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Technical Report REMR-CO-17
April 1993

US Army Corps of Engineers
Waterways Experiment Station

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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Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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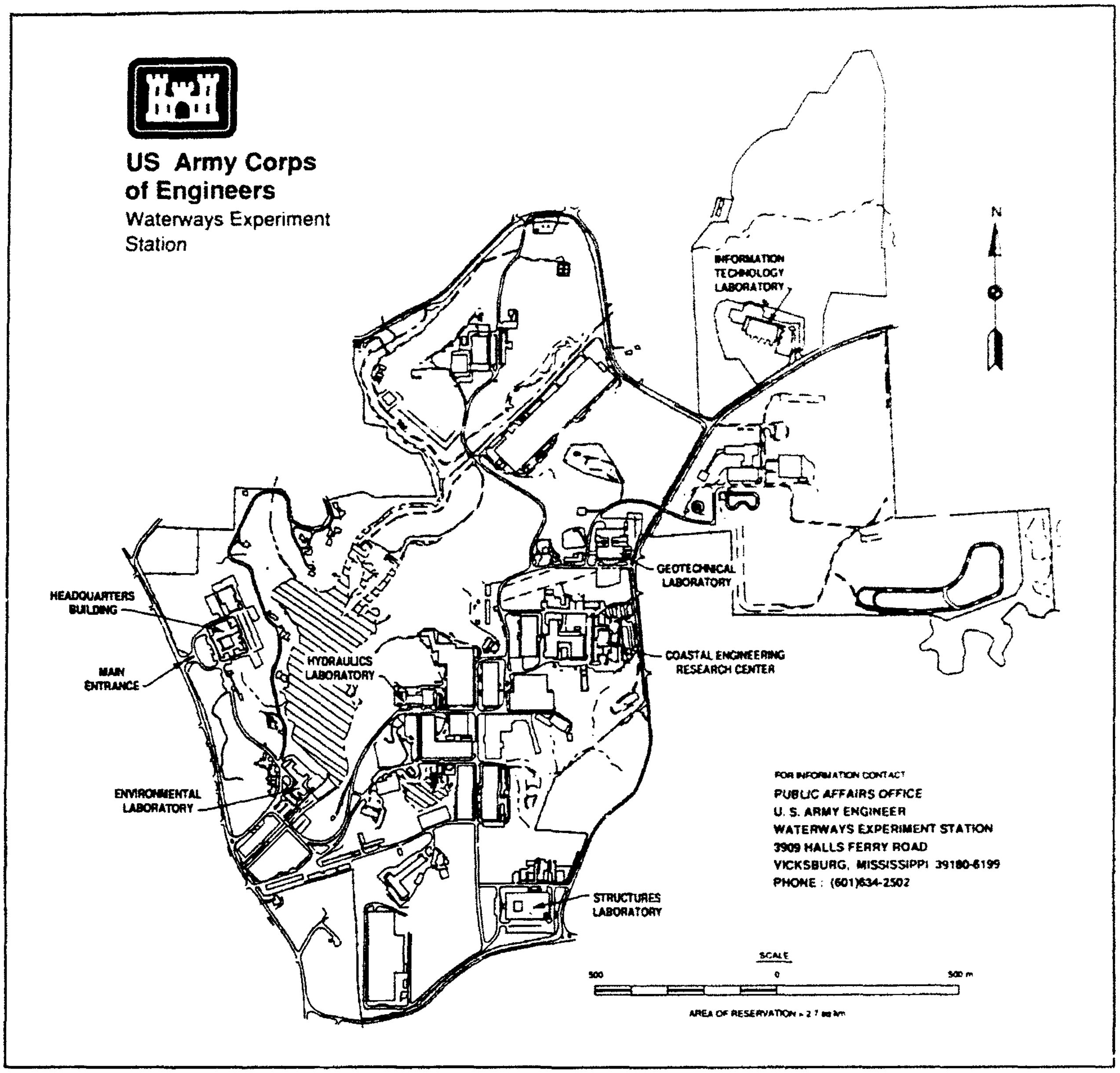

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PREFACE

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.

CONTENTS

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:

Multiply	By	To Obtain
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_{mo}) and are obtained as four times the square root of the zeroth moment of the potential energy spectrum. The H_{mo}'s of the incident spectra are separated from the H_{mo}'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_{mo}'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

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

where m_o 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).

$$Q_p = \frac{2}{(m_o)^2} \int f[S(f)]^2 \, df \qquad (2)$$

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

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

or, equivalently,

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

where

ξ = surf parameter

tan α = 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_{mo} 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).

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

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 wav. height is obtained as the product of the reflection coefficient and the ir.ident wave height.

$$H_r = K_r H_{mo} \tag{6}$$

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 spash 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.

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

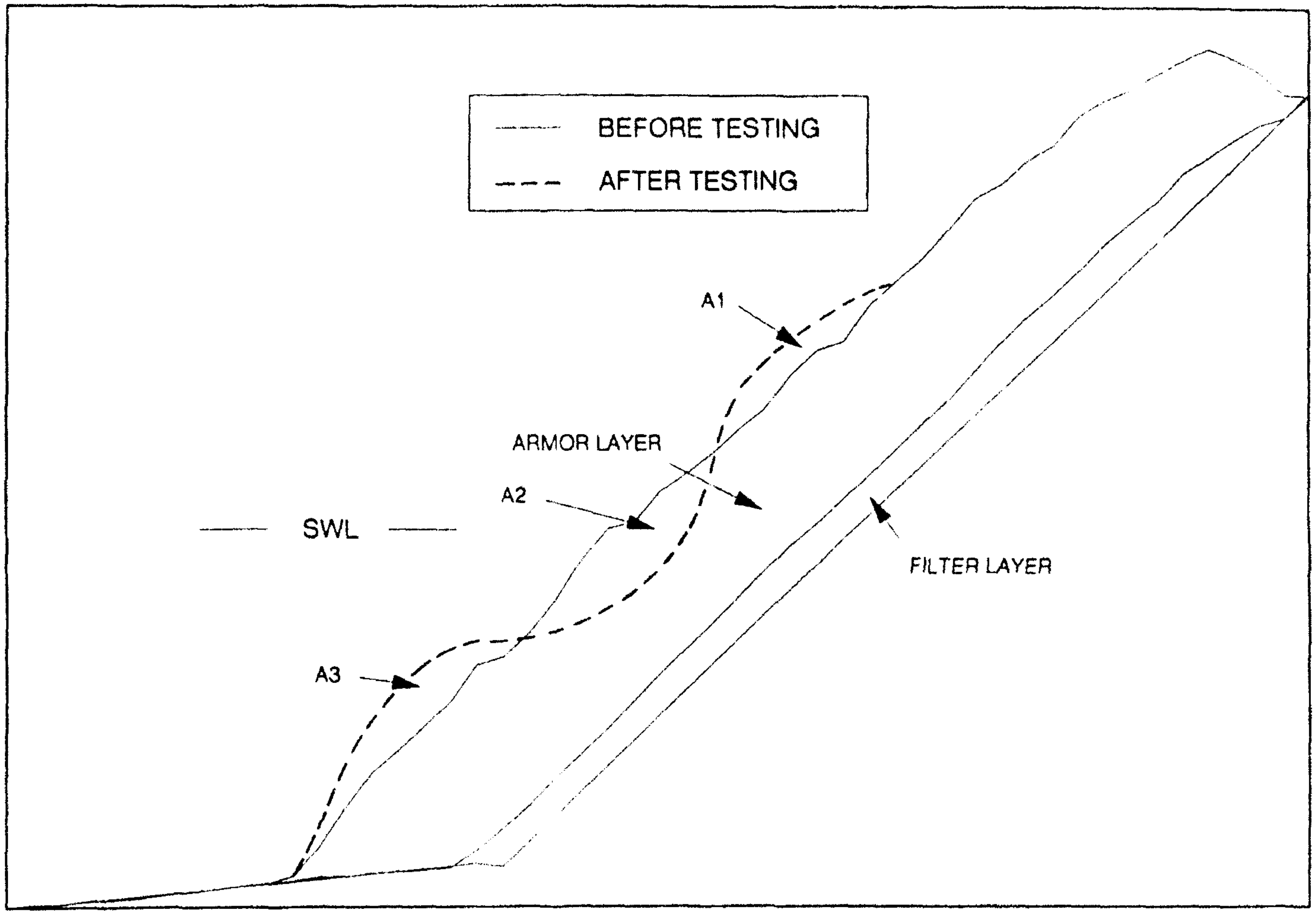

Figure 1. Typical damage profile on a riprap revetment

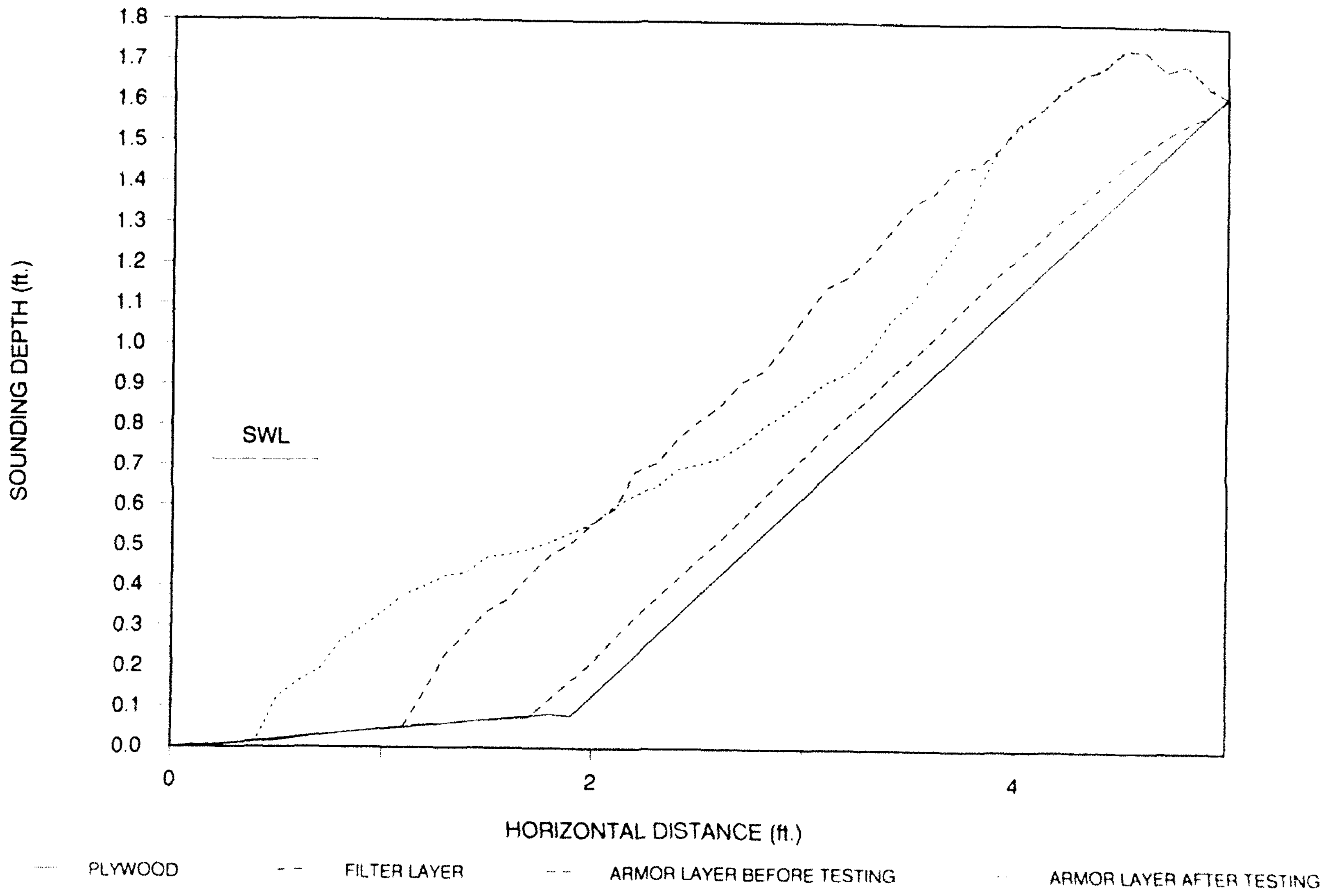

Figure 2. Damage profile from 2.25 sec T_P and 0.50 ft H_{mo}

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

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

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

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

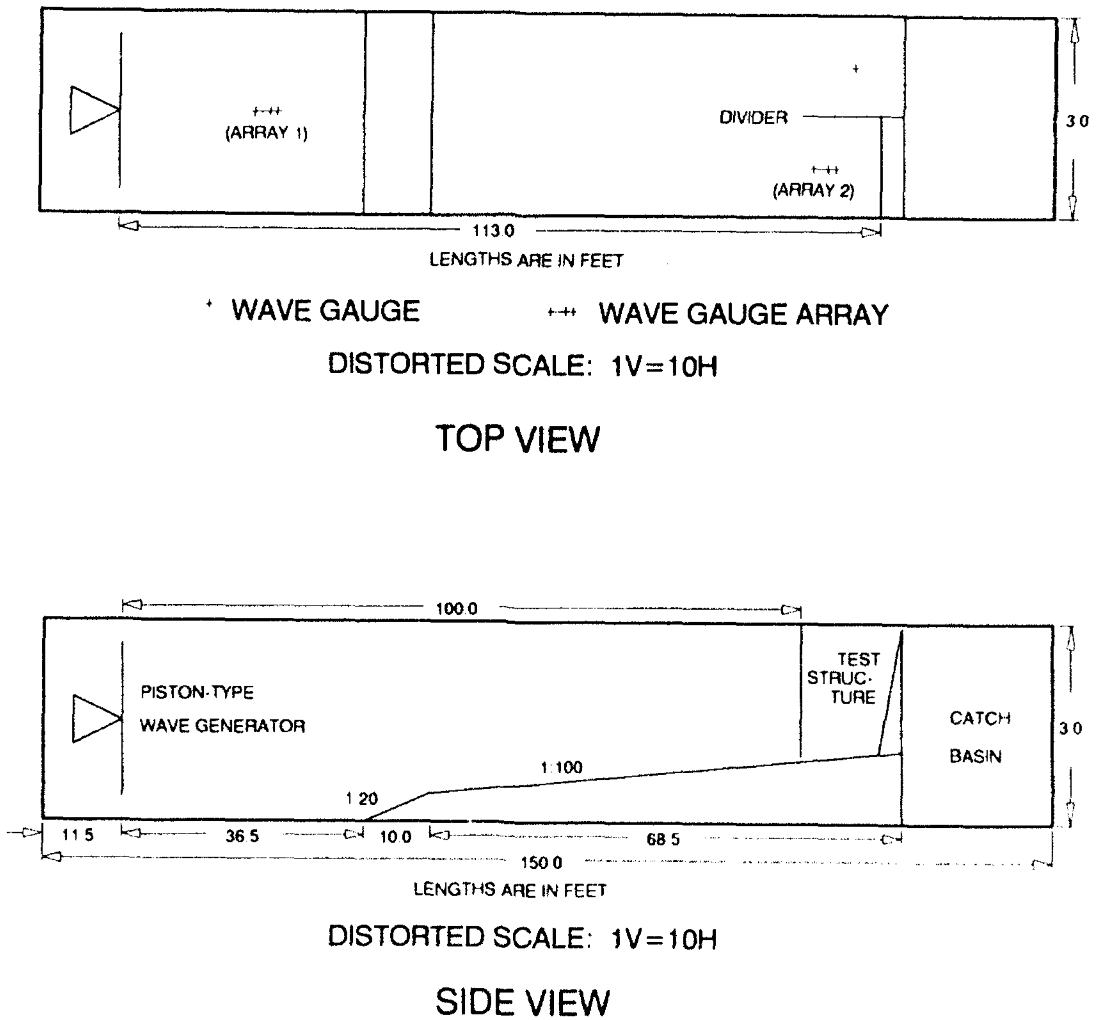
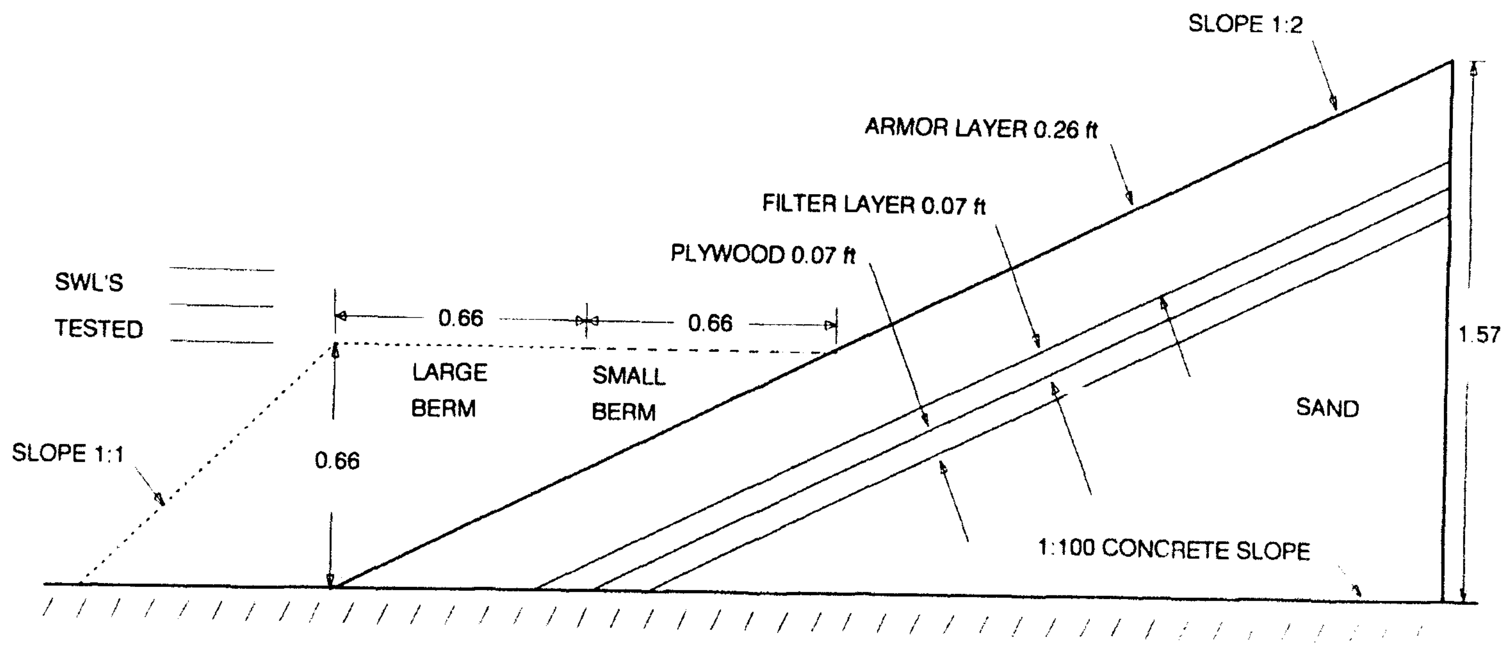


Figure 3. Plan and profile views of wave flume



NOTE: All measurements are in feet.

Figure 4. Test structure cross section including both berms tested

$$\frac{D_{85}}{D_{15}} = 1.79 \tag{9}$$

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

$$\frac{1}{8} W_{50} < W < 4 W_{50} \tag{10}$$

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.

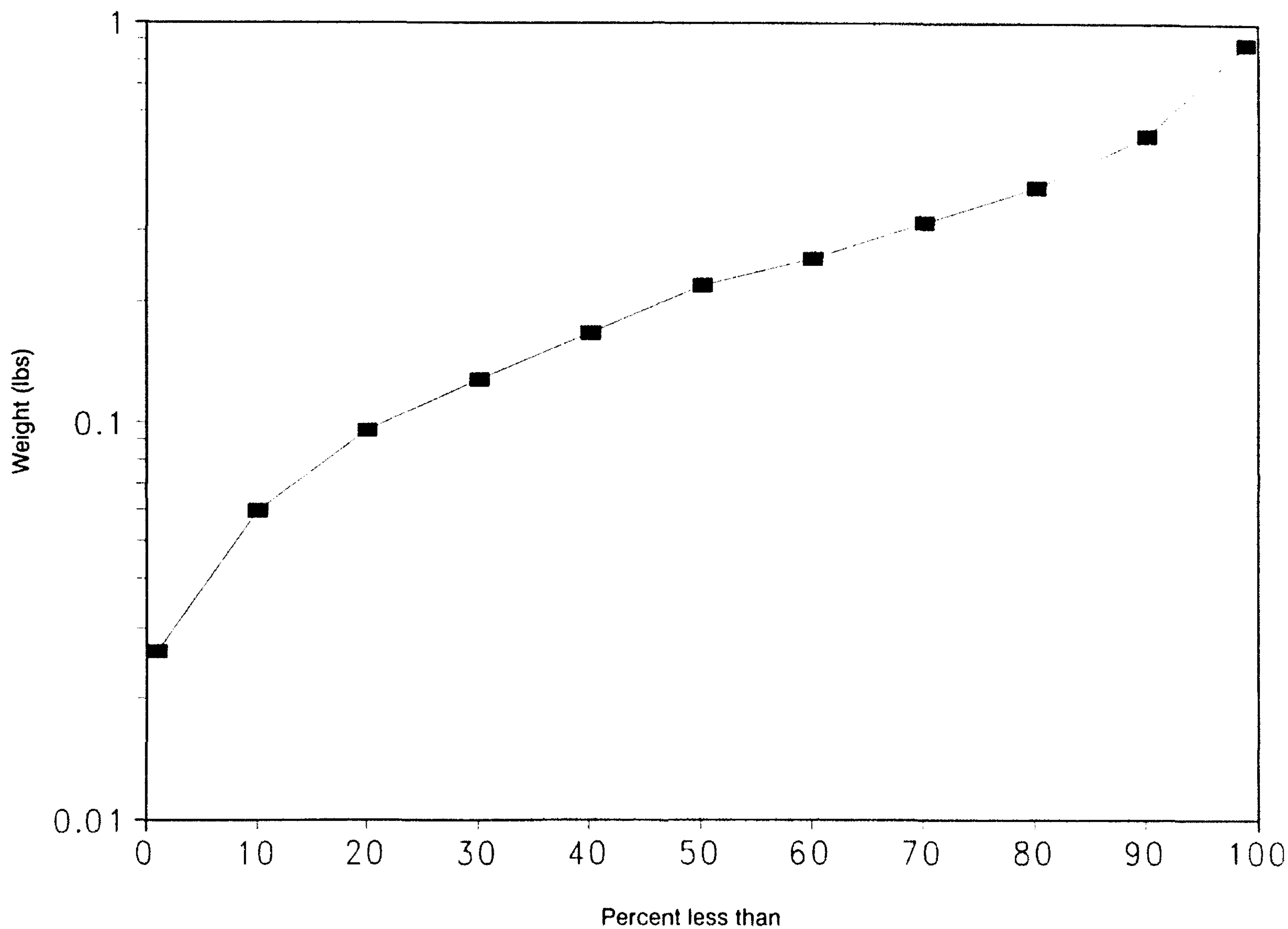


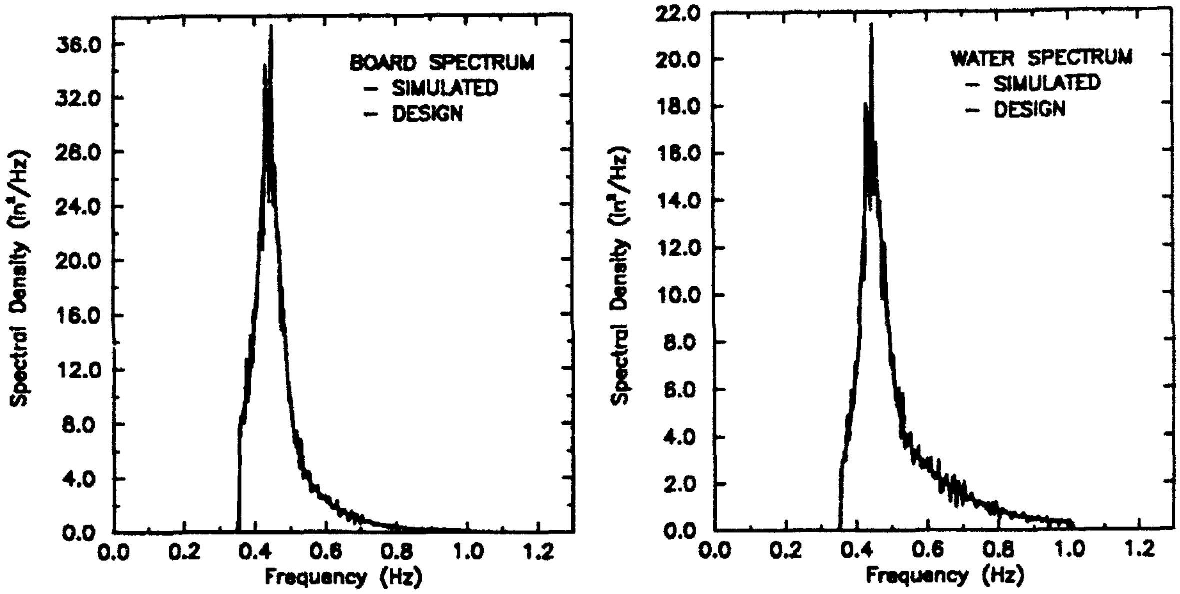
Figure 5. Armor stone gradation

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) WINDOW FRACTION = 0.10
DETREND MODE = 1 (MEAN REMOVED) BANDS AVERAGED = 10
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)

UNIDIRECTIONAL WAVE TANK PISTON-TYPE GENERATOR DIGITAL DRIVER FILE HEADER

OUTPUT FILE – OT2T225H6.DAT
GENERATOR TYPE – PISTON
TRANSFER FUNCTION JOHN AHRENS CORRECTION – NO
SPECTRUM – JONSWAP SPECTRUM 24.000 (INCHES) WATER DEPTH AT BOARD
2.250 (SEC) DESIGN PEAK PERIOD 0.030 X100PCT MO LOW FREQ. CUTOFF
6.000 (INCHES) DESIGN HMO 0.970 X100PCT MO HIGH FREQ. CUTOFF
3.30 GAMMA 1800 (SEC) TIME SERIES LENGTH
0.0700 SIGMA-LOW 10 (STEPS/SEC) UPDATE RATE
0.0900 SIGMA-HIGH 256 LINES IN SOURCE SPECTRUM

0.00319 COMPUTED ALPHA 1989 = RAND. NO. GEN. SEED
7.489 INCHES MAX. POS. BOARD STROKE 16.64 = (IN**2/HZ) DES. H20 SMAX
-8.228 INCHES MAX. NEG. BOARD STROKE 0.4444 = (HZ) DES. PEAK FREQ.
0.3544 (HZ) LOW FREQ. CUTOFF
1.0096 (HZ) HIGH FREQ. CUTOFF

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 (Hasselman 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

$$\frac{R_{max}}{H_{mo}} = \frac{a\,\xi}{1.0 + b\,\xi} \qquad (12)$$

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, $W_B/(H_{mo}L_o)^{1/2}$, 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_{mo}.

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

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.,

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

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

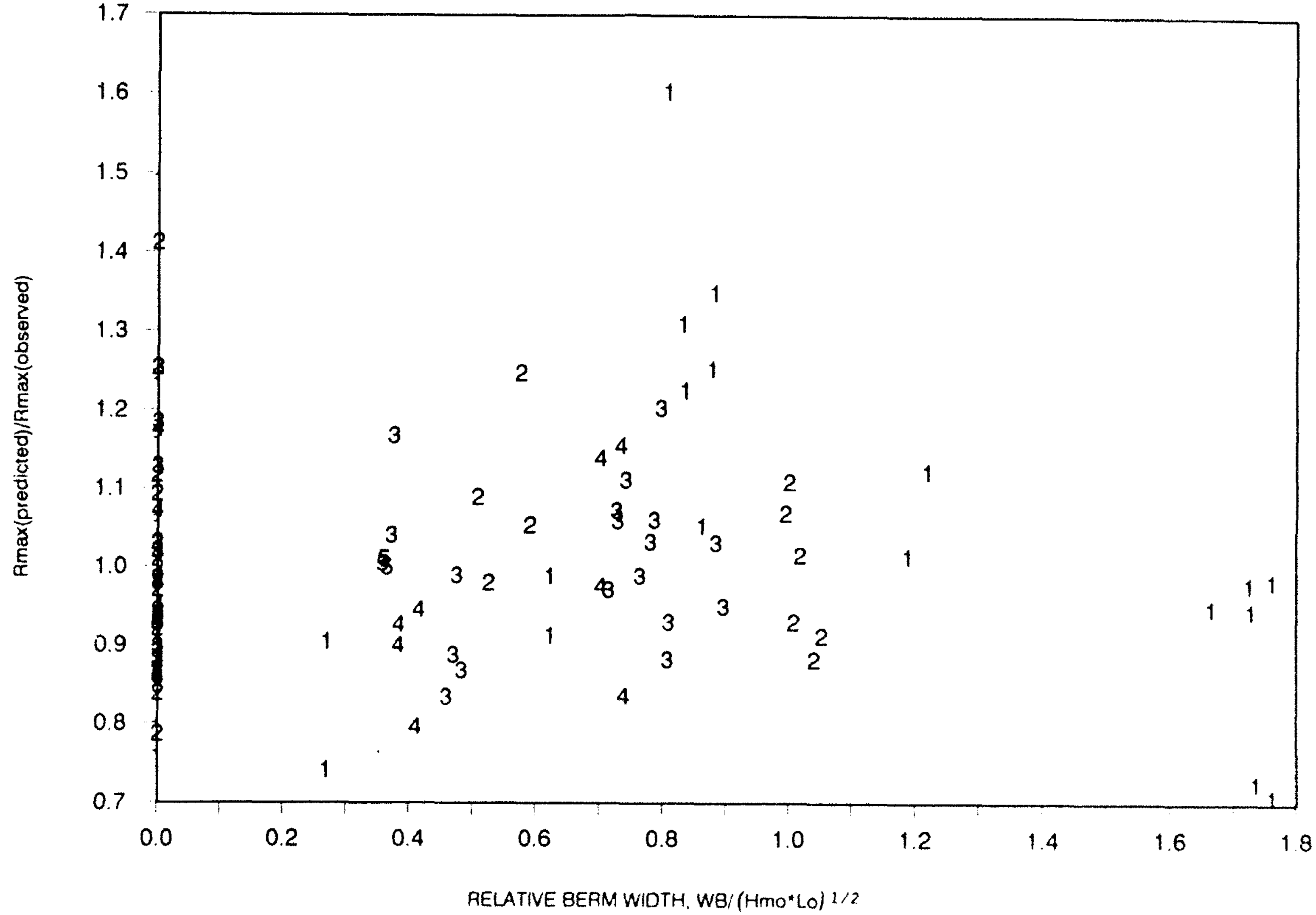


Figure 7. Ratio of predicted to observed runup as a function of relative berm width. Integers denote wave size, $H_{mo}/(D_n)_{50}$

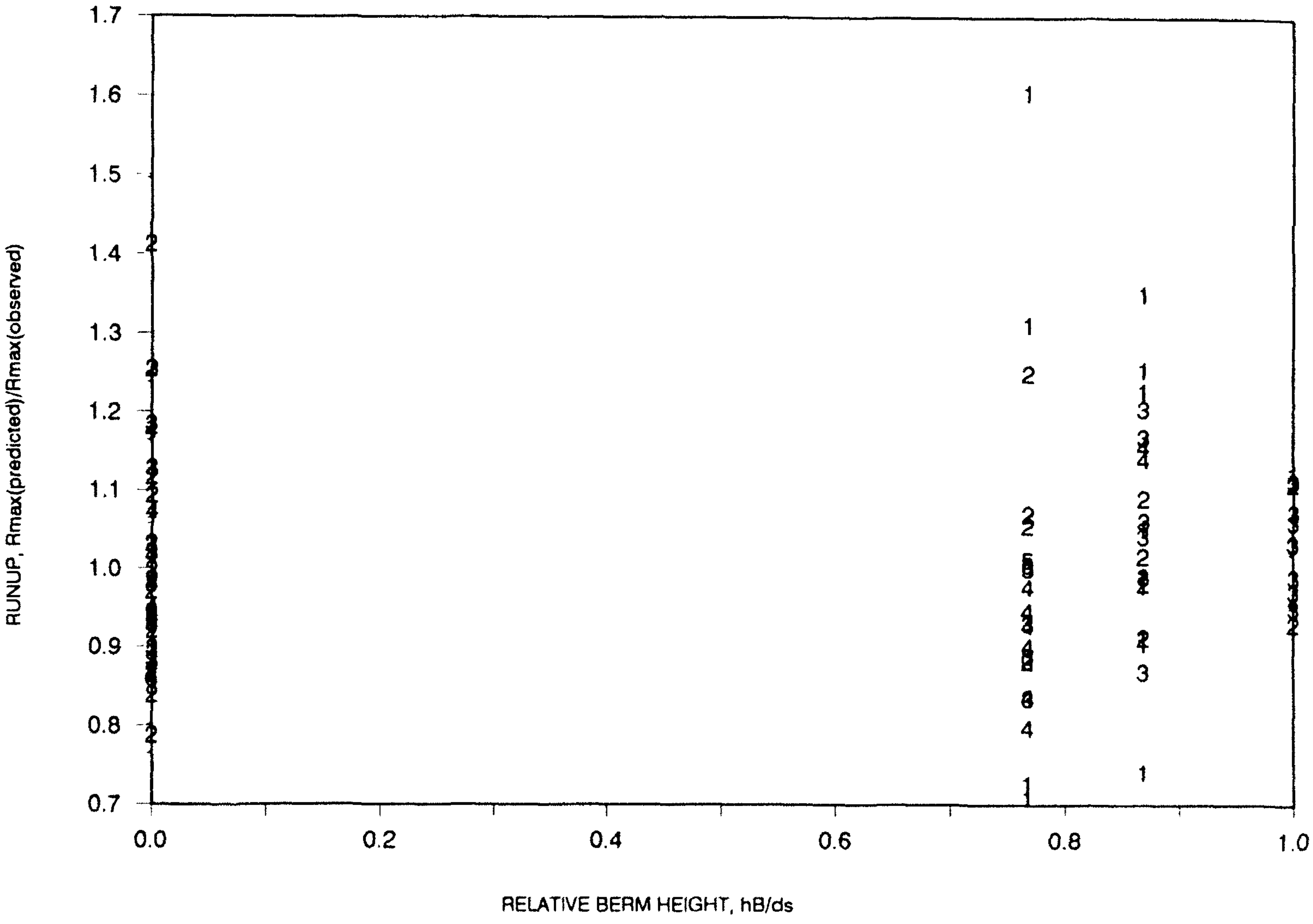


Figure 8. Ratio of predicted to observed runup as a function of relative berm height. Integers denote wave size, $H_{mo}/(D_n)_{50}$

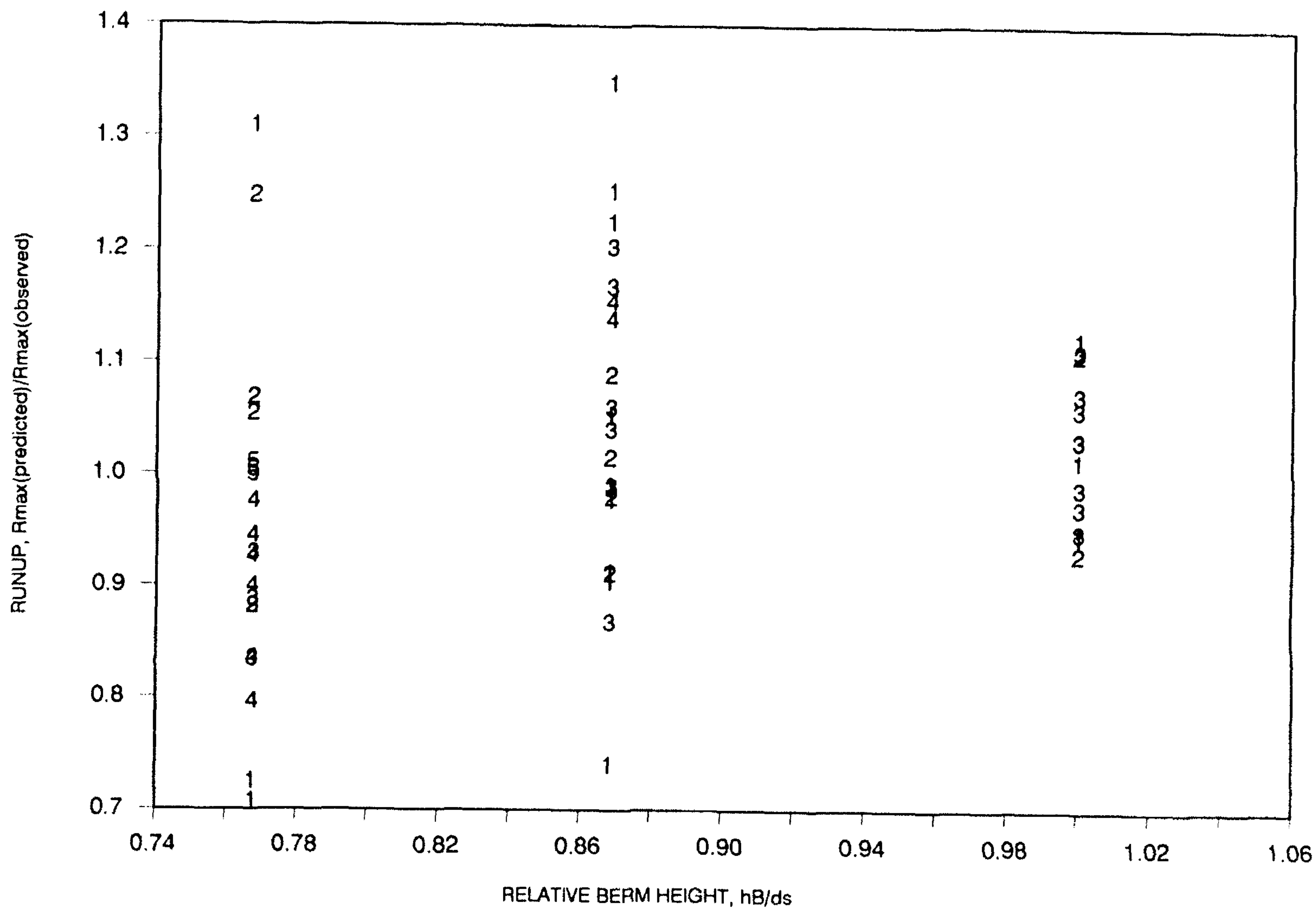


Figure 9. Section taken from Figure 8 enlarged to show detail

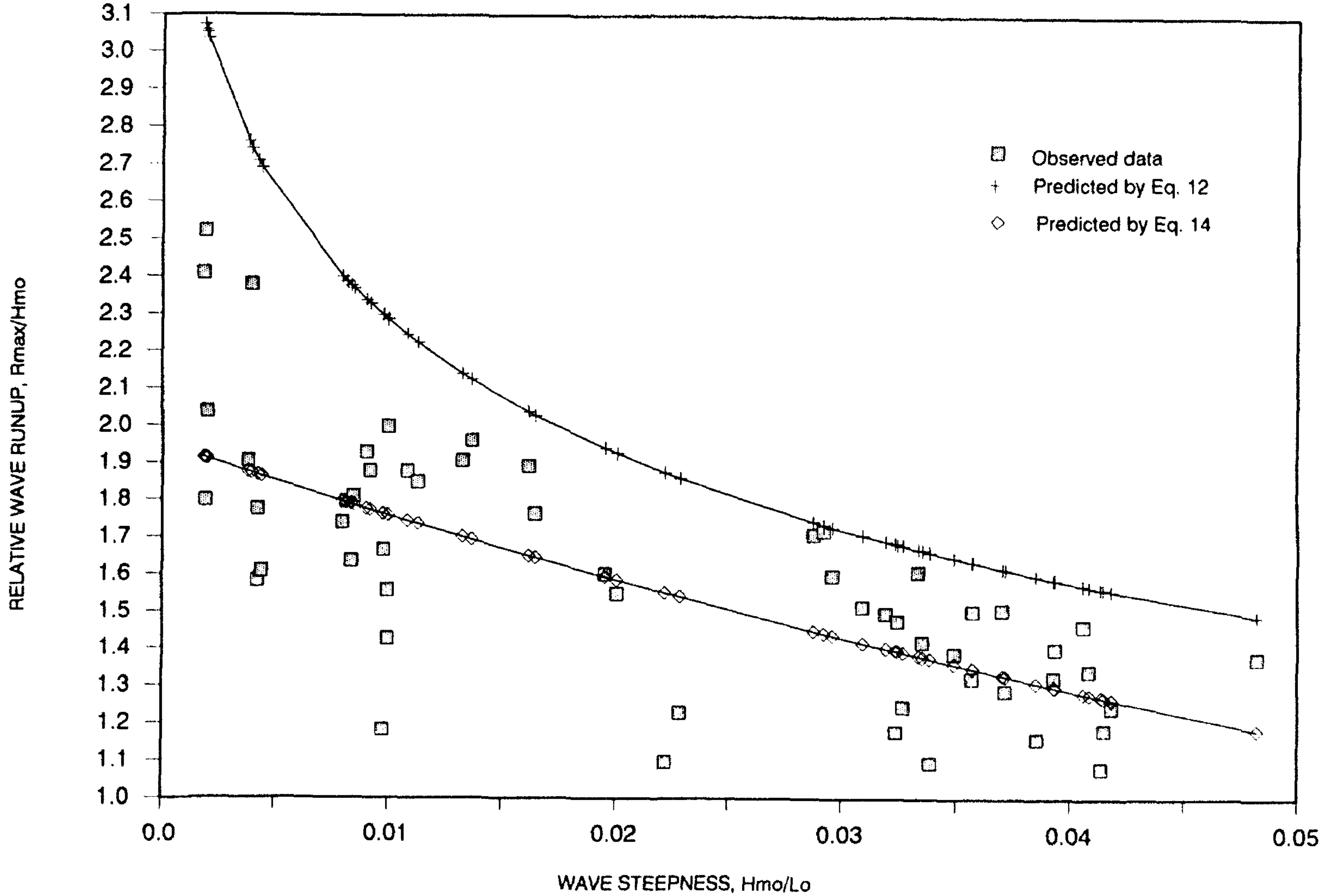


Figure 10. Observed and predicted wave runup as a function of deepwater wave steepness

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

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

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

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

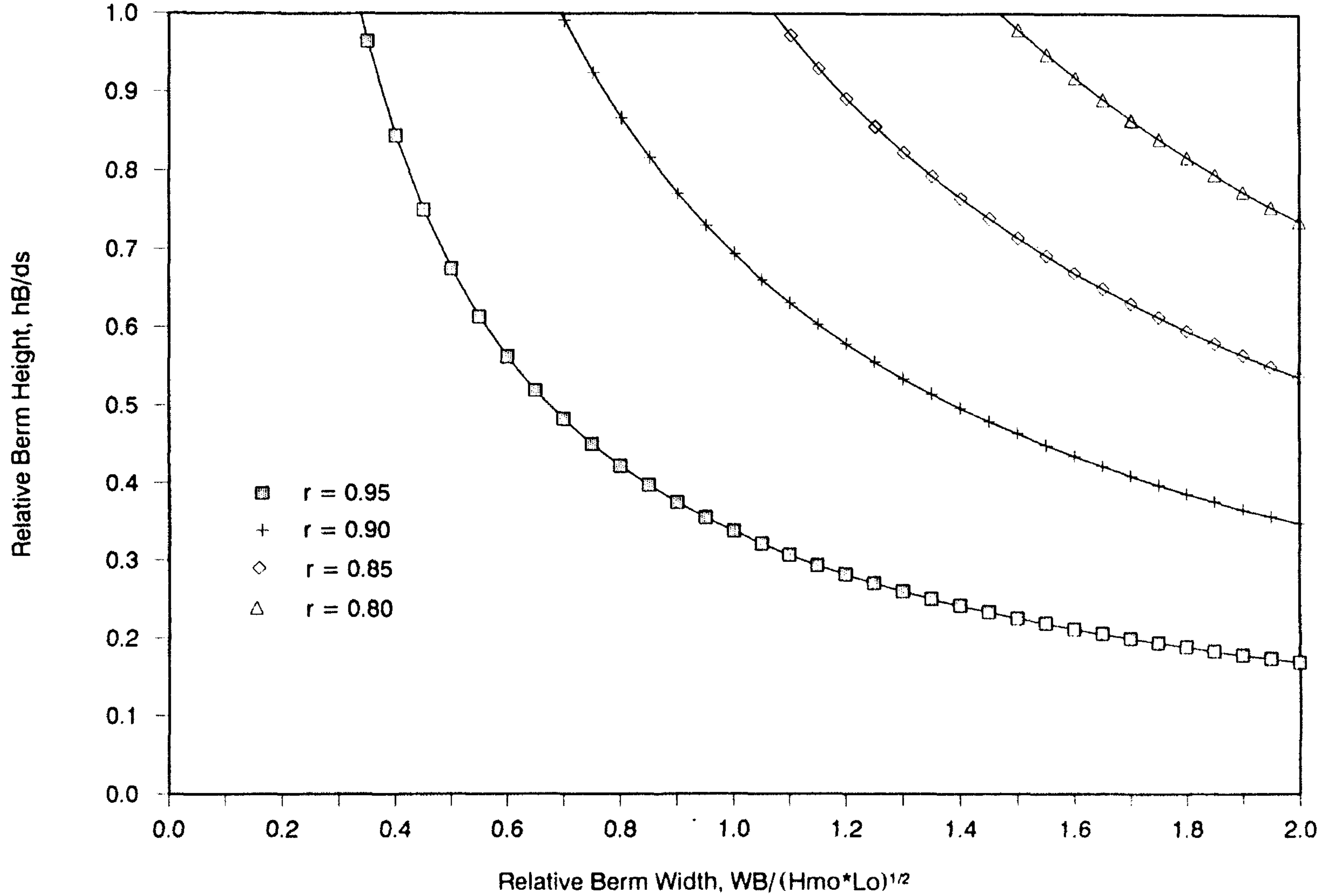


Figure 11. Runup reduction factor, r , as a function of relative berm height and width, using $C_2 = -0.152$ in Equation 15

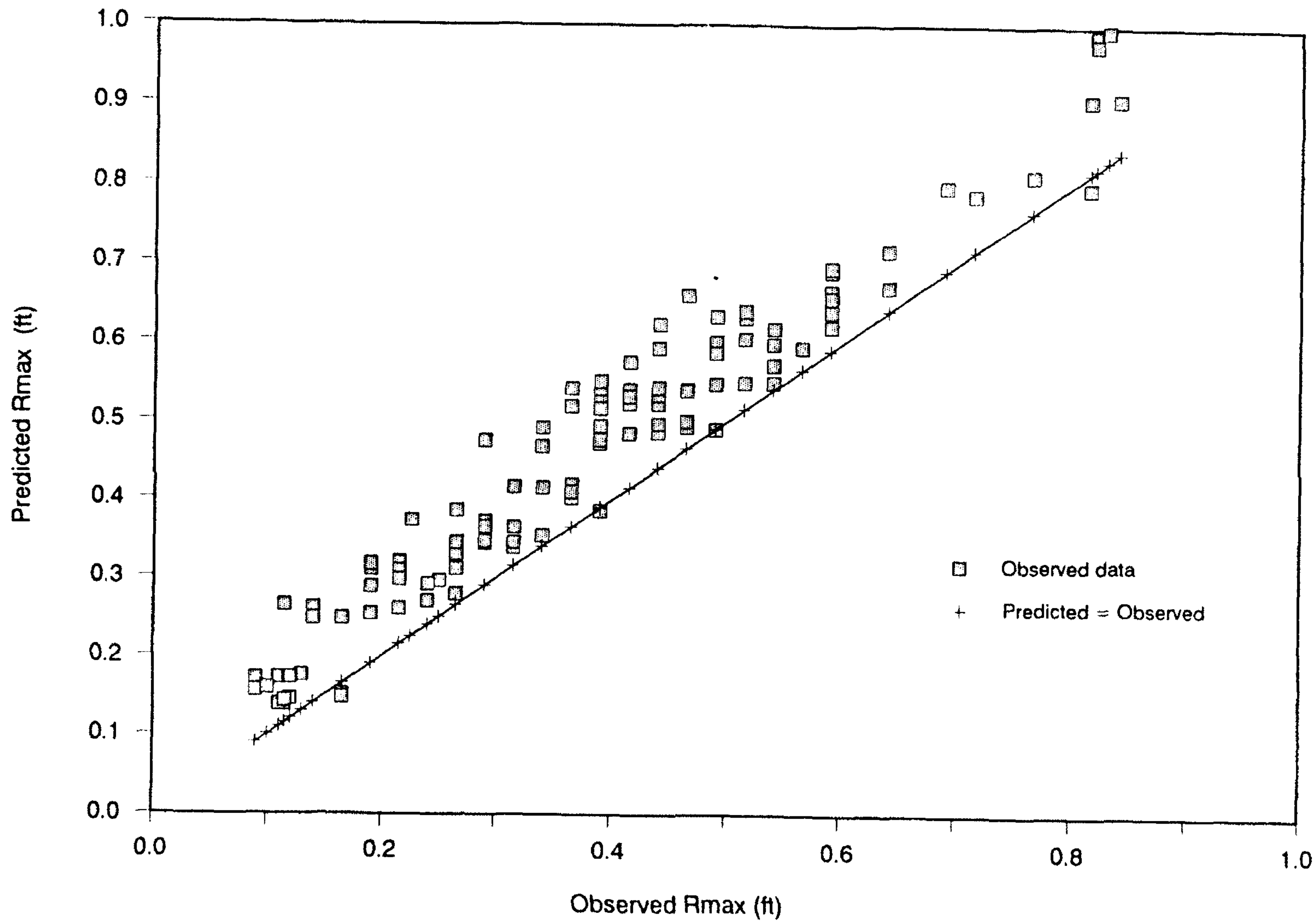
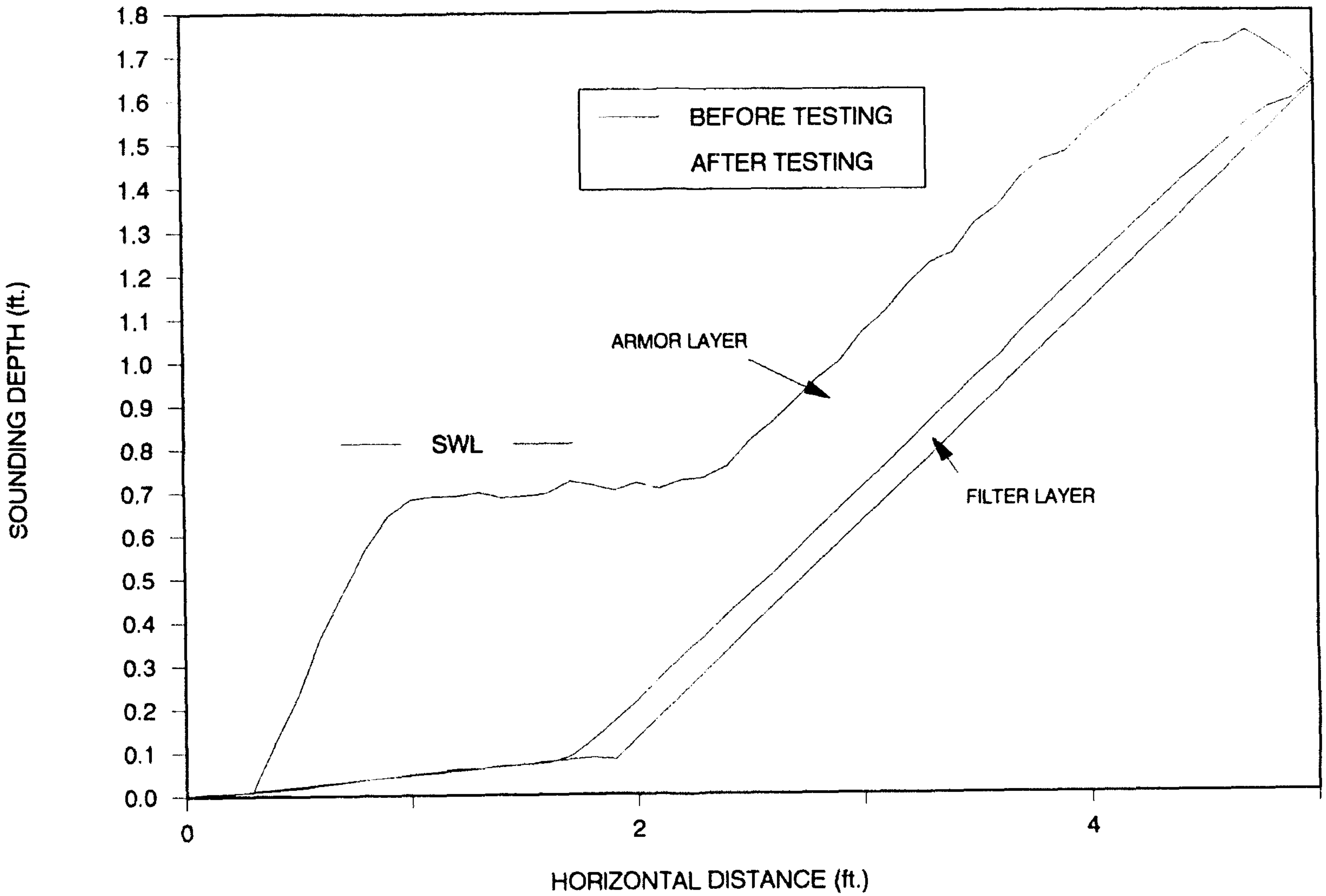


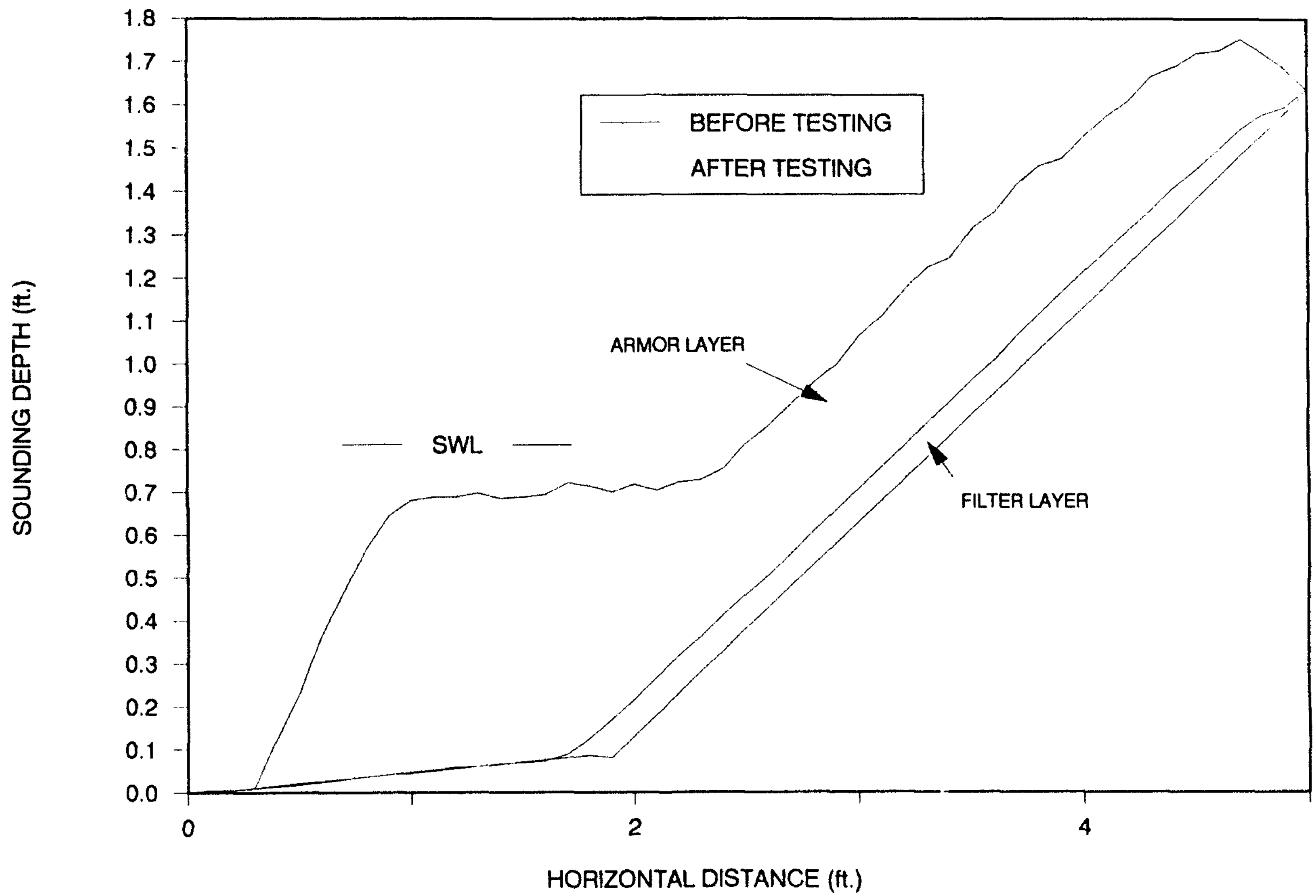
Figure 12. Maximum runup predicted by Equation 16 versus observed maximum runup



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

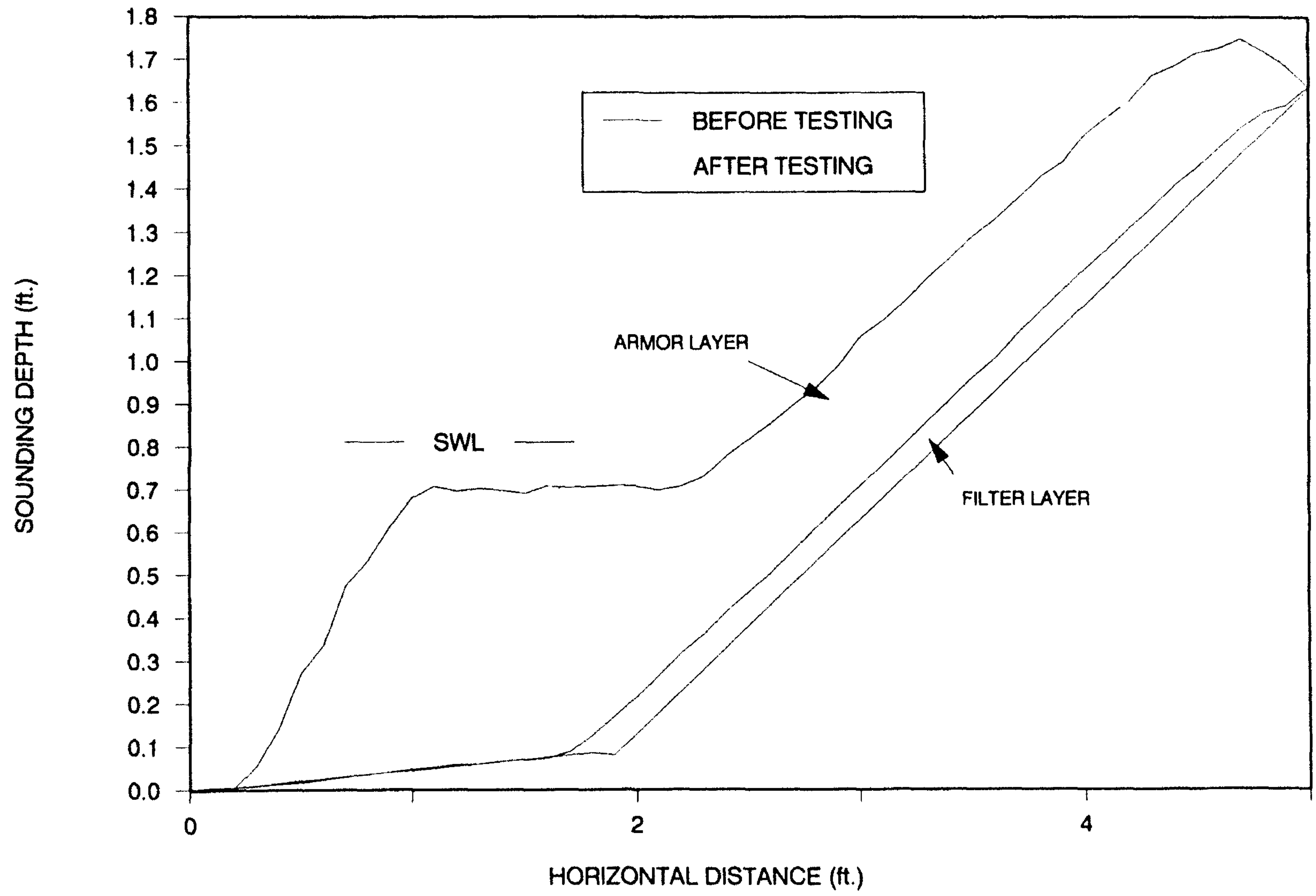
Figure 13. Bermed revetment damage profile after testing

(Sheet 1 of 4)



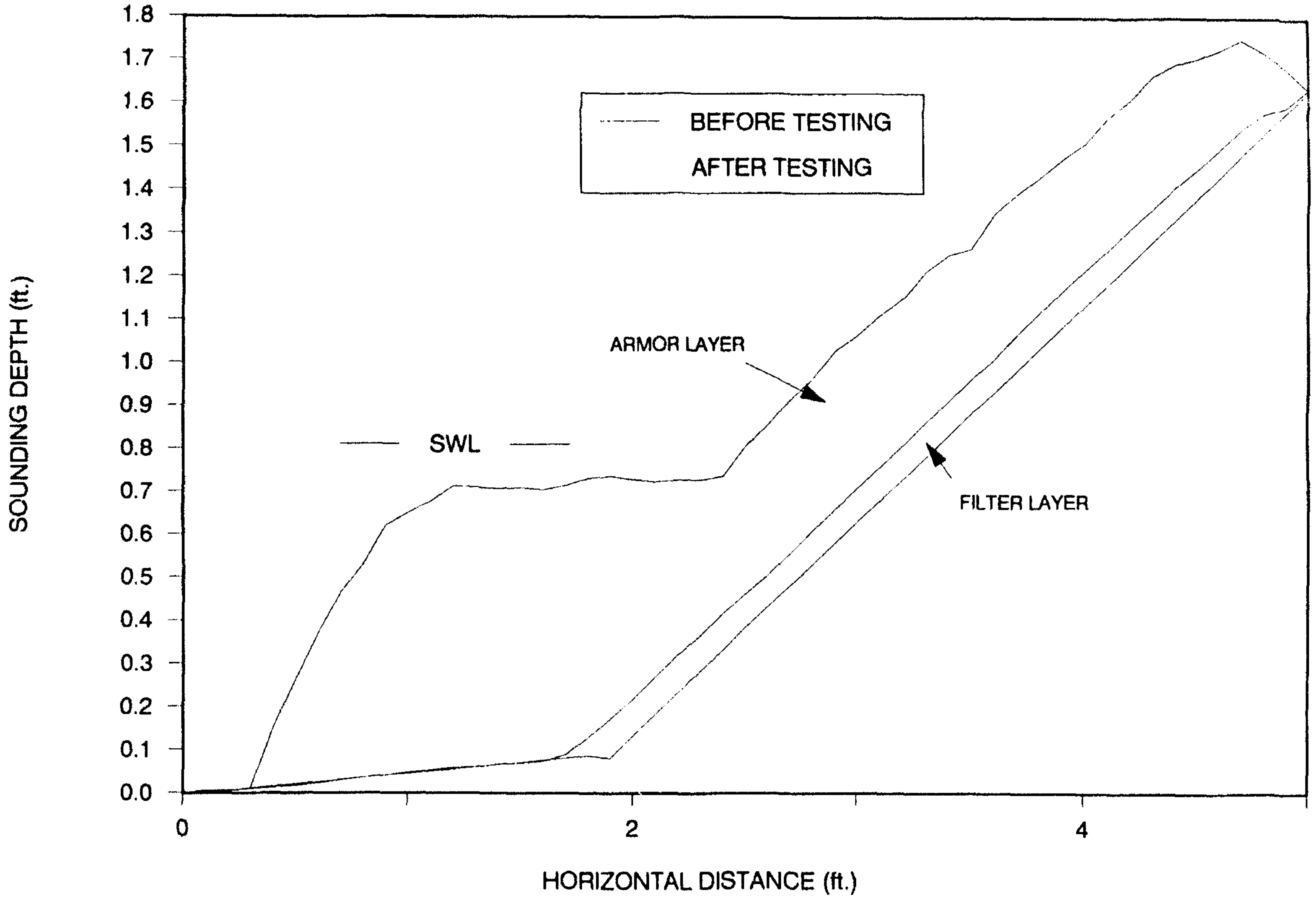
b. T_p = 2.25-sec, H_{mo} = 0.30-ft waves

Figure 13. (Sheet 2 of 4)



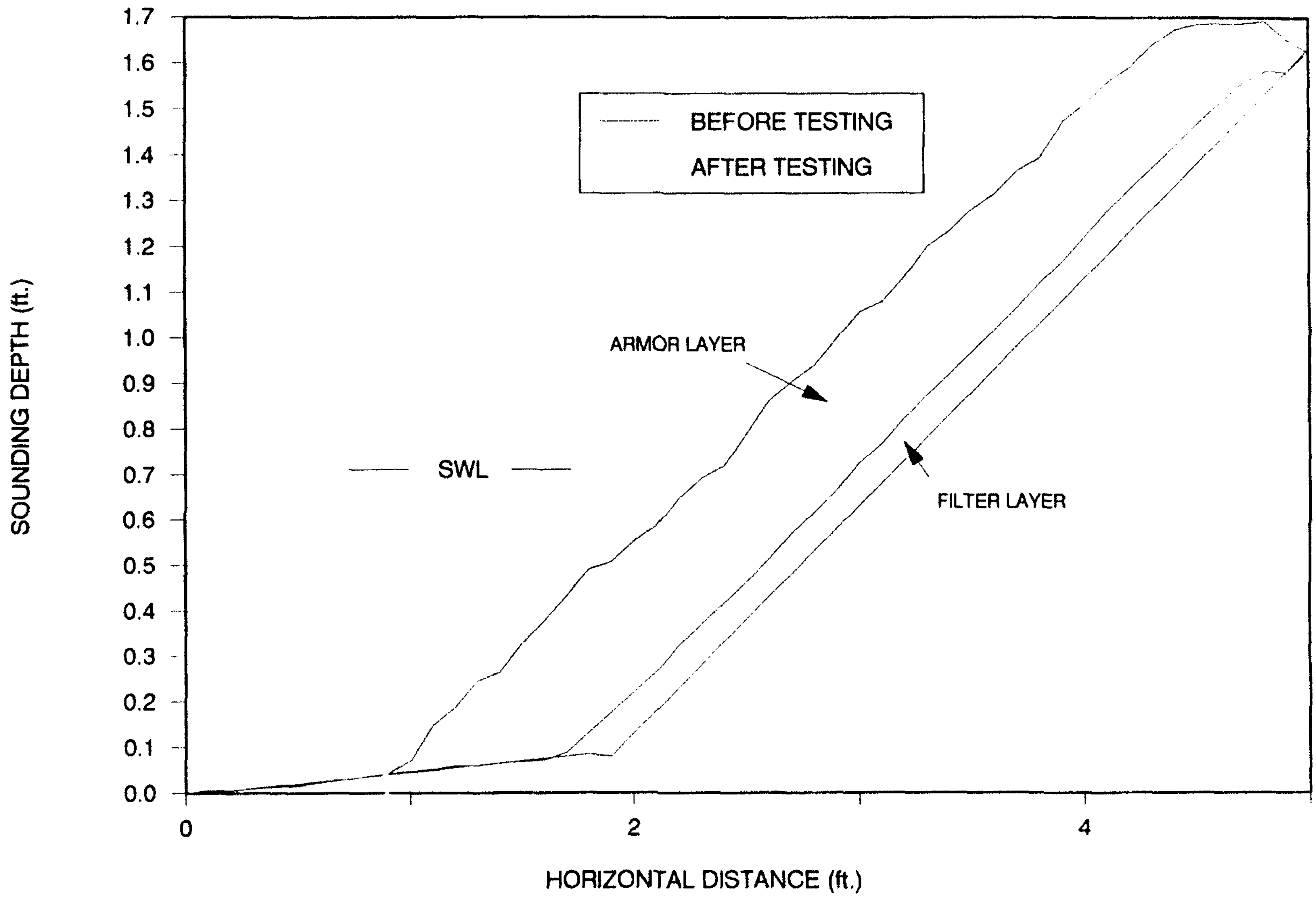
c. T_p = 2.25-sec, H_{mo} = 0.50-ft waves

Figure 13. (Sheet 3 of 4)



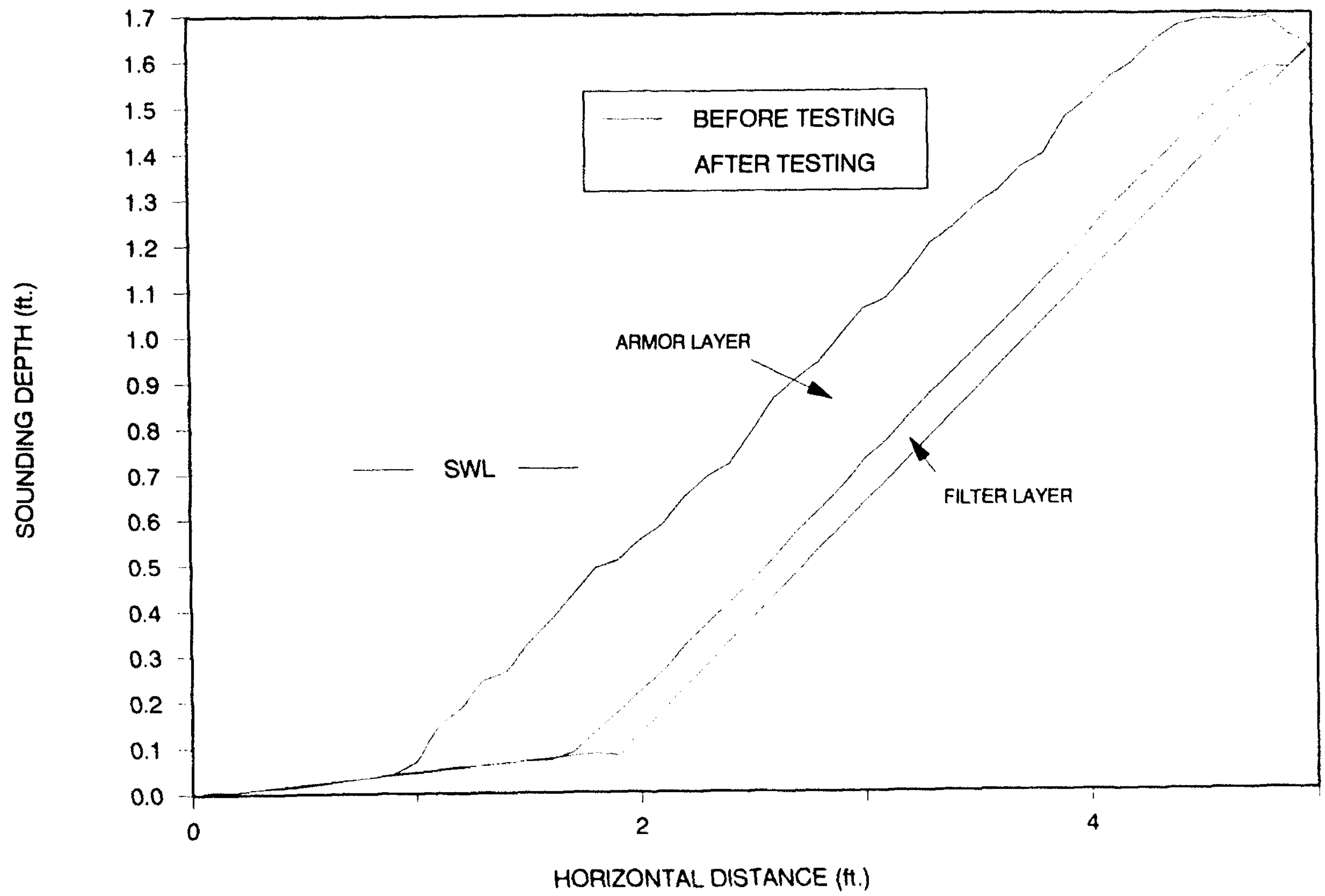
d. T_p = 2.25-sec, H_{mo} = 0.66-ft waves

Figure 13. (Sheet 4 of 4)



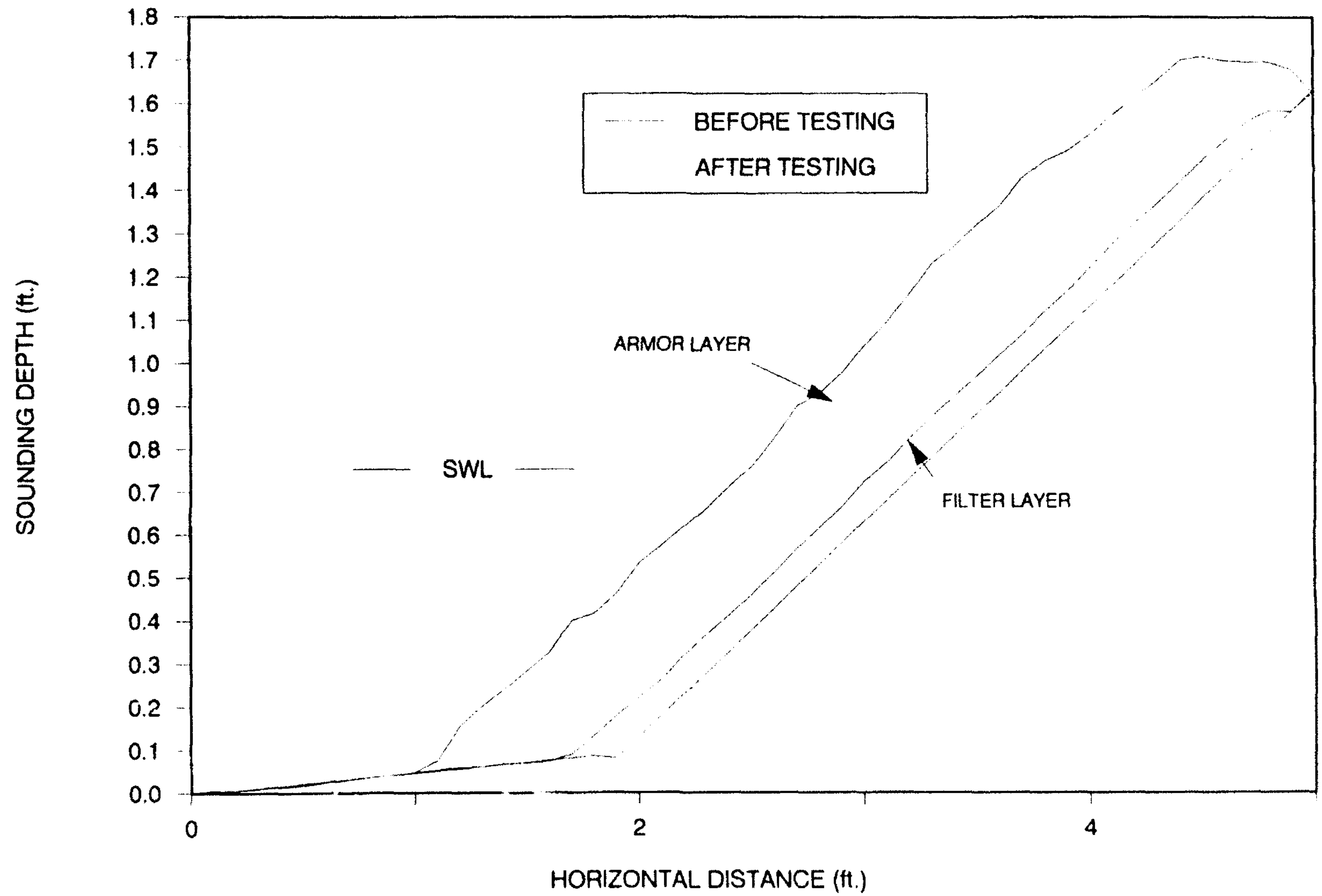
a. T_p = 2.25-sec, H_{mo} = 0.10-ft waves

Figure 14. Revetment damage profile after testing (Sheet 1 of 4)



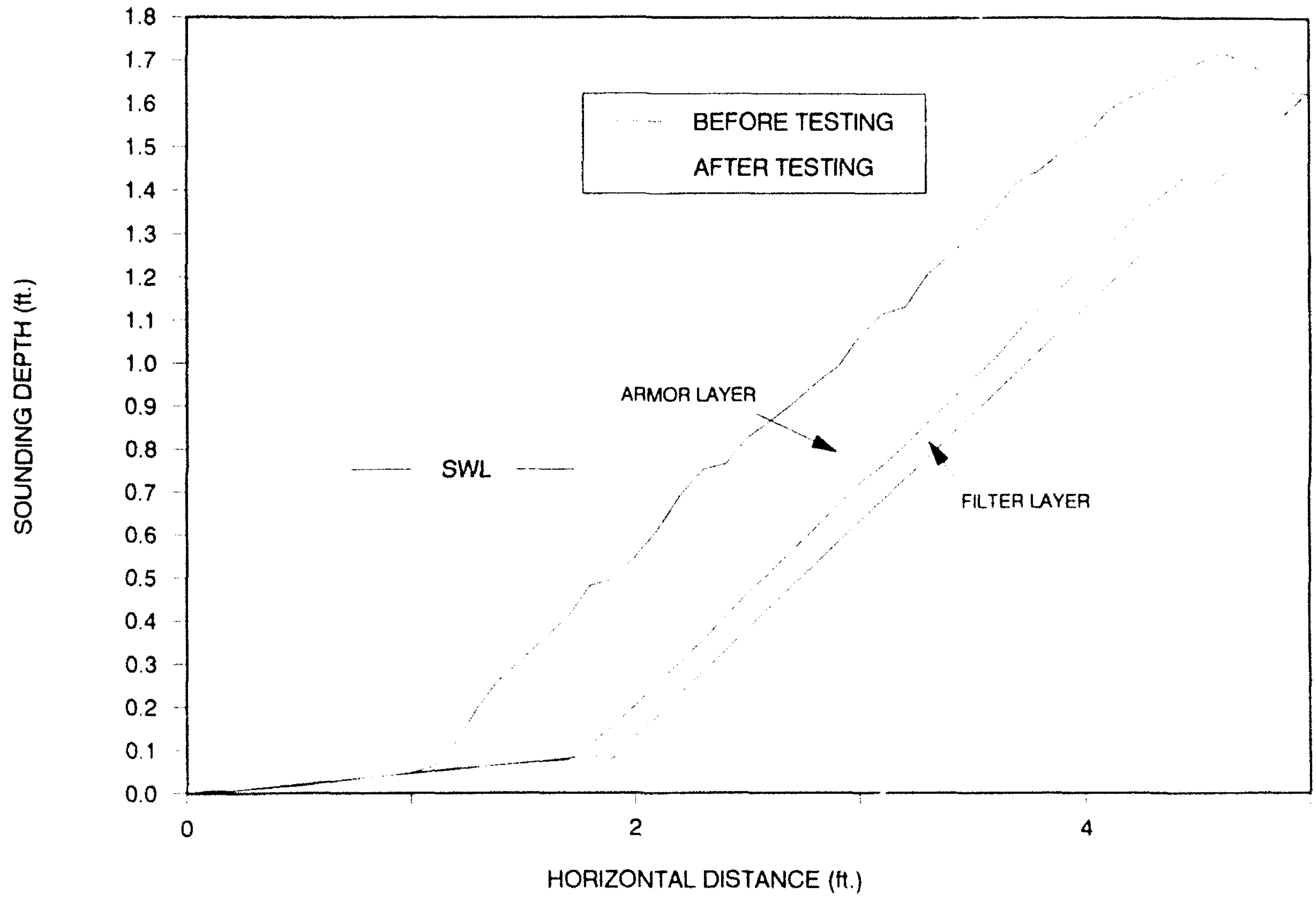
b. T_p = 2.25-sec, H_{mo} = 0.20-ft waves

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.

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

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

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

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

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:

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

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

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.

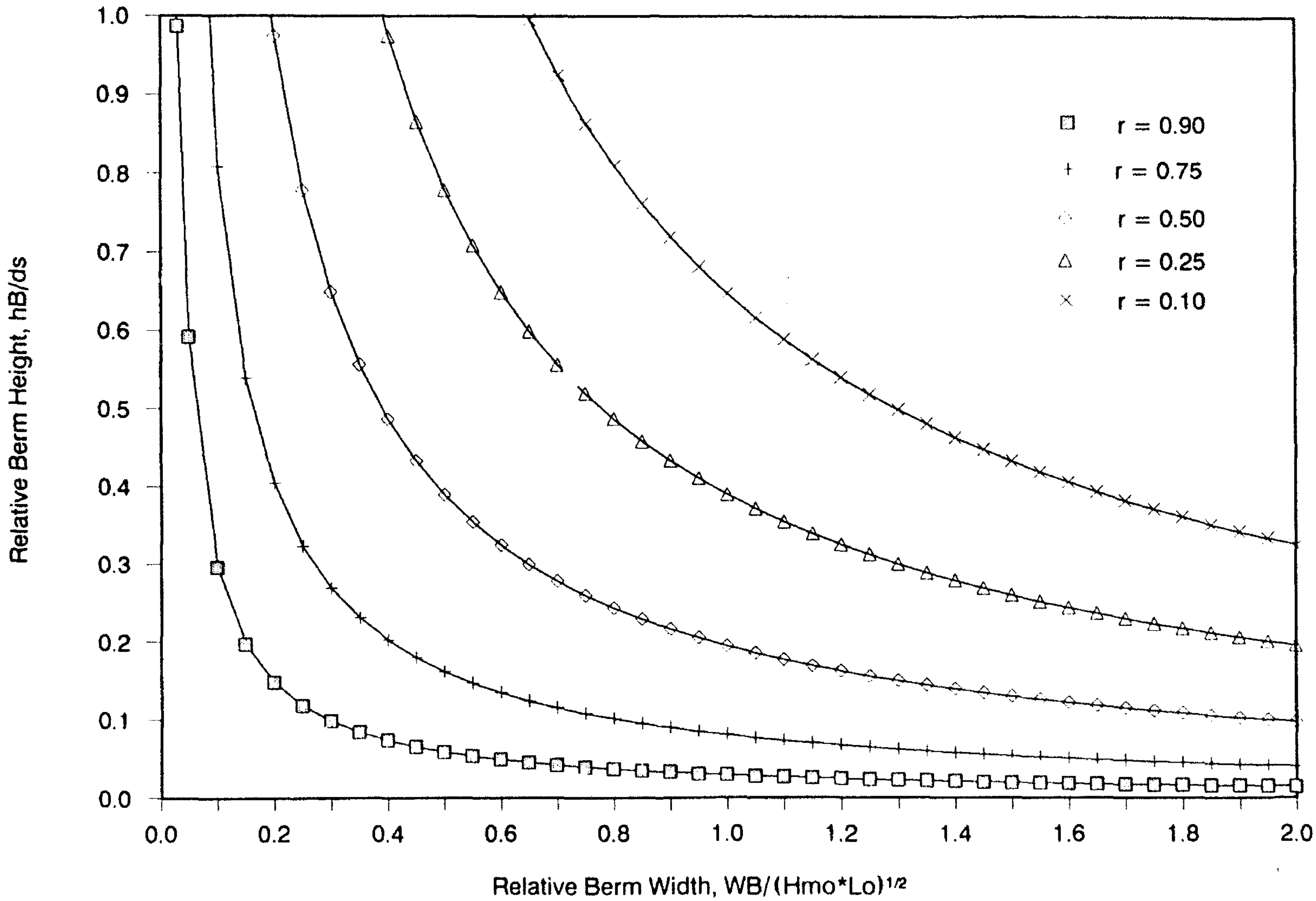


Figure 15. S_2 damage reduction factor, r_s, as a function of berm height and width

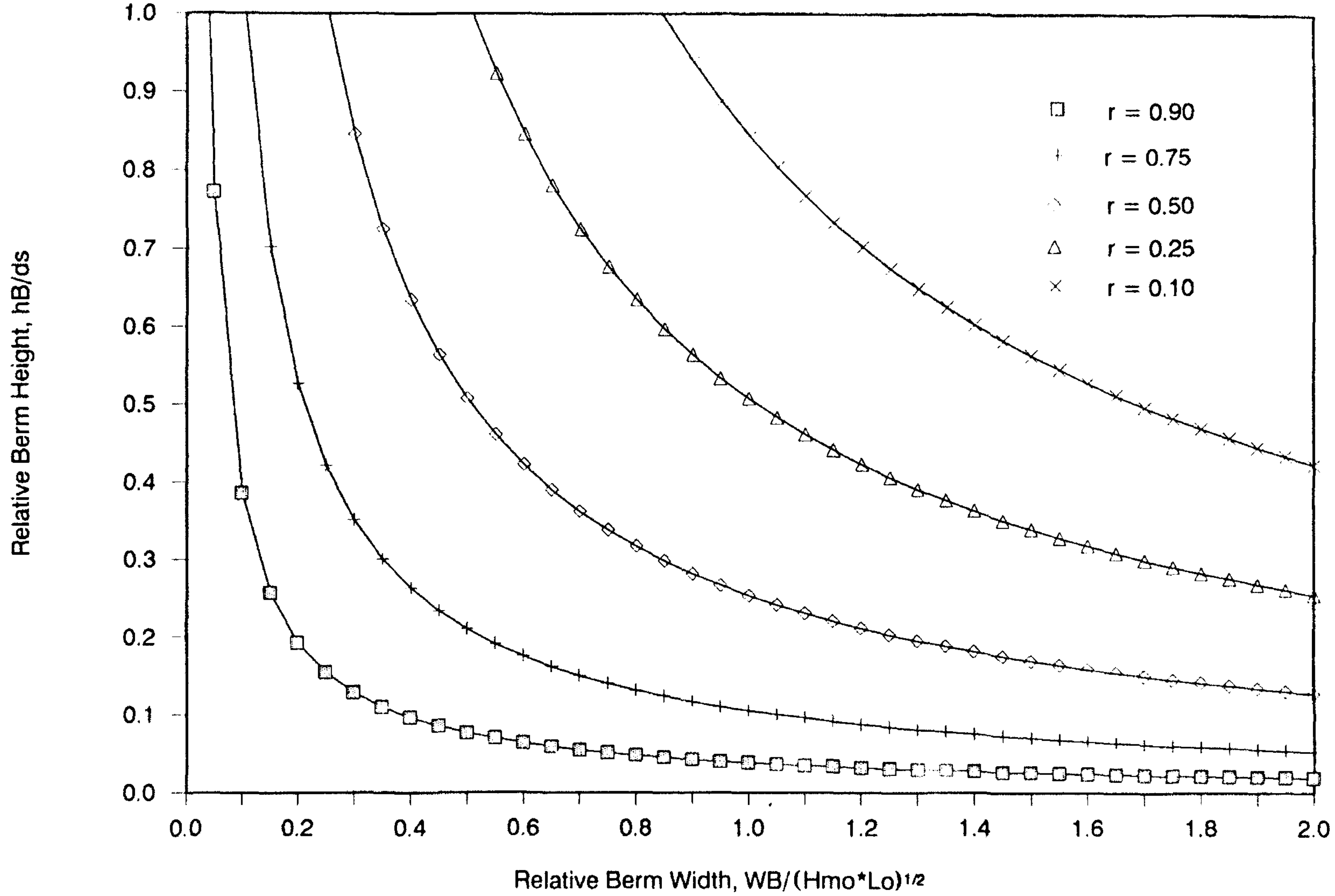


Figure 16. Erosion reduction factor, r_e, as a function of berm height and width

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 $r_s = 0.085$ (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 Priod Data for Revetment Without Berm

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 INCIDENT PEAK PER Tp(1) (sec)	ARRAY 2 INCIDENT PEAK PER Tp(2) (sec)	ARRAY 1 INCIDENT WAVE HT Hmo(1) (ft)	ARRAY 2 INCIDENT WAVE HT Hmo(2) (ft)	ARRAY 1 INCIDENT AVE PER Tz(1) (sec)	ARRAY 2 INCIDENT AVE PER Tz(2) (sec)	ARRAY 1 UPCROSS SIG HT Hs(1) (ft)	ARRAY 2 UPCROSS SIG HT Hs(2) (ft)
1a	0.66	1.25	0.10	1.258	1.226	0.084	0.078	1.199	1.246	0.089	0.087
1c	0.66	1.25	0.10	1.247	1.247	0.085	0.079	1.197	1.250	0.087	0.088
2a	0.66	1.25	0.20	1.258	1.226	0.170	0.158	1.202	1.256	0.180	0.175
2c	0.66	1.25	0.20	1.247	1.247	0.172	0.158	1.200	1.264	0.179	0.178
3a	0.66	1.25	0.30	1.258	1.234	0.262	0.244	1.207	1.272	0.284	0.275
3c	0.66	1.25	0.30	1.247	1.231	0.260	0.230	1.200	1.279	0.271	0.267
4a	0.66	1.25	0.40	1.258	1.369	0.336	0.294	1.206	1.286	0.353	0.335
4c	0.66	1.25	0.40	1.247	1.389	0.339	0.289	1.205	1.289	0.356	0.332
5a	0.66	1.25	0.50	1.258	1.369	0.413	0.335	1.214	1.302	0.432	0.375
5c	0.66	1.25	0.50	1.247	1.413	0.414	0.336	1.209	1.304	0.423	0.381
6a	0.66	1.25	0.60	1.267	1.369	0.460	0.346	1.218	1.315	0.467	0.378
6c	0.66	1.25	0.60	1.247	1.402	0.462	0.340	1.217	1.318	0.463	0.382
7a	0.66	1.25	0.66	1.267	1.382	0.513	0.388	1.228	1.323	0.519	0.418
7c	0.66	1.25	0.66	1.247	1.406	0.519	0.379	1.224	1.319	0.514	0.414
8a	0.66	2.25	0.10	2.338	2.338	0.101	0.120	1.917	1.933	0.099	0.130
8e	0.66	2.25	0.10	2.222	2.353	0.100	0.121	1.913	1.933	0.099	0.132
9a	0.66	2.25	0.20	2.338	2.338	0.203	0.232	1.900	1.808	0.201	0.263
9e	0.66	2.25	0.20	2.222	2.222	0.203	0.234	1.895	1.820	0.203	0.264
10a	0.66	2.25	0.30	2.338	2.338	0.302	0.319	1.881	1.737	0.300	0.378
10e	0.66	2.25	0.30	2.222	2.500	0.298	0.320	1.877	1.772	0.299	0.376
11a	0.66	2.25	0.40	2.137	2.338	0.397	0.375	1.855	1.685	0.395	0.460
11e	0.66	2.25	0.40	2.222	2.363	0.400	0.390	1.855	1.705	0.403	0.465
12a	0.66	2.25	0.50	2.154	2.419	0.495	0.423	1.828	1.673	0.496	0.513
12c	0.66	2.25	0.50	2.205	2.435	0.495	0.428	1.839	1.694	0.487	0.510
13a	0.66	3.50	0.10	3.638	3.653	0.099	0.133	2.875	2.495	0.095	0.192
14a	0.66	3.50	0.20	3.608	3.608	0.204	0.252	2.756	2.054	0.203	0.368
14g	0.66	3.50	0.20	3.564	3.638	0.206	0.252	2.781	2.064	0.205	0.360
15a	0.66	3.50	0.30	3.550	3.608	0.303	0.338	2.605	1.885	0.308	0.493
15g	0.66	3.50	0.30	3.564	3.638	0.305	0.339	2.621	1.905	0.306	0.483
16a	0.66	3.50	0.40	3.521	3.608	0.408	0.399	2.437	1.841	0.422	0.571
16d	0.66	3.50	0.40	3.493	3.623	0.413	0.405	2.500	1.841	0.424	0.562
17a	0.76	1.25	0.10	1.258	1.234	0.086	0.076	1.200	1.237	0.091	0.086
17c	0.76	1.25	0.10	1.247	1.229	0.087	0.078	1.201	1.239	0.091	0.086
18a	0.76	1.25	0.20	1.258	1.234	0.173	0.176	1.202	1.224	0.185	0.178
18c	0.76	1.25	0.20	1.247	1.223	0.175	0.178	1.202	1.221	0.184	0.179
19a	0.76	1.25	0.30	1.258	1.229	0.257	0.257	1.204	1.235	0.275	0.263
19c	0.76	1.25	0.30	1.247	1.223	0.259	0.260	1.201	1.232	0.273	0.268
20a	0.76	1.25	0.40	1.267	1.386	0.337	0.338	1.208	1.247	0.359	0.346
20c	0.76	1.25	0.40	1.247	1.413	0.338	0.334	1.205	1.241	0.356	0.347
21a	0.76	1.25	0.50	1.258	1.386	0.418	0.385	1.215	1.263	0.439	0.388
21c	0.76	1.25	0.50	1.247	1.413	0.418	0.383	1.210	1.251	0.430	0.390
22a	0.76	1.25	0.60	1.258	1.386	0.479	0.413	1.222	1.281	0.494	0.419
22c	0.76	1.25	0.60	1.247	1.396	0.481	0.419	1.219	1.266	0.484	0.422

(Continued)

Table A1 (Concluded)

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 INCIDENT PEAK PER Tp(1) (sec)	ARRAY 2 INCIDENT PEAK PER Tp(2) (sec)	ARRAY 1 INCIDENT WAVE HT Hmo(1) (ft)	ARRAY 2 INCIDENT WAVE HT Hmo(2) (ft)	ARRAY 1 INCIDENT AVE PER Tz(1) (sec)	ARRAY 2 INCIDENT AVE PER Tz(2) (sec)	ARRAY 1 UPCROSS SIG HT Hs(1) (ft)	ARRAY 2 UPCROSS SIG HT Hs(2) (ft)
23a	0.76	1.25	0.66	1.258	1.386	0.520	0.404	1.230	1.327	0.530	0.437
23c	0.76	1.25	0.66	1.247	1.392	0.523	0.407	1.225	1.311	0.520	0.441
24a	0.76	2.25	0.10	2.282	2.282	0.103	0.118	1.916	1.953	0.100	0.124
24e	0.76	2.25	0.10	2.287	2.287	0.101	0.118	1.907	1.955	0.101	0.127
25a	0.76	2.25	0.20	2.268	2.299	0.200	0.221	1.890	1.847	0.199	0.246
25e	0.76	2.25	0.20	2.273	2.273	0.202	0.227	1.893	1.843	0.203	0.254
26a	0.76	2.25	0.30	2.178	2.381	0.296	0.314	1.884	1.773	0.291	0.352
26e	0.76	2.25	0.30	2.252	2.283	0.297	0.315	1.884	1.757	0.298	0.359
27a	0.76	2.25	0.40	2.247	2.381	0.393	0.399	1.869	1.695	0.395	0.468
27c	0.76	2.25	0.40	2.262	2.415	0.401	0.410	1.879	1.707	0.392	0.460
28a	0.76	3.00	0.10	2.990	3.543	0.100	0.124	2.502	2.620	0.099	0.126
28f	0.76	3.00	0.10	2.990	3.550	0.101	0.128	2.510	2.637	0.098	0.130
29a	0.76	3.00	0.20	2.960	3.544	0.200	0.242	2.427	2.383	0.198	0.260
29f	0.76	3.00	0.20	2.971	3.527	0.203	0.246	2.438	2.397	0.203	0.268
30a	0.76	3.00	0.30	2.960	3.464	0.300	0.348	2.326	2.151	0.299	0.383
30c	0.76	3.00	0.30	3.012	3.488	0.309	0.345	2.335	2.189	0.305	0.377
31a	0.86	1.25	0.20	1.214	1.205	0.145	0.137	1.202	1.237	0.159	0.145
31c	0.86	1.25	0.20	1.250	1.309	0.152	0.143	1.201	1.237	0.159	0.153
32a	0.86	1.25	0.40	1.259	1.264	0.326	0.298	1.204	1.262	0.348	0.321
32c	0.86	1.25	0.40	1.248	1.335	0.331	0.297	1.201	1.260	0.343	0.326
33a	0.86	1.25	0.60	1.266	1.386	0.463	0.393	1.213	1.297	0.479	0.423
33c	0.86	1.25	0.60	1.247	1.258	0.476	0.395	1.207	1.283	0.480	0.424
34a	0.86	1.25	0.66	1.259	1.399	0.522	0.418	1.217	1.305	0.532	0.449
34c	0.86	1.25	0.66	1.247	1.253	0.534	0.425	1.216	1.297	0.531	0.448
35a	0.86	2.25	0.20	2.339	2.339	0.200	0.224	1.900	1.857	0.199	0.235
35e	0.86	2.25	0.20	2.228	2.223	0.203	0.228	1.895	1.856	0.200	0.239
36a	0.86	2.25	0.40	2.339	2.339	0.400	0.411	1.869	1.720	0.395	0.454
36b	0.86	2.25	0.40	2.228	2.399	0.390	0.405	1.859	1.725	0.388	0.448
37a	0.86	3.00	0.10	3.134	3.418	0.097	0.110	2.505	2.379	0.096	0.133
37f	0.86	3.00	0.10	2.893	3.433	0.100	0.115	2.528	2.399	0.100	0.141
38a	0.86	3.00	0.30	3.096	3.134	0.301	0.338	2.331	1.904	0.304	0.420
38f	0.86	3.00	0.30	2.971	3.433	0.308	0.347	2.347	1.914	0.318	0.434
39a	0.86	3.00	0.40	3.096	3.134	0.392	0.430	2.217	1.833	0.402	0.541

Table A2

Collected Data and Depths for Revetment Without Berm

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 SPECTRAL WIDTH Qp(1)	ARRAY 2 SPECTRAL WIDTH Qp(2)	ARRAY 2 REFLECT WAVE HT Hr(2) (ft)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT NRSHORE ARRAY D(n) (ft)	RUNUP (ft)
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	5.493	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 REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 SPECTRAL WIDTH Qp(1)	ARRAY 2 SPECTRAL WIDTH Qp(2)	ARRAY 2 REFLECT WAVE HT Hr(2) (ft)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT NRSHORE ARRAY D(n) (ft)	RUNUP (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	0.650	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 #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 INCIDENT PEAK PER Tp(1) (sec)	ARRAY 2 INCIDENT PEAK PER Tp(2) (sec)	ARRAY 1 INCIDENT WAVE HT Hmo(1) (ft)	ARRAY 2 INCIDENT WAVE HT Hmo(2) (ft)	ARRAY 1 INCIDENT AVE PER Tz(1) (sec)	ARRAY 2 INCIDENT AVE PER Tz(2) (sec)	ARRAY 1 UPCROSS SIG HT Hs(1) (ft)	ARRAY 2 UPCROSS SIG HT Hs(2) (ft)
40a	0.76	1.25	0.10	1.270	1.250	0.087	0.078	1.194	1.245	0.090	0.082
40c	0.76	1.25	0.10	1.247	1.247	0.089	0.081	1.193	1.246	0.089	0.083
42a	0.76	1.25	0.30	1.259	1.222	0.260	0.234	1.198	1.265	0.274	0.250
42c	0.76	1.25	0.30	1.247	1.222	0.264	0.236	1.195	1.271	0.271	0.252
44a	0.76	1.25	0.50	1.259	1.306	0.419	0.360	1.206	1.292	0.430	0.377
44c	0.76	1.25	0.50	1.247	1.414	0.426	0.359	1.203	1.298	0.423	0.376
47a	0.76	3.00	0.10	2.960	3.544	0.094	0.105	2.469	2.261	0.093	0.108
47f	0.76	3.00	0.10	2.960	3.544	0.095	0.106	2.466	2.254	0.095	0.109
48a	0.76	3.00	0.30	2.960	3.472	0.293	0.327	2.299	1.830	0.298	0.387
48f	0.76	3.00	0.30	2.971	3.179	0.298	0.327	2.300	1.860	0.308	0.403
49a	0.76	3.00	0.30	2.960	3.053	0.291	0.329	2.289	1.853	0.294	0.390
49f	0.76	3.00	0.30	2.971	3.179	0.297	0.327	2.300	1.878	0.305	0.398
50a	0.76	3.00	0.10	2.960	3.041	0.093	0.107	2.472	2.333	0.092	0.109
50f	0.76	3.00	0.10	2.971	2.971	0.097	0.112	2.480	2.309	0.096	0.116
51a	0.76	3.00	0.50	2.960	3.323	0.501	0.468	*NA	NA	0.520	0.566
51f	0.76	3.00	0.50	2.971	3.072	0.514	0.461	NA	NA	0.544	0.549
52a	0.76	1.25	0.66	1.255	1.316	0.520	0.411	NA	NA	0.523	0.432
52c	0.76	1.25	0.66	1.247	1.357	0.540	0.423	NA	NA	0.527	0.436
53a	0.76	1.25	0.60	1.259	1.306	0.432	0.359	1.204	1.285	0.451	0.390
53c	0.76	1.25	0.60	1.247	1.414	0.435	0.355	1.202	1.288	0.439	0.388
55a	0.76	1.25	0.30	1.259	1.250	0.259	0.234	1.197	1.258	0.277	0.255
55c	0.76	1.25	0.30	1.247	1.222	0.262	0.235	1.193	1.263	0.274	0.258
57a	0.76	1.25	0.10	1.270	1.270	0.088	0.078	1.193	1.238	0.092	0.081
57c	0.76	1.25	0.10	1.247	1.247	0.089	0.081	1.191	1.240	0.091	0.084
58a	0.76	2.25	0.10	2.320	2.320	0.097	0.102	1.886	1.891	0.094	0.101
58e	0.76	2.25	0.10	2.228	2.228	0.097	0.104	1.883	1.888	0.094	0.103
59a	0.76	2.25	0.30	2.320	2.339	0.292	0.312	1.868	1.731	0.288	0.336
59e	0.76	2.25	0.30	2.268	2.287	0.295	0.317	1.862	1.737	0.290	0.341
60a	0.76	2.25	0.50	2.320	2.383	0.490	0.452	1.829	1.654	0.488	0.515
60e	0.76	2.25	0.50	2.268	2.320	0.497	0.460	1.826	1.669	0.496	0.525
61a	0.76	2.25	0.66	2.320	2.569	0.652	0.502	1.770	1.645	0.657	0.549
61e	0.76	2.25	0.66	2.228	2.324	0.643	0.502	1.774	1.667	0.651	0.558
62a	0.86	1.25	0.10	1.222	1.222	0.088	0.083	1.198	1.232	0.095	0.089
62c	0.86	1.25	0.10	1.247	1.228	0.090	0.086	1.196	1.230	0.095	0.092
63a	0.86	1.25	0.30	1.259	1.250	0.257	0.244	1.200	1.250	0.279	0.268
63c	0.86	1.25	0.30	1.256	1.228	0.262	0.246	1.196	1.250	0.278	0.269
64a	0.86	1.25	0.50	1.259	1.250	0.421	0.369	1.206	1.281	0.444	0.404
64c	0.86	1.25	0.50	1.261	1.421	0.429	0.374	1.202	1.277	0.440	0.405

(Continued)

(Sheet 1 of 3)

Table A3 (Continued)

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 INCIDENT PEAK PER Tp(1) (sec)	ARRAY 2 INCIDENT PEAK PER Tp(2) (sec)	ARRAY 1 INCIDENT WAVE HT Hmo(1) (ft)	ARRAY 2 INCIDENT WAVE HT Hmo(2) (ft)	ARRAY 1 INCIDENT AVE PER Tz(1) (sec)	ARRAY 2 INCIDENT AVE PER Tz(2) (sec)	ARRAY 1 UPCROSS SIG HT Hs(1) (ft)	ARRAY 2 UPCROSS SIG HT Hs(2) (ft)
65a	0.86	1.25	0.66	1.259	1.399	0.525	0.440	1.219	1.305	0.534	0.463
65c	0.86	1.25	0.66	1.247	1.253	0.545	0.448	1.217	1.305	0.538	0.471
66a	0.86	2.25	0.10	2.282	2.339	0.100	0.108	1.890	1.908	0.097	0.110
66e	0.86	2.25	0.10	2.268	2.268	0.101	0.108	1.886	1.899	0.098	0.110
67a	0.86	2.25	0.20	2.246	2.320	0.201	0.215	1.885	1.824	0.195	0.219
67e	0.86	2.25	0.20	2.268	2.268	0.199	0.214	1.883	1.825	0.195	0.220
68a	0.86	2.25	0.30	2.339	2.339	0.328	0.319	1.870	1.775	0.325	0.338
68e	0.86	2.25	0.30	2.255	2.378	0.329	0.324	1.865	1.756	0.328	0.344
69a	0.86	2.25	0.40	2.320	2.339	0.401	0.409	1.863	1.725	0.394	0.447
69e	0.86	2.25	0.40	2.228	2.378	0.399	0.403	1.860	1.711	0.393	0.437
70a	0.86	2.25	0.50	2.320	2.320	0.497	0.486	1.848	1.689	0.488	0.531
70e	0.86	2.25	0.50	2.268	2.324	0.496	0.487	1.845	1.690	0.490	0.538
71a	0.86	2.25	0.60	2.320	2.320	0.590	0.537	1.821	1.653	0.582	0.583
71e	0.86	2.25	0.60	2.228	2.324	0.594	0.547	1.817	1.666	0.591	0.604
72a	0.86	2.25	0.66	2.320	2.339	0.656	0.545	1.805	1.633	0.649	0.587
72e	0.86	2.25	0.66	2.228	2.354	0.651	0.545	1.800	1.665	0.645	0.594
73a	0.66	1.25	0.10	1.266	1.266	0.087	0.081	1.199	1.251	0.094	0.087
73c	0.66	1.25	0.10	1.268	1.290	0.088	0.084	1.195	1.252	0.092	0.089
74a	0.66	1.25	0.20	1.266	1.266	0.172	0.163	1.201	1.261	0.187	0.179
74c	0.66	1.25	0.20	1.268	1.290	0.174	0.165	1.196	1.262	0.184	0.179
75a	0.66	1.25	0.30	1.266	1.279	0.256	0.237	1.204	1.283	0.280	0.267
75c	0.66	1.25	0.30	1.268	1.268	0.261	0.238	1.196	1.277	0.276	0.263
76a	0.66	1.25	0.40	1.266	1.296	0.336	0.295	1.209	1.296	0.361	0.331
76c	0.66	1.25	0.40	1.247	1.282	0.342	0.293	1.198	1.290	0.359	0.328
77a	0.66	1.25	0.50	1.266	1.382	0.404	0.332	1.215	1.304	0.428	0.365
77c	0.66	1.25	0.50	1.247	1.412	0.418	0.334	1.202	1.304	0.428	0.371
78a	0.66	1.25	0.60	1.266	1.382	0.478	0.370	1.223	1.325	0.495	0.410
78c	0.66	1.25	0.60	1.247	1.405	0.488	0.371	1.211	1.316	0.491	0.410
79a	0.66	1.25	0.66	1.266	1.382	0.519	0.384	1.230	1.333	0.529	0.417
79c	0.66	1.25	0.66	1.247	1.405	0.530	0.386	1.217	1.321	0.525	0.412
80a	0.66	2.25	0.10	2.317	2.165	0.096	0.110	1.910	1.893	0.094	0.109
80e	0.66	2.25	0.10	2.312	2.202	0.096	0.109	1.892	1.902	0.093	0.108
81a	0.66	2.25	0.20	2.317	2.165	0.191	0.207	1.901	1.800	0.186	0.219
81e	0.66	2.25	0.20	2.286	2.221	0.194	0.213	1.886	1.813	0.188	0.222
82a	0.66	2.25	0.30	2.317	2.349	0.285	0.305	1.887	1.742	0.278	0.344
82e	0.66	2.25	0.30	2.327	2.256	0.307	0.317	1.872	1.765	0.297	0.350
83a	0.66	2.25	0.40	2.317	2.349	0.398	0.387	1.867	1.674	0.390	0.455
83e	0.66	2.25	0.40	2.236	2.365	0.395	0.386	1.850	1.696	0.386	0.446

(Continued)

(Sheet 2 of 3)

Table A3 (Concluded)

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 INCIDENT PEAK PER Tp(1) (sec)	ARRAY 2 INCIDENT PEAK PER Tp(2) (sec)	ARRAY 1 INCIDENT WAVE HT Hmo(1) (ft)	ARRAY 2 INCIDENT WAVE HT Hmo(2) (ft)	ARRAY 1 INCIDENT AVE PER Tz(1) (sec)	ARRAY 2 INCIDENT AVE PER Tz(2) (sec)	ARRAY 1 UPCROSS SIG HT Hs(1) (ft)	ARRAY 2 UPCROSS SIG HT Hs(2) (ft)
84a	0.66	2.25	0.50	2.317	2.349	0.493	0.420	1.841	1.663	0.487	0.498
84e	0.66	2.25	0.50	2.327	2.365	0.493	0.429	1.823	1.660	0.487	0.504
85a	0.66	2.25	0.60	2.317	2.393	0.584	0.448	1.806	1.671	0.587	0.528
85e	0.66	2.25	0.60	2.327	2.498	0.586	0.459	1.791	1.675	0.586	0.536
86a	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	2.25	0.66	2.327	2.359	0.645	0.453	1.775	1.685	0.649	0.522
87a	0.66	3.00	0.10	3.015	3.100	0.091	0.112	2.489	2.289	0.086	0.113
87f	0.66	3.00	0.10	2.990	3.041	0.099	0.116	2.479	2.235	0.095	0.131
88a	0.66	3.00	0.20	3.100	3.100	0.202	0.234	2.393	2.008	0.195	0.282
88f	0.66	3.00	0.20	3.015	3.068	0.207	0.240	2.382	1.955	0.204	0.297
89a	0.66	3.00	0.30	3.015	3.046	0.237	0.311	2.403	1.881	0.229	0.366
89f	0.66	3.00	0.30	2.990	3.346	0.281	0.331	2.297	1.817	0.281	0.391
90a	0.66	3.00	0.40	3.015	3.333	0.371	0.403	2.199	1.791	0.377	0.504
90f	0.66	3.00	0.40	2.990	3.346	0.393	0.394	2.144	1.747	0.405	0.497
91a	0.66	3.00	0.50	2.857	3.409	0.288	0.431	2.275	1.841	0.297	0.530
91f	0.66	3.00	0.50	2.990	3.665	0.510	0.424	2.048	1.773	0.527	0.541

(Sheet 3 of 3)

Table A4

Collected Data and Depths for Revetment With Fronting Berm

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 SPECTRAL WIDTH Qp(1)	ARRAY 2 SPECTRAL WIDTH Qp(2)	ARRAY 2 REFLECT WAVE HT Hr(2) (ft)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT NRSHORE ARRAY D(n) (ft)	RUNUP (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	2.491	1.504	0.186	0.396	627	2.10	0.86	OVT
51f	0.76	3.00	0.50	2.544	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	479	2.10	0.86	0.340
53c	0.76	1.25	0.60	5.019	4.343	0.097	0.273	477	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 REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 SPECTRAL WIDTH Qp(1)	ARRAY 2 SPECTRAL WIDTH Qp(2)	ARRAY 2 REFLECT WAVE HT Hr(2) (ft)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT NRSHORE ARRAY D(n) (ft)	RUNUP (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)

Table A4 (Concluded)

RUN #	DESIGN CONDITIONS REVETMENT TOE DEPTH Ds (ft)	PEAK PERIOD Tp(des) (sec)	INCIDENT WAVE HT Hmo(des) (ft)	ARRAY 1 SPECTRAL WIDTH Qp(1)	ARRAY 2 SPECTRAL WIDTH Qp(2)	ARRAY 2 REFLECT WAVE HT Hr(2) (ft)	ARRAY 2 REFLECT COEF Kr(2)	NUMBER OF WAVES ANALYZED N	DEPTH AT OFFSHORE ARRAY D(o) (ft)	DEPTH AT NRSHORE ARRAY D(n) (ft)	RUNUP (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	757	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	689	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

(Sheet 3 of 3)

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 runup on a revetment is 15 percent higher than the freeboard.

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

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

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

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 runup

h = height of structure crest along the bottom

d_s = depth at the structure toe

This may be rewritten as (Ahrens and Heimbaugh 1986)

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

where F is the freeboard of the structure.

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

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

If a berm reduces the runup by 10 percent, then

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

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

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

---

* See References at the end of the main text.

or,

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

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:

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

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

Since W_B, H_B, H_{mo}, 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:

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

or

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

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

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* 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

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13. ABSTRACT *(Maximum 200 words)*

Laboratory tests with irregular waves to determine wave runup characteristics and armor stability of riprap revetments are discussed. Tests include conventional, plane, 1 on 2 slope revetments, and conventional revetments fronted by rubble berms. Rubble berms tested reduced the maximum runup by rather modest amounts, typically around 10 percent, but produced substantial improvement in the armor stability. These effects are discussed and quantified. This study demonstrates the need for a reliable irregular wave run-up gage for laboratory studies of rough, porous coastal structures.

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