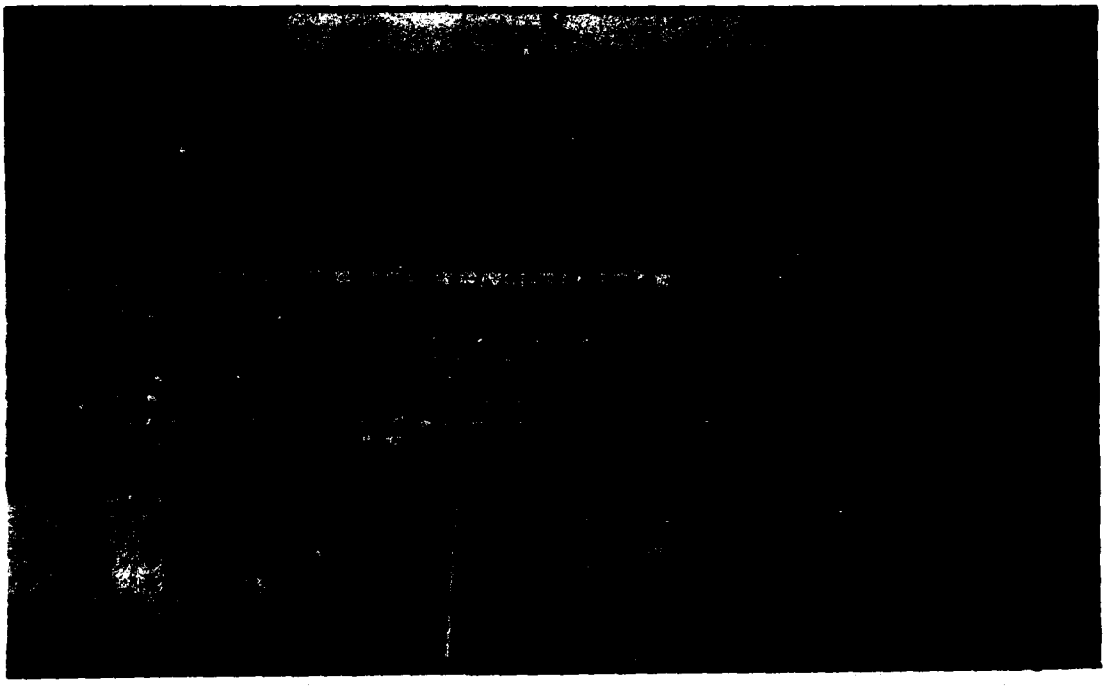


Figure 22. Plan 2, after exposure to 2.0-sec, 1.75-ft, 4.0-sec, 3.0-ft, and 6.0-sec, 2.5-ft nonbreaking waves; wave direction 3

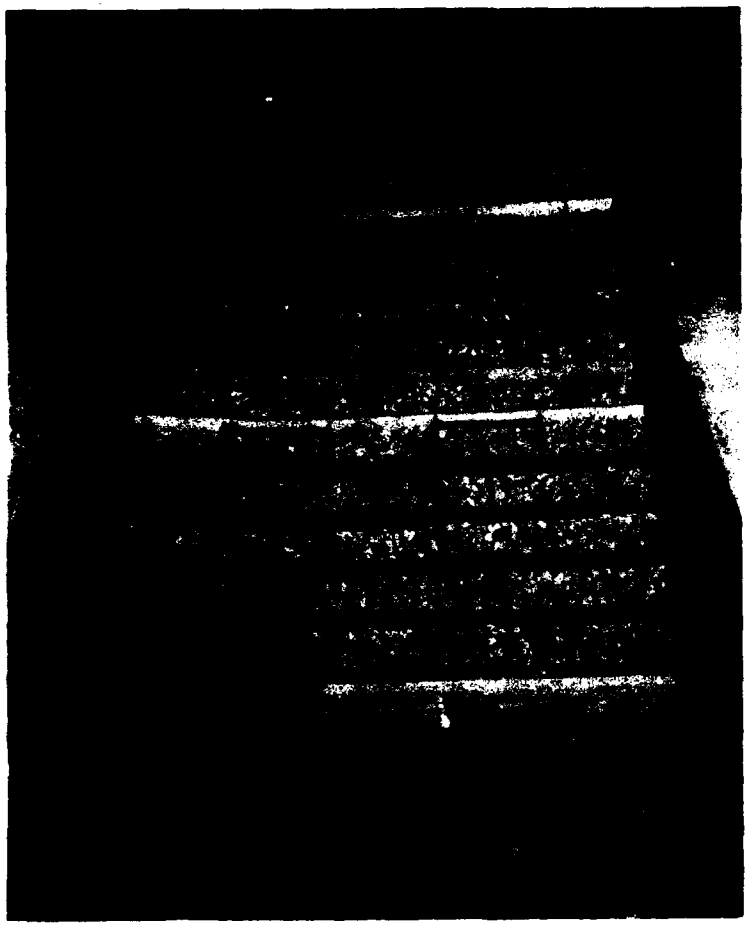


Figure 23. Plan 3, before wave attack from wave direction 1

Figure 24. Plan 3, after exposure to 2.0-sec, 1.0- to 2.0-ft nonbreaking waves; wave direction 1

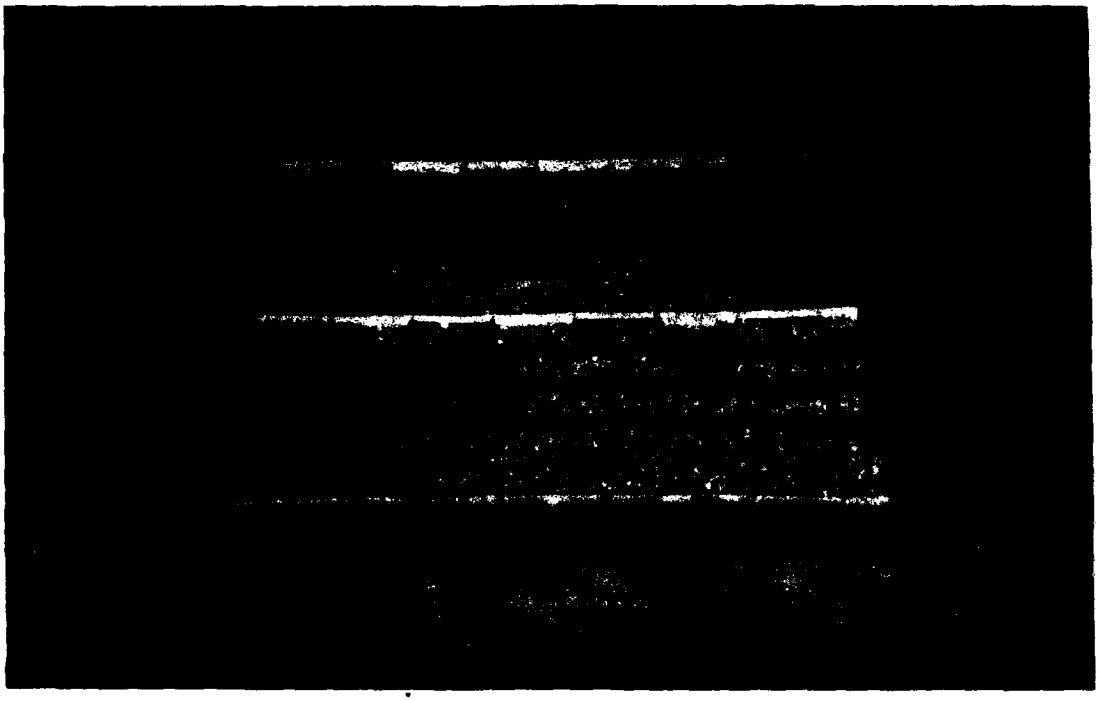


Figure 25. Plan 3, before wave attack from wave direction 2

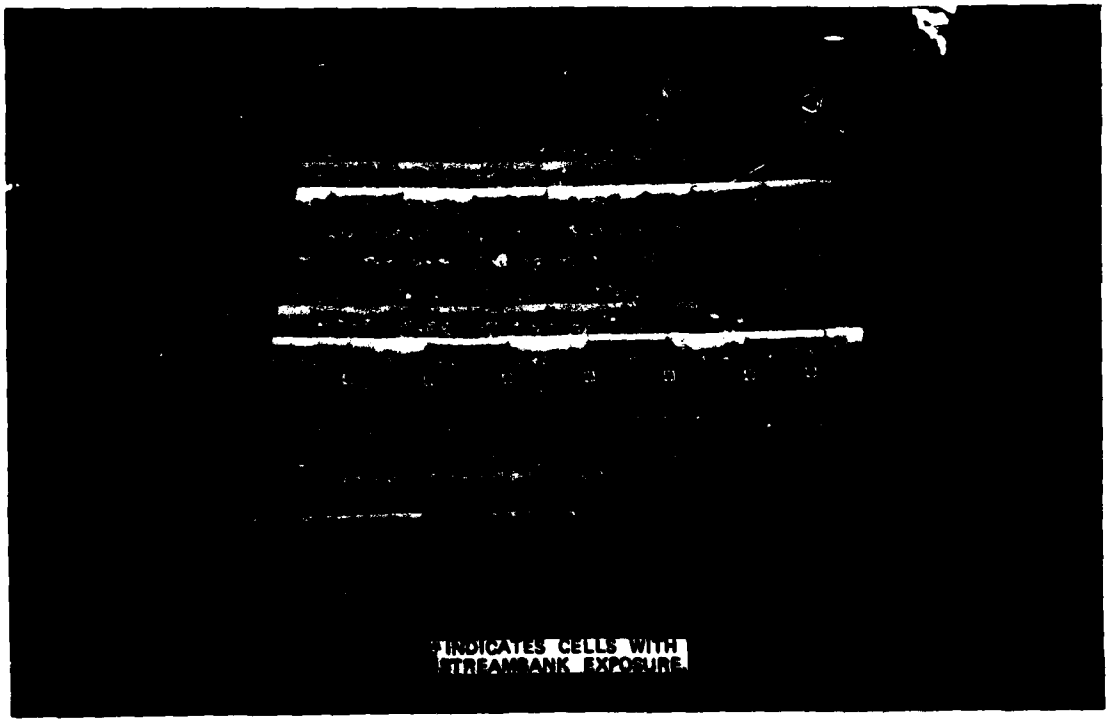


Figure 26. Plan 3, after exposure to 2.0-sec, 1.0- to 2.0-ft nonbreaking waves; wave direction 2

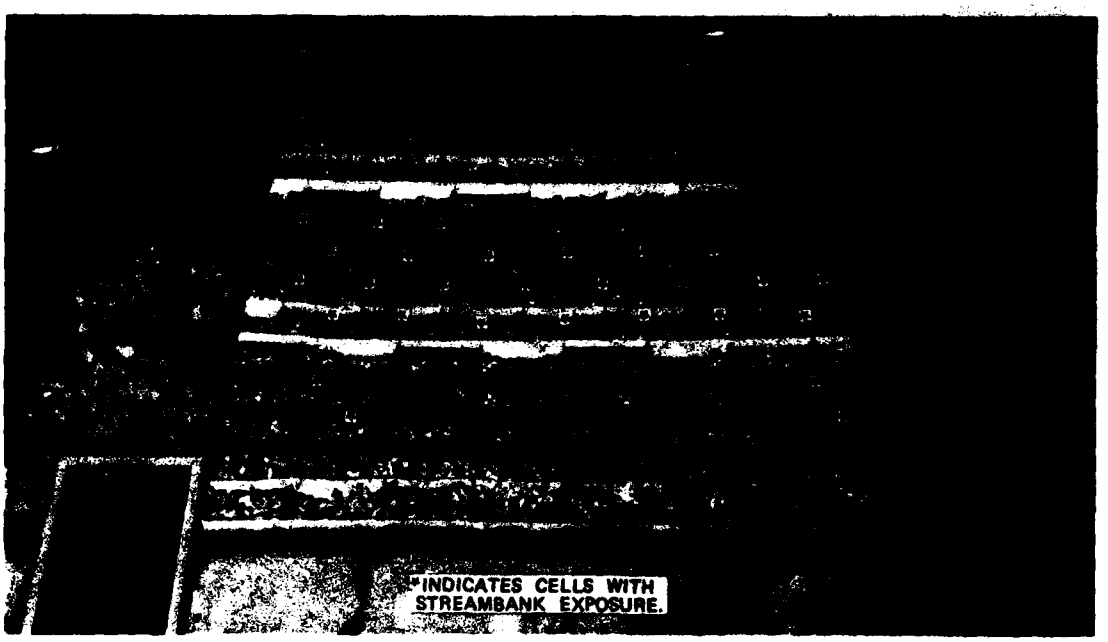


Figure 27. Plan 3, after exposure to 6.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 2

exposure of the streambank in the upper side of some cells. The bank exposure is indicated in after-test photographs, Figures 24, 26, 27, 29, and 30. For the 2.0-sec wave period, the 90- and 60-deg incident wave angles produced more riprap movement than the 30-deg incident wave angle. For the 6.0-sec wave period, riprap movement in the cells was similar for all three incident wave angles.

12. The 6.0-sec wave period produced the most severe wave attack and riprap movement during testing of Plan 3. For this reason, Plan 4 (Figures 31, 35, and 39) was only tested for the 6.0-sec wave period. Nonbreaking wave heights from 1.0 to 3.0 ft were tested for incident wave angles of 90, 60, and 30 deg. Plan 4 sustained its most severe damage from the 60-deg wave attack with the 30-deg wave attack causing somewhat less damage and the 90-deg wave attack causing the least damage. For all three angles of wave attack, no streambank exposure occurred for wave heights up to and including 2.0 ft. The 3.0-ft wave heights caused bank exposure for the 60- and 30-deg wave attack angles but only a maximum of two-thirds emptying of some cells for the 90-deg angle of wave

attack. As with all plans previously reported, riprap movement had stopped at the end of the tests and Figures 32, 36, and 40 show the conditions of Plan 4 after testing.

13. During the testing of Plan 4, photographs were taken to show the wave action produced by the three angles of wave attack. The wave runup and rundown are shown in Figures 33, 34, 37, and 38 for the 90- and 60-deg wave attack angles. Figure 41 shows the waves moving across the cells being exposed to an incident angle of 30 deg.

14. Runup (R_u) and rundown (R_d) were observed and recorded for all the wave conditions tested on Plans 1-4. Runup is the distance a wave progresses upslope, measured vertically above the swl, and the rundown is the distance a wave progresses downslope, measured vertically below the swl. These data are presented in Table 1. Relative runup (R_u/H) as a function of wave steepness (H/L) and relative depth (d/L) are presented in Plates 5-8 and 9-11, respectively, where d = water depth , H = wave height , and L = wavelength . Plates 12-15 and 16-18 present relative rundown (R_d/H) as a function of H/L and d/L , respectively. Due to the very limited data for Plan 4, plots of R_u and R_d versus d/L are not presented.

15. These data show both R_u and R_d for Plans 1-4 subjected to nonbreaking waves to be functions of H/L , d/L , and angle of wave attack. In general, the 60-deg angle of wave attack produced the largest R_u and R_d with the 90-deg angle of wave attack showing the next highest values. The 30-deg angle of wave attack produced the smallest values of R_u and R_d . There were sufficient data on Plans 1 and 3 to see a general trend for both R_u and R_d to decrease with increasing values of H/L and d/L . Due to the limited amount of data on Plans 2 and 4, trends of R_u and R_d as functions of H/L and d/L are not well defined.

16. No major differences in R_u and R_d were observed for the two cell sizes tested. When the cells of Plans 1 and 4 were full of riprap the R_u and R_d were larger than what occurred for the same wave conditions in Plans 2 and 3, respectively. As riprap was displaced

and the cells of Plans 1 and 4 became partially emptied, the R_u and R_d decreased and were similar to what occurred in Plans 2 and 3, respectively.

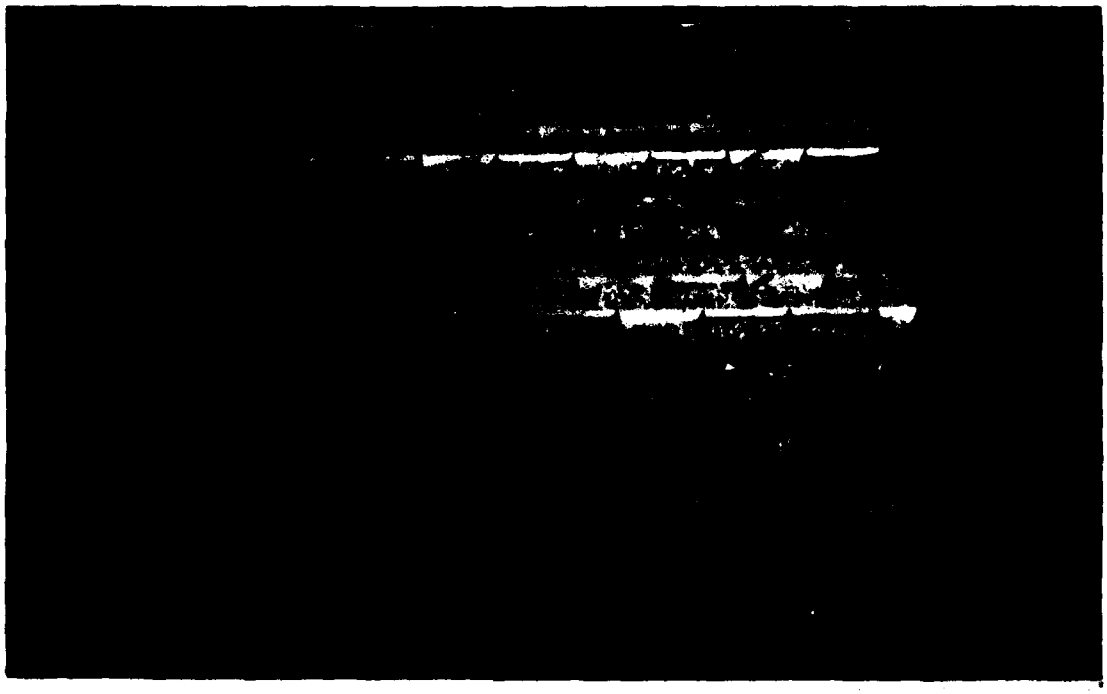


Figure 28. Plan 3, before wave attack from wave direction 3

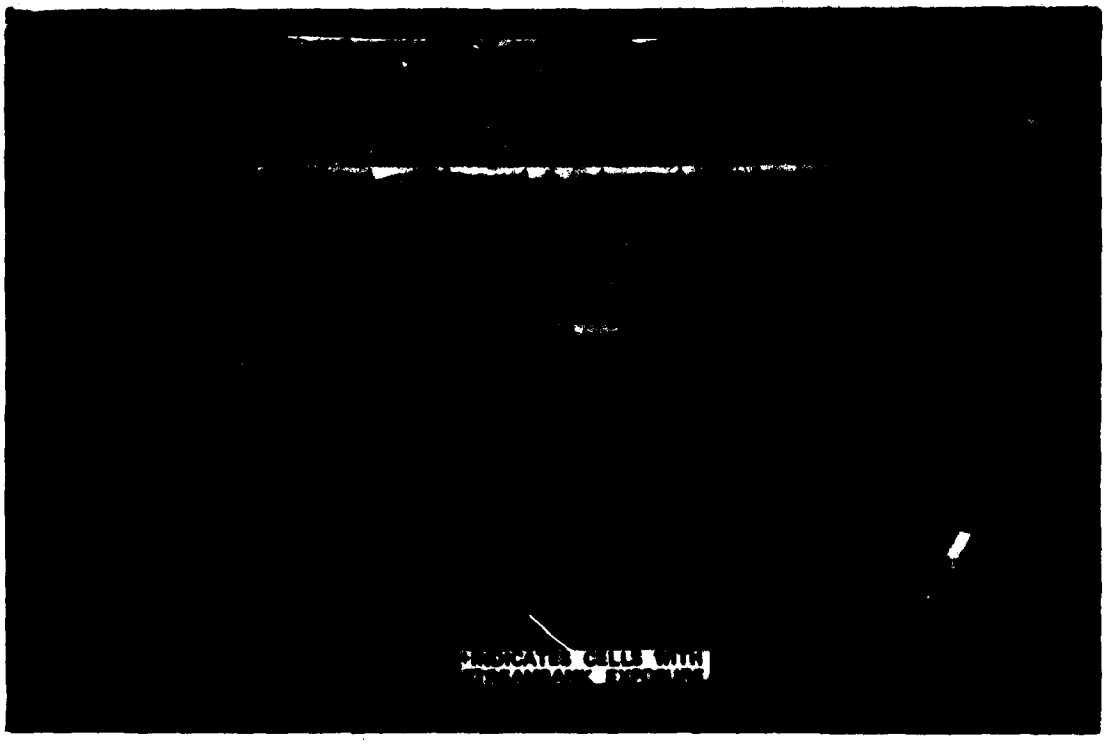


Figure 29. Plan 3, after exposure to 2.0-sec, 1.0- to 2.0-ft nonbreaking waves; wave direction 3

Figure 30. Plan 3, after exposure to 6.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 3

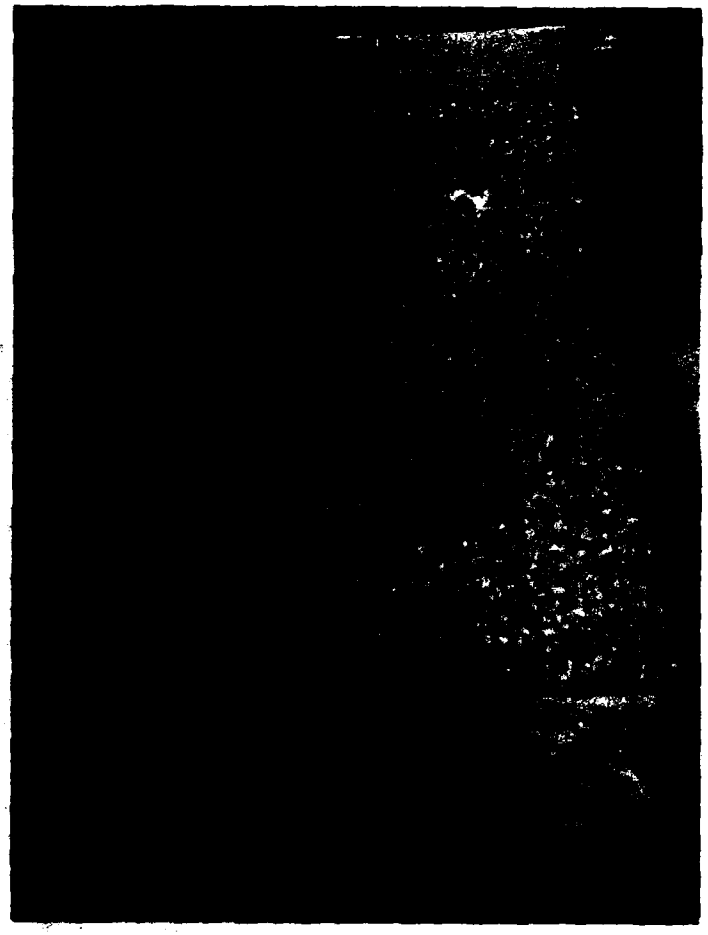


Figure 31. Plan 4, before wave attack from wave direction 1

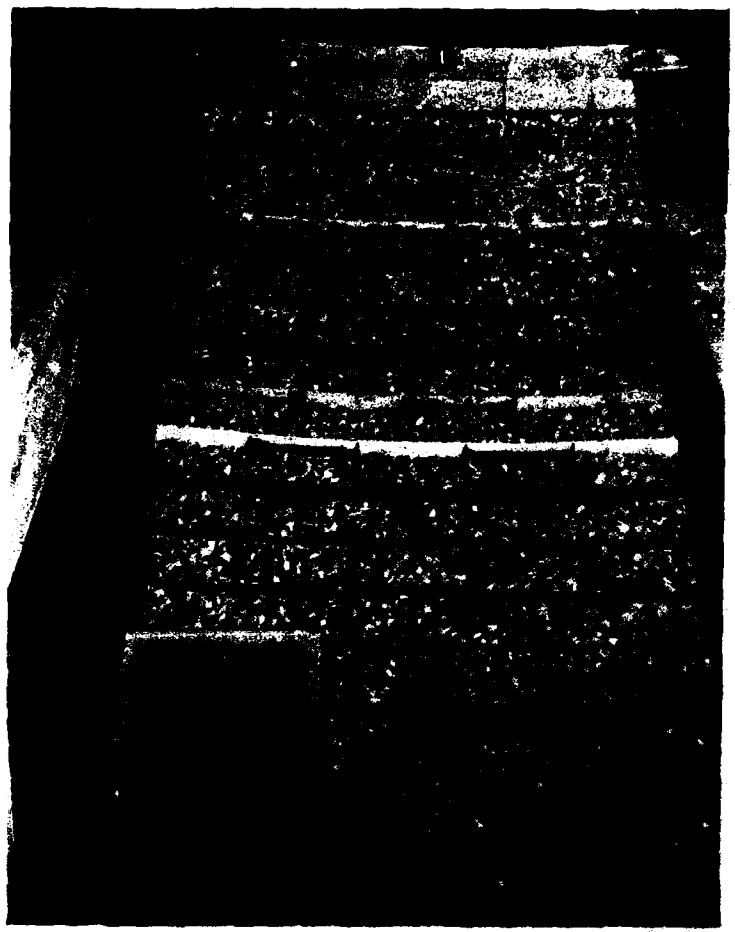


Figure 32. Plan 4, after exposure to 6.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 1

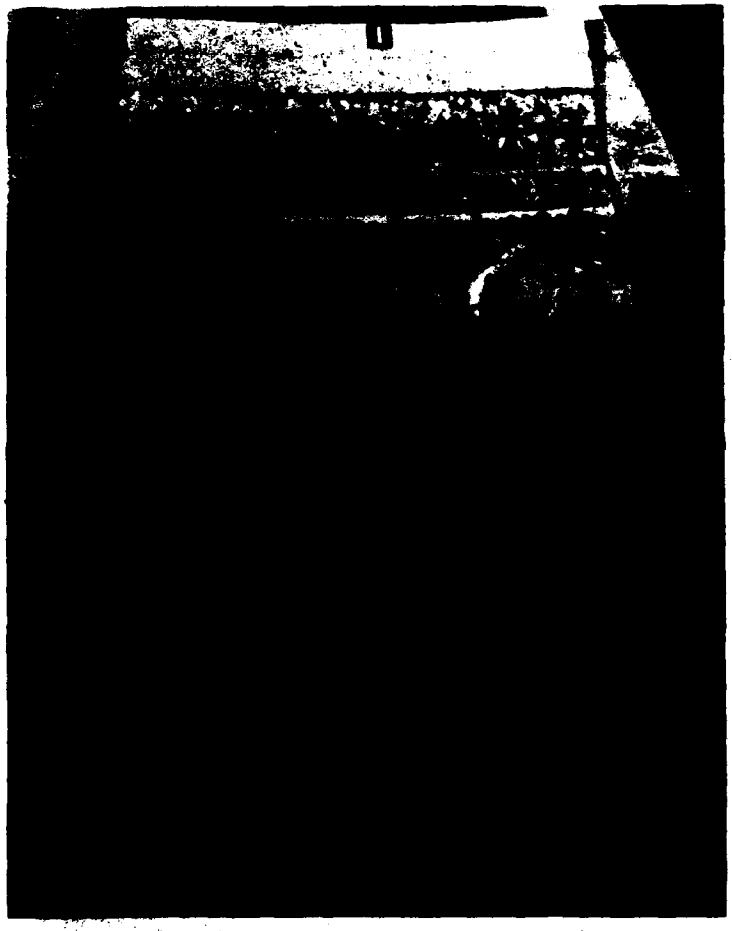


Figure 33. Wave runup on Plan 4 for 6.0-sec, 3.0-ft nonbreaking waves; wave direction 1

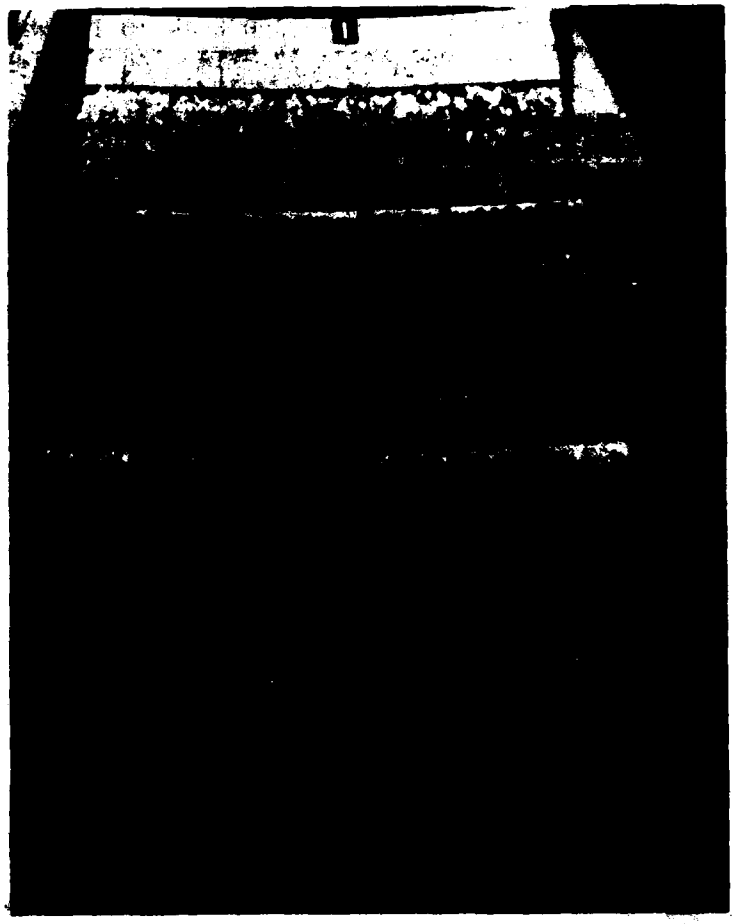


Figure 34. Wave rundown on Plan 4 for 6.0-sec, 3.0-ft nonbreaking waves; wave direction 1

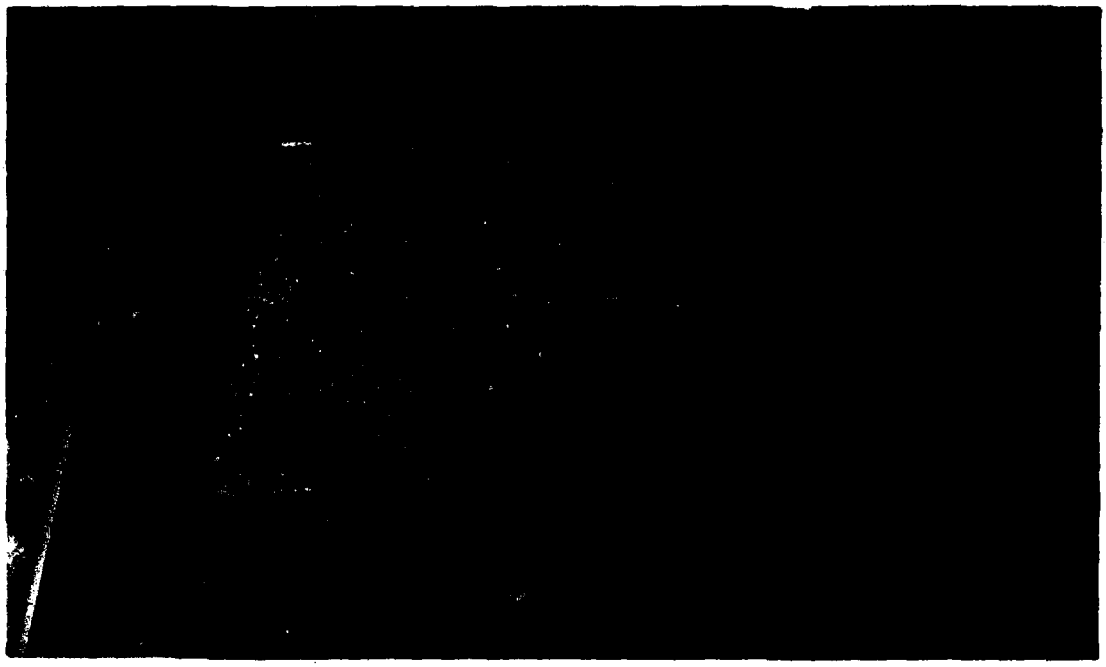


Figure 35. Plan 4, before wave attack from wave direction 2

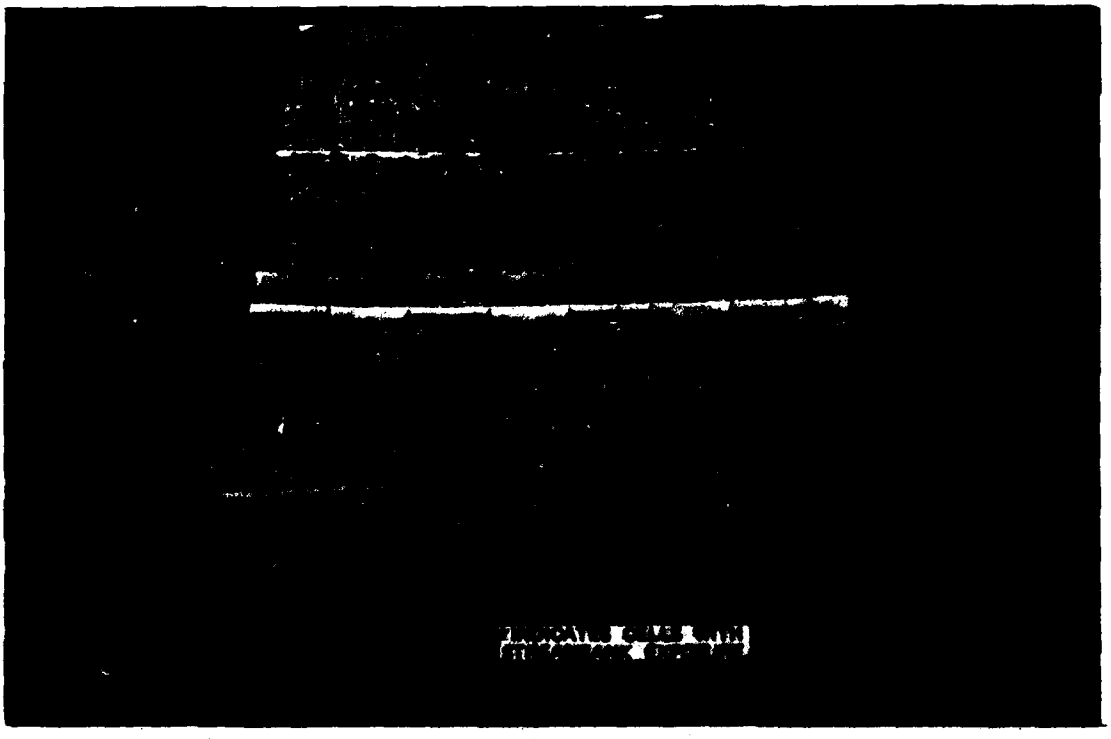


Figure 36. Plan 4, after exposure to 6.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 2

Figure 37. Wave runup on Plan 4 for 6.0-sec, 3.0-ft nonbreaking waves; wave direction 2

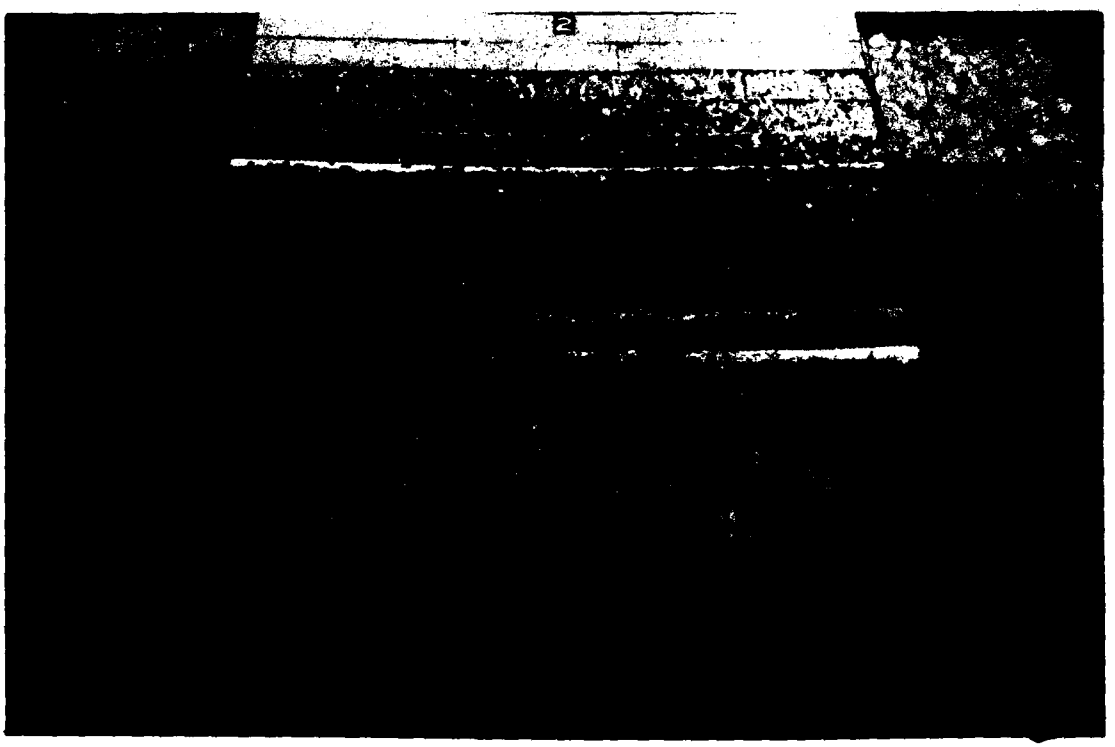


Figure 38. Wave rundown on Plan 4 for 6.0-sec, 3.0-ft nonbreaking waves; wave direction 2

Figure 39. Plan 4, before wave attack from wave direction 3

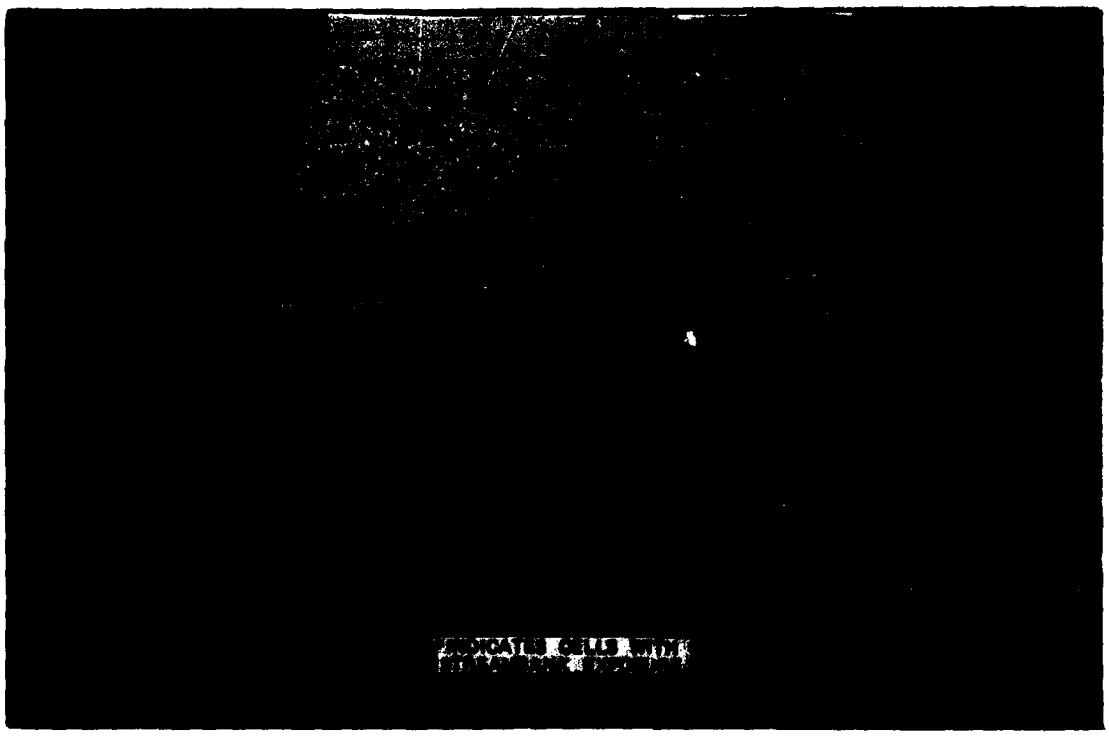


Figure 40. Plan 4, after exposure to 6.0-sec, 1.0- to 3.0-ft nonbreaking waves; wave direction 3

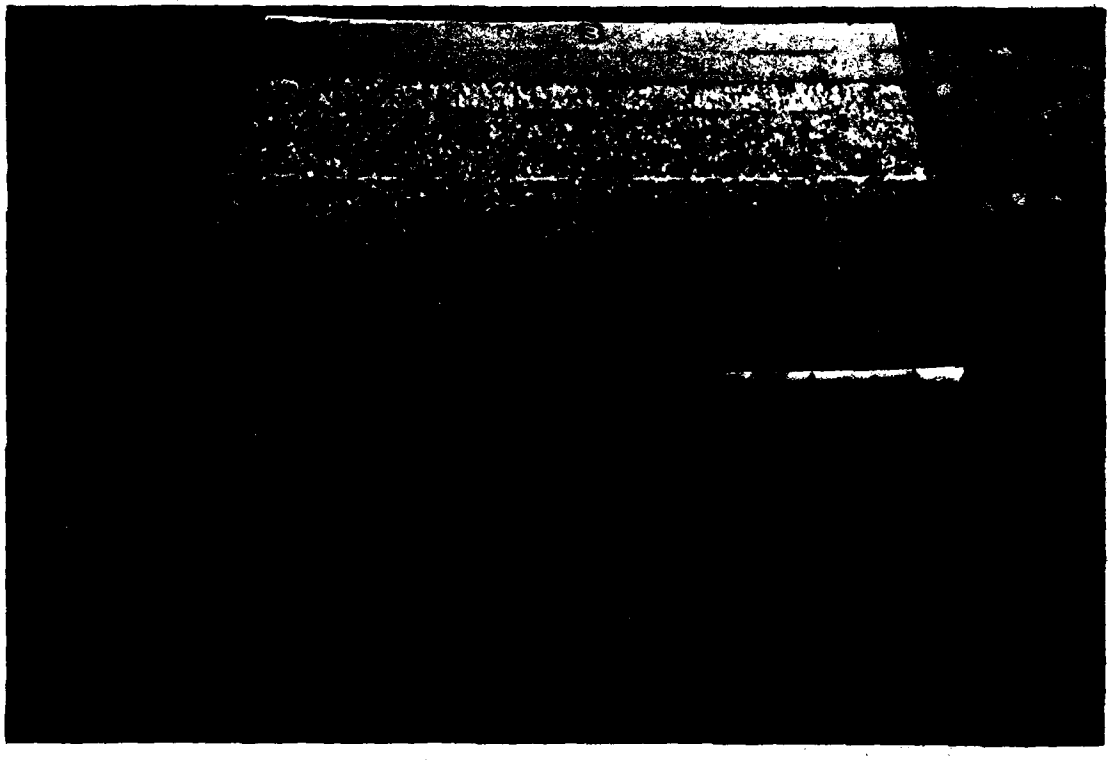


Figure 41. Wave runup on Plan 4 for 6.0-sec, 3.0-ft nonbreaking waves, wave direction 3

PART IV: CONCLUSIONS FROM 1:4-SCALE MODEL TESTS

17. Based on the 1:4-scale model tests and results reported herein for the "riprap-filled cells" bank protection placed on 1V-on-2H streambank slopes that are assumed to be stable and impermeable and for angles of wave attack of 90, 60, and 30 deg, it is concluded that:

a. Plans 1 and 2 (1-ft-cube cells, full and half-full) are stable (no streambank exposure) for 2.0-sec, 1.0- to 1.75-ft, 4.0-sec, 1.0- to 3.0-ft, and 6.0-sec, 1.0- to 2.5-ft nonbreaking waves.

b. Plan 3 (rectangular cells, half-full) was stable for nonbreaking wave heights up to and including 1.5 ft for wave periods of 2.0 and 6.0 sec. Wave heights exceeding this produced spot exposures of the streambank.

c. Plan 4 (rectangular cells, full) was stable for 6.0-sec, nonbreaking wave heights up to and including 2.0 ft. Wave heights exceeding 2.0 ft produced spot exposures of the streambank.

d. Both runup (R_u) and rundown (R_d) for Plans 1-4 subjected to nonbreaking waves appear to be functions of wave steepness (H/L), relative depth (d/L), and angle of wave attack. The angles of wave attack, listed in descending magnitudes of R_u and R_d produced, are 60, 90, and 30 deg. Plans 1 and 3 show trends of decreasing R_u and R_d for increasing values of H/L and d/L. Insufficient data are available for these trends to be well defined for Plans 2 and 4.

PART V: DISCUSSION AND RECOMMENDATIONS

18. Limited 2-D tests at a 1:1 scale have been conducted on the 1-ft-cube cells with both gravel and riprap fill. These tests indicate that as with other bank protection concepts, care must be taken to provide an adequate filter between the cells and the streambank composed of noncohesive soils. More detailed results of these tests are reported by Markle (1983)

19. The cell depth (Figure 42) needed for stability of riprap fill increases with increasing steepness of the streambank slope and increasing

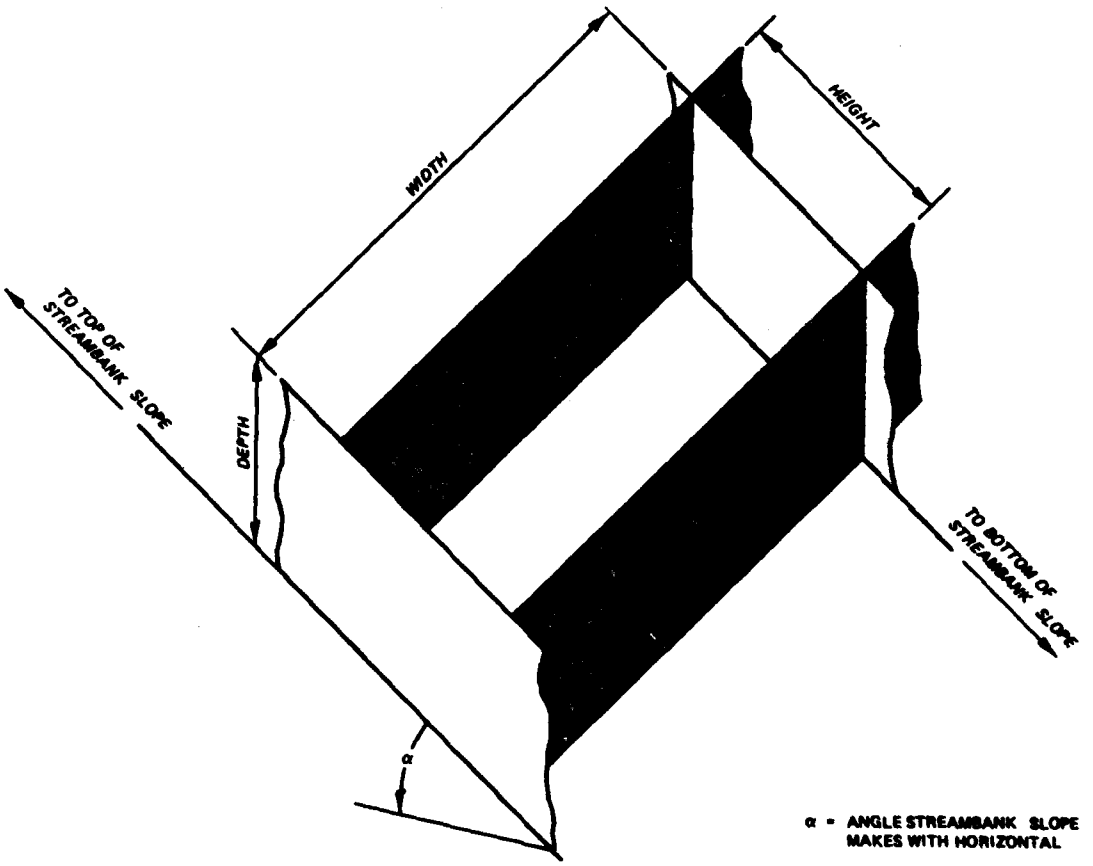


Figure 42. Nomenclature for cell sizing

* Dennis G. Markle. "Wave and Seepage Flow Effects on Sand Streambanks and Their Protective Cover Layers; Demonstration Hydraulic Model" (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

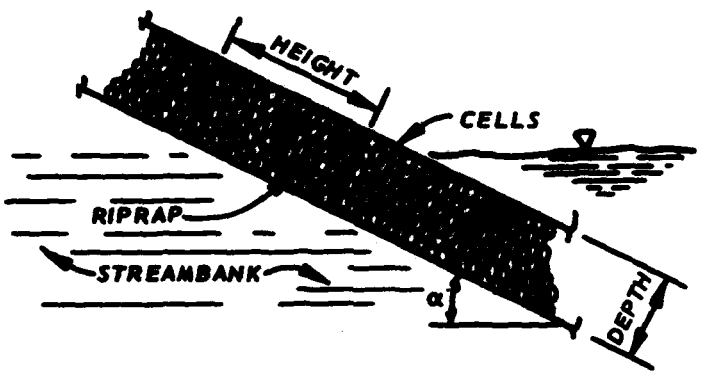
height of the individual cells. If the cell is full of riprap and begins to empty under wave attack, the riprap surface usually approaches approximately a horizontal profile. If the cell is not deep enough to contain the riprap for the cell height and streambank slope, bank exposure will occur in the upper portion of the cells (Figures 43a and 43b, and Figures 24, 26, 27, and 30). Partial emptying of the cells will most likely not cause streambank exposure if a sufficient cell depth is used for a given streambank slope and cell height (Figures 43c and 43d). The following equation could be used as a starting point for selecting the cell depth.

$$\text{Depth} \geq 1.33 \times \tan \alpha \times \text{Height} \tag{3}$$

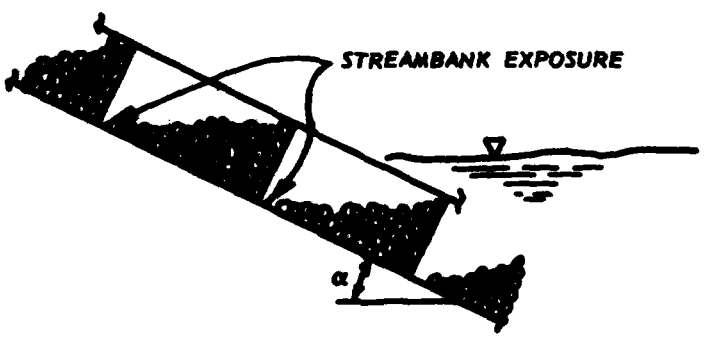
To allow for an adequate thickness of riprap a cell height of less than 10 to 12 in. would not be recommended. Even so, this cell height will not assure that streambank exposure will not occur. If the riprap is too light relative to the incident wave energy, the cell could be emptied more than what is depicted in Figure 43d.

20. As stated earlier, model cells were constructed of galvanized sheet metal due to ease of construction. Methods and material for prototype construction have not been investigated. It is recommended that close scrutiny be given to the economics of building and placing the cells. Once the cost of prototype construction is better understood, an economic analysis could be done to determine the most economical bank protection method. In some cases, transporting larger riprap to an area lacking a local source may be less costly than the construction and placing of the riprap-filled cells.

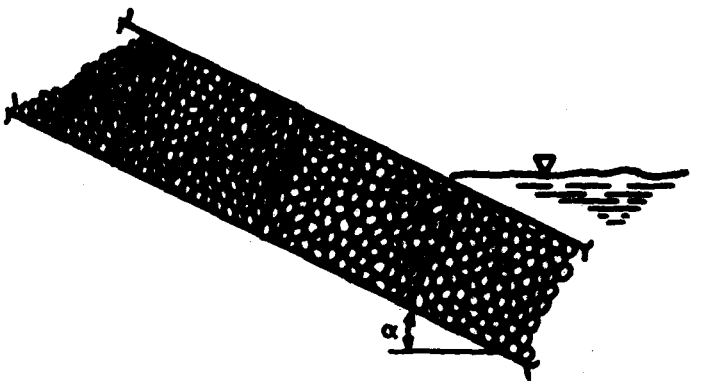
21. Further testing is needed to gain more insight into the riprap-filled cells concept. Additional testing should pursue the optimizing of cell size and geometry and riprap weight relative to incident wave periods, wave heights, angles of wave attack, current velocity, and streambank slopes.



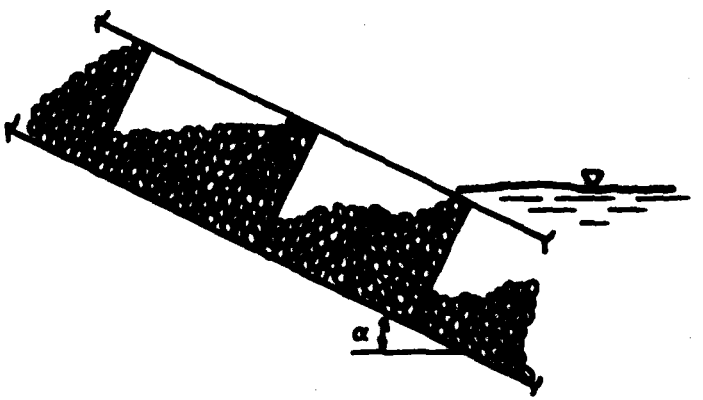
a. Cells filled before wave attack;
α = angle streambank slope makes with horizontal



b. Cells partially emptied by wave attack



c. Cells filled before wave attack.



d. Cells partially emptied by wave attack.

Figure 43. Cross-sectional views of riprap-filled cells

Table 1

Values of R_u/H and R_d/H for Riprap-Filled Cells

d/L	T, sec	H, ft	H/L	R_u, ft	R_u/H	R_d, ft	R_d/H
Plan 1, 90-deg Wave Attack							
0.09	6.0	1.0	0.011	1.56	1.56	1.56	1.56
0.09	6.0	1.5	0.016	2.45	1.63	1.56	1.04
0.09	6.0	2.0	0.022	2.92	1.46	2.02	1.01
0.09	6.0	2.5	0.027	3.81	1.52	2.45	0.98
0.14	4.0	1.0	0.017	1.56	1.56	1.56	1.56
0.14	4.0	1.5	0.026	2.24	1.49	1.56	1.04
0.14	4.0	2.0	0.035	3.35	1.68	1.34	0.67
0.14	4.0	2.5	0.043	3.94	1.58	2.45	0.98
0.14	4.0	3.0	0.052	4.75	1.58	2.02	0.67
0.40	2.0	1.0	0.050	1.13	1.13	0.89	0.89
0.40	2.0	1.5	0.074	1.79	1.19	0.89	0.59
0.40	2.0	1.75	0.087	1.56	0.89	0.68	0.39
Plan 1, 60-deg Wave Attack							
0.09	6.0	1.0	0.011	2.02	2.02	1.56	1.56
0.09	6.0	1.5	0.016	3.35	2.23	2.02	1.35
0.09	6.0	2.0	0.022	4.24	2.12	2.45	1.23
0.09	6.0	2.5	0.027	5.60	2.24	2.45	0.98
0.14	4.0	1.0	0.017	1.79	1.79	1.79	1.79
0.14	4.0	1.5	0.026	3.13	2.09	1.56	1.04
0.14	4.0	2.0	0.035	3.81	1.91	1.56	0.78
0.14	4.0	2.5	0.043	4.70	1.88	2.45	0.98
0.14	4.0	3.0	0.052	5.60	1.89	1.79	0.60
0.40	2.0	1.0	0.050	0.89	0.89	0.45	0.45
0.40	2.0	1.5	0.074	1.79	1.19	0.89	0.59
0.40	2.0	1.75	0.087	1.56	0.89	1.13	0.65
Plan 1, 30-deg Wave Attack							
0.09	6.0	1.0	0.011	1.56	1.56	1.13	1.13
0.09	6.0	1.5	0.016	2.02	1.35	1.56	1.04
0.09	6.0	2.0	0.022	—	—	2.45	1.23
0.09	6.0	2.5	0.027	2.45	0.98	1.79	0.72
0.14	4.0	1.0	0.017	1.13	1.13	1.34	1.34
0.14	4.0	1.5	0.026	1.79	1.19	1.56	1.04
0.14	4.0	2.0	0.035	2.45	1.23	2.02	1.01
0.14	4.0	2.5	0.043	2.24	0.90	2.45	0.98
0.14	4.0	3.0	0.052	2.92	0.97	2.45	0.82

(Continued)

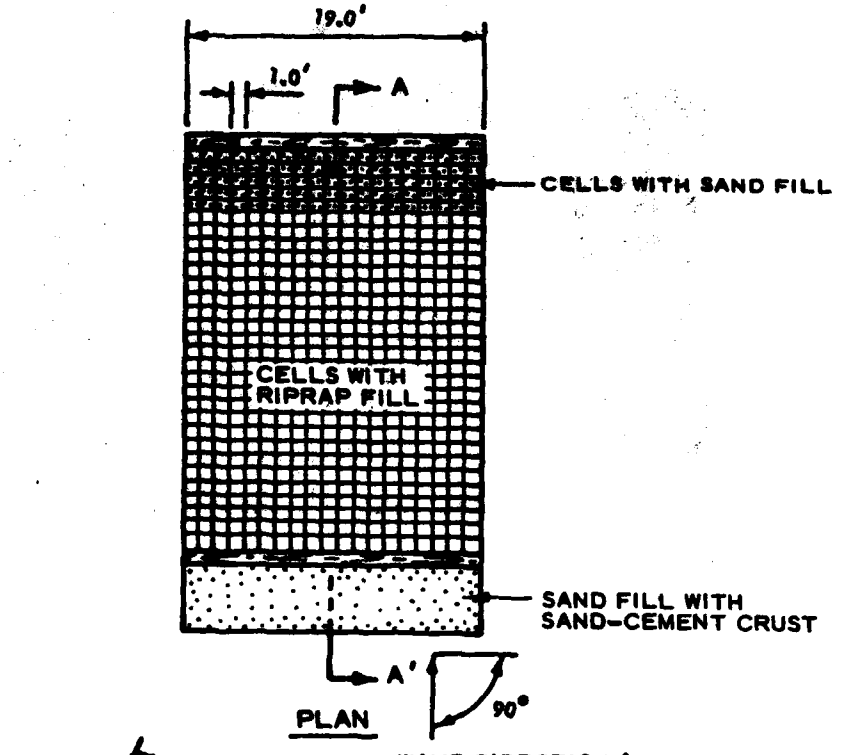
Table 1 (Continued)

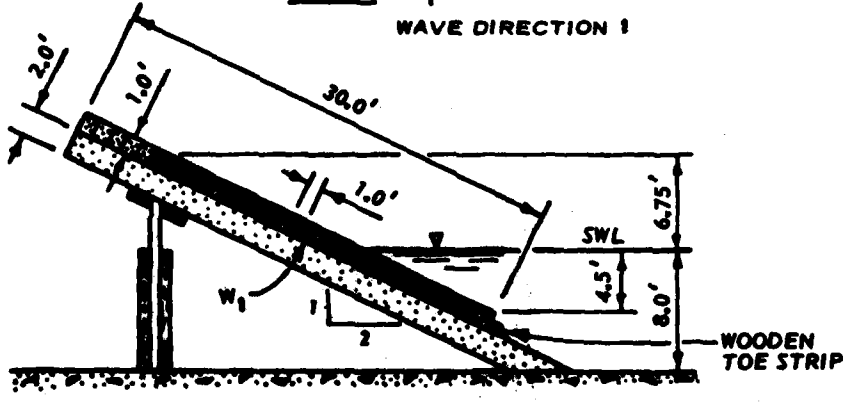
d/L	T , sec	H , ft	H/L	R_u , ft	R_u/H	R_d , ft	R_d/H
			Plan 1, 30-deg Wave Attack (Continued)				
0.40	2.0	1.0	0.050	1.34	1.34	0.45	0.45
0.40	2.0	1.5	0.074	1.34	0.89	1.13	0.75
0.40	2.0	1.75	0.087	0.68	0.39	1.13	0.65
			Plan 2, 90-deg Wave Attack				
0.09	6.0	2.5	0.027	4.24	1.70	4.5	1.80
0.14	4.0	3.0	0.052	5.60	1.87	4.5	1.50
0.40	2.0	1.75	0.087	2.45	1.37	0.89	0.51
			Plan 2, 60-deg Wave Attack				
0.09	6.0	2.5	0.027	4.70	1.88	2.29	0.92
0.14	4.0	3.0	0.052	6.03	2.01	3.35	1.12
0.40	2.0	1.75	0.087	2.24	1.28	0.89	0.51
			Plan 2, 30-deg Wave Attack				
0.09	6.0	2.5	0.027	2.45	0.98	2.68	1.07
0.14	4.0	3.0	0.052	2.24	0.75	2.02	0.67
0.40	2.0	1.75	0.087	1.56	0.89	0.89	0.51
			Plan 3, 90-deg Wave Attack				
0.09	6.0	1.0	0.011	1.07	1.07	1.97	1.97
0.09	6.0	2.0	0.022	2.50	1.25	1.97	0.99
0.09	6.0	3.0	0.033	3.76	1.25	2.68	0.89
0.40	2.0	1.0	0.050	0.72	0.72	1.07	1.07
0.40	2.0	1.5	0.074	1.16	0.77	1.07	0.71
0.40	2.0	1.75	0.087	1.61	0.92	1.43	0.82
0.40	2.0	2.0	0.099	1.61	0.81	1.61	0.81
			Plan 3, 60-deg Wave Attack				
0.09	6.0	1.0	0.011	1.61	1.61	2.33	2.33
0.09	6.0	2.0	0.022	3.22	1.61	2.15	1.08
0.09	6.0	3.0	0.033	5.72	1.91	3.04	1.01
0.40	2.0	1.0	0.050	0.72	0.72	1.07	1.07
0.40	2.0	1.5	0.074	1.25	0.83	1.07	0.71
0.40	2.0	1.75	0.087	1.79	1.02	1.79	1.02
0.40	2.0	2.0	0.099	1.79	0.90	1.61	0.81

(Continued)

Table 1 (Concluded)

d/L	T , sec	H , ft	H/L	R_u , ft	R_u/H	R_d , ft	R_d/H
			Plan 3, 30-deg Wave Attack				
0.09	6.0	1.0	0.011	0.72	0.72	1.07	1.07
0.09	6.0	2.0	0.022	2.15	1.08	2.15	1.08
0.09	6.0	3.0	0.033	2.68	0.89	2.15	0.72
0.40	2.0	1.0	0.050	0.54	0.54	0.89	0.89
0.40	2.0	1.5	0.074	1.07	0.71	0.89	0.59
0.40	2.0	1.75	0.087	0.89	0.51	1.25	0.71
0.40	2.0	2.0	0.099	0.89	0.45	1.07	0.54
			Plan 4, 90-deg Wave Attack				
0.09	6.0	1.0	0.011	1.43	1.43	1.25	1.25
0.09	6.0	2.0	0.022	2.68	1.34	2.33	1.17
0.09	6.0	3.0	0.033	4.47	2.68	1.16	0.89
			Plan 4, 60-deg Wave Attack				
0.09	6.0	1.0	0.011	1.79	1.79	2.15	2.15
0.09	6.0	2.0	0.022	3.58	1.79	2.86	1.43
0.09	6.0	3.0	0.033	6.44	2.15	4.50	1.50
			Plan 4, 30-deg Wave Attack				
0.09	6.0	1.0	0.011	0.89	0.89	1.25	1.25
0.09	6.0	2.0	0.022	2.15	1.08	1.97	0.99
0.09	6.0	3.0	0.033	3.22	1.07	2.86	0.95





SECTION A-A'

MATERIAL CHARACTERISTICS

MODEL: W_1 = 0.072 - 0.009-LB STONE @ 165 PCF

PROTOTYPE**: W_1 = 4.61 - 0.58-LB STONE @ 165 PCF

NOTE: ALL DIMENSIONS ARE PROTOTYPE MEASUREMENTS

* PLAN 1, CELLS FULL OF RIPRAP
PLAN 2, CELLS HALF-FULL OF RIPRAP

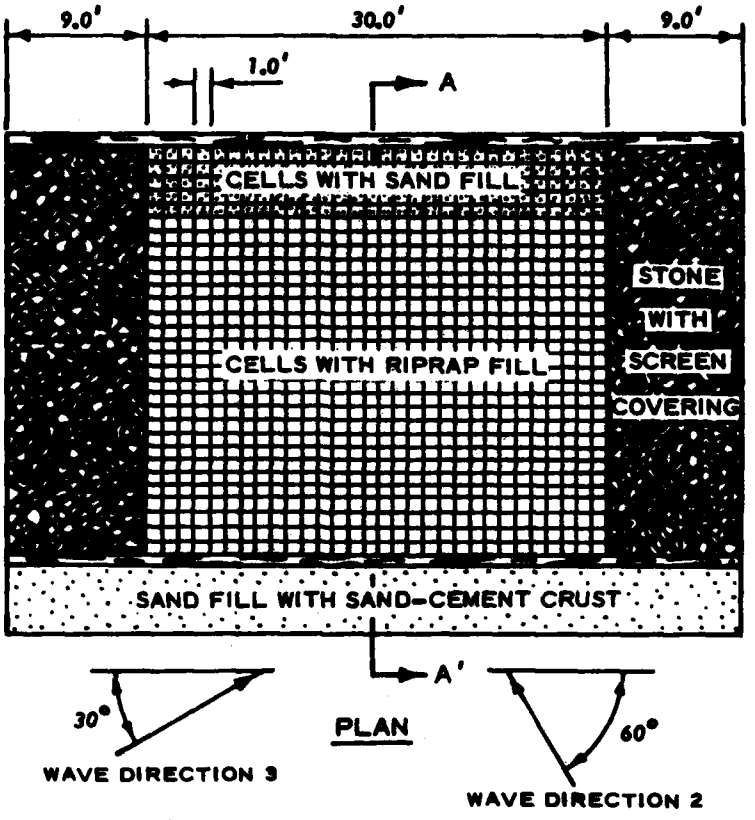
** SEE FIGURE 4 FOR RIPRAP GRADATION

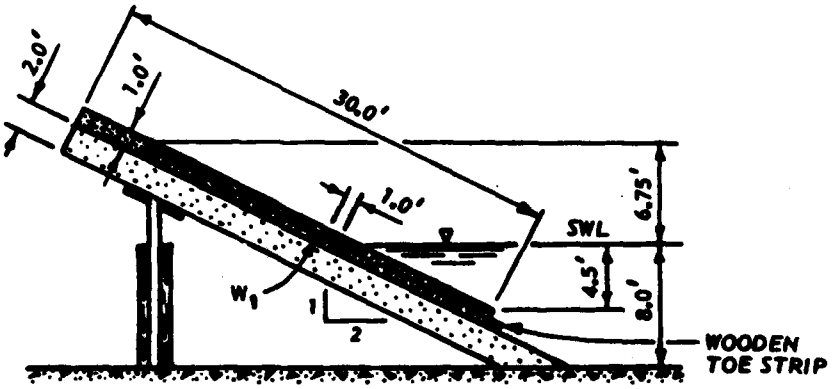
RIPRAP-FILLED CELLS 2-DIMENSIONAL MODEL

PLANS 1 AND 2*

MODEL SCALE 1:4

PLATE 1





SECTION A-A'

MATERIAL CHARACTERISTICS

MODEL: W_1 = 0.072 - 0.009-LB STONE @ 165 PCF

PROTOTYPE**: W_1 = 4.61 - 0.58-LB STONE @ 165 PCF

NOTE: ALL DIMENSIONS ARE PROTOTYPE MEASUREMENTS

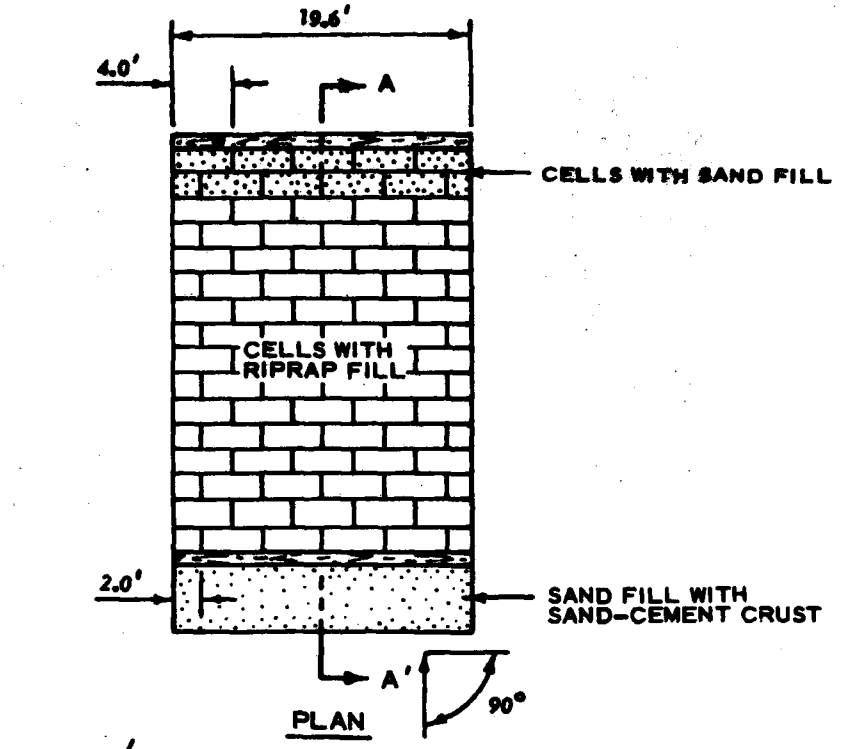
* PLAN 1, CELLS FULL OF RIPRAP
PLAN 2, CELLS HALF-FULL OF RIPRAP

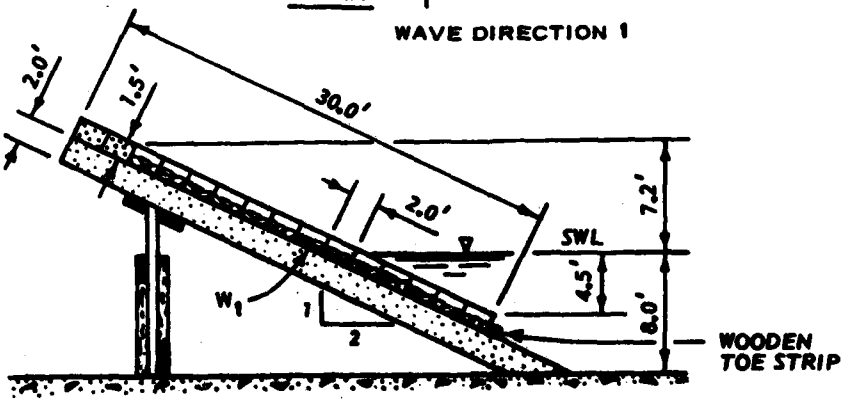
** SEE FIGURE 4 FOR RIPRAP GRADATION

RIPRAP-FILLED CELLS 3-DIMENSIONAL MODEL

PLANS 1 AND 2*
MODEL SCALE 1:4

PLATE 2





SECTION A–A'

MATERIAL CHARACTERISTICS

MODEL: W_1 = 0.072 – 0.009–LB STONE @ 165 PCF

PROTOTYPE**: W_1 = 4.61 – 0.58–LB STONE @ 165 PCF

NOTE: ALL DIMENSIONS ARE PROTOTYPE MEASUREMENTS

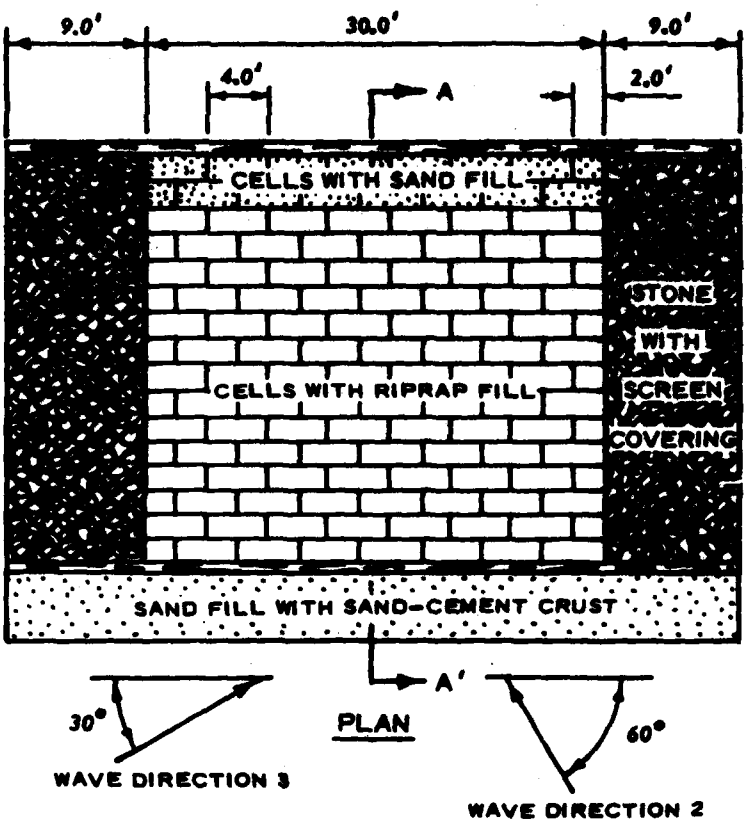
* PLAN 3, CELLS HALF–FULL OF RIPRAP
PLAN 4, CELLS FULL OF RIPRAP

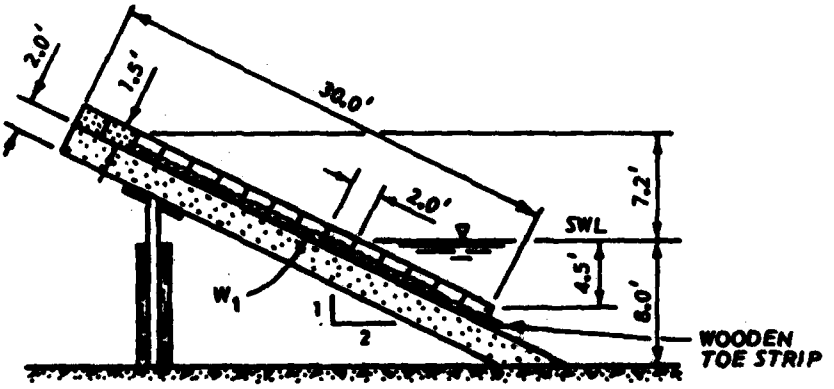
** SEE FIGURE 4 FOR RIPRAP GRADATION

RIPRAP–FILLED CELLS 2–DIMENSIONAL MODEL

PLANS 3 AND 4*
MODEL SCALE 1:4

PLATE 3





SECTION A–A'

MATERIAL CHARACTERISTICS

MODEL: W_1 = 0.072 – 0.009–LB STONE @ 165 PCF

PROTOTYPE**: W_1 = 4.61 – 0.58–LB STONE @ 165 PCF

NOTE: ALL DIMENSIONS ARE PROTOTYPE MEASUREMENTS

* PLAN 3, CELLS HALF-FULL OF RIPRAP
PLAN 4, CELLS FULL OF RIPRAP

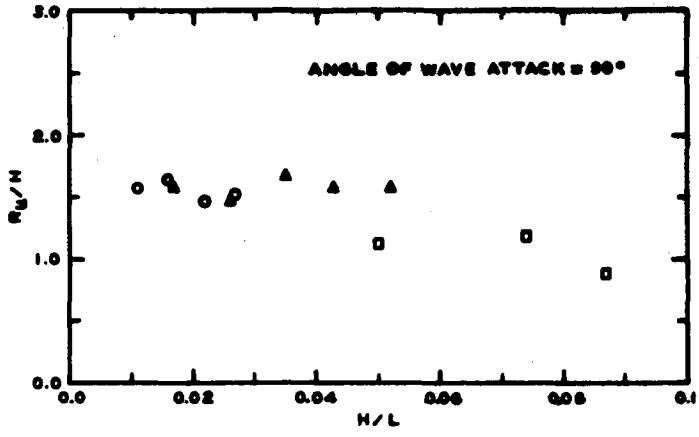
** SEE FIGURE 4 FOR RIPRAP GRADATION

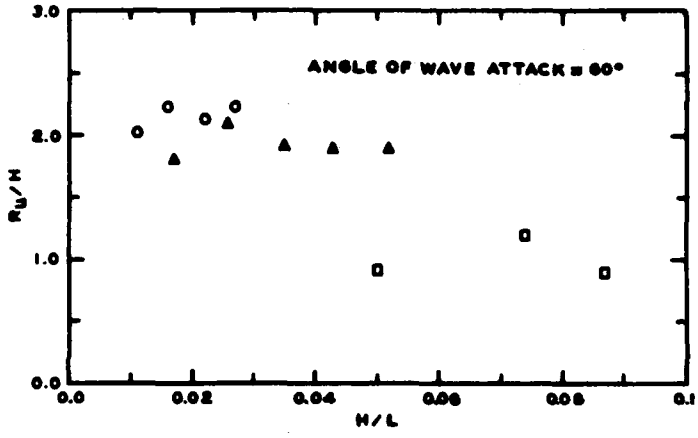
RIPRAP-FILLED CELLS 3-DIMENSIONAL MODEL

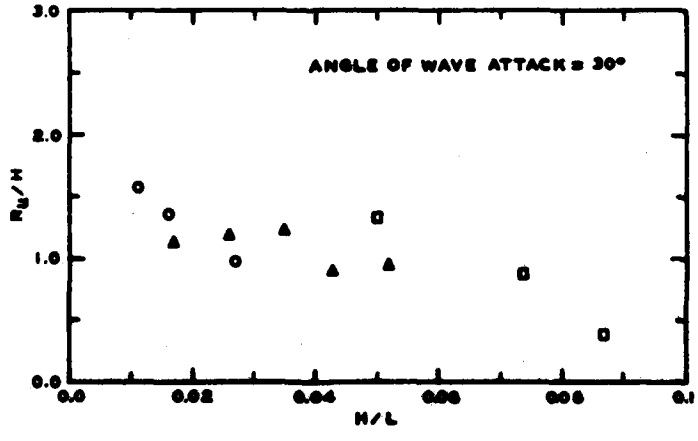
PLANS 3 AND 4*

MODEL SCALE 1:4

PLATE 4





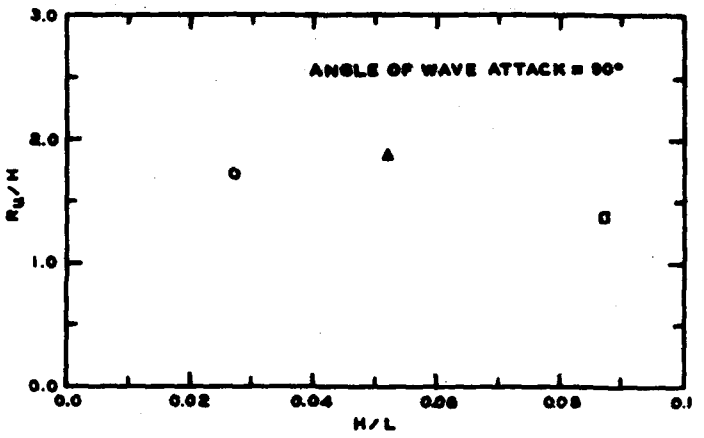


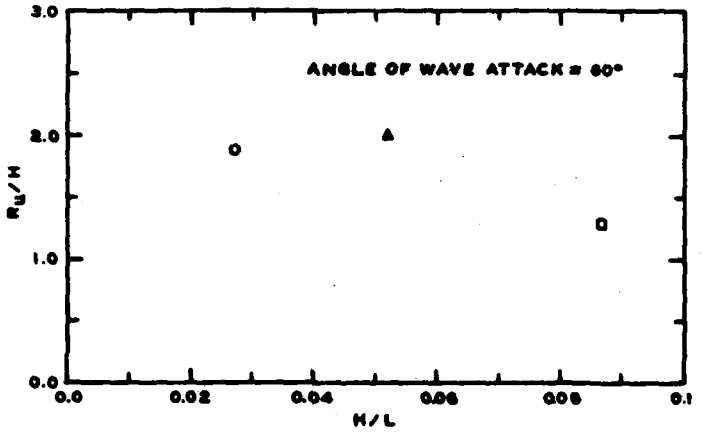
LEGEND

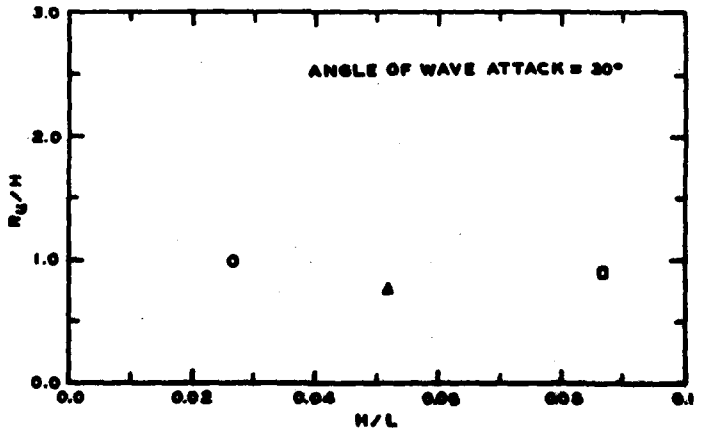
SYMBOL	d/L	T, SEC
○	0.08	6.0
△	0.14	4.0
□	0.40	2.0

RELATIVE RUNUP (R_u/H)
VS
WAVE STEEPNESS (H/L)
PLAN I

PLATE 5





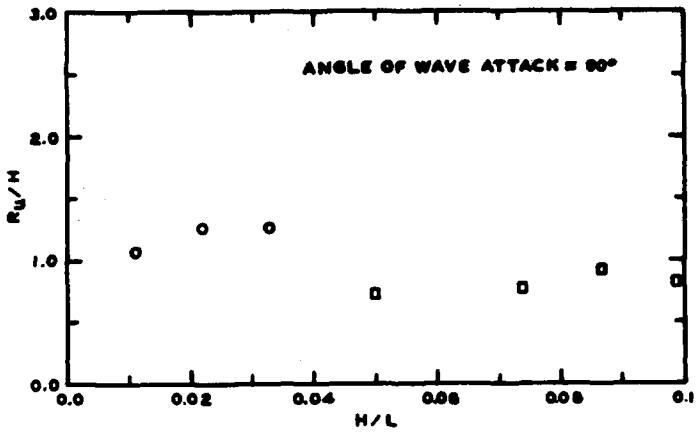


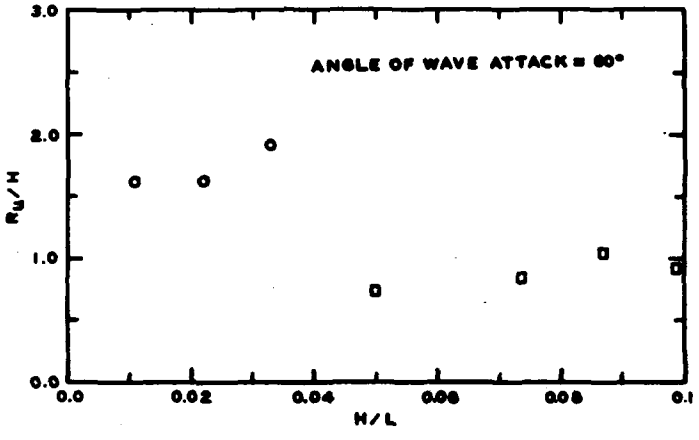
LEGEND

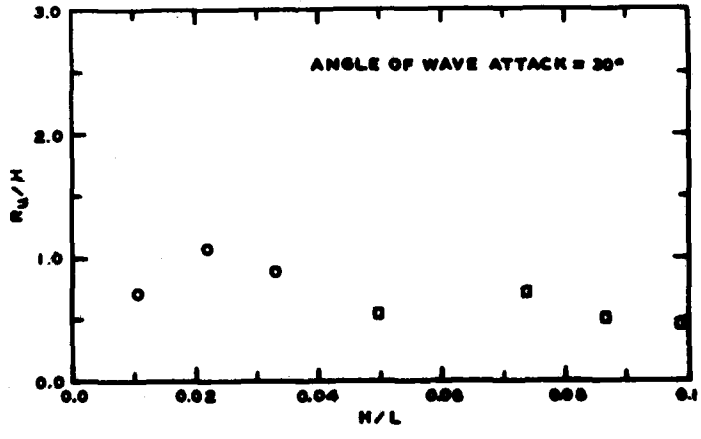
SYMBOL	d/L	T, SEC
○	0.09	6.0
△	0.14	4.0
□	0.40	2.0

RELATIVE RUNUP (R_u/H)
VS
WAVE STEEPNESS (H/L)
PLAN 2

PLATE 6





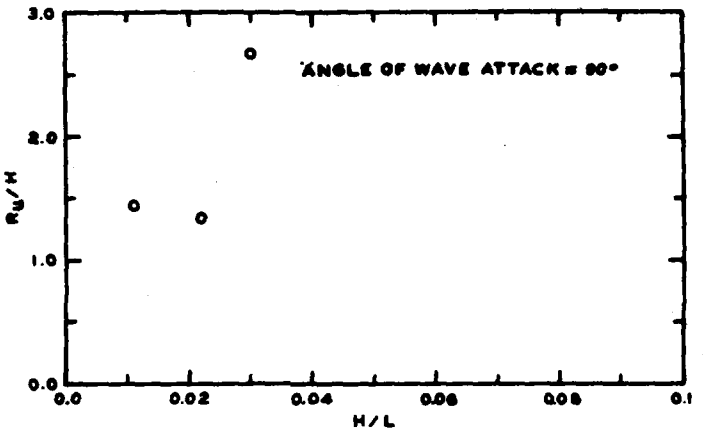


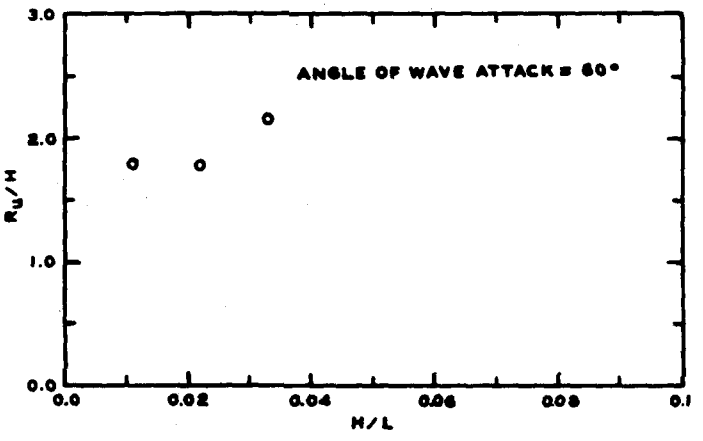
LEGEND

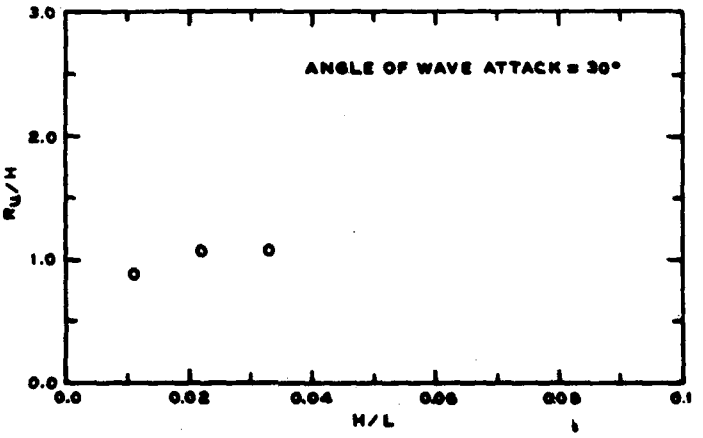
SYMBOL	d/L	T, SEC
o	0.08	6.0
□	0.40	2.0

RELATIVE RUNUP (R_u/H)
VS
WAVE STEEPNESS (H/L)
PLAN 3

PLATE 7





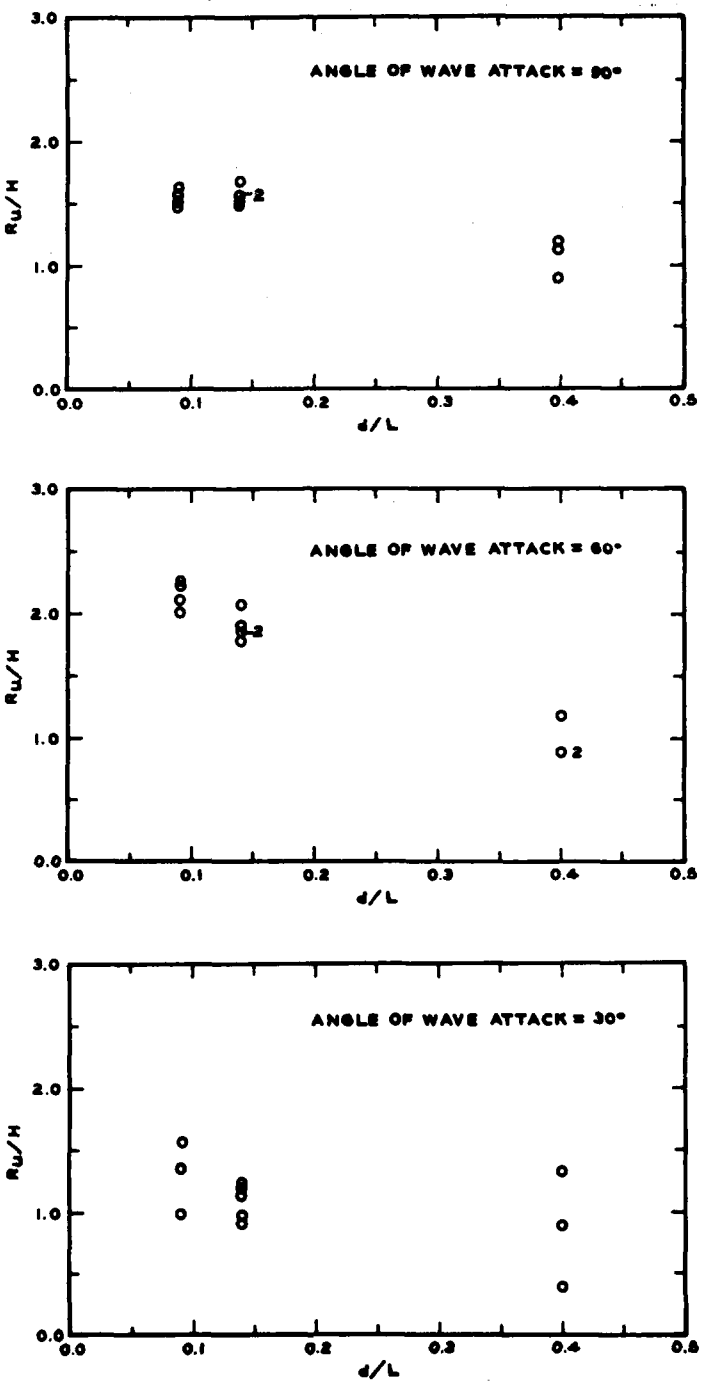


LEGEND

SYMBOL	d/L	T, SEC
o	0.08	6.0

RELATIVE RUNUP (R_u/H) VS WAVE STEEPNESS (H/L)
PLAN 4

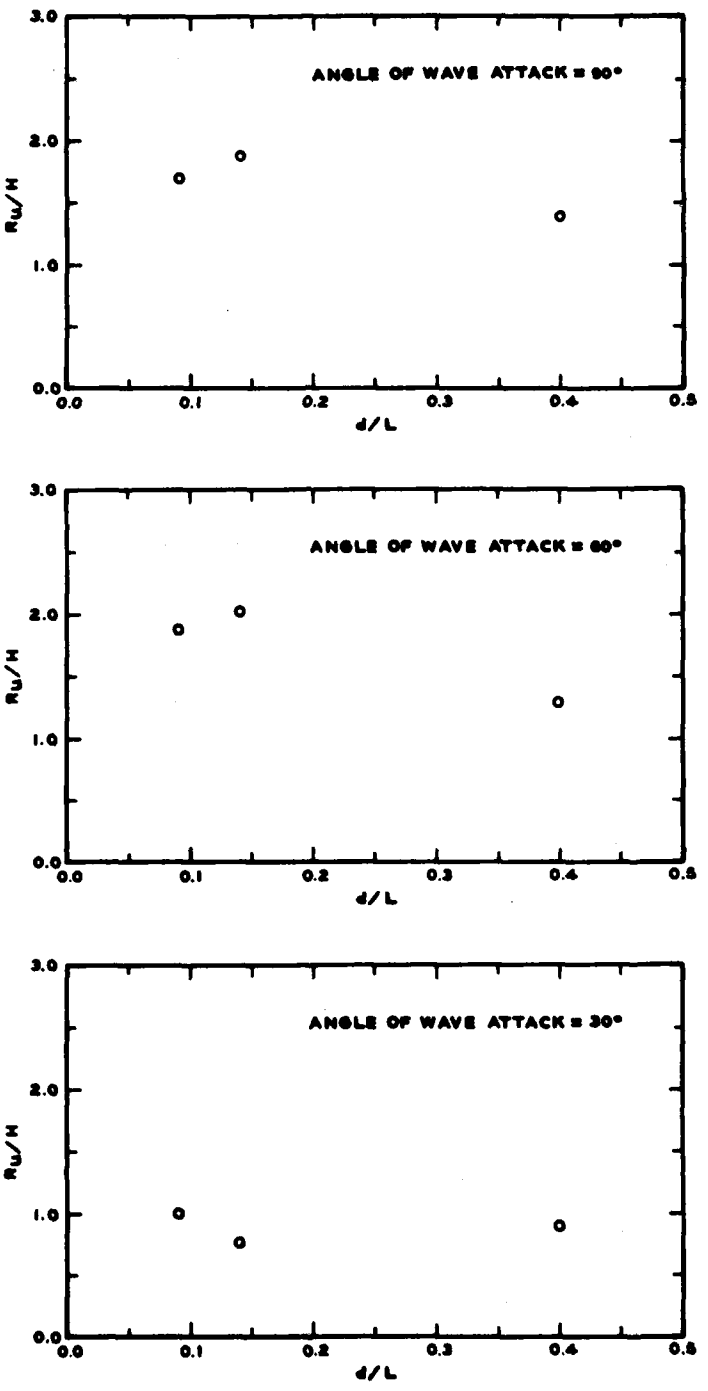
PLATE 8



NOTE. NUMBERS BESIDE DATA POINTS INDICATE THAT THE NUMBER OF DATA POINTS EXCEED ONE.

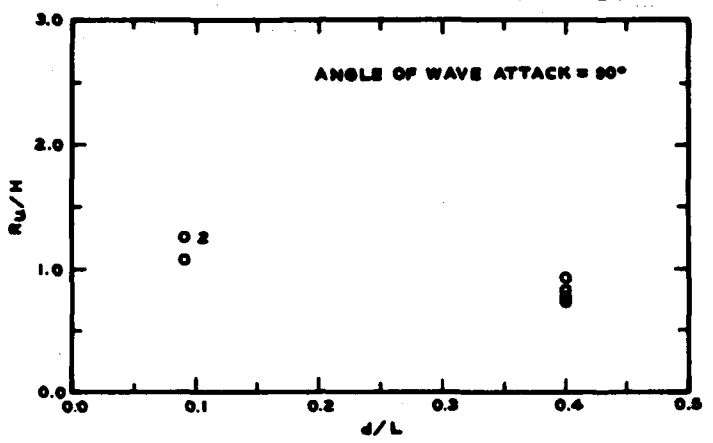
RELATIVE RUNUP (R_u/H)
VS
RELATIVE DEPTH (d/L)
PLAN 1

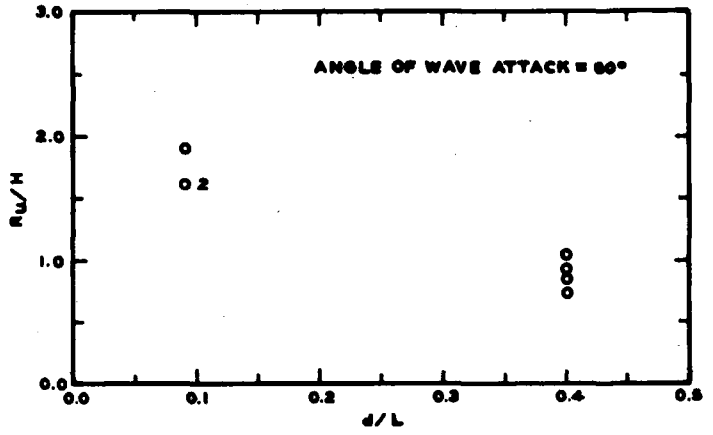
PLATE 9

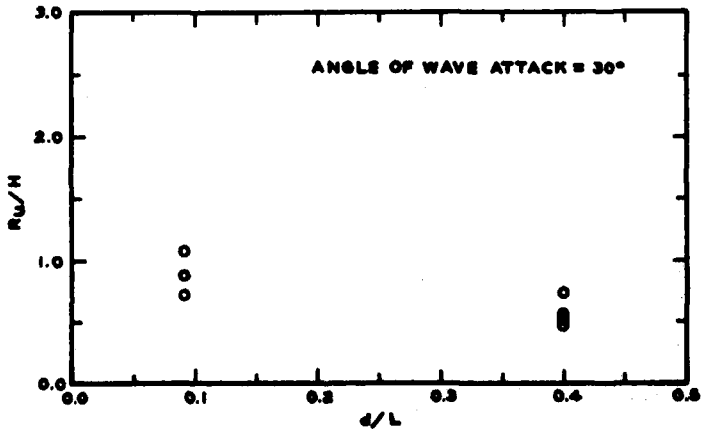


RELATIVE RUNUP (R_u/H)
VS
RELATIVE DEPTH (d/L)
PLAN 2

PLATE 10



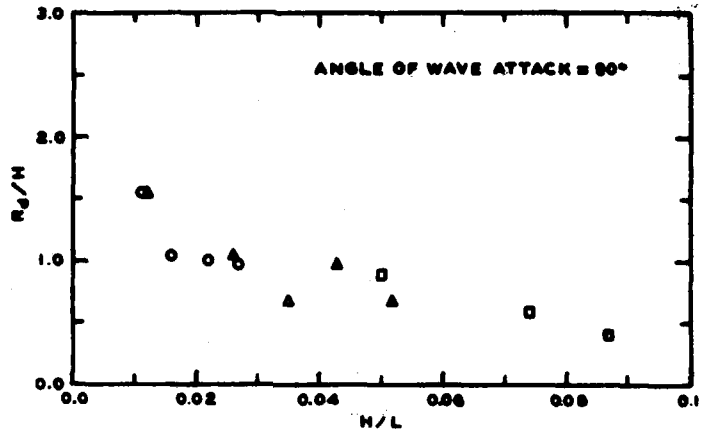


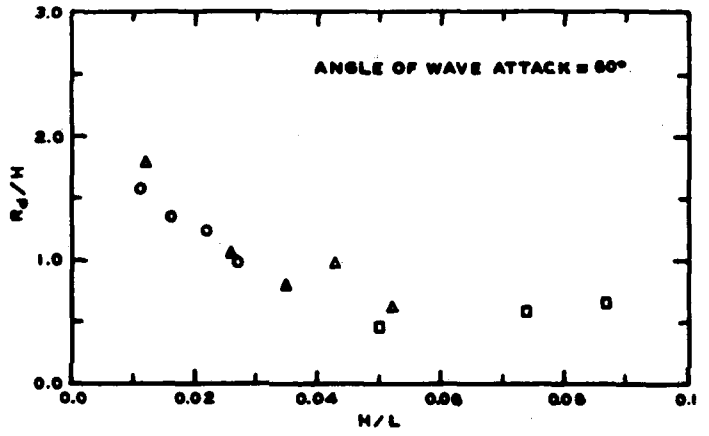


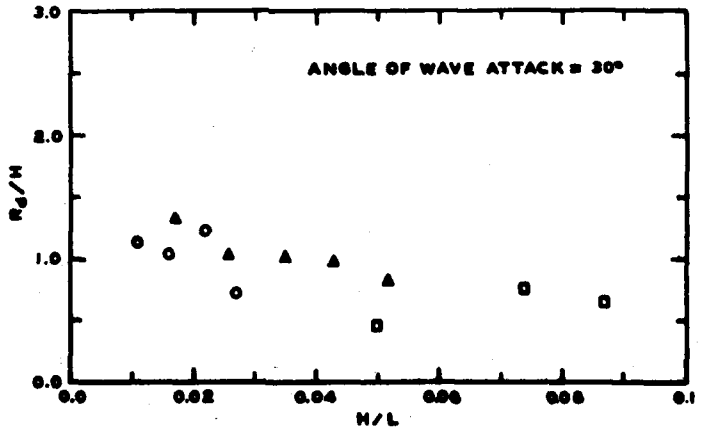
NOTE: NUMBERS BESIDE DATA POINTS INDICATE THAT THE NUMBER OF DATA POINTS EXCEED ONE

RELATIVE RUNUP (R_u/H)
VS
RELATIVE DEPTH (d/L)
PLAN 3

PLATE 11





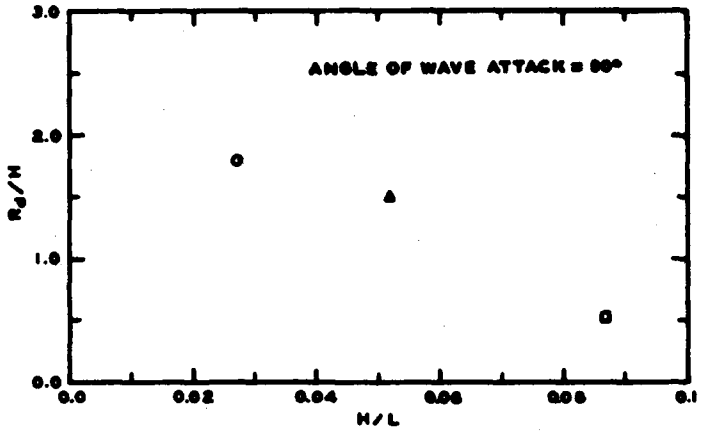


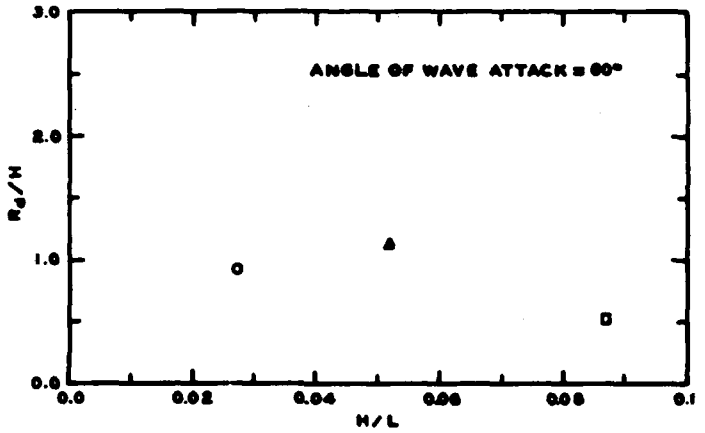
LEGEND

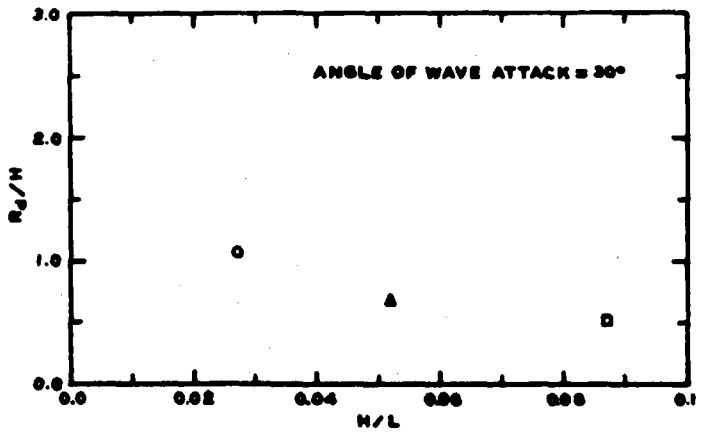
SYMBOL	d/L	T, SEC
○	0.08	6.0
△	0.14	4.0
□	0.40	2.0

RELATIVE RUNDOWN (R_d/H)
VS
WAVE STEEPNESS (H/L)
PLAN I

PLATE 12





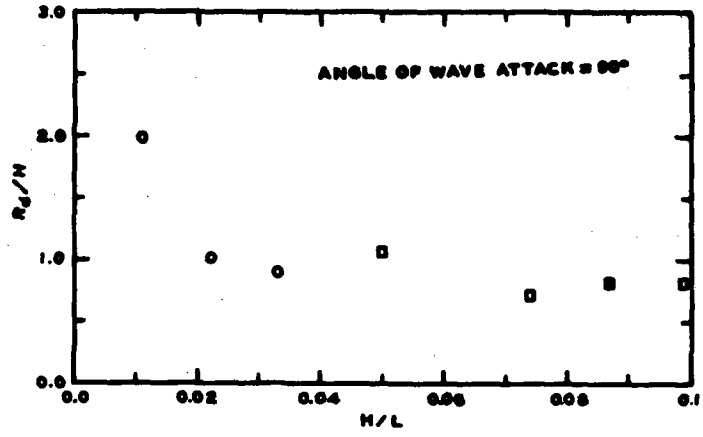


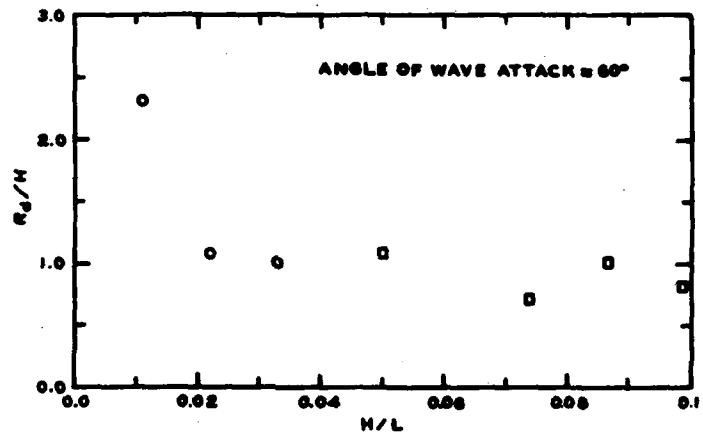
LEGEND

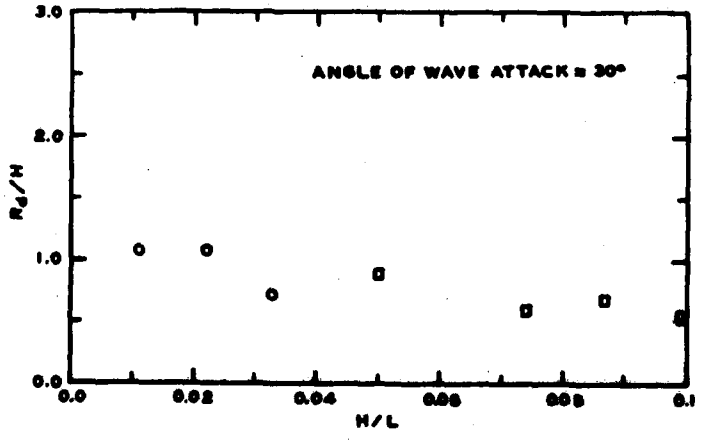
SYMBOL	d/L	T, SEC
○	0.09	6.0
△	0.14	4.0
□	0.40	2.0

RELATIVE RUNDOWN (R_d/H)
VS
WAVE STEEPNESS (H/L)
PLAN 2

PLATE 13





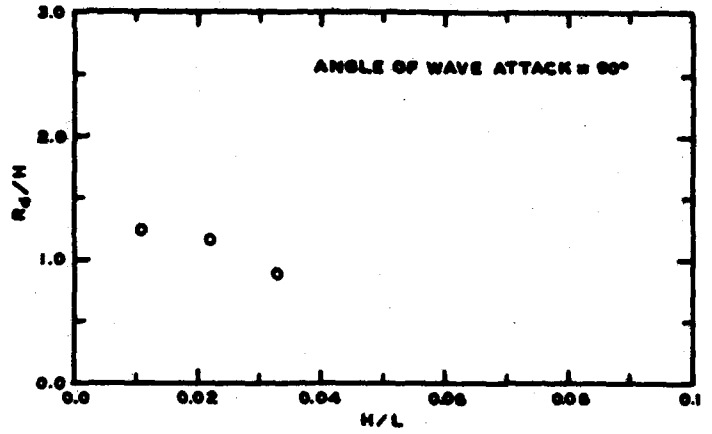


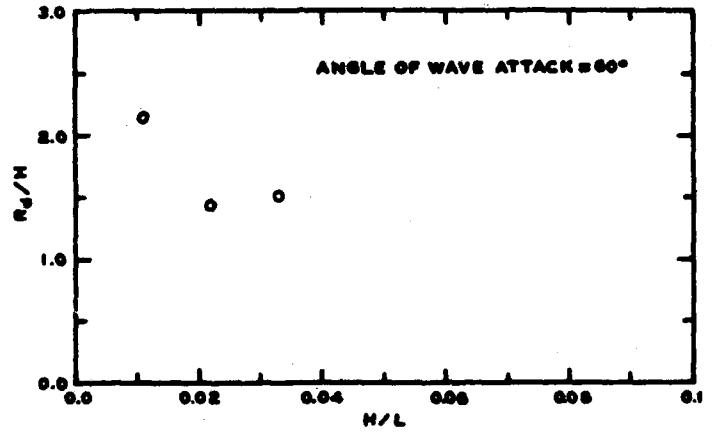
LEGEND

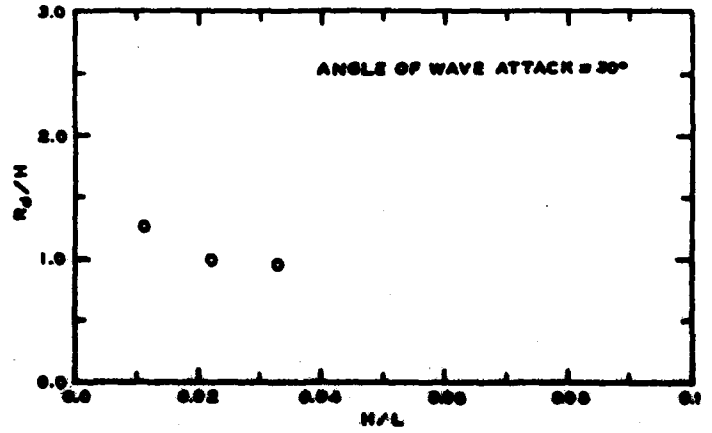
SYMBOL	d/L	T, SEC
○	0.09	6.0
□	0.40	2.0

RELATIVE RUNDOWN (R_d/H)
VS
WAVE STEEPNESS (H/L)
PLAN 3

PLATE 14





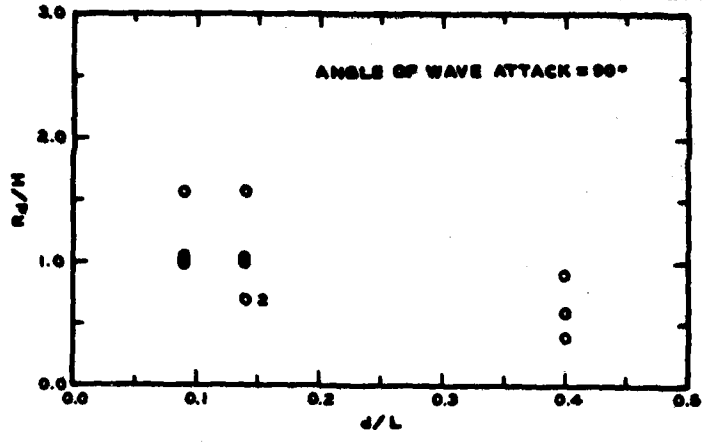


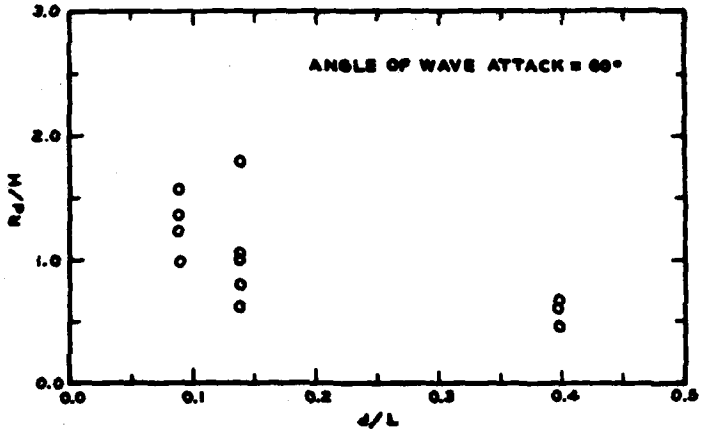
LEGEND

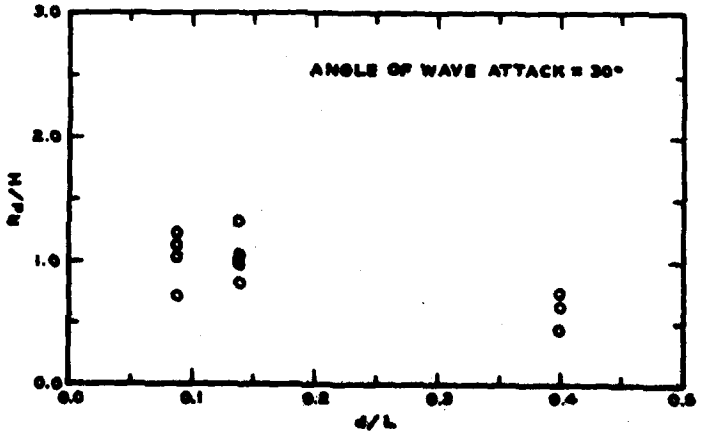
SYMBOL	d/L	T, SEC
○	0.00	0.0

RELATIVE RUNDOWN (R_d/H)
VS
WAVE STEEPNESS (H/L)
PLAN 4

PLATE 15



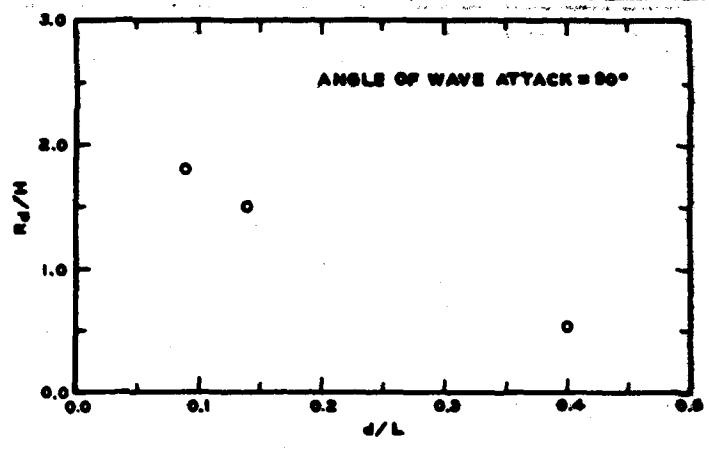


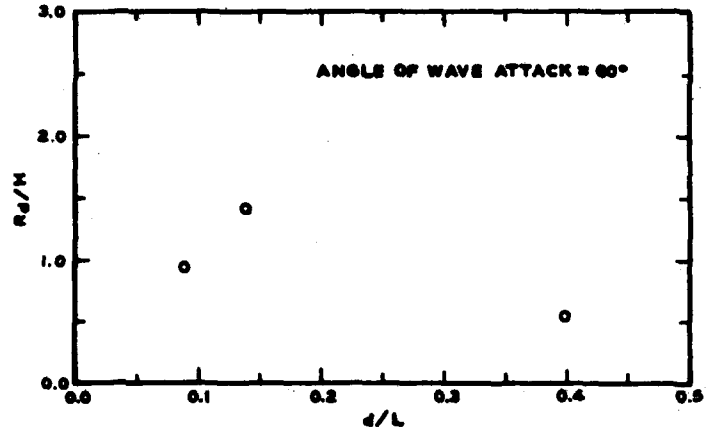


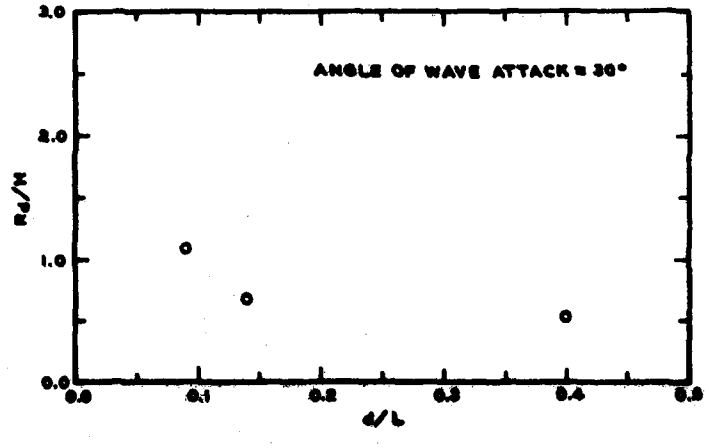
NOTE: NUMBERS BESIDE DATA POINTS INDICATE THAT THE NUMBER OF DATA POINTS EXCEED ONE.

RELATIVE RUNDOWN (R_d/H)
VS
RELATIVE DEPTH (d/L)
PLAN 1

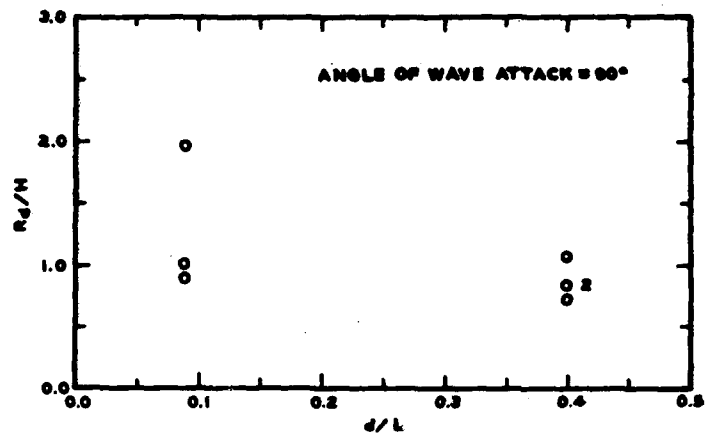
PLATE 16

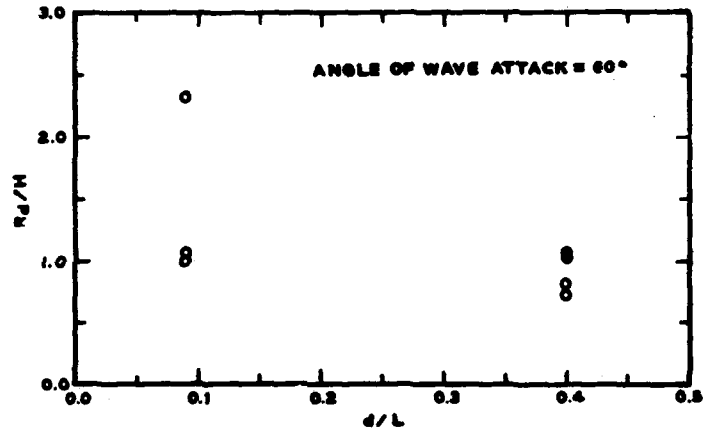


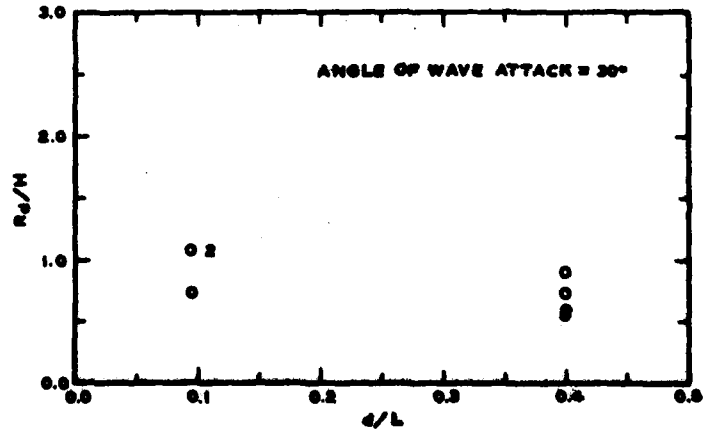




RELATIVE RUNDOWN (R_d/H)
VS
RELATIVE DEPTH (d/L)
PLAN 2







NOTE: NUMBERS BESIDE DATA POINTS INDICATE THAT THE NUMBER OF DATA POINTS EXCEED ONE.

RELATIVE RUNDOWN (R_d/H)
VS
RELATIVE DEPTH (d/L)
PLAN 2

PLATE 18

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Markle, Dennis G.
Wave stability study of riprap-filled cells : Hydraulic Model Investigation / by Dennis G. Markle (Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1983.
41 p. in various pagings, 18 p. of plates : ill. ; 27 cm. -- (Miscellaneous paper ; HL-83-2)
Cover title.
"April 1983."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army."

1. Erosion. 2. Hydraulic models. 3. Water waves. I. United States. Army. Corps of Engineers. Office of the Chief of Engineers. II. U.S. Army Engineer Waterways Experiment Station. Hydraulics Laboratory. III. Title IV. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; HL-83-2.
TA7.W34m no.HL-83-2