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Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Use of a Rubble Berm for Reducing Runup, Overtopping, and Damage on a 1V to 2H Riprap Slope

Experimental Model Investigation

by Donald L. Ward, John P. Ahrens
Coastal Engineering Research Center

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CS	Concrete and Steel Structures	EM	Electrical and Mechanical
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Experimental Model Investigation

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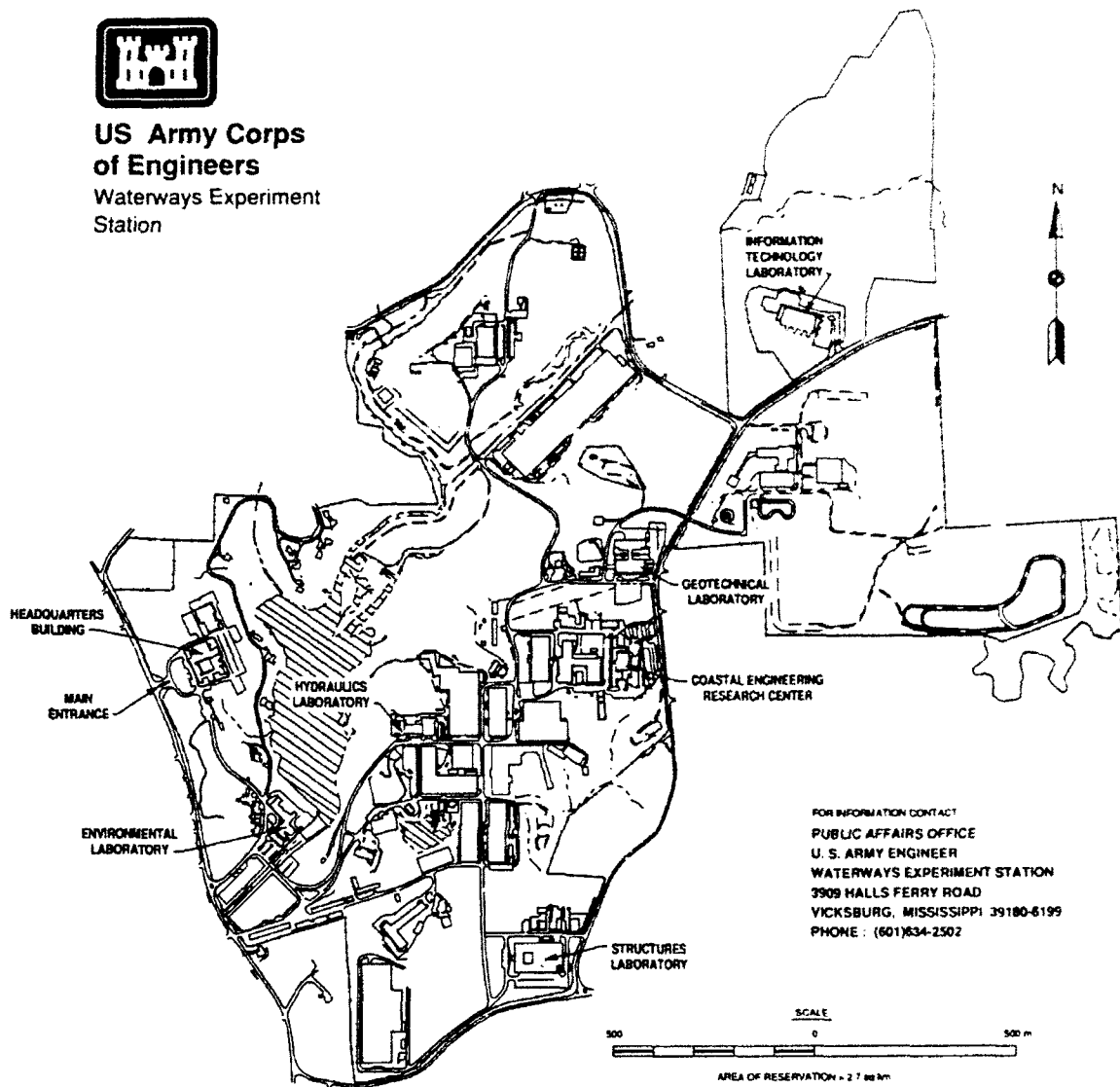
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**US Army Corps
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PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Coastal Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32415, "Experimental Testing of Methods for Reducing Wave Runup and Overtopping on Structures," for which Mr. John P. Ahrens was Principal Investigator. Mr. John H. Lockhart, Jr. (CECW-EH), was the REMR Technical Monitor for this work.

Mr. William N. Rushing (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-O) and Dr. Tony C. Liu (CECW-EG) served as the REMR Overview Committee; Mr. William F. McCleese, US Army Engineer Waterways Experiment Station (WES), was the REMR Program Manager. Mr. D. D. Davidson, Wave Dynamics Division (WDD), Coastal Engineering Research Center (CERC), WES, was the Problem Area Leader.

The work was performed at WES, and this report was prepared by Mr. Donald L. Ward and Mr. Ahrens, WDD, CERC, under the general supervision of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC; and under the direct supervision of Mr. C. E. Chatham, Chief, WDD, and Mr. Davidson, Chief, Wave Research Branch, WDD. The models were operated by Mr. Robert L. Tingle, Jr., Laboratory Technician, WDD.

During publication of this report, Dr. Robert W. Whalin was Director of WES. COL Leonard G. Hassell, EN, was Commander.

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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>
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square inches	6.4516	square centimetres

USE OF A RUBBLE BERM FOR REDUCING RUNUP, OVERTOPPING,
AND DAMAGE ON A 1V TO 2H RIPRAP SLOPE
Experimental Model Investigation

PART I: INTRODUCTION

Background

1. Erosion of exposed soil embankments by waves and currents is a serious problem along coastal and inland shores. A protective revetment of graded quarry stone or "riprap" is commonly used to provide shore protection because of its relatively low cost, durability, and availability, and because the roughness and porosity of the stone is effective in dissipating wave energy and runup.

2. Rising water levels, larger boat wakes, and increasing values of land protected by revetments may necessitate improvements to a revetment to increase the protection provided. One method of improving the performance of a revetment is to add an attached berm in front of the revetment. Unfortunately, there is very little design guidance on the use of revetments with fronting berms.

Purpose

3. The purpose of this investigation was to develop design guidance on methods of reducing runup and overtopping of revetments based on data collected from laboratory tests of wave runup and overtopping on riprap revetments with a slope of 1:2 (1V to 2H). Tests were conducted in a wave flume with spectral capabilities at the Coastal Engineering Research Center (CERC) of the US Army Engineers Waterways Experiment Station (WES) in Vicksburg, MS.

PART II: DEFINITION OF TEST PARAMETERS

4. Inconsistencies among authors in notations, definitions of parameters, and the methods by which a value for a parameter is obtained greatly complicate the task of comparing results from different studies. In this report, notations will follow guidelines published by the International Association for Hydraulic Research in its "List of Sea State Parameters" (1986). Additional parameters, definitions, and method used to determine the value of certain parameters, are given below.

5. Wave heights used in this report are the heights of the zeroth moment (H_{m0}) and are obtained as four times the square root of the zeroth moment of the potential energy spectrum. The H_{m0} 's of the incident spectra are separated from the H_{m0} 's of the reflected spectra by the method of Goda and Suzuki (1976), using a three-gage array. Two arrays are used, one to measure the H_{m0} 's near the wave board (Array 1) and one near the structure toe (Array 2).

6. Peak period (T_p) is the wave period associated with the highest energy density of the spectrum. This T_p was obtained by dividing the spectrum into 256 bands and taking the reciprocal of the midpoint frequency causing the highest energy density over 11 adjacent bandwidths.

7. Wave heights and periods are frequently reported in other investigations in terms of significant wave height (H_s) and average wave period (T_z), where H_s is the average of the one-third highest waves. Both H_s and T_z are included in the data in this report to simplify comparison to other investigations. Average wave periods in this report were determined as

$$T_z = \left[\frac{m_0}{m_2} \right]^{1/2} \quad (1)$$

where m_0 and m_2 are the zeroth and second moments of the potential energy spectrum, respectively.

8. The spectral width or peakedness determined from the wave record is given as Q_p , defined by Goda (1970) as

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

$$O_p = \frac{2}{(m_o)^2} \int f [S(f)]^2 df \quad (2)$$

where f is frequency and $S(f)$ is the wave spectral density function for the given frequency.

9. The surf parameter, the ratio of structure slope to square root of wave steepness, is frequently used as an indicator of wave conditions at the structure (Battjes 1974) and as a means of nondimensionalizing the wave period. The surf parameter is defined as

$$\xi = \frac{\tan \alpha}{\left(\frac{2 \pi H}{gT^2} \right)^{1/2}} \quad (3)$$

or, equivalently,

$$\xi = \frac{\tan \alpha}{\left(\frac{H}{L_o} \right)^{1/2}} \quad (4)$$

where

ξ = surf parameter

$\tan \alpha$ = tangent of the angle of the revetment to the horizontal

g = acceleration of gravity

L_o = deepwater wavelength determined from the wave period, T

The wave height (H) and period used to determine ξ in this report are H_{m0} and T_p . The physical rationale for this parameter is discussed in Battjes (1974).

10. The reflection coefficient is commonly defined as the ratio of reflected wave height to incident wave height. This definition is clearly inappropriate when reflected and incident wave heights are described by different spectra. Reflection coefficients were therefore determined by the energy of the respective spectra, following the method of Goda and Suzuki (1976).

$$K_r = \left(\frac{E_R}{E_I} \right)^{1/2} \quad (5)$$

where K_r is the reflection coefficient and E_R and E_I are the energy of the reflected and incident spectra, respectively.

11. Reflected wave height is obtained as the product of the reflection coefficient and the incident wave height.

$$H_r = K_r H_{mo} \quad (6)$$

where H_r is the reflected wave height.

12. Runup (R_{max}) is defined as the vertical distance above the still-water level (swl) that a wave surges up the revetment, or the upper limit of "green" water since it does not include splash or spray. The elevation of maximum runup was determined visually and then measured with a point gage.

13. The berm in front of the revetment is described by its height and width. Berm width (W_b) is defined as the distance along the horizontal top of the berm. Height of the berm (h_b) is defined as the vertical distance from the toe of the revetment without the berm to the top of the berm.

14. Figure 1 illustrates a typical damage profile on a riprap slope. An area of erosion (A_2) is seen near the still-water level, with the stones displaced from the area of erosion being deposited on the lower slope (A_3) or, particularly on very flat slopes, on the upper slope (A_1). Damage to the revetment was determined based on the area of erosion.

15. To obtain the respective areas, the six sounding points on each of the horizontal sounding lines (paragraph 23) were averaged to give a single cross-sectional profile of the slope. The points on the profile then were connected by cubic splines, and the before- and after-testing profiles compared. The area of erosion was determined as the area between the two curves where the after-testing curve lay below the before-testing curve. The area was calculated by integrating between the two lines. The damage profile from $T_p = 2.25$ -sec, $H_{mo} = 0.50$ ft wave conditions is shown in Figure 2.

16. Damage to the revetment was defined by two methods: maximum perpendicular penetration of the erosion into the armor layer (e_{max}) and S_2 damage.

$$S_2 = \frac{A_2}{[(D_n)_{50}]^2} \quad (7)$$

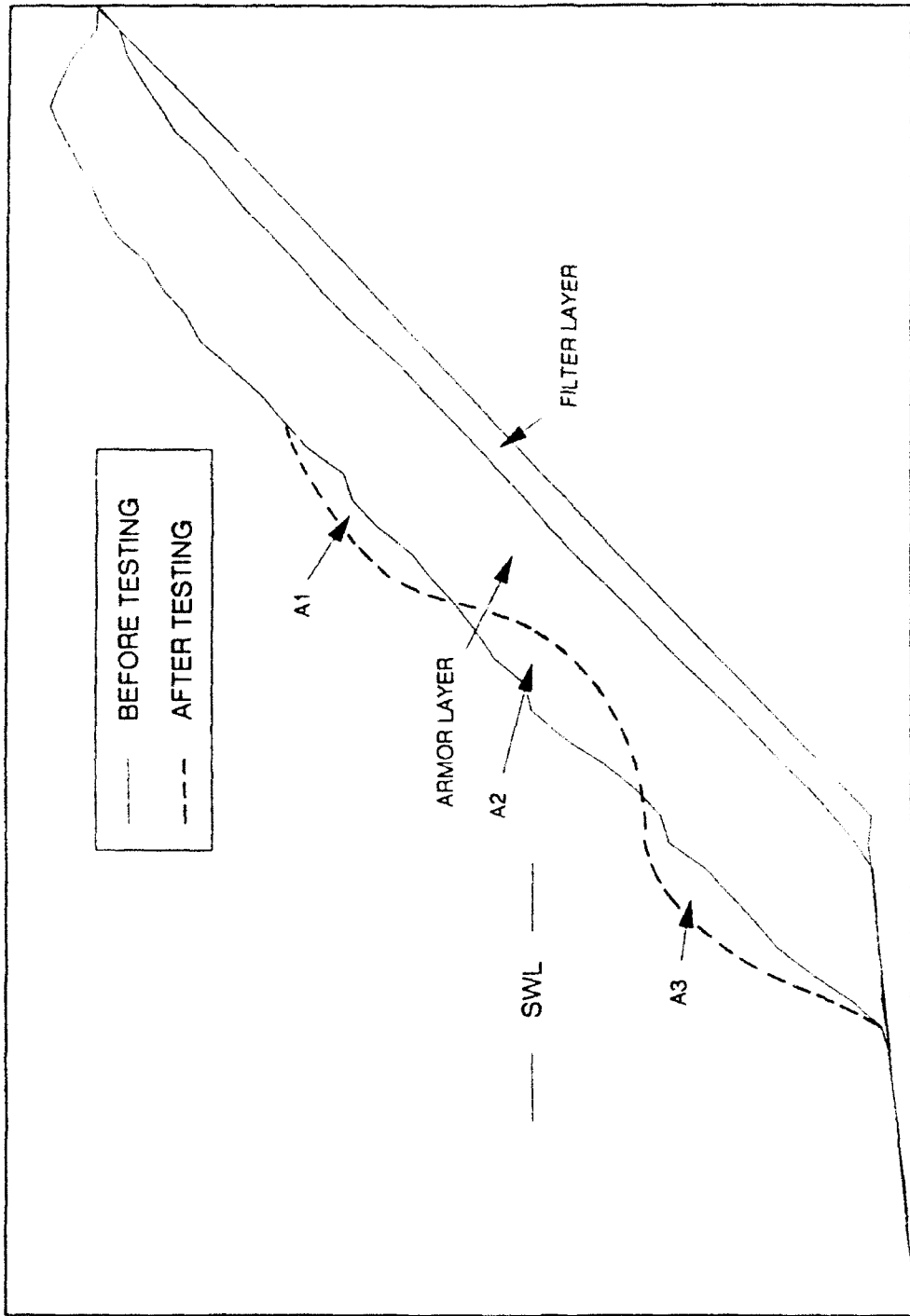


Figure 1. Typical damage profile on a riprap revetment

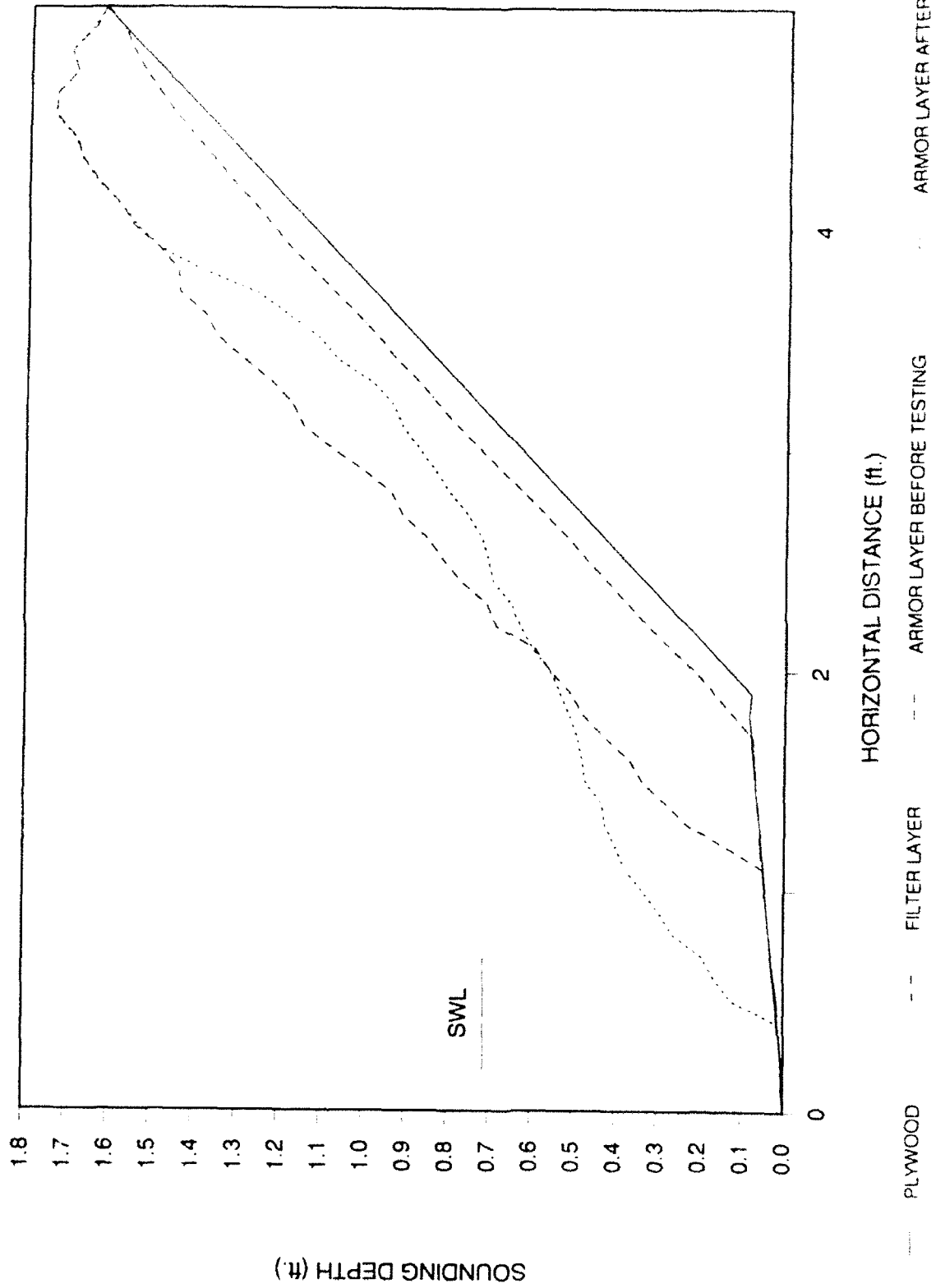


Figure 2. Damage profile from 2.25 sec T_p and 0.50 ft H_{mo}

where $(D_n)_{50}$ is the nominal diameter of the median armor stone size, defined as

$$(D_n)_{50} = \left[\frac{W_{50}}{w_r} \right]^{1/3} \quad (8)$$

where W_{50} is the median armor stone weight and w_r is the unit weight of the armor stone.

PART III: THE MODEL

Test Facility

17. All tests were conducted in a 3.0-ft-wide* by 150-ft-long by 3.0-ft-deep wave flume (Figure 3). A 1:20 slope was installed in the bottom of the flume starting 36.5 ft from the wave board and extending for 10 ft, followed by a 1:100 slope extending to the test structure.

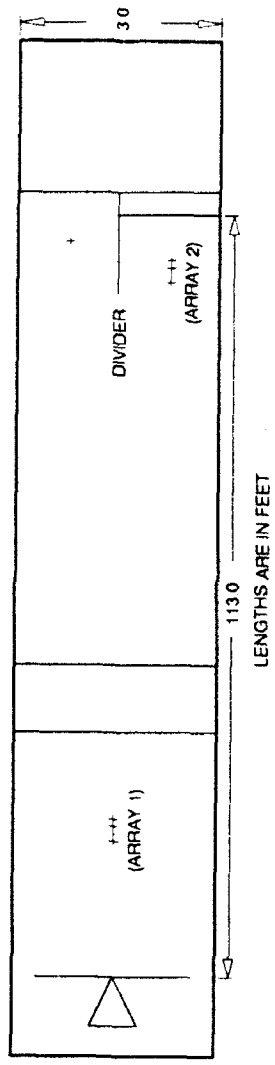
18. The flume was divided lengthwise into two 1.5-ft-wide channels starting 100 ft from the wave board and extending past the structure. A wave absorber was placed in one channel while the structure was placed in the other channel (113 ft from the wave board) thus minimizing the amount of reflection in the flume. An array of three wave gages was centered 21.5 ft in front of the wave board to monitor the generated signal. A similar array was placed in the side of the flume with the test structure, centered 104.5 ft from the wave board, to be used in separating the incident and reflected wave trains. Wire resistance staff gages were read at 10 Hz to monitor the water surface elevation.

19. The wave flume was equipped with a piston-type wave generator powered by an electro-hydraulic pump and controlled by a computer-generated signal.

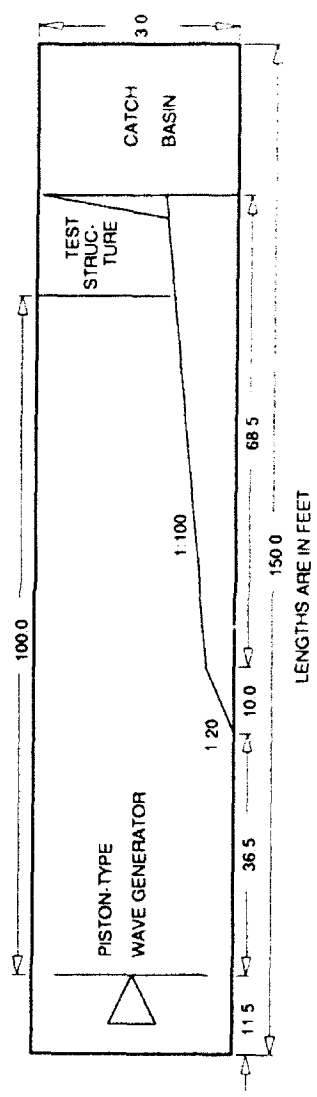
Test Structure

20. The test structure modeled a 1:2 slope of an impervious substratum protected by a filter layer and a layer of riprap (Figure 4). Sand was glued to a plywood board to provide the necessary roughness, and the board installed in the flume to represent the existing slope. A 0.07-ft-thick layer of crushed stone averaging 0.04 oz/stone was used for the filter layer. The armor layer was 0.26-ft-thick and constructed of a crushed limestone with a specific gravity of 2.70, blocky to angular shape, and gradation of

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

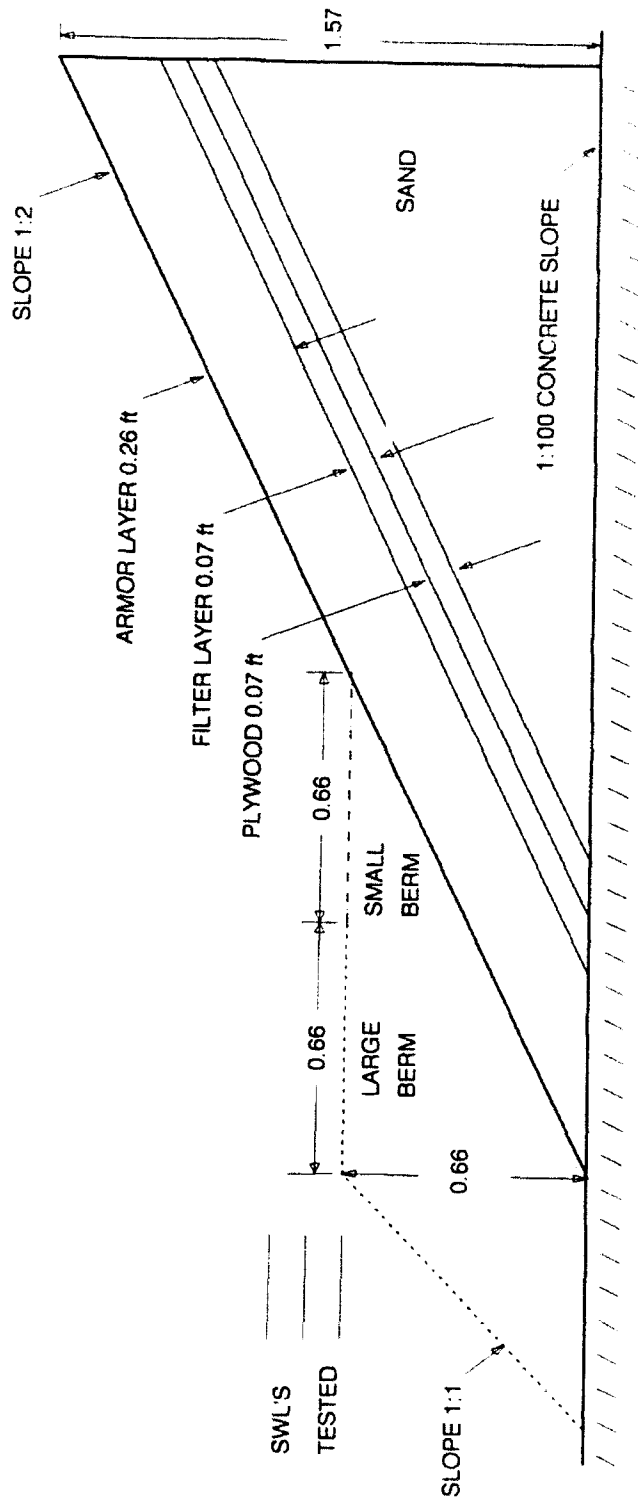


TOP VIEW



SIDE VIEW

Figure 3. Plan and profile views of wave flume



NOTE: All measurements are in feet.

Figure 4. Test structure cross section including both berms tested

$$\frac{D_{85}}{D_{15}} = 1.79 \quad (9)$$

where D_{85} and D_{15} are the 85- and 15-percentile diameters, respectively, on a grain size distribution curve, with all armor stones falling within the range

$$\frac{1}{8} W_{50} < W < 4 W_{50} \quad (10)$$

where W is the weight of an individual stone. Gradation of the armor stone used in this test series is shown in Figure 5.

21. Riprap is commonly sized by either the W_{50} or the nominal diameter, $(D_n)_{50}$. The armor layer used in these tests had a W_{50} of 0.22 lb and a $(D_n)_{50}$ of 0.11 ft. These dimensions correspond to a design section based on Hudson's equation (Hudson and Jackson 1962) for a design wave height of 0.30 ft. Hudson's equation is given as

$$W_{50} = \frac{W_r H^3}{K_{RR} (S_r - 1) \cot \theta}$$

where

- H = monochromatic wave height
- K_{RR} = stability coefficient
- S_r = relative specific gravity defined as specific gravity of armor stone divided by specific gravity of water
- $\cot \theta$ = is the cotangent of the revetment slope

The stability coefficient for graded angular quarrystone for breaking waves is taken from the Shore Protection Manual (SPM) (1984) as 2.2. For irregular wave tests, design is based on the average of the highest 10 percent of waves (H_{10}). The design H_{10} of 0.3 ft corresponds to a H_{mo} of about 0.24 ft.

22. The filter and armor stone layers were placed by dumping from a small shovel in a manner to simulate prototype construction with a bucket loader. The toe of the structure was 113 ft from the wave board.

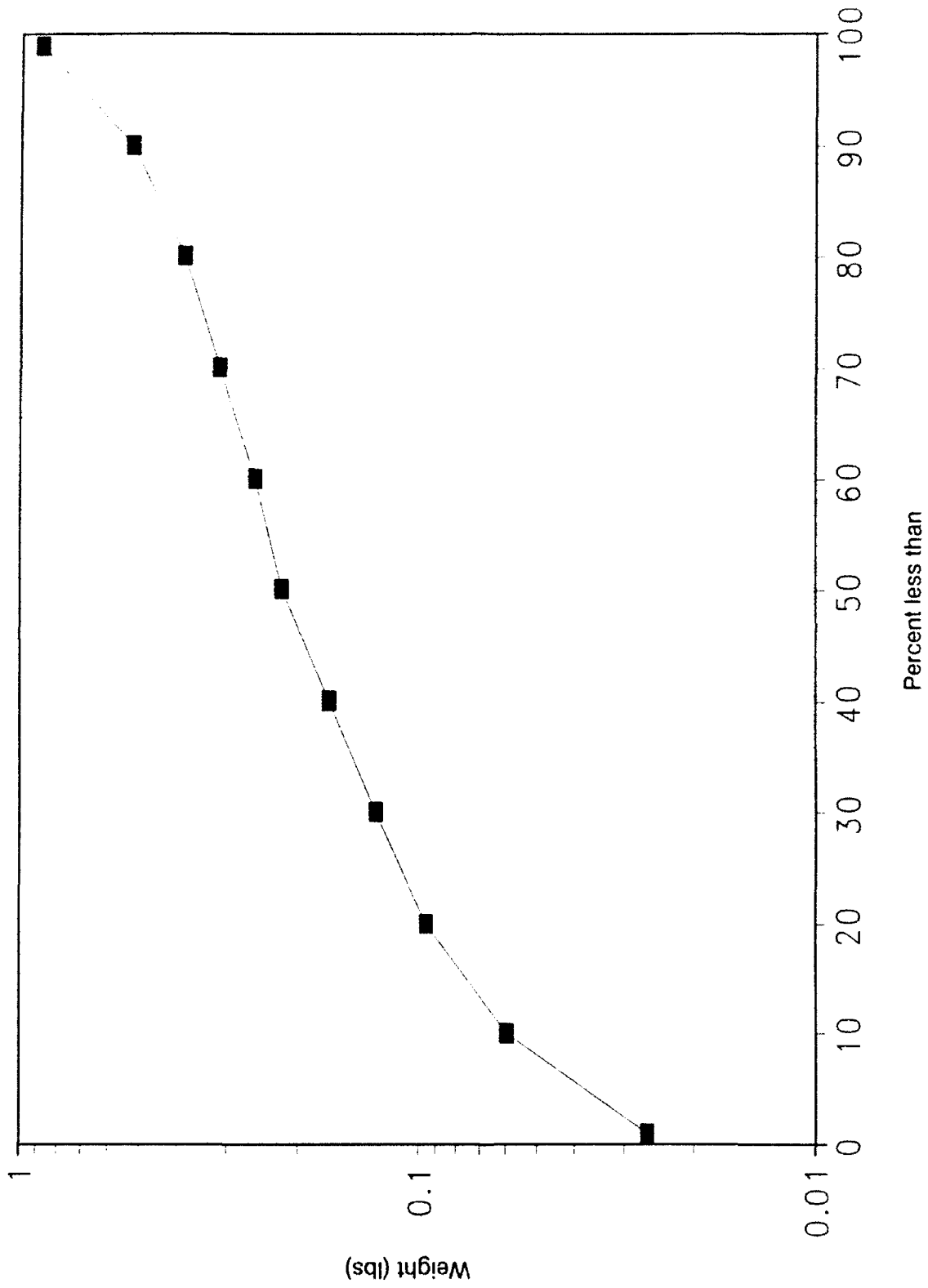


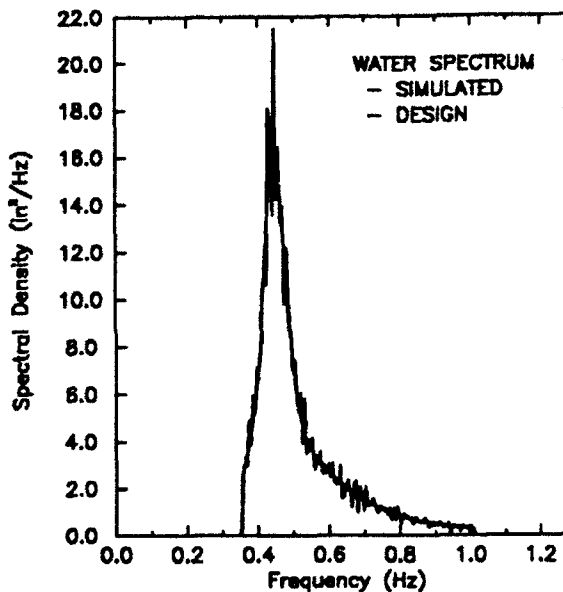
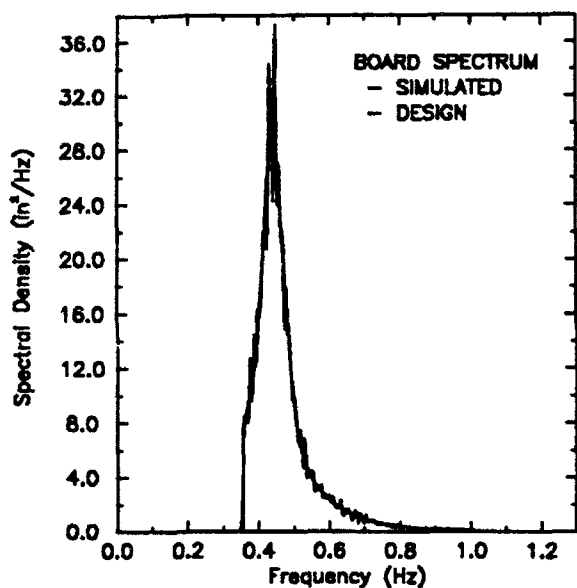
Figure 5. Armor stone gradation

Sounding Equipment

23. After placement, the filter and armor layers were surveyed by sounding. The sounding apparatus consisted of a row of six vertical rods spaced across the half of the flume width containing the test structure, with the outer rods located 0.36 ft from the edge of the flume section and the center rods spaced at 0.15-ft intervals. Each of the rods had a flat circular foot, 0.10 ft in diameter, attached to the rod by a ball and socket joint. The rods were used to take a row of soundings across the test structure. A row of soundings was taken at horizontal intervals of 0.10 ft down the entire slope of the revetment. Soundings were taken before and after each test.

Signal Generation

24. Software was developed at CERC to generate a spectral signal to control the wave board. A signal was generated to simulate a JONSWAP (JOint North Sea Wave Project) spectrum for each peak period using high- and low-frequency cutoffs of 3.0 percent of the energy spectrum, high-side decay factor of 0.09, low-side decay factor of 0.07, peak enhancement factor of 3.3, and a wave height (H_{mo}) at least as large as the largest H_{mo} in the test series. Different H_{mo} 's for the tests were obtained by varying the gain to the electro-hydraulic pump controlling the wave board. Computer limitations dictated that 30 min was the maximum signal length that could be stored; therefore a separate signal was generated for each 30 min of a test run, using a different random seed for each signal. The design spectrum is compared with the generated spectrum in Figure 6 for the first 30 min period of the $T_p = 2.25$ -sec test series.



WINDOW MODE = 1 (COSINE SQUARED)

DETREND MODE = 1 (MEAN REMOVED)

WATER DETREND FUNCTION = (0.2005E-03) + (0.0000E+00)*T + (0.0000E+00)*(T**2)

BOARD DETREND FUNCTION = (0.2325E-03) + (0.0000E+00)*T + (0.0000E+00)*(T**2)

WINDOW FRACTION = 0.10

BANDS AVERAGED = 10

UNIDIRECTIONAL WAVE TANK PISTON-TYPE GENERATOR DIGITAL DRIVER FILE HEADER

OUTPUT FILE - OT2T225H6.DAT

GENERATOR TYPE - PISTON

TRANSFER FUNCTION

SPECTRUM - JONSWAP SPECTRUM

2.250 (SEC) DESIGN PEAK PERIOD

6.000 (INCHES) DESIGN HMO

3.30 GAMMA

0.0700 SIGMA-LOW

0.0900 SIGMA-HIGH

JOHN AHRENS CORRECTION - NO

24.000 (INCHES) WATER DEPTH AT BOARD

0.030 X100PCT MO LOW FREQ. CUTOFF

0.970 X100PCT MO HIGH FREQ. CUTOFF

1800 (SEC) TIME SERIES LENGTH

10 (STEPS/SEC) UPDATE RATE

256 LINES IN SOURCE SPECTRUM

0.00319 COMPUTED ALPHA

7.489 INCHES MAX. POS. BOARD STROKE 16.64

-8.228 INCHES MAX. NEG. BOARD STROKE 0.4444

0.3544 (HZ) LOW FREQ. CUTOFF

1.0096 (HZ) HIGH FREQ. CUTOFF

1989 = RAND. NO. GEN. SEED

= (IN**2/HZ) DES. H2O SMAX

= (HZ) DES. PEAK FREQ.

Figure 6. Design and simulated spectra for first 30 min of 2.25-sec wave period tests

PART IV: TEST PROCEDURES AND TEST RESULTS

Selection of Test Conditions

25. Tests were conducted for water depths at the toe of the revetment of 0.66, 0.76, and 0.86 ft, with offshore water depths of 2.00, 2.10, and 2.20 ft, respectively. Peak wave periods tested included 1.25-, 2.25-, 3.0-, and 3.5-sec waves, and wave heights of the zeroth moment for each period included 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, and 0.66 ft.

26. The length of each test run was 3,500 times the peak period of the test, or until failure occurred, whichever came first. Failure was defined as having the filter layer exposed. If failure was observed, tests with that period were suspended and larger H_{mo} 's were not tested. All tests were conducted with a JONSWAP spectrum (Hasselmann et al. 1973).

Test Procedures

27. Each test was run in cycles of approximately 30 min each. For example, the tests with a 2.25-sec peak wave period were run for 7,875 sec (3,500 times 2.25 sec), or 131.25 min, in four cycles of about 30 min each plus one short cycle to obtain the total time required. Wave data were collected for approximately 500 waves near the beginning and end of each test. A test was terminated if failure occurred.

28. Wave runup was observed for 256 sec near the middle of a test run. The elevation of the maximum runup observed then was measured with reference to a specified datum by use of a point gage.

29. Soundings were taken before and after each test, and the structure was completely rebuilt whenever significant damage was observed. The procedure used for the tests is given below.

- a. Place and survey the filter stone.
- b. Place and survey the armor stone (including the berm, if used).
- c. Generate waves for 3,500 times the design peak period.
 - (1) Collect wave data for 500 waves near the start of the test.

- (2) Measure the runup.
 - (3) Collect wave data for 500 waves near the end of the test. If failure is expected, collect data for 500 waves prior to the expected failure.
- d. Survey the riprap layer and berm.
 - e. Measure the water in the overtopping catch basin.
 - f. Rebuild the structure.

30. If the damage was slight, only the riprap layer and berm were rebuilt, and the procedure for testing the next wave height was begun at step b, above. The structure was always torn down and rebuilt from the plywood board before the next series of tests with a new wave period was conducted.

Test Results

31. Test results are given in Appendix A as Tables A1, A2, A3, A4, and A5. Tables A1 and A2 list data from the tests of the revetment without berm; Tables A3 and A4 list the results from the revetment with berm, and Table A5 lists damage to the structure as determined by the soundings.

32. As discussed in paragraph 27, multiple cycles were required for each test run. Each cycle was labeled consecutively a, b, c, etc., and data were collected during the first and last cycle. For example, tests with a 2.25-sec peak wave period, which required four cycles, had data collected during cycles a and d. The letter following the run number in Tables A1 through A4 refers to the cycle during which the data were collected. The structure was surveyed only after the end of the test run. Therefore the damage information in Table A5 refers only to the run number and does not include the cycles. Because damage to the berm was not considered as damage to the revetment, only damage values for the upper part of the revetment (above the level of the berm) are used in this report and are referred to simply as S_2 .

33. Scale effects in hydraulic model investigations are an important consideration, but one that is difficult to address due to conflicting results from different studies. For the range of tests presented here, Hudson and Davidson (1975) indicate that stability numbers in the model tests will be conservative by about 10 percent compared with prototype results, Burcharth and Frigaard (1988) report that scale effects will be negligible, and

Broderick and Ahrens (1982) show that scale effects in the filter layer may cause the runup values in the model tests to be greater than would be found at prototype scales. Although scale effects are probably present in this data set, it seems reasonable to assume that they are either negligible or conservative.

PART V: DISCUSSION AND ANALYSIS

34. Wave runup and overtopping data were collected from a typical revetment design subjected to spectral wave attack. As a means of reducing the runup and overtopping of the revetment, a berm has been added in front of the revetment. Comparisons of results of the tests with and without the berm will be used to develop design guidance for use by the field to reduce runup and overtopping of rubble revetments. Structural stability and reflection characteristics also are being documented.

Wave Runup

35. Ahrens and McCartney (1975) documented the influence of surf conditions on runup, and an empirical model using the surf parameter to predict maximum runup has been developed by Ahrens and Heimbaugh (1988). The empirical model is given by

$$\frac{R_{\max}}{H_{m0}} = \frac{a \xi}{1.0 + b \xi} \quad (12)$$

where R_{\max} is maximum wave runup and a and b are dimensionless runup coefficients determined from regression analysis. Values of a and b were determined as 1.022 and 0.247, respectively.

36. Analysis of the data collected in this study indicates that two additional terms are needed to account for the influence of a berm. These additional terms account for the height and width of the berm. Through data analysis, it was found that the most effective variables were relative berm width, $W_B/(H_{m0}L_o)^{1/2}$, and relative berm height, h_B/d_s . Multivariable analysis was used to determine the following equation to predict the relative runup, R_{\max}/H_{m0} .

$$\frac{R_{\max}}{H_{m0}} = \exp \left[C_0 + C_1 \left(\frac{H_{m0}}{L_o} \right) + C_2 \left(\frac{W_B}{(H_{m0}L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (13)$$

where C_0 , C_1 , and C_2 are dimensionless regression coefficients given by

$$C_0 = 0.669$$

$$C_1 = -10.4$$

$$C_2 = -0.152$$

37. Equation 13 shows little or no systematic error in predicting R_{max} as shown by error analysis in Figures 7, 8, and 9. Figure 7 gives the ratio of the predicted R_{max} to the observed R_{max} as a function of the relative berm width. Figure 8 has the same ordinate as Figure 7 plotted versus the relative berm height. Figure 9 is an enlargement of the portion of Figure 8 for tests with berms so that the data point symbols can be more readily identified. In Figures 7, 8, and 9, all data points are denoted by an integer based on the relative wave size, $H_{mo}/(D_n)_{50}$. Since deterioration of the berm increases with increasing wave size relative to the stone size, the purpose of using the relative wave size in the figures is to see if berm derioration affects the prediction of R_{max} . Figures 7, 8, and 9 indicate there is little systematic error in predicting R_{max} for tests with a berm.

38. Figure 10 shows relative runup versus wave steepness, H_{mo}/L_o , for tests without a berm. On a planar riprap slope without a berm, wave steepness is the most important variable influencing relative runup. Also shown in Figure 10 is the portion of Equation 13 without the berm effects correction factor, i.e.,

$$\frac{R_{max}}{H_{mo}} = \exp \left[C_0 + C_1 \left(\frac{H_{mo}}{L_o} \right) \right] \quad (14)$$

where C_0 and C_1 are the same as given with Equation 13. For tests without berms, the berm effects term in Equation 13 drops out to leave Equation 14. In Figure 10, it can be seen that the data scatter around Equation 14 appears random, indicating a lack of systemic error associated with wave steepness. Figure 10 also shows the runup equation developed by Ahrens and Heimbaugh (1988) for plane riprap slopes (Equation 12). In Figure 10 it can be seen that Equation 12 overpredicts the relative runup but follows the data trend well. It is believed that this difference is caused by systematic differences in the visual readings of R_{max} between observers.

39. The portion of Equation 13 containing the berm characteristics can be thought of as a runup reduction factor that can be defined by

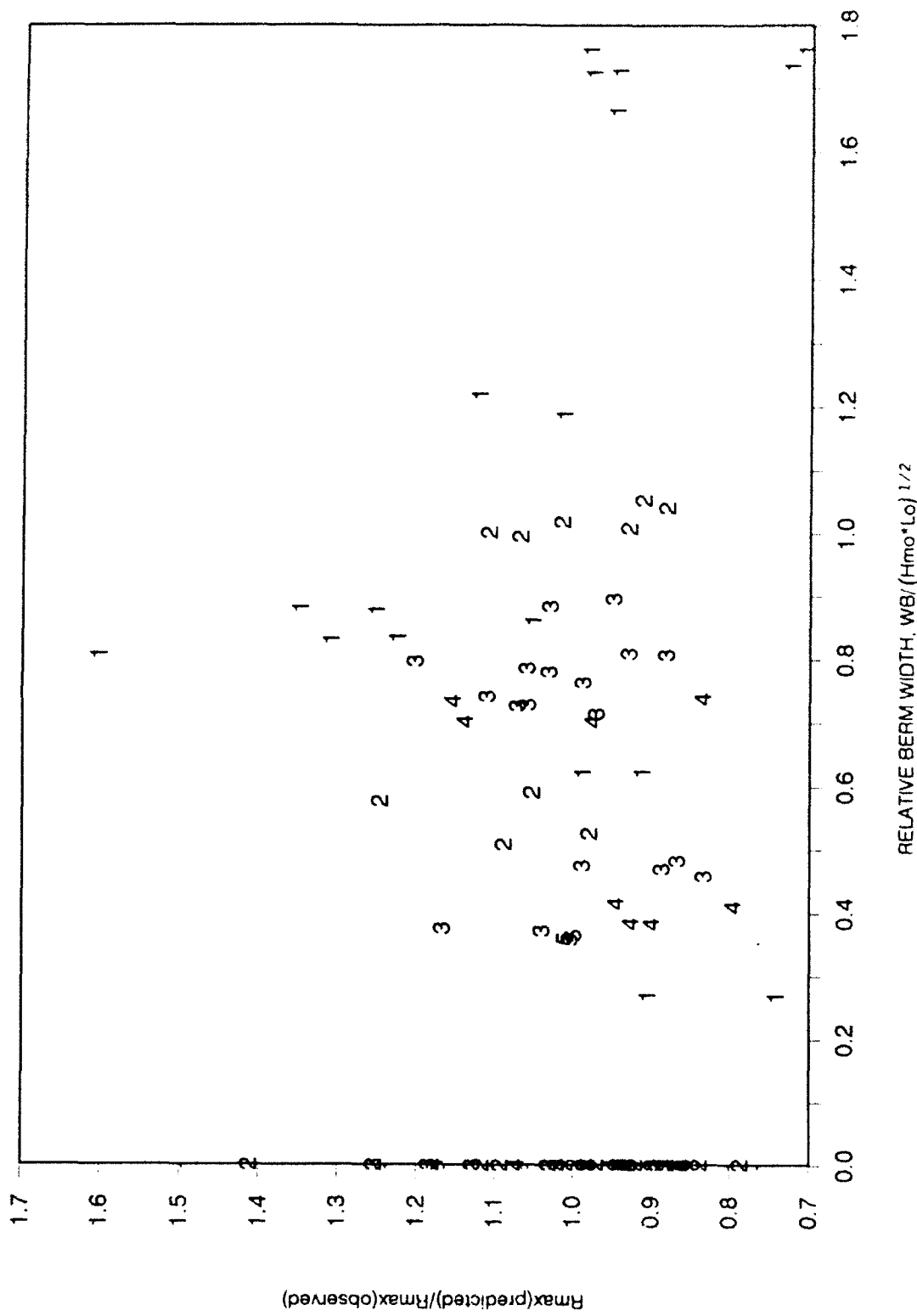


Figure 7. Ratio of predicted to observed runup as a function of relative berm width. Integers denote wave size, $H_{mo}/(D_n)_{50}$

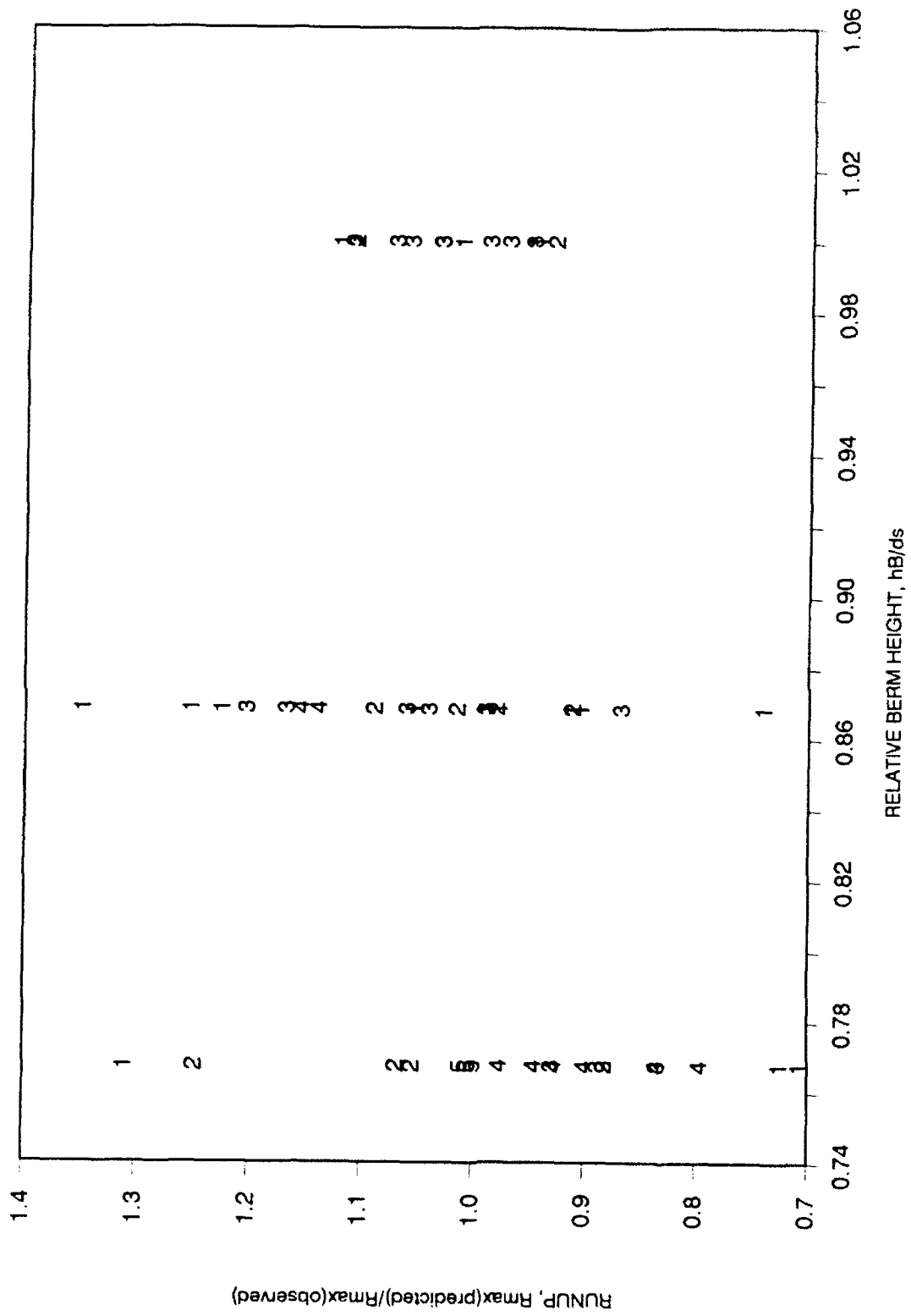


Figure 9. Section taken from Figure 8 enlarged to show detail

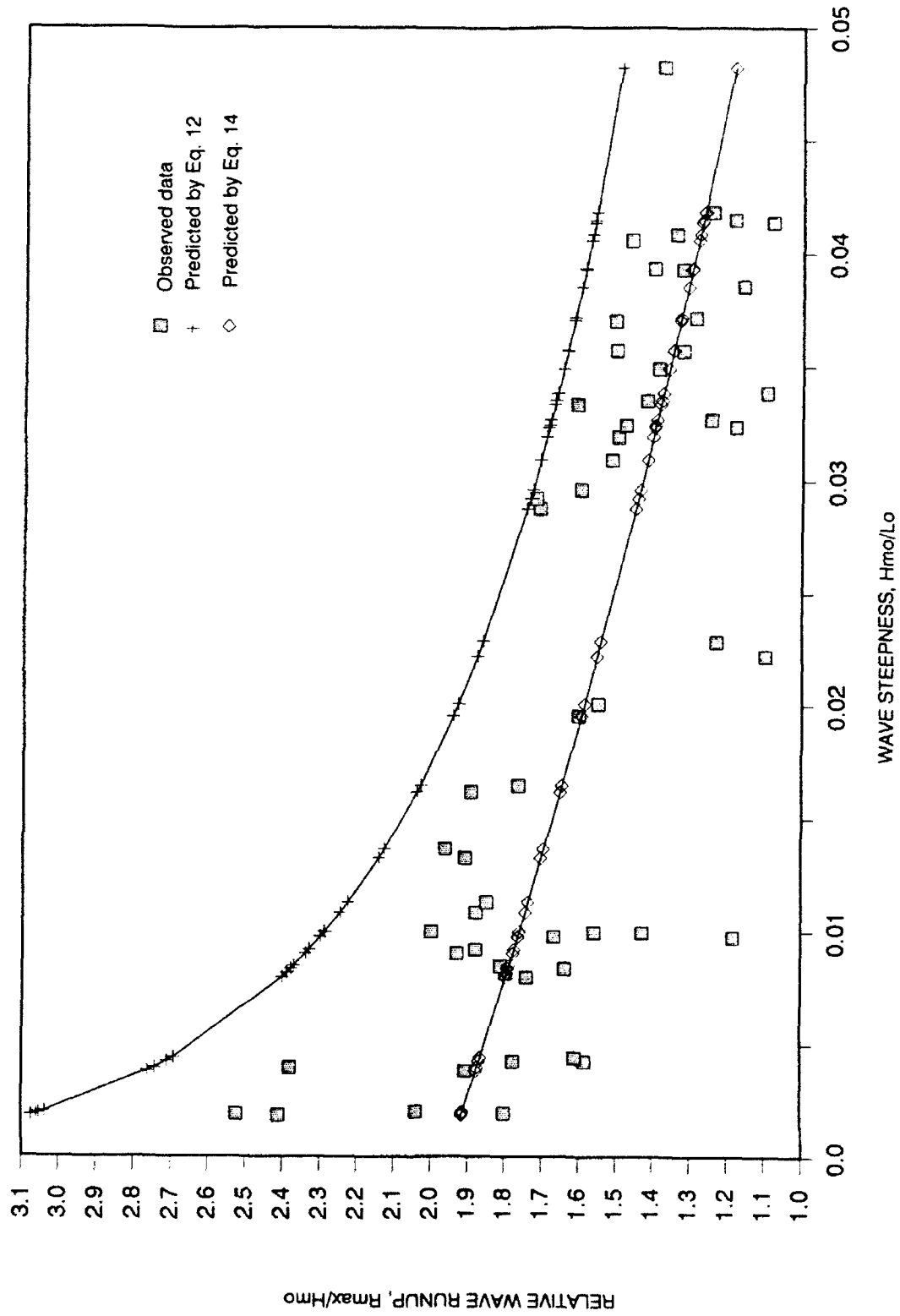


Figure 10. Observed and predicted wave runup as a function of deepwater wave steepness

$$r = \exp \left[C_2 \left(\frac{W_B}{(H_{mo} L_o)^{1/2}} * \frac{h_b}{d_s} \right) \right] \quad (15)$$

Figure 11 shows lines of constant r as a function of the relative berm width and relative berm height over the range of data collected in this study based on the value of $C_2 = -0.152$. Figure 11 helps to visualize the joint influence of berm width and berm height in reducing wave runup and also demonstrates that Equation 15 has a logical functional form.

40. To further generalize the findings from this study, Equations 12 and 13 were combined in the following manner

$$\frac{R_{max}}{H_{mo}} = \frac{r\xi}{1 + b\xi} \quad (16)$$

The "a" runup coefficient was dropped from Equation 12 since it is very close to 1.0 and replaced with r , which has a limiting value of 1.0 for plane slope revetments. Figure 12 is a scatter plot of R_{max} predicted using Equation 16 versus observed R_{max} . It is clear from Figure 12 that Equation 16 follows the trend of the data well but provides conservative estimates of R_{max} . As noted in paragraph 38, systemic differences between runup observations in this study and those in Ahrens and Heimbaugh (1988) may account for the differences in observed and predicted runup in Figure 12.

Damage Level

41. In addition to reducing wave runup and overtopping, the rubble berm also reduced damage levels on the revetment slope above the berm. Figures 13a through 13d show the progressive deterioration of the berm with increasing wave heights. The protection furnished to the revetment is obvious, as seen when these figures are compared with Figures 14a through 14d. Figures 14a through 14d show the progressive deterioration of a revetment without a berm after being subjected to the same wave conditions used in Figures 13a through 13d.

42. Quantification of the improvement can be presented in a manner similar to the method used for wave runup in Figure 11, i.e., by using a reduction factor. Damage to the structure above the berm can be quantified

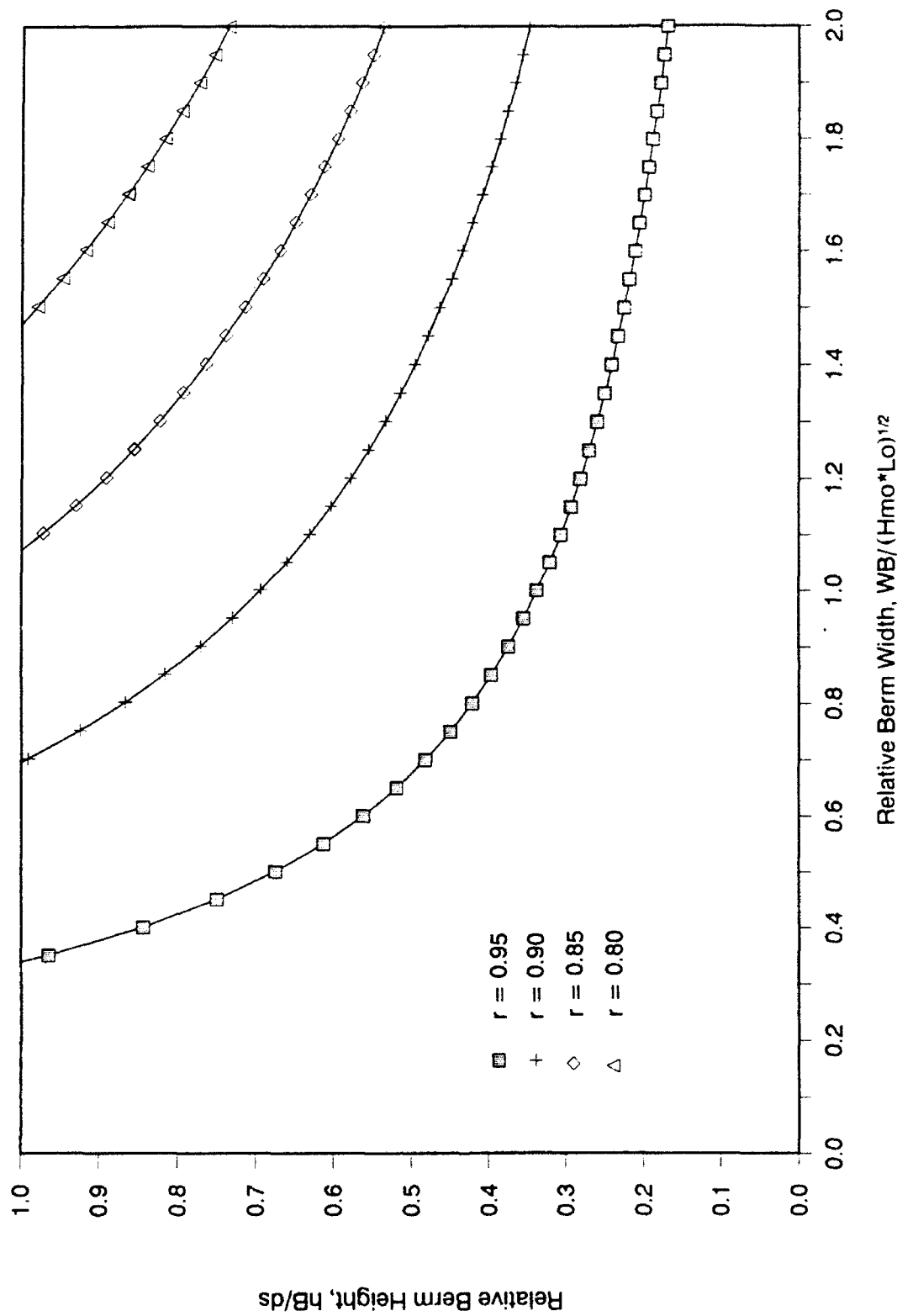


Figure 11. Runup reduction factor, r , as a function of relative berm height and width, using $C_2 = -0.152$ in Equation 15

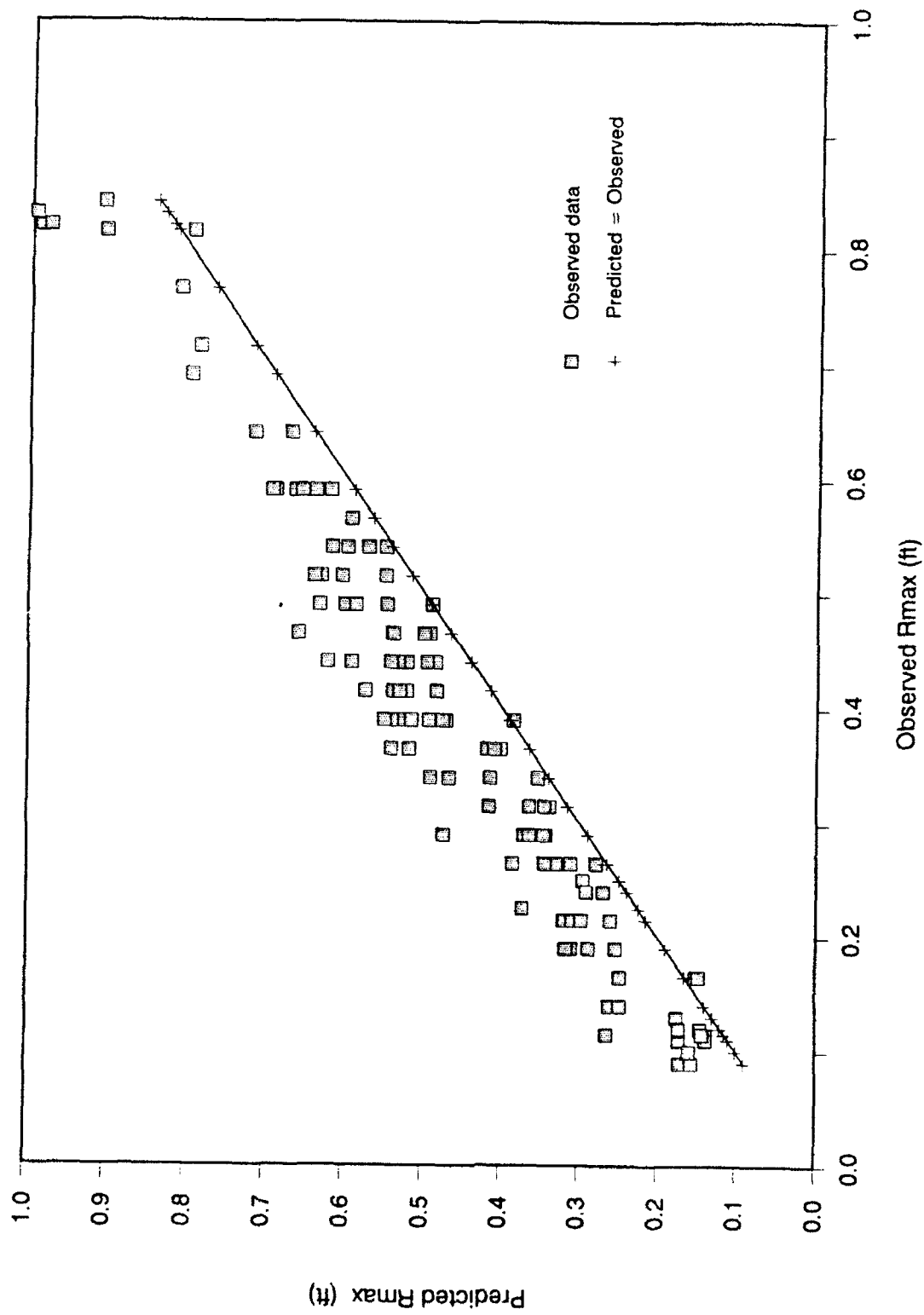
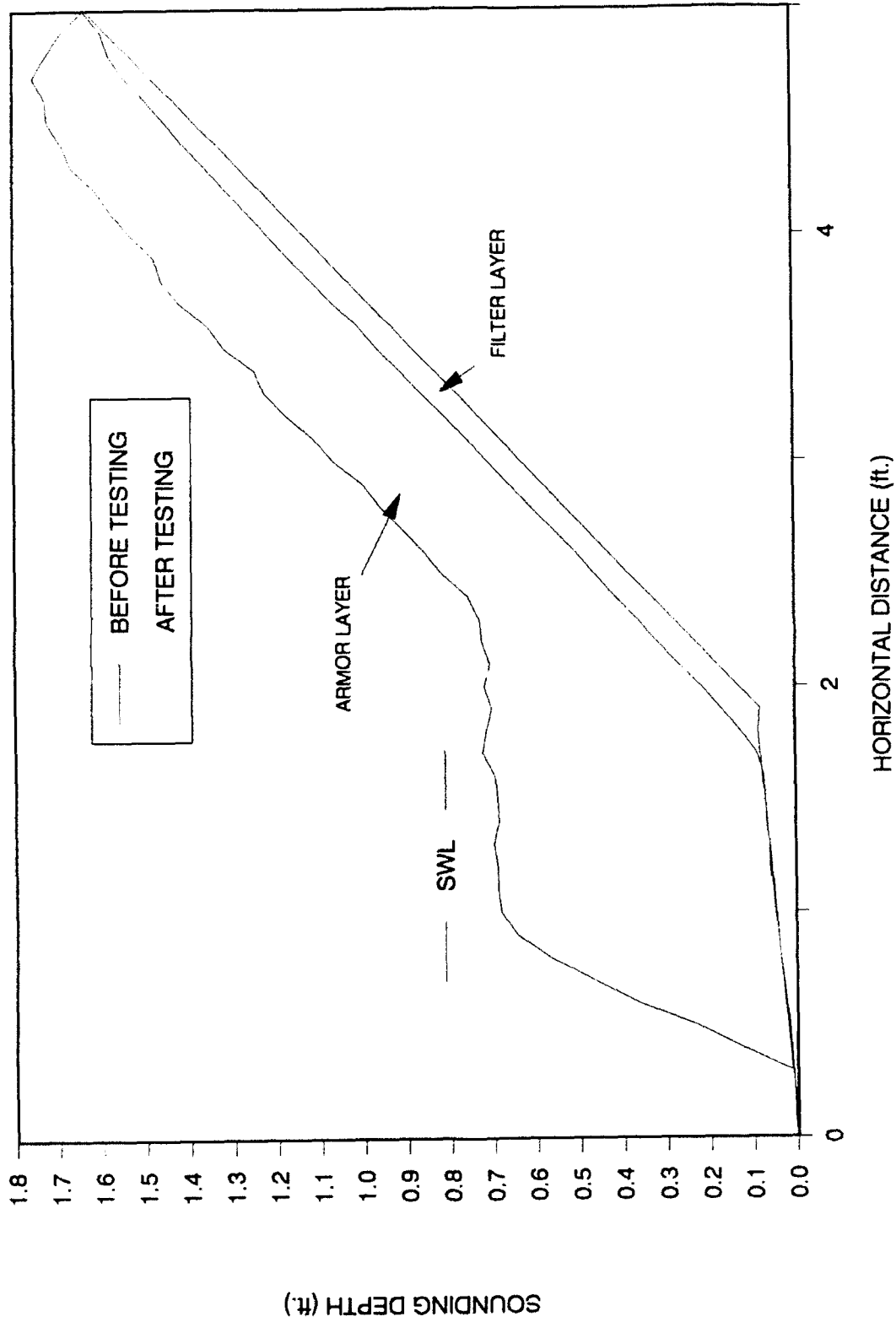
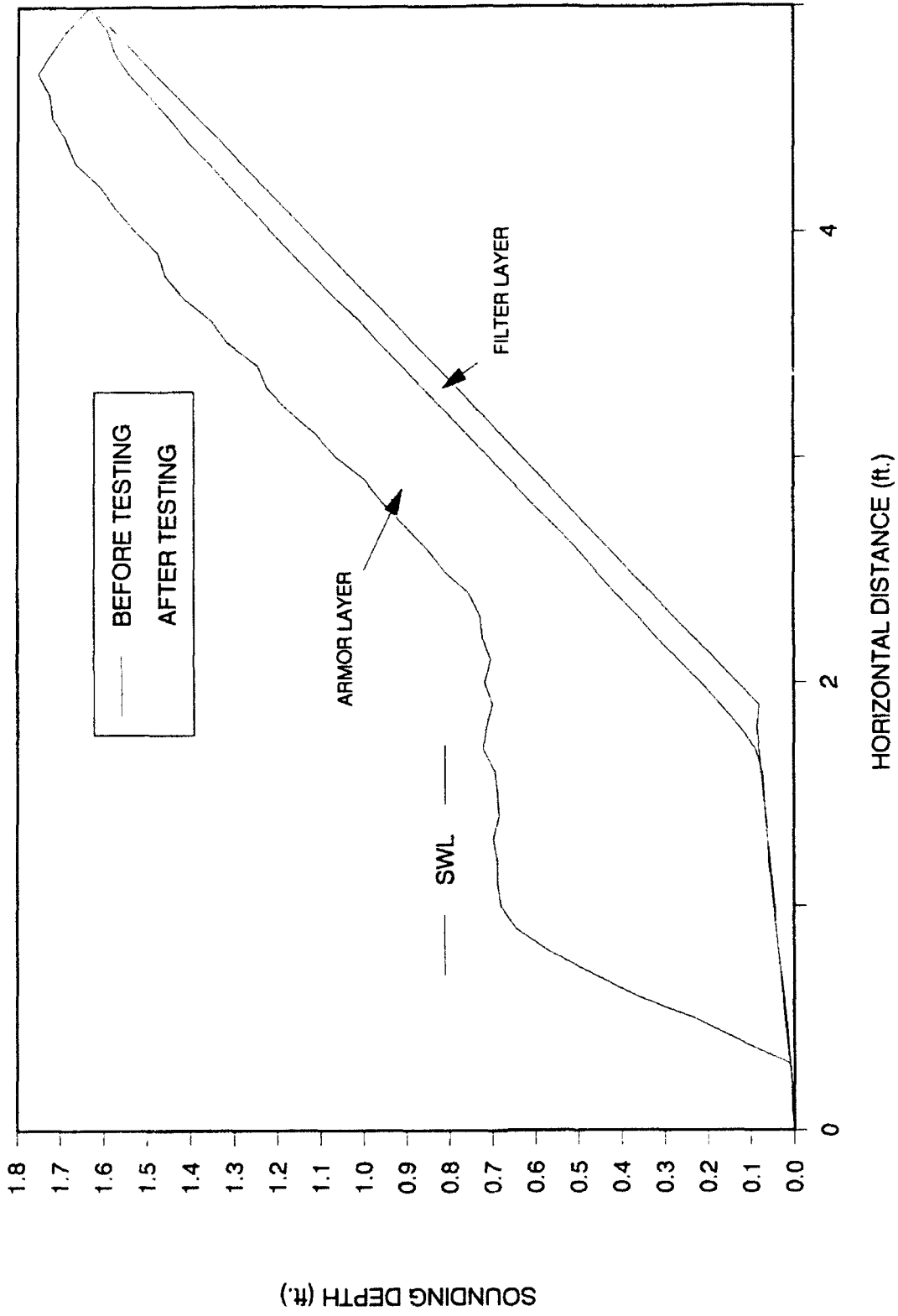


Figure 12. Maximum runoff predicted by Equation 16 versus observed maximum runoff



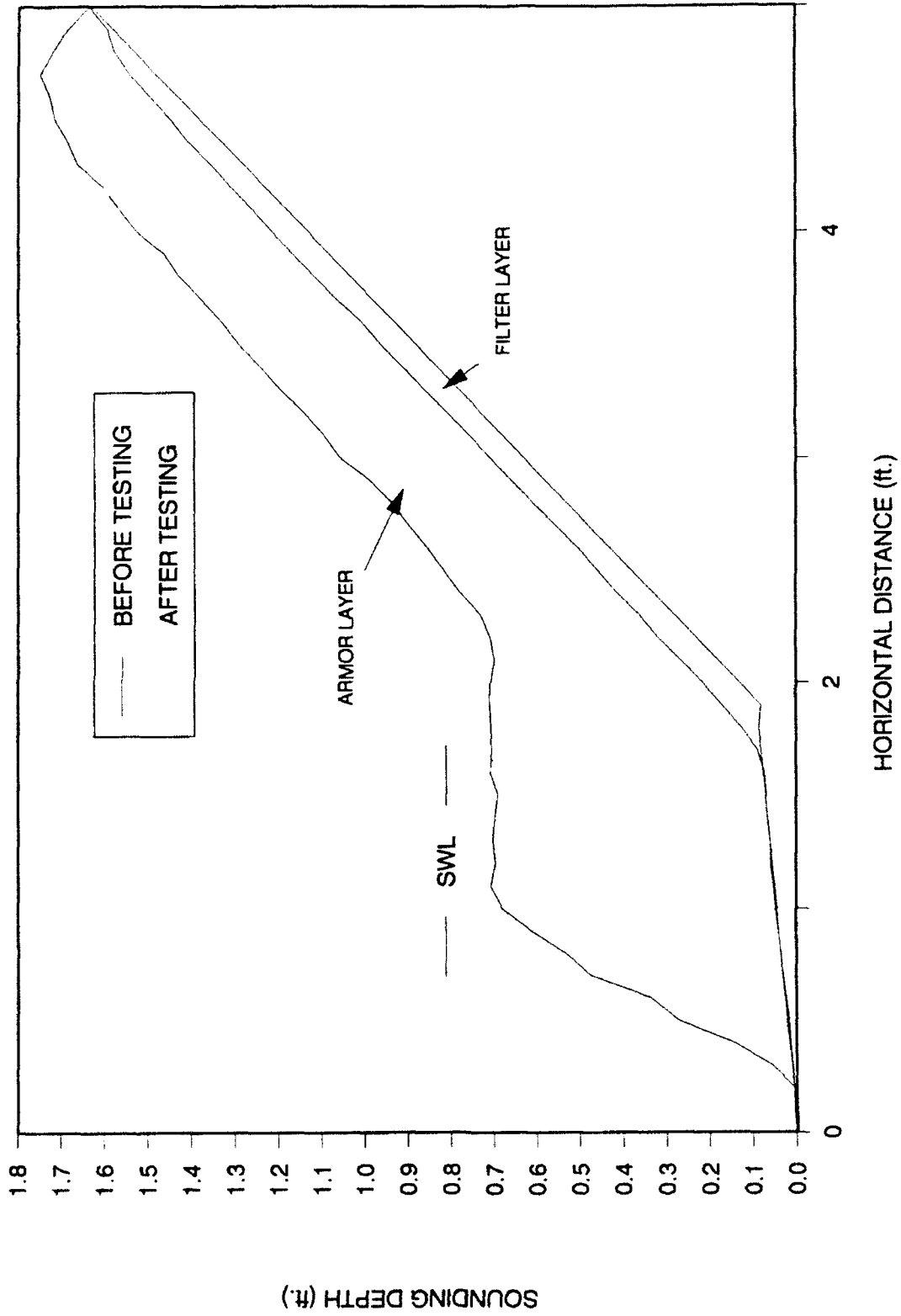
a. $T_p = 2.25\text{-sec}$, $H_{mo} = 0.10\text{-ft waves}$

Figure 13. Bermed revetment damage profile after testing
(Sheet 1 of 4)



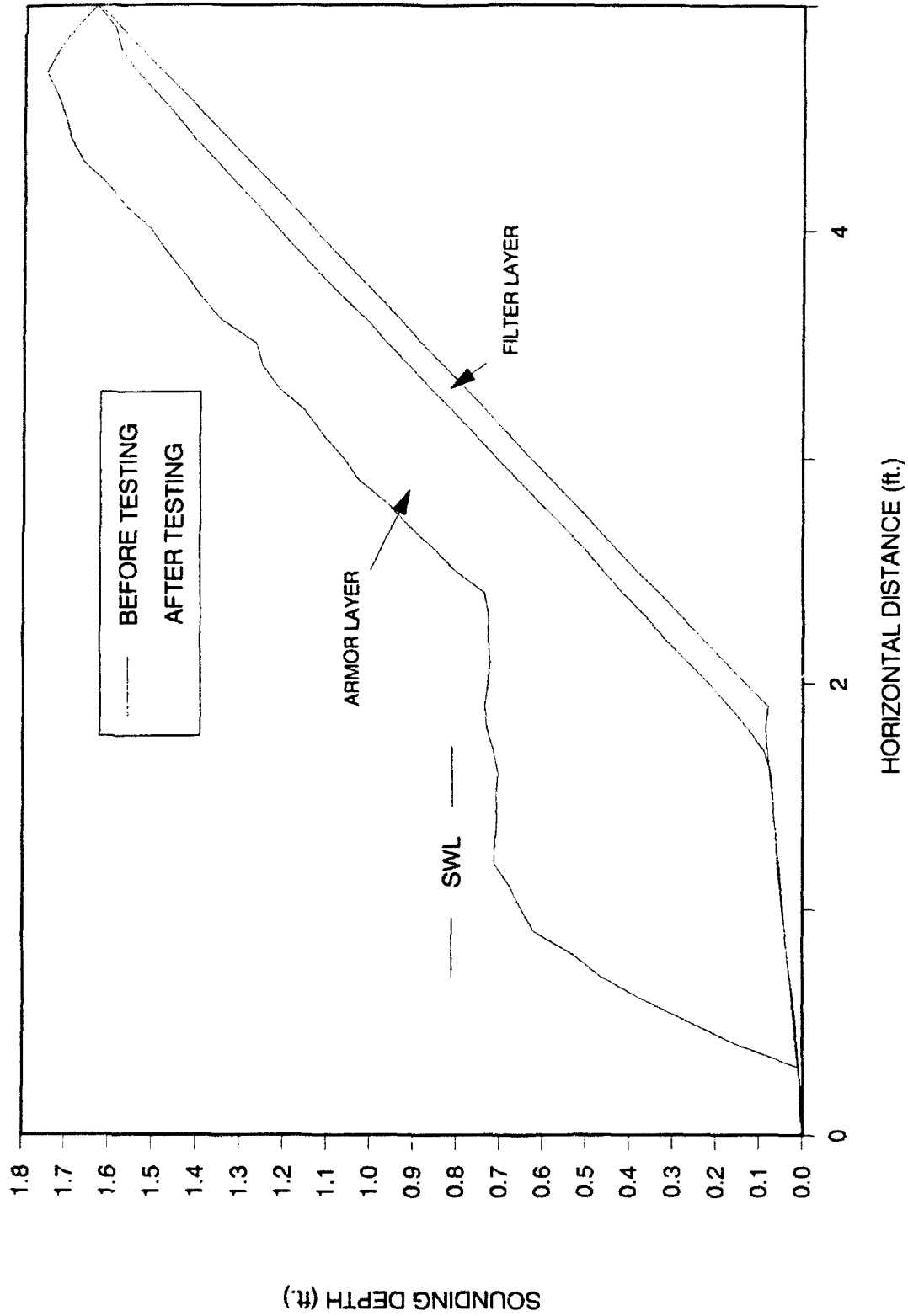
b. $T_p = 2.25$ -sec, $H_{mo} = 0.30$ -ft waves

Figure 13. (Sheet 2 of 4)

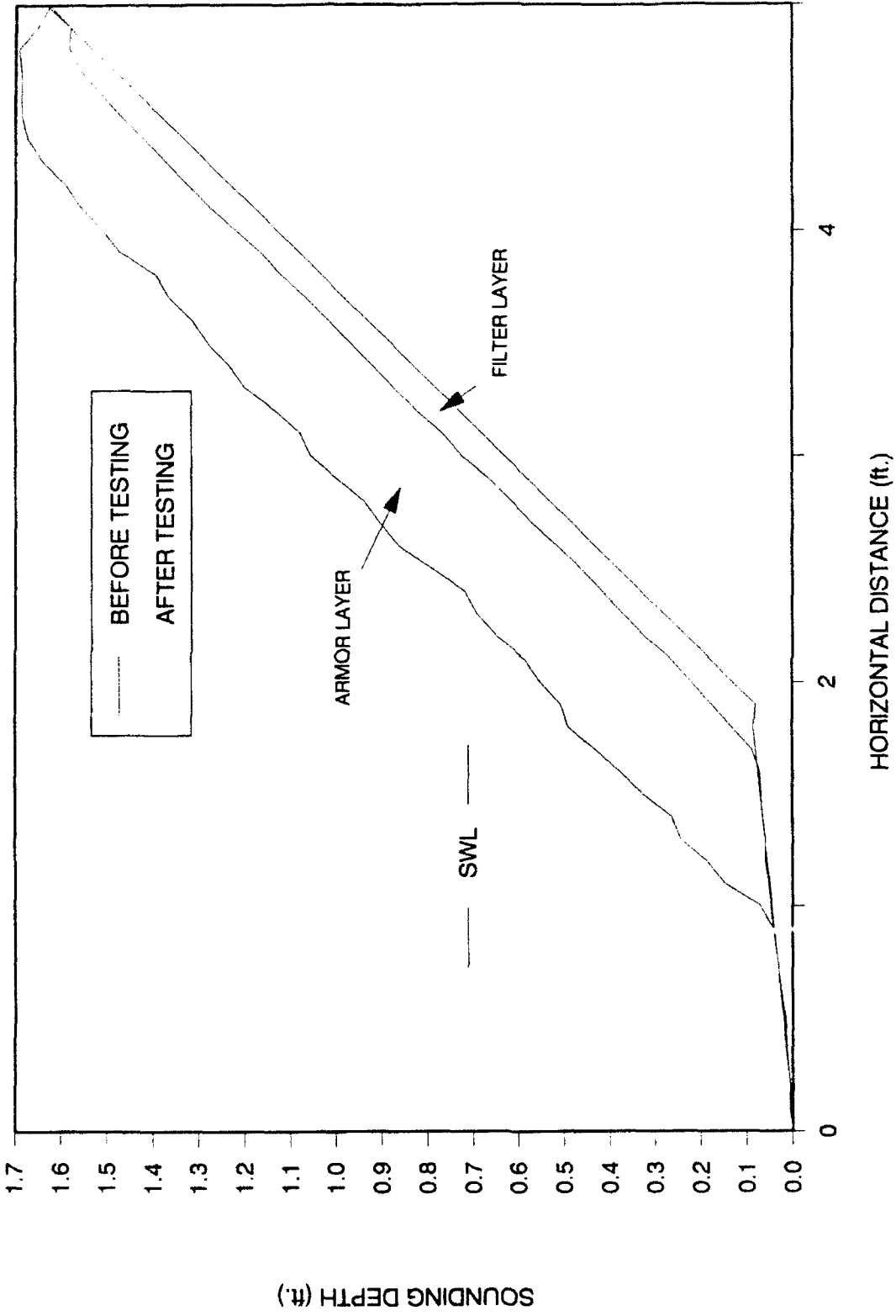


c. $T_p = 2.25$ -sec, $H_{mo} = 0.50$ -ft waves

Figure 13. (Sheet 3 of 4)



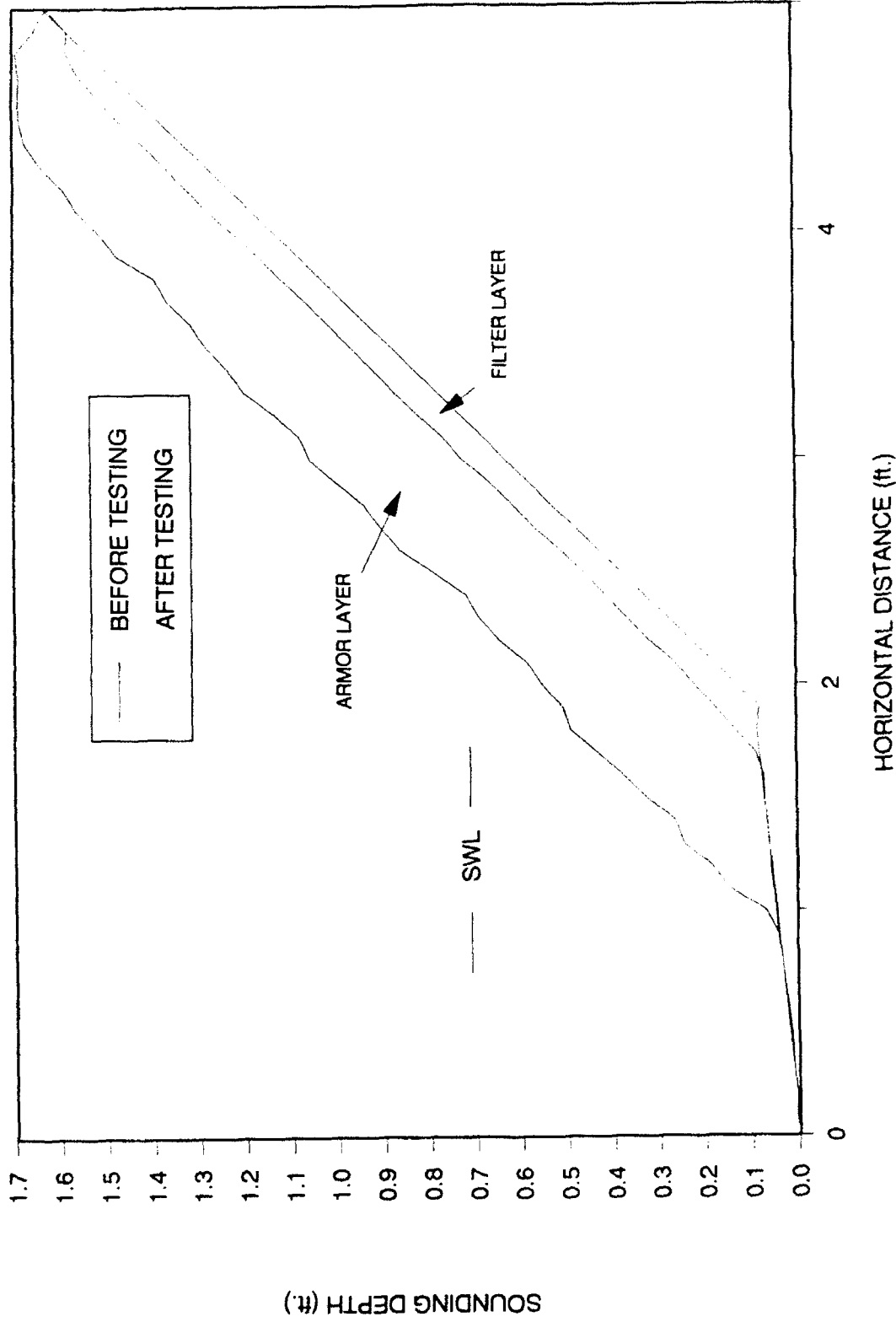
d. $T_p = 2.25$ -sec, $H_{mo} = 0.66$ -ft waves
Figure 13. (Sheet 4 of 4)



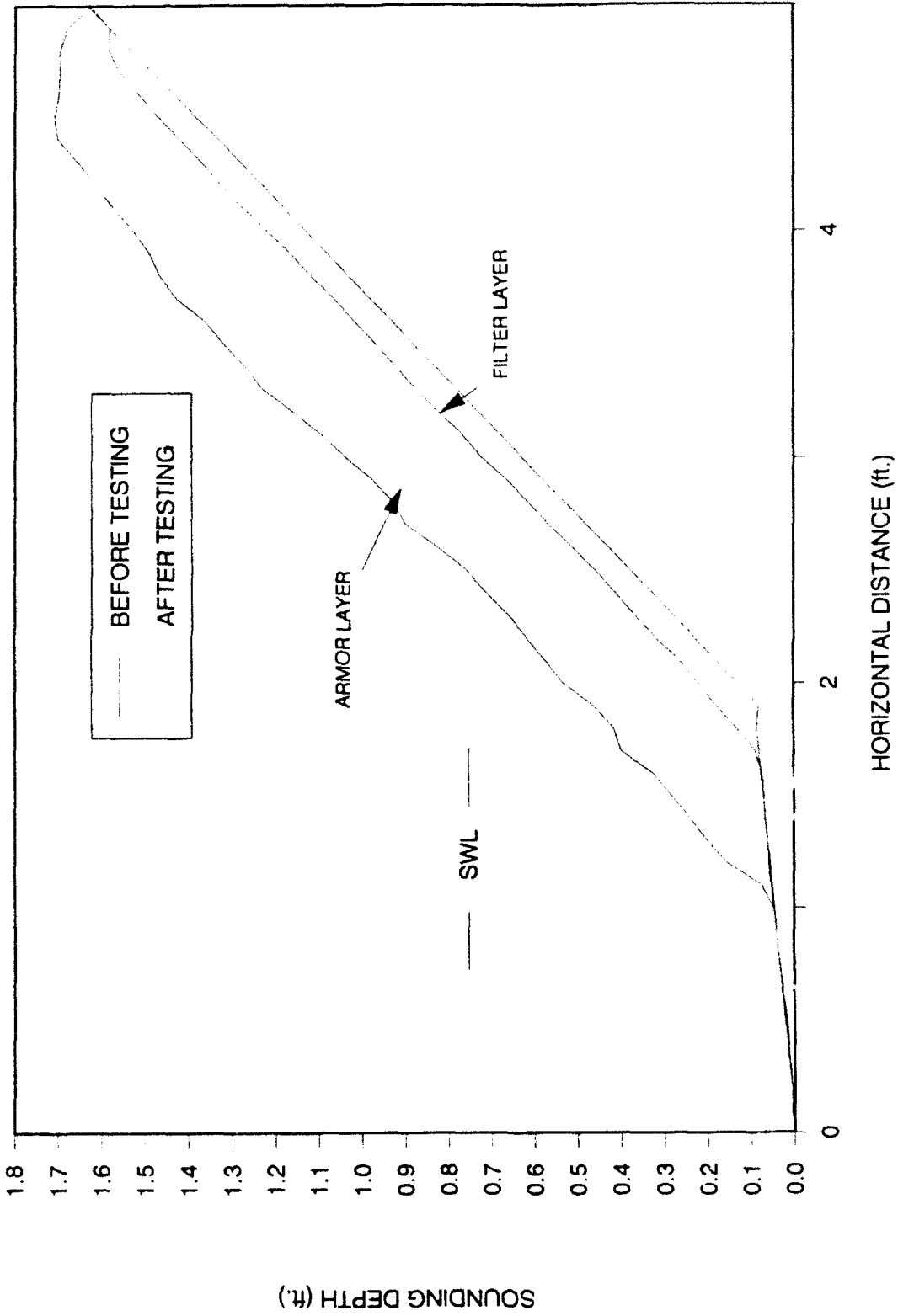
a. $T_p = 2.25$ -sec, $H_{mo} = 0.10$ -ft waves

Figure 14. Revetment damage profile after testing

(Sheet 1 of 4)

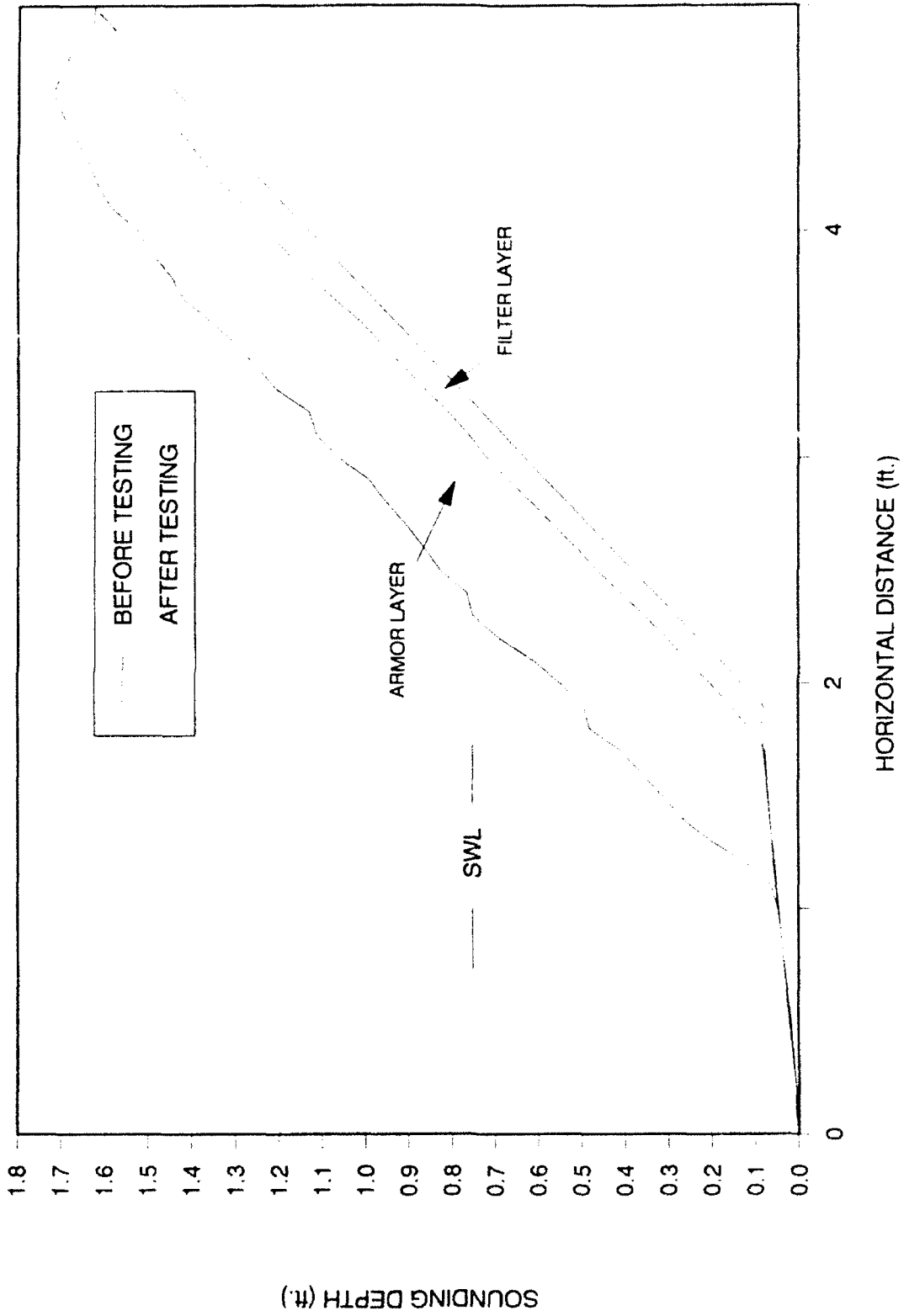


b. $T_p = 2.25$ -sec, $H_{m0} = 0.20$ -ft waves
Figure 14. (Sheet 2 of 4)



c. $T_p = 2.25$ -sec, $H_{mo} = 0.30$ -ft waves

Figure 14. (Sheet 3 of 4)



d. $T_p = 2.25$ -sec, $H_{mo} = 0.40$ -ft waves

Figure 14. (Sheet 4 of 4)

either by defining the S_2 damage for the region above the berm, or by the depth of erosion into the armor layer, e_{max} . The following equations were developed using multivariable analysis to predict damage levels.

$$S_2 = 1.0 (N_s)^{C_3} \exp \left[C_4 \left(\frac{W_B}{(H_{mo} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (17)$$

$$\frac{e_{max}}{t_a} = C_5 (N_s)^{C_6} \exp \left[C_7 \left(\frac{W_B}{(H_{mo} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (18)$$

where N_s is the stability number, defined below, t_a is the armor layer thickness, and C_3 through C_7 are dimensionless regression coefficients given by

$$C_3 = 2.96$$

$$C_4 = -3.56$$

$$C_5 = 0.104$$

$$C_6 = 2.08$$

$$C_7 = -2.73$$

The stability number is defined as

$$N_s = \frac{W_r^{1/3} H_{mo}}{W_{50}^{1/3} (S_r - 1)} \quad (19)$$

43. Equations 17 and 18 were developed to show how the reduction factor concept introduced for runup can also be applied to damage levels and are not necessarily recommended for prediction purposes since data scatter is very high in the damage variables. However, all terms in the equations are highly significant and the equations seem to reflect the trends in the data.

44. Damage can be defined as follows:

$$r_s = \exp \left[C_4 \left(\frac{W_B}{(H_{mo} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (20)$$

$$r_e = \exp \left[C_7 \left(\frac{W_B}{(H_{mo} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (21)$$

where r_s and r_e are the reduction factors for S_2 damage and e_{\max} damage, respectively. Figures 15 and 16 show curves of constant reduction as functions of relative berm width and relative berm height based on Equations 20 and 21. These figures help visualize the influence of a berm in reducing damage to a revetment.

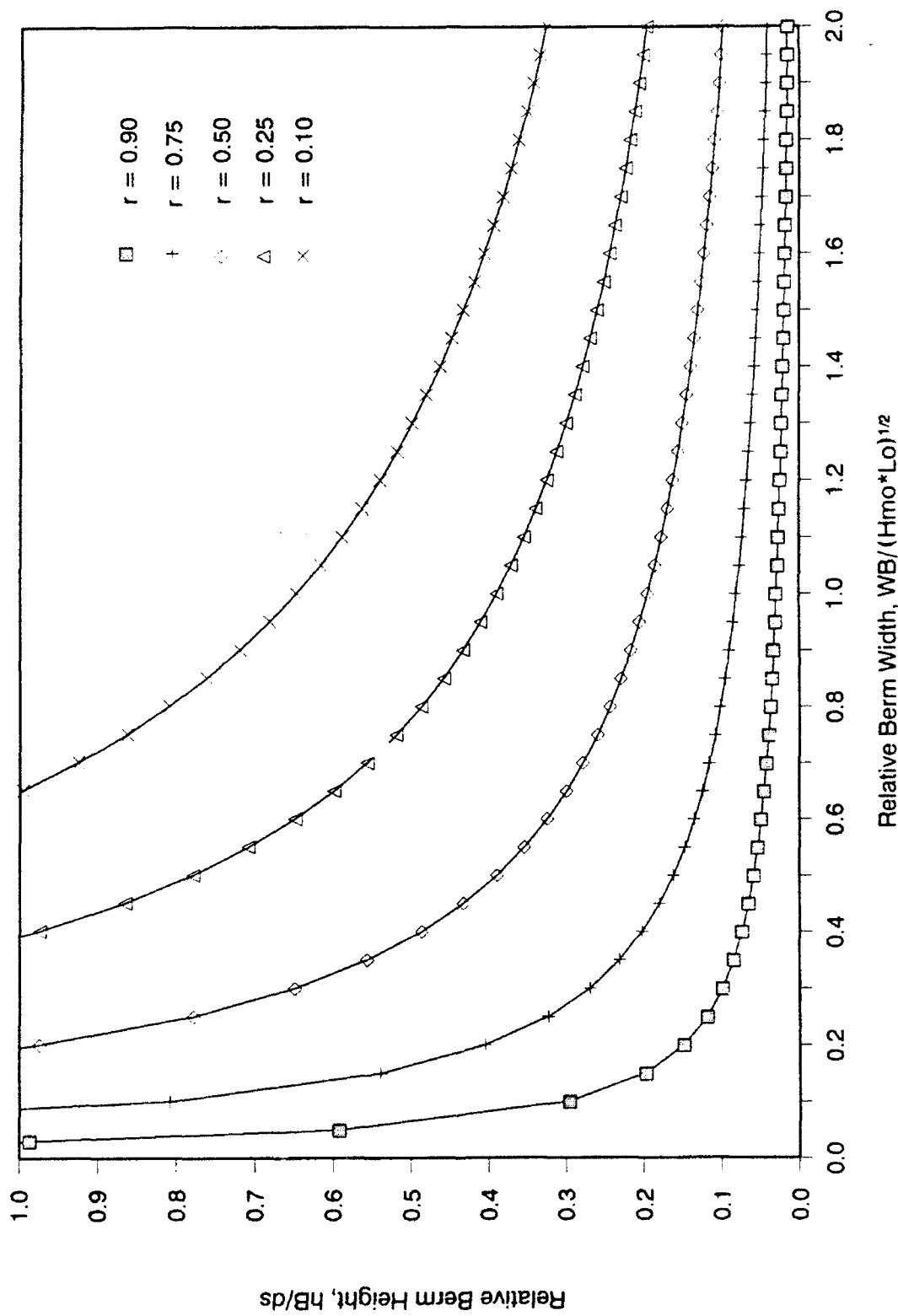


Figure 15. S_2 damage reduction factor, r_s , as a function of berm height and width

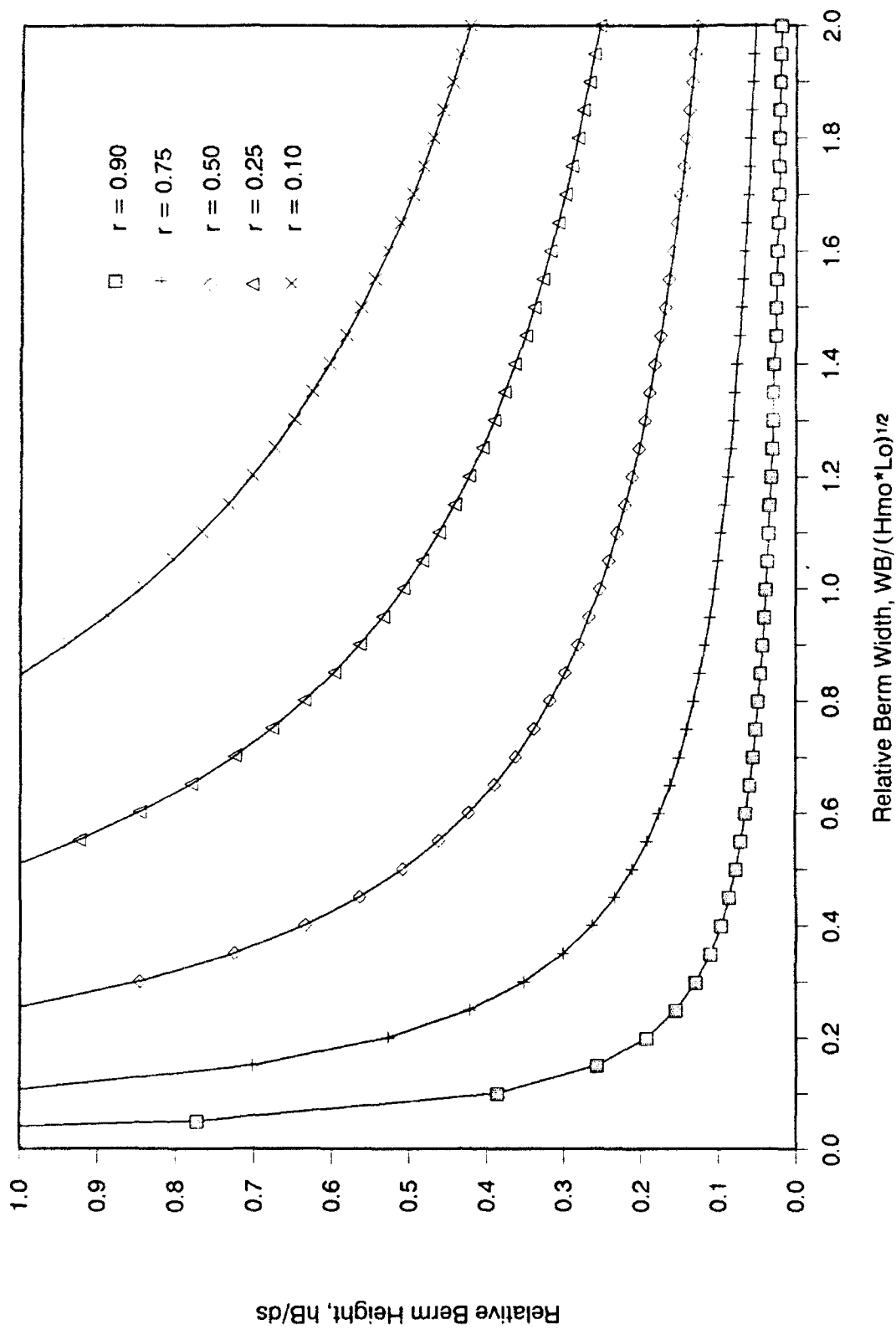


Figure 16. Erosion reduction factor, r_e , as a function of berm height and width

PART VI: CONCLUSIONS AND RECOMMENDATIONS

45. This study developed an equation (Equation 16) to predict the upper limit of irregular wave runup on planar riprap revetments or on riprap revetments fronted by a rubble berm. The equation considers both the height and width of the berm and provides a way to estimate the effectiveness of a berm in reducing wave runup. Although the berm was only tested with a 1:2 slope, the reduction factor is believed to be applicable to other slopes when used in Equation 16. Since Equation 16 can be used to calculate the runup on both bermed and plane riprap revetments, it is superior to the method proposed in Repair, Evaluation, Maintenance, and Rehabilitation Research (REMR) Program Technical Note CO-RR-1.3, Supplement 3, which provided only a reduction factor for runup due to the influence of a berm. In addition, Equation 16 is based on a larger data set and subsequent analysis beyond that given in REMR Technical Note CO-RR-1.3. An updated version of REMR Technical Note CO-RR-1.3 will be available in Supplement 6 to reflect these changes.

46. A rubble berm not only reduces wave runup but also increases the stability of the revetment. The berm's influence on stability is considerably greater, as a percent, than the reduction in runup; i.e. a modest reduction in runup corresponds to a substantial improvement in stability. Typical reductions in runup due to a berm observed during this study were in the range of 5 to 15 percent. It is also believed that a modest reduction in runup will translate into a large reduction in overtopping rates. These intuitive concepts can be supported by making a few logical assumptions and calculating the consequences.

47. The reduction in overtopping can be estimated by using the method shown in the SPM and discussed further by Weggel (1976). Assume that $R_{max} = 1.15 * F$; i.e. the potential maximum runup is 15 percent greater than the freeboard of a plane slope riprap revetment. To reduce the overtopping rate, a berm is added to the revetment that reduces the maximum runup 10 percent or $R_{max} = (1.15 * 0.90) * F = 1.035 * F$, where F is the structure freeboard. This rather modest reduction in runup causes a reduction in the overtopping volume by a factor of about 8.8 if a value of Weggel's overtopping parameter $\alpha = 0.07$ is used (see Example 1, Appendix B). These reductions are in the volume of water per unit length of structure for the maximum potential runup. The average overtopping rates could be expected to be reduced more than the

maximum rates since the berm would allow fewer waves to overtop. Values of alpha selected are reasonable for a riprap revetment based on estimating overtopping rates using the potential runup approach given by Weggel and the SPM.

48. Reductions in damage for modest reductions in runup are equally impressive as the reductions in overtopping rates. Compare the reduction factors for runup and S_2 damage given by Equations 15 and 19 for a berm producing a 10-percent reduction in runup. The S_2 damage reduction factor corresponding to $r = 0.90$ is $r_2 = 0.085$ (see Example 2, Appendix B). This comparison indicates that a 10-percent reduction in runup will reduce S_2 damage by a factor of almost 12.

49. Although comparable reductions in runup and overtopping may be obtained with a smaller volume by increasing the crest height of the revetment rather than adding a berm, the use of a berm should prove of value in locations where an increased crest height is not possible or undesirable. The advantages of increased protection provided by the berm should also be considered.

50. Maximum runup elevations from this study are based on visual observations. These observations appear to be consistently lower than similar observations made during other studies (Ahrens and Heimbaugh 1988). For this reason, data analysis was biased towards a conservative interpretation of the findings from this study. Because of the difficulty in achieving consistent results among different observers of maximum runup elevations, it is recommended that an electronic runup gage be developed. A runup gage would not only give consistent results from study to study, but could also provide more information about irregular wave runup elevations on rough and porous slopes. With a gage, it is anticipated that statistically stabler runup parameters could be computed that would yield better insight into the ability of a berm to improve the performance of a rubble structure. Using a maximum value contributed to the considerable data scatter in this study and the difficulty in interpreting results.

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APPENDIX A: DATA TABLES

Table A1

Wave Height and Period Data for Revetment Without Berm

RUN #	DESIGN CONDITIONS										ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2	
	REVESTMENT TOE DEPTH	PERIOD	PEAK	INCIDENT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT	HT
Ds	TP(des)	TP(sec)	Hmo(ft)	Hmo(des)	TP(1)	TP(2)	Hmo(1)	Hmo(2)	Hmo(1)	Hmo(2)	TP(1)	TP(2)	Hmo(1)	Hmo(2)	TP(1)	TP(2)	Hmo(1)	Hmo(2)	TP(1)	TP(2)	Hs(1)	Hs(2)
1a	0.66	1.25	1.258	0.10	1.258	1.226	0.084	0.078	1.199	1.246	1.199	1.246	0.089	0.087	1.199	1.246	0.089	0.087	1.199	1.246	0.089	0.087
1c	0.66	1.25	1.247	0.10	1.247	1.247	0.085	0.079	1.197	1.250	1.197	1.250	0.087	0.088	1.197	1.250	0.087	0.088	1.197	1.250	0.087	0.088
2a	0.66	1.25	1.258	0.20	1.258	1.226	0.170	0.158	1.202	1.256	1.202	1.256	0.180	0.175	1.202	1.256	0.180	0.175	1.202	1.256	0.180	0.175
2c	0.66	1.25	1.247	0.20	1.247	1.247	0.172	0.158	1.200	1.264	1.200	1.264	0.179	0.178	1.200	1.264	0.179	0.178	1.200	1.264	0.179	0.178
3a	0.66	1.25	1.258	0.30	1.258	1.234	0.262	0.244	1.207	1.272	1.207	1.272	0.284	0.275	1.207	1.272	0.284	0.275	1.207	1.272	0.284	0.275
3c	0.66	1.25	1.247	0.30	1.247	1.231	0.260	0.230	1.200	1.279	1.200	1.279	0.271	0.267	1.200	1.279	0.271	0.267	1.200	1.279	0.271	0.267
4a	0.66	1.25	1.258	0.40	1.258	1.369	0.336	0.294	1.206	1.286	1.206	1.286	0.353	0.335	1.206	1.286	0.353	0.335	1.206	1.286	0.353	0.335
4c	0.66	1.25	1.247	0.40	1.247	1.389	0.339	0.289	1.205	1.289	1.205	1.289	0.356	0.332	1.205	1.289	0.356	0.332	1.205	1.289	0.356	0.332
5a	0.66	1.25	1.258	0.50	1.258	1.369	0.413	0.335	1.214	1.302	1.214	1.302	0.432	0.375	1.214	1.302	0.432	0.375	1.214	1.302	0.432	0.375
5c	0.66	1.25	1.247	0.50	1.247	1.413	0.414	0.336	1.209	1.304	1.209	1.304	0.423	0.381	1.209	1.304	0.423	0.381	1.209	1.304	0.423	0.381
6a	0.66	1.25	1.267	0.60	1.267	1.369	0.460	0.346	1.218	1.315	1.218	1.315	0.467	0.378	1.218	1.315	0.467	0.378	1.218	1.315	0.467	0.378
6c	0.66	1.25	1.247	0.60	1.247	1.402	0.462	0.340	1.217	1.318	1.217	1.318	0.463	0.382	1.217	1.318	0.463	0.382	1.217	1.318	0.463	0.382
7a	0.66	1.25	1.267	0.66	1.267	1.382	0.513	0.388	1.228	1.323	1.228	1.323	0.519	0.418	1.228	1.323	0.519	0.418	1.228	1.323	0.519	0.418
7c	0.66	1.25	1.247	0.66	1.247	1.406	0.519	0.379	1.224	1.319	1.224	1.319	0.514	0.414	1.224	1.319	0.514	0.414	1.224	1.319	0.514	0.414
8a	0.66	2.25	2.338	0.10	2.338	2.338	0.101	0.120	1.917	1.933	1.917	1.933	0.099	0.132	1.917	1.933	0.099	0.132	1.917	1.933	0.099	0.132
8e	0.66	2.25	2.222	0.10	2.222	2.353	0.100	0.121	1.913	1.933	1.913	1.933	0.099	0.132	1.913	1.933	0.099	0.132	1.913	1.933	0.099	0.132
9a	0.66	2.25	2.338	0.20	2.338	2.338	0.203	0.232	1.900	1.808	1.900	1.808	0.201	0.263	1.900	1.808	0.201	0.263	1.900	1.808	0.201	0.263
9e	0.66	2.25	2.222	0.20	2.222	2.222	0.203	0.234	1.895	1.820	1.895	1.820	0.203	0.264	1.895	1.820	0.203	0.264	1.895	1.820	0.203	0.264
10a	0.66	2.25	2.338	0.30	2.338	2.338	0.302	0.319	1.881	1.737	1.881	1.737	0.300	0.378	1.881	1.737	0.300	0.378	1.881	1.737	0.300	0.378
10e	0.66	2.25	2.222	0.30	2.222	2.500	0.298	0.320	1.877	1.772	1.877	1.772	0.299	0.376	1.877	1.772	0.299	0.376	1.877	1.772	0.299	0.376
11a	0.66	2.25	2.137	0.40	2.137	2.338	0.397	0.375	1.855	1.685	1.855	1.685	0.395	0.460	1.855	1.685	0.395	0.460	1.855	1.685	0.395	0.460
11e	0.66	2.25	2.222	0.40	2.222	2.363	0.400	0.390	1.855	1.705	1.855	1.705	0.403	0.465	1.855	1.705	0.403	0.465	1.855	1.705	0.403	0.465
12a	0.66	2.25	2.154	0.50	2.154	2.419	0.495	0.423	1.828	1.673	1.828	1.673	0.496	0.513	1.828	1.673	0.496	0.513	1.828	1.673	0.496	0.513
12c	0.66	2.25	2.205	0.50	2.205	2.435	0.495	0.428	1.839	1.694	1.839	1.694	0.487	0.510	1.839	1.694	0.487	0.510	1.839	1.694	0.487	0.510
13a	0.66	3.50	3.638	0.10	3.638	3.638	0.099	0.133	2.875	2.495	2.875	2.495	0.095	0.192	2.875	2.495	0.095	0.192	2.875	2.495	0.095	0.192
13a	0.66	3.50	3.608	0.20	3.608	3.608	0.204	0.252	2.756	2.054	2.756	2.054	0.203	0.368	2.756	2.054	0.203	0.368	2.756	2.054	0.203	0.368
14a	0.66	3.50	3.564	0.20	3.564	3.638	0.206	0.252	2.781	2.064	2.781	2.064	0.205	0.360	2.781	2.064	0.205	0.360	2.781	2.064	0.205	0.360
14g	0.66	3.50	3.550	0.30	3.550	3.608	0.303	0.338	2.621	1.885	2.621	1.885	0.308	0.493	2.621	1.885	0.308	0.493	2.621	1.885	0.308	0.493
15a	0.66	3.50	3.564	0.30	3.564	3.638	0.305	0.339	2.621	1.905	2.621	1.905	0.306	0.483	2.621	1.905	0.306	0.483	2.621	1.905	0.306	0.483
15g	0.66	3.50	3.521	0.40	3.521	3.608	0.408	0.399	2.437	1.841	2.437	1.841	0.422	0.571	2.437	1.841	0.422	0.571	2.437	1.841	0.422	0.571
16a	0.66	3.50	3.493	0.40	3.493	3.623	0.413	0.405	2.500	1.841	2.500	1.841	0.424	0.562	2.500	1.841	0.424	0.562	2.500	1.841	0.424	0.562
16d	0.66	0.76	1.258	0.10	1.258	1.234	0.086	0.076	1.200	1.237	1.200	1.237	0.091	0.086	1.200	1.237	0.091	0.086	1.200	1.237	0.091	0.086
17a	0.76	1.25	1.247	0.10	1.247	1.229	0.087	0.076	1.201	1.239	1.201	1.239	0.091	0.086	1.201	1.239	0.091	0.086	1.201	1.239	0.091	0.086
17c	0.76	1.25	1.258	0.20	1.258	1.234	0.173	0.176	1.202	1.224	1.202	1.224	0.185	0.178	1.202	1.224	0.185	0.178	1.202	1.224	0.185	0.178
18a	0.76	1.25	1.247	0.20	1.247	1.223	0.175	0.178	1.202	1.221	1.202	1.221	0.184	0.179	1.202	1.221	0.184	0.179	1.202	1.221	0.184	0.179
18c	0.76	1.25	1.258	0.20	1.258	1.229	0.257	0.257	1.204	1.235	1.204	1.235	0.275	0.263	1.204	1.235	0.275	0.263	1.204	1.235	0.275	0.263
19a	0.76	1.25	1.247	0.30	1.247	1.223	0.259	0.260	1.201	1.232	1.201	1.232	0.273	0.268	1.201	1.232	0.273	0.268	1.201	1.232	0.273	0.268
19c	0.76	1.25	1.247	0.30	1.247	1.223	0.259	0.260	1.201	1.232	1.201	1.232	0.273	0.268	1.201	1.232	0.273	0.268	1.201	1.232	0.273	0.268
20a	0.76	1.25	1.247	0.40	1.247	1.386	0.337	0.338	1.208	1.247	1.208	1.247	0.359	0.346	1.208	1.247	0.359	0.346	1.208	1.247	0.359	0.346
20c	0.76	1.25	1.247	0.40	1.247	1.413	0.338	0.334	1.205	1.241	1.205	1.241	0.356	0.347	1.205	1.241	0.356	0.347	1.205	1.241	0.356	0.347
21a	0.76	1.25	1.258	0.50	1.258	1.386	0.418	0.385	1.215	1.263	1.215	1.263	0.439	0.388	1.215	1.263	0.439	0.388	1.215	1.263	0.439	0.388
21c	0.76	1.25	1.247	0.50	1.247	1.413	0.418	0.383	1.210	1.251	1.210	1.251	0.430	0.390	1.210	1.251	0.430	0.390	1.210	1.251	0.430	0.390
22a	0.76	1.25	1.258	0.60	1.258	1.386	0.479	0.413	1.222	1.281	1.222	1.281	0.494	0.419	1.222	1.281	0.494	0.419	1.222	1.281	0.494	0.419
22c	0.76	1.25	1.247	0.60	1.247	1.396	0.481	0.419	1.219	1.266	1.219	1.266	0.484	0.422	1.219	1.266	0.484	0.422	1.219	1.266	0.484	0.422

(Continued)

Table A1 (Concluded)

RUN #	REVETMENT TOE DEPTH Ds (ft)	DESIGN CONDITIONS PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2	
				INCIDENT PEAK PERIOD Tp(1) (sec)	INCIDENT WAVE HT Hmo(1) (ft)	INCIDENT PEAK PERIOD Tp(2) (sec)	INCIDENT WAVE HT Hmo(2) (ft)	INCIDENT AVE PER Tz(1) (sec)	INCIDENT AVE PER Tz(2) (sec)	UPCROSS SIG HT Hs(1) (ft)	UPCROSS SIG HT Hs(2) (ft)	UPCROSS SIG HT Hs(1) (ft)	UPCROSS SIG HT Hs(2) (ft)		
23a	0.76	1.25	0.66	1.258	1.386	1.258	0.520	1.230	1.327	0.530	0.437				
23c	0.76	1.25	0.66	1.247	1.392	1.247	0.523	1.225	1.311	0.520	0.441				
24a	0.76	2.25	0.10	2.282	2.282	2.282	0.103	1.916	1.953	0.100	0.124				
24e	0.76	2.25	0.10	2.287	2.287	2.287	0.101	1.907	1.955	0.101	0.127				
25a	0.76	2.25	0.20	2.268	2.299	2.268	0.200	1.890	1.847	0.199	0.246				
25e	0.76	2.25	0.20	2.273	2.273	2.273	0.202	1.893	1.843	0.203	0.254				
26a	0.76	2.25	0.30	2.178	2.381	2.178	0.296	1.884	1.773	0.291	0.352				
26e	0.76	2.25	0.30	2.252	2.283	2.252	0.297	1.884	1.757	0.298	0.359				
27a	0.76	2.25	0.40	2.247	2.381	2.247	0.393	1.869	1.695	0.395	0.468				
27c	0.76	2.25	0.40	2.262	2.415	2.262	0.401	1.879	1.707	0.392	0.460				
28a	0.76	3.00	0.10	2.990	3.543	2.990	0.100	2.502	2.620	0.099	0.126				
28f	0.76	3.00	0.10	2.990	3.550	2.990	0.101	2.510	2.637	0.098	0.130				
29a	0.76	3.00	0.20	2.960	3.544	2.960	0.200	2.427	2.383	0.198	0.260				
29f	0.76	3.00	0.20	2.971	3.527	2.971	0.203	2.438	2.397	0.203	0.268				
30a	0.76	3.00	0.30	2.960	3.464	2.960	0.300	2.326	2.151	0.299	0.383				
30c	0.76	3.00	0.30	3.012	3.488	3.012	0.309	2.335	2.189	0.305	0.377				
31a	0.86	1.25	0.20	1.214	1.205	1.214	0.145	1.202	1.237	0.159	0.145				
31c	0.86	1.25	0.20	1.250	1.309	1.250	0.152	1.201	1.237	0.159	0.153				
32a	0.86	1.25	0.40	1.259	1.264	1.259	0.326	1.204	1.262	0.348	0.321				
32c	0.86	1.25	0.40	1.248	1.335	1.248	0.331	1.201	1.260	0.343	0.326				
33a	0.86	1.25	0.60	1.266	1.386	1.266	0.463	1.213	1.297	0.479	0.423				
33c	0.86	1.25	0.60	1.247	1.258	1.247	0.476	1.207	1.283	0.480	0.424				
34a	0.86	1.25	0.66	1.259	1.399	1.259	0.522	1.217	1.305	0.532	0.449				
34c	0.86	1.25	0.66	1.247	1.253	1.247	0.534	1.216	1.297	0.531	0.448				
35a	0.86	2.25	0.20	2.339	2.339	2.339	0.200	1.900	1.857	0.199	0.235				
35e	0.86	2.25	0.20	2.228	2.223	2.223	0.203	1.895	1.856	0.200	0.239				
36a	0.86	2.25	0.40	2.339	2.339	2.339	0.400	1.869	1.720	0.395	0.454				
36b	0.86	2.25	0.40	2.228	2.399	2.228	0.390	1.859	1.725	0.388	0.448				
37a	0.86	3.00	0.10	3.134	3.418	3.134	0.097	2.505	2.379	0.096	0.133				
37f	0.86	3.00	0.10	2.893	3.433	2.893	0.100	2.528	2.399	0.100	0.141				
38a	0.86	3.00	0.30	3.096	3.134	3.096	0.301	2.331	1.904	0.304	0.420				
38f	0.86	3.00	0.30	2.971	3.433	2.971	0.308	2.347	1.914	0.318	0.434				
39a	0.86	3.00	0.40	3.096	3.134	3.096	0.392	2.217	1.833	0.402	0.541				

Table A2

Collected Data and Depths for Revetment Without Berm

RUN #	REVETMENT TOE DEPTH Ds (ft)	DESIGN CONDITIONS			ARRAY 1		ARRAY 2		DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT MRSHORE ARRAY D(n) (ft)	RUNUP (ft)
		PEAK PERIOD Tp(sec)	INCIDENT WAVE HT Hmo(des)	SPECTRAL WIDTH Qp(1)	SPECTRAL WIDTH Qp(2)	REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N				
1a	0.66	1.25	0.10	5.340	6.393	0.023	0.289	522	2.00	0.76	0.120
1c	0.66	1.25	0.10	5.180	6.170	0.023	0.286	545	2.00	0.76	0.130
2a	0.66	1.25	0.20	5.360	6.111	0.041	0.260	519	2.00	0.76	0.240
2c	0.66	1.25	0.20	5.173	5.787	0.042	0.262	533	2.00	0.76	0.250
3a	0.66	1.25	0.30	5.420	5.446	0.067	0.276	517	2.00	0.76	0.365
3c	0.66	1.25	0.30	5.117	4.990	0.065	0.281	533	2.00	0.76	0.390
4a	0.66	1.25	0.40	5.361	4.939	0.068	0.232	519	2.00	0.76	0.465
4c	0.66	1.25	0.40	5.144	4.527	0.074	0.256	515	2.00	0.76	0.490
5a	0.66	1.25	0.50	5.427	4.441	0.085	0.253	498	2.00	0.76	0.465
5c	0.66	1.25	0.50	5.213	4.111	0.086	0.257	506	2.00	0.76	0.490
6a	0.66	1.25	0.60	5.453	4.276	0.093	0.269	494	2.00	0.76	0.515
6c	0.66	1.25	0.60	5.233	3.942	0.099	0.292	491	2.00	0.76	0.540
7a	0.66	1.25	0.66	5.510	4.426	0.114	0.294	486	2.00	0.76	0.540
7c	0.66	1.25	0.66	5.301	3.898	0.104	0.275	490	2.00	0.76	0.565
8a	0.66	2.25	0.10	3.954	5.185	0.064	0.535	585	2.00	0.76	0.190
8e	0.66	2.25	0.10	3.987	4.922	0.065	0.536	576	2.00	0.76	0.215
9a	0.66	2.25	0.20	3.521	3.737	0.120	0.517	583	2.00	0.76	0.415
9e	0.66	2.25	0.20	3.555	3.652	0.121	0.514	579	2.00	0.76	0.440
10a	0.66	2.25	0.30	3.280	2.470	0.156	0.490	586	2.00	0.76	0.590
10e	0.66	2.25	0.30	3.350	2.591	0.147	0.460	578	2.00	0.76	0.640
11a	0.66	2.25	0.40	3.239	1.852	0.184	0.491	583	2.00	0.76	0.715
11e	0.66	2.25	0.40	3.272	2.022	0.170	0.436	573	2.00	0.76	0.765
12a	0.66	2.25	0.50	3.210	1.657	0.204	0.481	573	2.00	0.76	*OVT
12c	0.66	2.25	0.50	3.265	1.701	0.184	0.429	580	2.00	0.76	OVT
13a	0.66	3.50	0.10	3.894	4.593	0.091	0.683	607	2.00	0.76	**NA
14a	0.66	3.50	0.20	3.277	2.540	0.147	0.584	611	2.00	0.76	NA
14g	0.66	3.50	0.20	3.465	2.231	0.147	0.581	624	2.00	0.76	NA
15a	0.66	3.50	0.30	3.003	1.938	0.191	0.566	632	2.00	0.76	NA
15g	0.66	3.50	0.30	3.086	1.705	0.179	0.527	623	2.00	0.76	NA
16a	0.66	3.50	0.40	2.703	1.647	0.219	0.550	618	2.00	0.76	NA
16d	0.66	3.50	0.40	2.844	1.510	0.201	0.495	612	2.00	0.76	NA
17a	0.76	1.25	0.10	5.405	6.182	0.018	0.241	534	2.10	0.86	0.090
17c	0.76	1.25	0.10	5.246	5.853	0.019	0.237	541	2.10	0.86	0.110
18a	0.76	1.25	0.20	5.435	5.931	0.054	0.308	529	2.10	0.86	0.190
18c	0.76	1.25	0.20	5.218	5.461	0.054	0.305	535	2.10	0.86	0.215
19a	0.76	1.25	0.30	5.469	5.493	0.075	0.292	523	2.10	0.86	0.315
19c	0.76	1.25	0.30	5.174	5.102	0.081	0.313	528	2.10	0.86	0.365
20a	0.76	1.25	0.40	5.196	5.196	0.097	0.286	510	2.10	0.86	0.365
20c	0.76	1.25	0.40	5.226	4.853	0.108	0.322	519	2.10	0.86	0.390
21a	0.76	1.25	0.50	5.548	4.882	0.110	0.286	507	2.10	0.86	0.440
21c	0.76	1.25	0.50	5.257	4.559	0.124	0.324	510	2.10	0.86	0.490
22a	0.76	1.25	0.60	5.501	4.667	0.131	0.318	487	2.10	0.86	0.440
22c	0.76	1.25	0.60	5.306	4.328	0.135	0.323	496	2.10	0.86	0.490

(Continued)

Table A2 (Concluded)

RUN #	DESIGN CONDITIONS				ARRAY 1		ARRAY 2		ARRAY 2		NUMBER		DEPTH AT		RUNUP (ft)
	TOE DEPTH Ds (ft)	PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	SPECTRAL WIDTH qp(1)	SPECTRAL WIDTH qp(2)	REFLECT WAVE HT Kr(2) (ft)	REFLECT WAVE HT Kr(2) (ft)	COEF ANALYZED Kr(2)	OF WAVES ANALYZED N	OFFSHORE ARRAY D(o) (ft)	AT DEPTH AT NRSHORE ARRAY D(n) (ft)				
23a	0.76	1.25	0.66	5.488	4.593	0.105	0.259	481	2.10	0.86	0.540				
23c	0.76	1.25	0.66	5.269	4.006	0.100	0.245	490	2.10	0.86	0.590				
24a	0.76	2.25	0.10	3.924	5.488	0.065	0.550	568	2.10	0.86	0.190				
24e	0.76	2.25	0.10	4.004	5.840	0.065	0.549	578	2.10	0.86	0.190				
25a	0.76	2.25	0.20	3.545	3.804	0.117	0.529	520	2.10	0.86	0.365				
25e	0.76	2.25	0.20	3.592	4.075	0.117	0.514	520	2.10	0.86	0.415				
26a	0.76	2.25	0.30	3.316	2.513	0.152	0.484	571	2.10	0.86	0.590				
26e	0.76	2.25	0.30	3.485	2.586	0.132	0.419	513	2.10	0.86	OVT				
27a	0.76	2.25	0.40	3.325	1.839	0.179	0.449	508	2.10	0.86	OVT				
27c	0.76	2.25	0.40	3.410	2.141	0.144	0.351	523	2.10	0.86	OVT				
28a	0.76	3.00	0.10	3.859	5.584	0.131	1.061	721	2.10	0.86	0.225				
28f	0.76	3.00	0.10	3.792	5.497	0.136	1.061	722	2.10	0.86	0.265				
29a	0.76	3.00	0.20	3.288	4.044	0.257	1.062	603	2.10	0.86	0.465				
29f	0.76	3.00	0.20	3.371	3.549	0.259	1.056	623	2.10	0.86	0.590				
30a	0.76	3.00	0.30	2.962	2.966	0.367	1.053	605	2.10	0.86	OVT				
30c	0.76	3.00	0.30	3.068	2.743	0.364	1.055	632	2.10	0.86	OVT				
31a	0.86	1.25	0.20	5.188	5.855	0.031	0.225	453	2.20	0.96	0.240				
31c	0.86	1.25	0.20	5.238	5.653	0.032	0.225	467	2.20	0.96	0.265				
32a	0.86	1.25	0.40	5.297	5.482	0.064	0.214	488	2.20	0.96	0.390				
32c	0.86	1.25	0.40	5.248	4.969	0.065	0.218	584	2.20	0.96	0.440				
33a	0.86	1.25	0.60	5.390	4.851	0.084	0.213	513	2.20	0.96	0.515				
33c	0.86	1.25	0.60	5.451	4.728	0.090	0.227	521	2.20	0.96	0.540				
34a	0.86	1.25	0.66	5.493	4.646	0.100	0.238	466	2.20	0.96	0.515				
34c	0.86	1.25	0.66	5.355	4.669	0.091	0.215	467	2.20	0.96	OVT				
35a	0.86	2.25	0.20	3.717	4.406	0.112	0.498	592	2.20	0.96	0.390				
35e	0.86	2.25	0.20	3.937	4.907	0.113	0.495	574	2.20	0.96	0.440				
36a	0.86	2.25	0.40	3.379	2.241	0.171	0.416	585	2.20	0.96	OVT				
36b	0.86	2.25	0.40	3.470	2.253	0.140	0.345	583	2.20	0.96	OVT				
37a	0.86	3.00	0.10	3.634	3.232	0.072	0.652	610	2.20	0.96	0.265				
37f	0.86	3.00	0.10	3.682	3.402	0.075	0.652	602	2.20	0.96	0.290				
38a	0.86	3.00	0.30	2.943	1.836	0.181	0.537	614	2.20	0.96	OVT				
38f	0.86	3.00	0.30	3.023	1.800	0.185	0.533	599	2.20	0.96	OVT				
39a	0.86	3.00	0.40	2.663	1.559	0.218	0.508	614	2.20	0.96	OVT				

*OVT: Revetment was overtopped

**NA: Data not available

Table A3

Wave Height and Period Data for Revetment With Fronting Berm

RUN #	TOE DEPTH Ds (ft)	DESIGN CONDITIONS PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2	
				PEAK PER Tp(1) (sec)	INCIDENT WAVE HT Hmo(1) (ft)	PEAK PER Tp(2) (sec)	INCIDENT WAVE HT Hmo(2) (ft)	AVE PER Tz(1) (sec)	INCIDENT WAVE HT Hs(1) (ft)	AVE PER Tz(2) (sec)	INCIDENT WAVE HT Hs(2) (ft)	UPCROSS SIG HT (ft)	UPCROSS SIG HT (ft)		
40a	0.76	1.25	0.10	1.270	0.087	1.250	0.078	1.194	0.090	1.245	0.082	0.090	0.082	0.082	0.082
40c	0.76	1.25	0.10	1.247	0.089	1.247	0.081	1.193	0.089	1.246	0.083	0.089	0.083	0.083	0.083
42a	0.76	1.25	0.30	1.259	0.260	1.222	0.234	1.198	0.274	1.265	0.250	0.274	0.250	0.250	0.250
42c	0.76	1.25	0.30	1.247	0.264	1.222	0.236	1.195	0.271	1.271	0.252	0.271	0.252	0.252	0.252
44a	0.76	1.25	0.50	1.259	0.419	1.306	0.360	1.206	0.430	1.292	0.377	0.430	0.377	0.377	0.377
44c	0.76	1.25	0.50	1.247	0.426	1.414	0.359	1.203	0.423	1.298	0.376	0.423	0.376	0.376	0.376
47a	0.76	3.00	0.10	2.960	0.094	3.544	0.105	2.469	0.093	2.261	0.108	0.093	0.108	0.108	0.108
47f	0.76	3.00	0.10	2.960	0.095	3.544	0.106	2.466	0.095	2.254	0.109	0.095	0.109	0.109	0.109
48a	0.76	3.00	0.30	2.960	0.293	3.472	0.327	2.299	0.298	1.830	0.387	0.298	0.387	0.387	0.387
48f	0.76	3.00	0.30	2.971	0.298	3.179	0.327	2.300	0.308	1.860	0.403	0.308	0.403	0.403	0.403
49a	0.76	3.00	0.30	2.960	0.291	3.053	0.329	2.289	0.294	1.853	0.390	0.294	0.390	0.390	0.390
49f	0.76	3.00	0.30	2.971	0.297	3.179	0.327	2.300	0.305	1.878	0.398	0.305	0.398	0.398	0.398
50a	0.76	3.00	0.10	2.960	0.093	3.041	0.107	2.472	0.092	2.333	0.109	0.092	0.109	0.109	0.109
50f	0.76	3.00	0.10	2.971	0.097	2.971	0.112	2.480	0.096	2.309	0.116	0.096	0.116	0.116	0.116
51a	0.76	3.00	0.50	2.960	0.501	3.323	0.468	*NA	0.520	NA	0.566	0.520	0.566	0.566	0.566
51f	0.76	3.00	0.50	2.971	0.514	3.072	0.461	NA	0.544	NA	0.549	0.544	0.549	0.549	0.549
52a	0.76	1.25	0.66	1.255	0.520	1.316	0.411	NA	0.523	NA	0.432	0.523	0.432	0.432	0.432
52c	0.76	1.25	0.66	1.247	0.540	1.357	0.423	NA	0.527	NA	0.436	0.527	0.436	0.436	0.436
53a	0.76	1.25	0.60	1.259	0.432	1.306	0.359	1.204	0.451	1.285	0.390	0.451	0.390	0.390	0.390
53c	0.76	1.25	0.60	1.259	0.435	1.414	0.355	1.202	0.439	1.288	0.388	0.439	0.388	0.388	0.388
55a	0.76	1.25	0.30	1.259	0.259	1.259	0.234	1.197	0.255	1.258	0.255	0.255	0.255	0.255	0.255
55c	0.76	1.25	0.30	1.247	0.262	1.222	0.235	1.193	0.274	1.263	0.258	0.274	0.258	0.258	0.258
57a	0.76	1.25	0.10	1.270	0.088	1.270	0.078	1.193	0.092	1.238	0.081	0.092	0.081	0.081	0.081
57c	0.76	1.25	0.10	1.247	0.089	1.247	0.081	1.191	0.094	1.240	0.084	0.094	0.084	0.084	0.084
58a	0.76	2.25	0.10	2.320	0.097	2.320	0.102	1.886	0.094	1.891	0.101	0.094	0.101	0.101	0.101
58e	0.76	2.25	0.10	2.228	0.097	2.228	0.104	1.883	0.094	1.888	0.103	0.094	0.103	0.103	0.103
59a	0.76	2.25	0.30	2.320	0.292	2.339	0.312	1.868	0.288	1.731	0.336	0.288	0.336	0.336	0.336
59e	0.76	2.25	0.30	2.268	0.295	2.287	0.317	1.862	0.290	1.737	0.341	0.290	0.341	0.341	0.341
60a	0.76	2.25	0.50	2.320	0.490	2.383	0.452	1.829	0.488	1.654	0.515	0.488	0.515	0.515	0.515
60e	0.76	2.25	0.50	2.268	0.497	2.320	0.460	1.826	0.496	1.669	0.525	0.496	0.525	0.525	0.525
61a	0.76	2.25	0.66	2.320	0.652	2.569	0.502	1.770	0.657	1.645	0.549	0.657	0.549	0.549	0.549
61e	0.76	2.25	0.66	2.228	0.643	2.324	0.502	1.774	0.651	1.667	0.558	0.651	0.558	0.558	0.558
62a	0.86	1.25	0.10	1.222	0.088	1.222	0.083	1.198	0.095	1.232	0.089	0.095	0.089	0.089	0.089
62c	0.86	1.25	0.10	1.247	0.090	1.228	0.086	1.196	0.095	1.230	0.092	0.095	0.092	0.092	0.092
63a	0.86	1.25	0.30	1.259	0.257	1.250	0.244	1.200	0.279	1.250	0.268	0.279	0.268	0.268	0.268
63c	0.86	1.25	0.30	1.256	0.262	1.228	0.246	1.196	0.278	1.250	0.269	0.278	0.269	0.269	0.269
64a	0.86	1.25	0.50	1.259	0.421	1.259	0.369	1.206	0.444	1.281	0.404	0.444	0.404	0.404	0.404
64c	0.86	1.25	0.50	1.261	0.429	1.421	0.374	1.202	0.440	1.277	0.405	0.440	0.405	0.405	0.405

(Continued)

(Sheet 1 of 3)

Table A3 (Continued)

RUN #	DESIGN CONDITIONS		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2	
	REVETMENT TOE DEPTH Ds (ft)	PERIOD Tp(des) (sec)	INCIDENT WAVE HT (ft)	INCIDENT WAVE HT Hmo(des)	PEAK PERIOD Tp(1) (sec)	INCIDENT WAVE HT Hmo(1) (ft)	PERIOD Tp(2) (sec)	INCIDENT WAVE HT Hmo(2) (ft)	AVE PER Tz(1) (sec)	INCIDENT WAVE HT Hmo(2) (ft)	PERIOD Tz(2) (sec)	AVE PER Tz(1) (sec)	INCIDENT WAVE HT Hmo(2) (ft)	UPCROSS SIG HT Hs(2) (ft)
65a	0.86	1.25	0.66	0.66	1.259	0.525	1.399	0.440	1.219	1.305	1.219	0.534	0.463	
65c	0.86	1.25	0.66	0.66	1.247	0.545	1.253	0.448	1.217	1.305	1.217	0.538	0.471	
66a	0.86	2.25	0.10	0.10	2.282	0.100	2.339	0.108	1.890	1.908	1.890	0.097	0.110	
66e	0.86	2.25	0.20	0.20	2.268	0.201	2.268	0.108	1.886	1.899	1.886	0.098	0.110	
67a	0.86	2.25	0.20	0.20	2.246	0.201	2.320	0.215	1.885	1.824	1.885	0.195	0.219	
67e	0.86	2.25	0.30	0.30	2.268	0.328	2.268	0.214	1.883	1.825	1.883	0.195	0.220	
68a	0.86	2.25	0.30	0.30	2.339	0.328	2.339	0.324	1.870	1.775	1.870	0.325	0.338	
68e	0.86	2.25	0.40	0.40	2.255	0.401	2.378	0.324	1.865	1.756	1.865	0.328	0.344	
69a	0.86	2.25	0.40	0.40	2.320	0.401	2.339	0.409	1.863	1.725	1.863	0.394	0.447	
69e	0.86	2.25	0.50	0.50	2.228	0.399	2.378	0.403	1.860	1.711	1.860	0.393	0.437	
70a	0.86	2.25	0.50	0.50	2.320	0.497	2.320	0.486	1.848	1.689	1.848	0.488	0.531	
70e	0.86	2.25	0.60	0.60	2.268	0.496	2.324	0.487	1.845	1.690	1.845	0.490	0.538	
71a	0.86	2.25	0.60	0.60	2.320	0.590	2.320	0.537	1.821	1.653	1.821	0.582	0.583	
71e	0.86	2.25	0.60	0.60	2.228	0.594	2.324	0.547	1.817	1.666	1.817	0.591	0.604	
72a	0.86	2.25	0.66	0.66	2.320	0.656	2.339	0.545	1.805	1.633	1.805	0.649	0.587	
72e	0.86	2.25	0.66	0.66	2.228	0.651	2.354	0.545	1.800	1.665	1.800	0.645	0.594	
73a	0.66	1.25	0.10	0.10	1.266	0.087	1.266	0.081	1.199	1.251	1.199	0.094	0.087	
73c	0.66	1.25	0.10	0.10	1.268	0.088	1.290	0.084	1.195	1.252	1.195	0.092	0.089	
74a	0.66	1.25	0.20	0.20	1.266	0.172	1.266	0.163	1.201	1.261	1.201	0.187	0.179	
74c	0.66	1.25	0.20	0.20	1.268	0.174	1.290	0.165	1.196	1.262	1.196	0.184	0.179	
75a	0.66	1.25	0.30	0.30	1.266	0.256	1.279	0.237	1.204	1.283	1.204	0.280	0.267	
75c	0.66	1.25	0.30	0.30	1.268	0.261	1.268	0.238	1.196	1.277	1.196	0.276	0.263	
76a	0.66	1.25	0.40	0.40	1.266	0.336	1.296	0.295	1.209	1.296	1.209	0.361	0.331	
76c	0.66	1.25	0.40	0.40	1.247	0.342	1.282	0.293	1.198	1.290	1.198	0.359	0.328	
77a	0.66	1.25	0.50	0.50	1.266	0.404	1.382	0.332	1.215	1.304	1.215	0.428	0.365	
77c	0.66	1.25	0.50	0.50	1.247	0.418	1.412	0.334	1.203	1.304	1.203	0.428	0.371	
78a	0.66	1.25	0.60	0.60	1.266	0.478	1.382	0.370	1.223	1.325	1.223	0.495	0.410	
78c	0.66	1.25	0.60	0.60	1.247	0.488	1.405	0.371	1.211	1.316	1.211	0.491	0.410	
79a	0.66	1.25	0.66	0.66	1.266	0.519	1.382	0.384	1.230	1.333	1.230	0.529	0.417	
79c	0.66	1.25	0.66	0.66	1.247	0.530	1.405	0.386	1.217	1.321	1.217	0.525	0.412	
80a	0.66	2.25	0.10	0.10	2.317	0.096	2.165	0.110	1.910	1.893	1.910	0.094	0.109	
80e	0.66	2.25	0.10	0.10	2.312	0.096	2.202	0.109	1.892	1.902	1.892	0.093	0.108	
81a	0.66	2.25	0.20	0.20	2.317	0.191	2.165	0.207	1.901	1.800	1.901	0.186	0.219	
81e	0.66	2.25	0.20	0.20	2.286	0.194	2.221	0.213	1.886	1.813	1.886	0.188	0.222	
82a	0.66	2.25	0.30	0.30	2.317	0.285	2.349	0.305	1.887	1.742	1.887	0.278	0.344	
82e	0.66	2.25	0.30	0.30	2.327	0.307	2.256	0.317	1.872	1.765	1.872	0.297	0.350	
83a	0.66	2.25	0.40	0.40	2.317	0.398	2.349	0.387	1.867	1.674	1.867	0.390	0.455	
83e	0.66	2.25	0.40	0.40	2.236	0.395	2.365	0.386	1.850	1.696	1.850	0.386	0.446	

(Continued)

(Sheet 2 of 3)

Table A3 (Concluded)

RUN #	DESIGN CONDITIONS		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2		ARRAY 1		ARRAY 2	
	REVERTMENT Ds (ft)	TOE DEPTH (ft)	PERIOD Tp(des) (sec)	INCIDENT WAVE Ht (ft)	INCIDENT WAVE Ht (ft)	PERIOD Tp(1) (sec)	PERIOD Tp(2) (sec)	INCIDENT WAVE HT Hmo(1) (ft)	INCIDENT WAVE HT Hmo(2) (ft)	AVE PER Tz(1) (sec)	AVE PER Tz(2) (sec)	UPCROSS SIG HT Hs(1) (ft)	UPCROSS SIG HT Hs(2) (ft)	
84a	0.66	0.50	2.25	0.50	2.317	2.349	0.493	0.420	1.841	1.663	0.487	0.498		
84e	0.66	0.50	2.25	0.50	2.327	2.365	0.493	0.429	1.823	1.660	0.487	0.504		
85a	0.66	0.60	2.25	0.60	2.317	2.393	0.584	0.448	1.806	1.671	0.587	0.528		
85e	0.66	0.60	2.25	0.60	2.327	2.498	0.586	0.459	1.791	1.675	0.586	0.536		
86a	0.66	0.66	2.25	0.66	2.317	2.317	0.649	0.447	1.783	1.663	0.655	0.524		
86e	0.66	0.66	2.25	0.66	2.327	2.359	0.645	0.453	1.775	1.685	0.649	0.522		
87a	0.66	0.10	3.00	0.10	3.015	3.100	0.091	0.112	2.489	2.289	0.086	0.113		
87f	0.66	0.10	3.00	0.10	2.990	3.041	0.099	0.116	2.479	2.235	0.095	0.131		
88a	0.66	0.20	3.00	0.20	3.100	3.100	0.202	0.234	2.393	2.008	0.195	0.282		
88f	0.66	0.20	3.00	0.20	3.015	3.088	0.207	0.240	2.382	1.955	0.204	0.297		
89a	0.66	0.30	3.00	0.30	3.015	3.046	0.237	0.311	2.403	1.881	0.229	0.366		
89f	0.66	0.30	3.00	0.30	2.990	3.346	0.281	0.331	2.297	1.817	0.281	0.391		
90a	0.66	0.40	3.00	0.40	3.015	3.333	0.371	0.403	2.199	1.791	0.377	0.504		
90f	0.66	0.40	3.00	0.40	2.990	3.346	0.393	0.394	2.144	1.747	0.405	0.497		
91a	0.66	0.50	3.00	0.50	2.857	3.409	0.288	0.431	2.275	1.841	0.297	0.530		
91f	0.66	0.50	3.00	0.50	2.990	3.665	0.510	0.424	2.048	1.773	0.527	0.541		

Table A4
Collected Data and Depths for Revetment With Fronting Berm

RUN #	DESIGN CONDITIONS		ARRAY 1		ARRAY 2		NUMBER ANALYZED	DEPTH AT		RUNUP (ft)	
	REVETMENT TOE Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE Ht (ft)	SPECTRAL WIDTH Qp(1)	SPECTRAL WIDTH Qp(2)	REFLECT WAVE Ht Hr(2)		REFLECT COEF Kr(2)	OFFSHORE ARRAY D(o) (ft)		NRSHORE ARRAY D(n) (ft)
40a	0.76	1.25	0.10	5.309	6.045	0.020	0.257	510	2.10	0.86	0.090
40c	0.76	1.25	0.10	5.197	5.869	0.020	0.245	513	2.10	0.86	0.100
42a	0.76	1.25	0.30	5.417	5.584	0.049	0.210	498	2.10	0.86	0.290
42c	0.76	1.25	0.30	5.145	5.303	0.051	0.214	504	2.10	0.86	0.315
44a	0.76	1.25	0.50	5.573	5.006	0.086	0.240	489	2.10	0.86	0.390
44c	0.76	1.25	0.50	5.193	4.599	0.089	0.247	481	2.10	0.86	0.440
47a	0.76	3.00	0.10	3.380	2.474	0.044	0.415	612	2.10	0.86	0.215
47f	0.76	3.00	0.10	3.370	2.459	0.044	0.412	614	2.10	0.86	0.265
48a	0.76	3.00	0.30	2.899	1.714	0.155	0.474	609	2.10	0.86	*OVT
48f	0.76	3.00	0.30	2.991	1.572	0.158	0.483	619	2.10	0.86	OVT
49a	0.76	3.00	0.30	2.920	1.834	0.122	0.369	623	2.10	0.86	OVT
49f	0.76	3.00	0.30	3.068	1.670	0.124	0.379	627	2.10	0.86	OVT
50a	0.76	3.00	0.10	3.341	2.911	0.026	0.247	628	2.10	0.86	0.190
50f	0.76	3.00	0.10	3.464	2.892	0.029	0.260	644	2.10	0.86	0.215
51a	0.76	3.00	0.50	2.544	1.504	0.186	0.396	627	2.10	0.86	OVT
51f	0.76	3.00	0.50	2.491	1.408	0.179	0.389	641	2.10	0.86	OVT
52a	0.76	1.25	0.66	5.487	4.888	0.098	0.239	509	2.10	0.86	0.390
52c	0.76	1.25	0.66	5.377	3.829	0.097	0.230	509	2.10	0.86	0.415
53a	0.76	1.25	0.60	5.394	5.063	0.107	0.298	477	2.10	0.86	0.340
53c	0.76	1.25	0.60	5.019	4.343	0.097	0.273	479	2.10	0.86	0.390
55a	0.76	1.25	0.30	5.194	5.652	0.065	0.276	494	2.10	0.86	0.290
55c	0.76	1.25	0.30	4.992	5.414	0.067	0.285	507	2.10	0.86	0.315
57a	0.76	1.25	0.10	5.152	6.118	0.015	0.193	504	2.10	0.86	0.110
57c	0.76	1.25	0.10	5.060	6.036	0.015	0.188	507	2.10	0.86	0.115
58a	0.76	2.25	0.10	3.465	3.300	0.023	0.226	586	2.10	0.86	0.140
58e	0.76	2.25	0.10	3.566	3.431	0.023	0.224	589	2.10	0.86	0.165
59a	0.76	2.25	0.30	3.363	2.230	0.080	0.257	583	2.10	0.86	0.515
59e	0.76	2.25	0.30	3.474	2.482	0.081	0.256	586	2.10	0.86	0.590
60a	0.76	2.25	0.50	3.199	1.675	0.145	0.321	573	2.10	0.86	OVT
60e	0.76	2.25	0.50	3.396	1.725	0.149	0.324	573	2.10	0.86	OVT
61a	0.76	2.25	0.66	3.014	1.569	0.163	0.365	576	2.10	0.86	OVT
61e	0.76	2.25	0.66	3.188	1.615	0.176	0.350	579	2.10	0.86	OVT
62a	0.86	1.25	0.10	5.267	6.171	0.027	0.319	496	2.20	0.96	0.165
62c	0.86	1.25	0.10	5.208	6.012	0.027	0.313	514	2.20	0.96	0.165
63a	0.86	1.25	0.30	5.255	5.736	0.067	0.276	488	2.20	0.96	0.290
63c	0.86	1.25	0.30	5.158	5.740	0.069	0.281	504	2.20	0.96	0.340
64a	0.86	1.25	0.50	5.303	5.109	0.101	0.274	478	2.20	0.96	0.440
64c	0.86	1.25	0.50	5.187	4.989	0.096	0.257	479	2.20	0.96	0.465

(Continued)

(Sheet 1 of 3)

Table A4 (Continued)

RUN #	DESIGN CONDITIONS				ARRAY 1 SPECTRAL WIDTH qp(1)	ARRAY 2 SPECTRAL WIDTH qp(2)	ARRAY 2 REFLECT WAVE HT Kr(2)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT		RUNUP (ft)
	REVEMENT TOE DEPTH Ds (ft)	PERIOD Tp(sec)	PEAK INCIDENT WAVE HT Hmo(des)	DEPTH AT OFFSHORE ARRAY D(o) (ft)						DEPTH AT MRSHORE ARRAY D(n) (ft)		
65a	0.86	1.25	0.66	5.403	4.657	0.120	0.272	467	2.20	0.96	0.490	
65c	0.86	1.25	0.66	5.359	5.164	0.115	0.257	465	2.20	0.96	0.540	
66a	0.86	2.25	0.10	3.530	3.466	0.028	0.263	591	2.20	0.96	0.115	
66e	0.86	2.25	0.10	3.605	3.555	0.028	0.255	597	2.20	0.96	0.140	
67a	0.86	2.25	0.20	3.493	3.063	0.053	0.248	590	2.20	0.96	0.290	
67e	0.86	2.25	0.20	3.613	3.165	0.053	0.250	590	2.20	0.96	0.340	
68a	0.86	2.25	0.30	3.445	2.669	0.082	0.256	581	2.20	0.96	0.590	
68e	0.86	2.25	0.30	3.567	2.641	0.082	0.252	581	2.20	0.96	0.640	
69a	0.86	2.25	0.40	3.427	2.187	0.119	0.291	585	2.20	0.96	0.690	
69e	0.86	2.25	0.40	3.556	2.029	0.113	0.280	575	2.20	0.96	0.815	
70a	0.86	2.25	0.50	3.349	1.846	0.152	0.313	576	2.20	0.96	0.815	
70e	0.86	2.25	0.50	3.507	1.730	0.150	0.308	567	2.20	0.96	0.840	
71a	0.86	2.25	0.60	3.261	1.683	0.176	0.327	583	2.20	0.96	0.820	
71e	0.86	2.25	0.60	3.412	1.655	0.174	0.318	570	2.20	0.96	**NA	
72a	0.86	2.25	0.66	3.191	1.661	0.194	0.356	587	2.20	0.96	0.820	
72e	0.86	2.25	0.66	3.341	1.628	0.170	0.312	574	2.20	0.96	0.830	
73a	0.66	1.25	0.10	5.225	6.551	0.028	0.351	549	2.00	0.76	0.115	
73c	0.66	1.25	0.10	5.059	6.563	0.031	0.366	562	2.00	0.76	0.120	
74a	0.66	1.25	0.20	5.241	6.426	0.057	0.351	547	2.00	0.76	0.190	
74c	0.66	1.25	0.20	5.040	6.229	0.057	0.344	557	2.00	0.76	0.215	
75a	0.66	1.25	0.30	5.154	5.577	0.075	0.318	541	2.00	0.76	0.265	
75c	0.66	1.25	0.30	5.049	5.437	0.071	0.299	552	2.00	0.76	0.315	
76a	0.66	1.25	0.40	5.197	4.986	0.090	0.307	536	2.00	0.76	0.340	
76c	0.66	1.25	0.40	5.098	4.671	0.080	0.273	543	2.00	0.76	0.365	
77a	0.66	1.25	0.50	5.298	4.610	0.096	0.288	522	2.00	0.76	0.390	
77c	0.66	1.25	0.50	5.214	3.924	0.096	0.288	531	2.00	0.76	0.415	
78a	0.66	1.25	0.60	5.370	4.545	0.118	0.319	518	2.00	0.76	0.390	
78c	0.66	1.25	0.60	5.376	3.710	0.120	0.322	513	2.00	0.76	0.415	
79a	0.66	1.25	0.66	5.430	4.421	0.112	0.292	512	2.00	0.76	0.415	
79c	0.66	1.25	0.66	5.507	3.703	0.111	0.286	513	2.00	0.76	0.465	
80a	0.66	2.25	0.10	3.650	4.187	0.038	0.351	537	2.00	0.76	NA	
80e	0.66	2.25	0.10	3.561	4.296	0.040	0.362	540	2.00	0.76	NA	
81a	0.66	2.25	0.20	3.542	3.123	0.074	0.358	532	2.00	0.76	NA	
81e	0.66	2.25	0.20	3.490	3.503	0.076	0.357	538	2.00	0.76	NA	
82a	0.66	2.25	0.30	3.479	2.237	0.101	0.330	514	2.00	0.76	0.210	
82e	0.66	2.25	0.30	3.404	2.547	0.093	0.292	540	2.00	0.76	0.215	
83a	0.66	2.25	0.40	3.420	1.847	0.128	0.332	514	2.00	0.76	NA	
83e	0.66	2.25	0.40	3.323	1.979	0.115	0.299	532	2.00	0.76	NA	

(Continued)

(Sheet 2 of 3)

Table A4 (Concluded)

RUN #	DESIGN CONDITIONS			ARRAY 1		ARRAY 2		ARRAY 2		DEPTH AT DEPTH AT		RUNUP (ft)
	REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	SPECTRAL WIDTH qp(1)	SPECTRAL WIDTH qp(2)	REFLECT WAVE HT Hr(2) (ft)	REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE D(o) (ft)	DEPTH AT NRSHORE D(n) (ft)		
84a	0.66	2.25	0.50	3.327	1.709	0.144	0.342	520	2.00	0.76	NA	
84e	0.66	2.25	0.50	3.200	1.769	0.146	0.340	531	2.00	0.76	NA	
85a	0.66	2.25	0.60	3.230	1.690	0.162	0.361	524	2.00	0.76	NA	
85e	0.66	2.25	0.60	3.109	1.689	0.167	0.363	529	2.00	0.76	NA	
86a	0.66	2.25	0.66	3.177	1.648	0.162	0.362	521	2.00	0.76	NA	
86e	0.66	2.25	0.66	3.068	1.650	0.165	0.363	537	2.00	0.76	NA	
87a	0.66	3.00	0.10	3.372	2.920	0.040	0.361	730	2.00	0.76	NA	
87f	0.66	3.00	0.10	3.599	2.863	0.043	0.370	737	2.00	0.76	NA	
88a	0.66	3.00	0.20	3.162	2.258	0.091	0.391	746	2.00	0.76	NA	
88f	0.66	3.00	0.20	3.324	2.079	0.089	0.370	735	2.00	0.76	NA	
89a	0.66	3.00	0.30	3.035	1.731	0.121	0.388	699	2.00	0.76	NA	
89f	0.66	3.00	0.30	3.107	1.587	0.121	0.365	712	2.00	0.76	NA	
90a	0.66	3.00	0.40	2.733	1.616	0.158	0.392	712	2.00	0.76	NA	
90f	0.66	3.00	0.40	2.791	1.571	0.156	0.395	721	2.00	0.76	NA	
91a	0.66	3.00	0.50	3.106	1.459	0.181	0.420	110	2.00	0.76	NA	
91f	0.66	3.00	0.50	2.625	1.448	0.174	0.411	731	2.00	0.76	NA	

*OVT: Revetment was overtopped

**NA: Data not available

Table 5

Damage Sustained by the Revetment During Test Runs

RUN #	UPPER S2 DAMAGE	MAXIMUM PERPEN- DICULAR ARMOR EROSION	RUN #	UPPER S2 DAMAGE	MAXIMUM PERPEN- DICULAR ARMOR EROSION
1	0.560	0.010	37	0.189	0.006
2	0.883	0.024	38	16.858	0.194
3	0.558	0.013	40	0.257	0.008
4	1.323	0.053	42	0.495	0.014
5	2.161	0.049	44	0.927	0.018
6	6.517	0.112	47	0.244	0.008
7	11.473	0.121	48	4.881	0.076
8	0.514	0.008	49	2.479	0.048
9	1.252	0.036	50	0.301	0.004
10	5.538	0.090	51	6.491	0.088
11	11.219	0.157	52	1.758	0.058
12	21.797	0.215	53	0.283	0.006
17	0.458	0.006	55	0.209	0.004
18	0.458	0.006	57	0.086	0.004
19	0.770	0.036	59	1.946	0.036
20	1.220	0.030	60	6.944	0.129
21	3.637	0.085	61	9.695	0.125
22	9.358	0.126	63	0.624	0.010
23	8.765	0.158	64	0.693	0.015
24	0.338	0.007	65	1.510	0.041
25	1.523	0.037	67	0.973	0.036
26	12.590	0.137	68	1.306	0.054
27	25.188	0.191	69	6.841	0.123
28	0.486	0.017	70	9.876	0.104
29	2.442	0.044	71	17.981	0.175
30	12.220	0.171	85	2.152	0.044
32	3.258	0.097	86	1.171	0.030
33	12.191	0.146	88	0.890	0.021
34	17.883	0.195	89	0.730	0.017
35	1.240	0.030	90	0.538	0.016
36	37.603	0.286	91	1.610	0.047

APPENDIX B: EXAMPLE PROBLEMS

EXAMPLE 1

GIVEN: Potential runoff on a revetment is 15 percent higher than the freeboard.

FIND: Reduction in overtopping rate if a berm reduces the runoff by 10 percent.

SOLUTION: The current method given in the Shore Protection Manual (SPM) (1984)* to calculate overtopping rates is

$$Q = \left[(g Q_o^* H_o'^3)^{1/2} \exp \frac{0.1085}{\alpha} \ln \left(\frac{R + h - d_s}{R - h + d_s} \right) \right] \quad (B1)$$

where

- Q = overtopping rate per unit structure length
- Q_o^{*} and α = empirically determined coefficients based on incident wave conditions and structure geometry
- H_o' = equivalent deep water wave height
- R = maximum potential runoff
- h = height of structure crest along the bottom
- d_s = depth at the structure toe

This may be rewritten as (Ahrens and Heimbaugh 1986)

$$Q = \left[(g Q_o^* H_o'^3)^{1/2} \left(\frac{R - F}{R + F} \right) \frac{0.1085}{\alpha} \right] \quad (B2)$$

where F is the freeboard of the structure.

Given that the potential runoff without a berm is 15 percent greater than the freeboard, then

$$R_{\text{No Berm}} = 1.150F$$

If a berm reduces the runoff by 10 percent, then

$$R_{\text{Berm}} = 1.150F * 0.90 = 1.035F$$

The effect of the berm on the overtopping rate is given by

$$\frac{Q_{\text{No Berm}}}{Q_{\text{Berm}}} = \frac{\left[(g Q_o^* H_o'^3)^{1/2} \left(\frac{1.150F - F}{1.150F + F} \right) \frac{0.1085}{\alpha} \right]}{\left[(g Q_o^* H_o'^3)^{1/2} \left(\frac{1.035F - F}{1.035F + F} \right) \frac{0.1085}{\alpha} \right]} \quad (B3)$$

* See References at the end of the main text.

or,

$$\frac{Q_{\text{No Berm}}}{Q_{\text{Berm}}} = \left[\frac{\left(\frac{0.150F}{2.150F} \right)^{\frac{0.1085}{\alpha}}}{\left(\frac{0.035F}{2.035F} \right)} \right] \quad (\text{B4})$$

For $\alpha = 0.07$, the berm has reduced the overtopping rate by a factor of 8.8.

EXAMPLE 2

GIVEN: A given berm produces a 10-percent reduction in wave runup, i.e. $r = 0.90$.

FIND: What is the damage reduction factor (r_s)?

SOLUTION:

$$r = 0.90 = \exp \left[C_2 \left(\frac{W_B}{(H_{m0} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (\text{15 bis*})$$

$$r_s = ? = \exp \left[C_4 \left(\frac{W_B}{(H_{m0} L_o)^{1/2}} * \frac{h_B}{d_s} \right) \right] \quad (\text{20 bis**})$$

Since W_B , h_B , H_{m0} , L_o , and d_s are equal and $C_2 = -0.152$ (pp 25 of text) and $C_4 = -3.56$ (pp 36 of text), the above reduces to:

$$\frac{r}{r_s} = \exp \left(\frac{C_2}{C_4} \right) \quad (\text{B6})$$

or

$$\frac{\ln 0.90}{\ln (r_s)} = \frac{-0.152}{-3.56}$$

$$\frac{-0.105}{\ln (r_s)} = \frac{-0.152}{-3.56}$$

* See p 27 in the main text.

** See p 38 in the main text.

$$\ln r_s = -2.459$$

$$r_s = 0.085$$

APPENDIX C: NOTATION

a	Regression coefficient
A ₁	Area of accretion above the still water level
A ₂	Area of erosion
A ₃	Area of accretion below the still water level
alpha	Overtopping parameter
b	Regression coefficient
C ₀	Regression coefficient
C ₁	Regression coefficient
C ₂	Regression coefficient
C ₃	Regression coefficient
C ₄	Regression coefficient
C ₅	Regression coefficient
C ₆	Regression coefficient
C ₇	Regression coefficient
D ₁₅	15-percentile diameter on a grain size distribution curve
D ₈₅	85-percentile diameter on a grain size distribution curve
(D _n) ₅₀	Nominal diameter of the median stone size
d _s	Depth at structure toe
E _I	Energy of the incident wave spectrum
e _{max}	Maximum perpendicular penetration of erosion into armor layer
E _R	Energy of the reflected wave spectrum
f	Wave frequency
F	Structure freeboard
g	Gravitational acceleration
H	Wave height
h _B	Berm height
H _{mo}	Wave height of the zeroth moment
H _r	Reflected wave height
H _s	Average wave height of the one-third highest waves
K _r	Reflection coefficient
K _{rr}	Stability coefficient
L _o	Deepwater wavelength
m _o	zeroth moment of the potential energy spectrum

m_2	Second moment of the potential energy spectrum
N_s	Stability number
Q_p	Spectral width or peakedness
r	Runup reduction factor
r_e	Erosion reduction factor
r_s	S_2 damage reduction factor
R_{max}	Maximum vertical height above still water level of wave runup
S_2	Damage relative to size of armor unit
$S(f)$	Spectral density function
S_r	Relative specific gravity
T	Wave period
T_p	Wave period associated with the peak energy density
T_z	Average wave period
W	Weight of an individual armor unit
W_{50}	Median armor stone weight
W_B	Berm width
w_r	Unit weight of armor stone
α	Angle of the slope with the horizontal
ξ	Surf parameter
π	3.141592654

REPORT DOCUMENTATION PAGE

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