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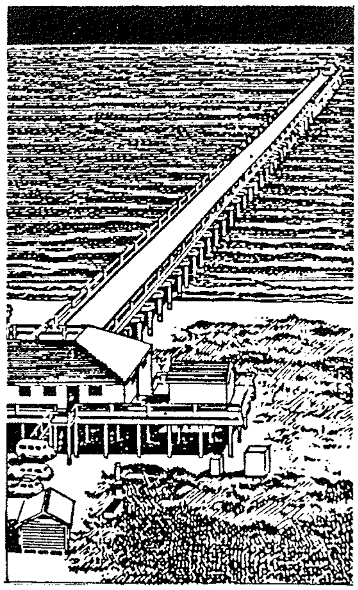

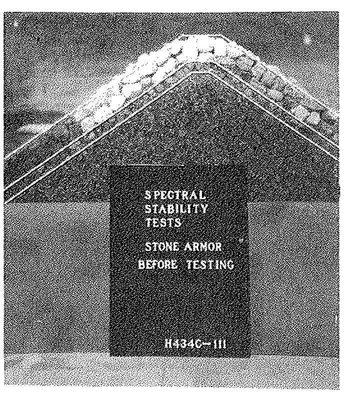

TECHNICAL REPORT CERC-89-2

STABILITY RESPONSE OF STONE- AND DOLOS-ARMORED, RUBBLE-MOUND BREAKWATER TRUNKS SUBJECTED TO SPECTRAL WAVES

by

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The purpose of the model investigation reported herein was to obtain design information for stone and dolos armor used on breakwater trunks and subjected to selected spectral wave conditions. More specifically, it was desired to determine the required weight of individual armor units (with given specific weights) needed for stability as a function of armor type, wave height and period, and sea-side slope of the breakwater.

Based on test results, it was concluded that:

a. Stability of both armor types is influenced by wave height, wave period, breakwater slope, and, to a lesser extent, water depth.

b. A new energy based stability number which correlates strongly with the relative depth was developed.

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c. Stone stability was more strongly influenced by changes in breakwater slope than was dolos stability.

d. Dolos test results showed more variability, i.e., were less repeatable than the stone stability tests.

PREFACE

Authority for the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), to conduct this study was granted by the US Army Corps of Engineers (USACE), under Work Unit 31269, "Stability of Breakwaters," Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development. USACE Technical Monitors for this research were Messrs. John H. Lockhart, Jr., John G. Housley, James E. Crews, and Charles W. Hummer. CERC Program Manager is Dr. C. Linwood Vincent.

The study was conducted by personnel of CERC under general direction of Dr. James R. Houston, Chief, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC. Direct supervision was provided by Messrs. C. Eugene Chatham, Chief, Wave Dynamics Division (CW), and D. Donald Davidson, Chief, Wave Research Branch (CW-R). This report was prepared by Mr. Robert D. Carver, Principal Investigator, and Ms. Brenda J. Wright, Engineering Technician, CW-R. The model was operated by Ms. Wright assisted by Messrs. Willie G. Dubose, C. Ray Herrington, Cornelius Lewis, and Marshall P. Thomas, Engineering Technicians, CW.

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

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
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

STABILITY RESPONSE OF STONE- AND DOLOS ARMORED RUBBLE-MOUND BREAKWATER TRUNKS SUBJECTED TO SPECTRAL WAVES

PART I: INTRODUCTION

Background

1. Previous investigations have yielded a significant quantity of design information for stone (Hudson 1958 and Carver 1980 and 1983), quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson 1968), dolosse (Carver and Davidson 1977 and Carver 1983), and toskane (Carver 1978). Results of these tests, as correlated by the Hudson stability equation, form the primary basis for design procedures presently given in the Shore Protection Manual (SPM) (1984) and EM 1110-2-2904 (Headquarters, US Army Corps of Engineers 1986).

2. During the past decade much consternation has arisen in the International coastal engineering community over the use of the Hudson stability equation. This reaction is not surprising if one accepts the fact that, based on state-of-the-art approaches, this approach to breakwater design is an oversimplification of a complex problem. Most researchers have the highest respect for the pioneering work accomplished by Hudson during the 1950's and 1960's; however, based on a detailed study of the original work, numerous conversations with Mr. Hudson, and an attempt to understand the physics of the problem, it has been concluded that the present formula is not totally adequate for breakwater design. Since the stability coefficient (K_D)* combines the effects of over 30 wave and structure variables it is reasonable to expect that it will vary from one investigation to another. Recent experience has shown this to be true.

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

3. Tests conducted by Carver (1983) using depth-limited monochromatic breaking waves on stone and dolos produced the following conclusions:

- a. Armor stability is influenced by wave steepness H/L , Ursell number L^2H/d^3 , relative wave height H/d , and breakwater slope.
- b. Effects of H/d , L^2H/d^3 , and H/L are more pronounced for dolos armor than for stone.
- c. In general, minimum stability for each armor type occurred for the larger values of H/d , intermediate values of H/L , and larger values of L^2H/d^3 .
- d. Linear Hudson data fits generally give a reasonable approximation of the stability number as a function of breakwater slope; however, the influences of H/d , H/L , and L^2H/d^3 are strong enough to merit their consideration in selection of armor unit weight.

Based on these conclusions, it was recommended that armor stability for breaking waves be presented as a function of wave height, wave period, and water depth (e.g., Ursell number).

Purpose of Study

4. The purpose of the present investigation was to obtain a better understanding of the stability response of stone and dolos armor when used on breakwater trunks and subjected to selected spectral wave conditions. More specifically, it was desired to determine the required weight of individual armor units (with given specific weights) needed for stability as a function of armor type, wave height and period, and sea-side slope of the breakwater.

PART II: TESTS

Stability Scale Effects

5. If the absolute sizes of experimental breakwater materials and wave dimensions become too small, flow around the armor units enters the laminar regime; and the induced drag forces become a direct function of the Reynolds number. Under these circumstances prototype phenomena are not properly simulated, and stability scale effects are induced. Hudson (1975) presents a detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater tests and concludes that scale effects will be negligible if

$$R_N = \frac{g^{1/2} H^{1/2} \ell_a}{\nu} \tag{1}$$

where

R_N = Reynolds stability number
g = acceleration due to gravity, ft/sec^2*
H = wave height, ft
ℓ_a = characteristic length of armor unit, ft
ν = kinematic viscosity

is equal to or greater than 3×10^4. For all tests reported herein, the sizes of experimental armor and wave dimensions were selected such that scale effects were insignificant (i.e., R_N was greater than 3×10^4).

Method of Constructing Test Sections

6. All experimental breakwater sections were constructed to reproduce as closely as possible results of the usual methods of constructing full-scale breakwaters. The core material was dampened as it was dumped by bucket or shovel into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype

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

structure. Once the core material was in place, it was sprayed with a low-velocity water hose to ensure adequate compaction of the material. The underlayer stone then was added by shovel and smoothed to grade by hand or with trowels. Armor units used in the cover layers were placed in a random manner corresponding to work performed by a general coastal contractor; i.e., they were individually placed but were laid down without special orientation or fitting. After each test the armor units were removed from the breakwater, all of the underlayer stones were replaced to the grade of the original test section, and the armor was replaced.

Test Equipment and Materials

Equipment

7. Tests were conducted in a 6-ft-wide, 6-ft-deep, 300-ft-long concrete wave flume. The flume is equipped with an electrohydraulic wave generator capable of producing monochromatic and spectral waves of various periods and heights. The wave board can be operated in a horizontal-displacement, flap, or combination horizontal-displacement and flap mode. Changes in water surface elevation as a function of time (wave heights) were measured by electrical resistance gages at selected locations. The wave machine was controlled by and data were collected with an on-line MicroVAX. Data were then transferred to a VAX 750 for analysis.

Materials

8. Rough hand-shaped granitic stone W_a with an average length of about two times its width, average weight of 0.38 lb, and a specific weight of 167 pcf was used to armor the stone sections. Dolos sections were armored with 0.276-lb model units. Sieve-sized limestone (unit weight = 165 pcf) was used for the underlayers and core.

Selection of Test Conditions

9. Important variables influencing breakwater stability include type and weight of armor, slope on which the armor is placed, depth of water in which the structure is sited, and characteristic shape, period, and height of the incident spectra. All tests were conducted with the JONSWAP spectrum using a peak enhancement factor γ of 3.3 as shown in Figure 1 where σ_{low}

and σ_{high} are held constant at 0.07 and 0.09, respectively, such that all results are functions only of the peak enhancement factor, γ . The wave basin was calibrated for periods of 1.2, 1.45, 1.8, 2.25, and 3.0 sec; thus assuring that a wide range of relative depths (d/L's) would be available for testing. Goda and Suzuki's (1976) method was used to resolve the incident and reflected spectra.

10. All tests were conducted on stone and dolos sections of the type shown in Figures 2 and 3 and Photos 1-8. Sea-side slopes of 1V on 1.5H and 1V on 2.25H were investigated, while the beach-side slope was held constant at 1V on 1.5H.

11. Design wave heights for the no-damage criterion were determined by subjecting the test sections to spectral waves successively larger in height in 0.01- to 0.02-ft increments until the maximum heights for which the armor was stable were reached. Each spectrum was allowed to attack the breakwater for a time equivalent to at least 1,000 peak wave periods. Then the test sections were rebuilt prior to attack by the next added increment wave. This 1,000-wave duration allowed sufficient time for a statistically stable spectrum to develop in the wave tank and was sufficient for the test sections to stabilize (no pun intended).

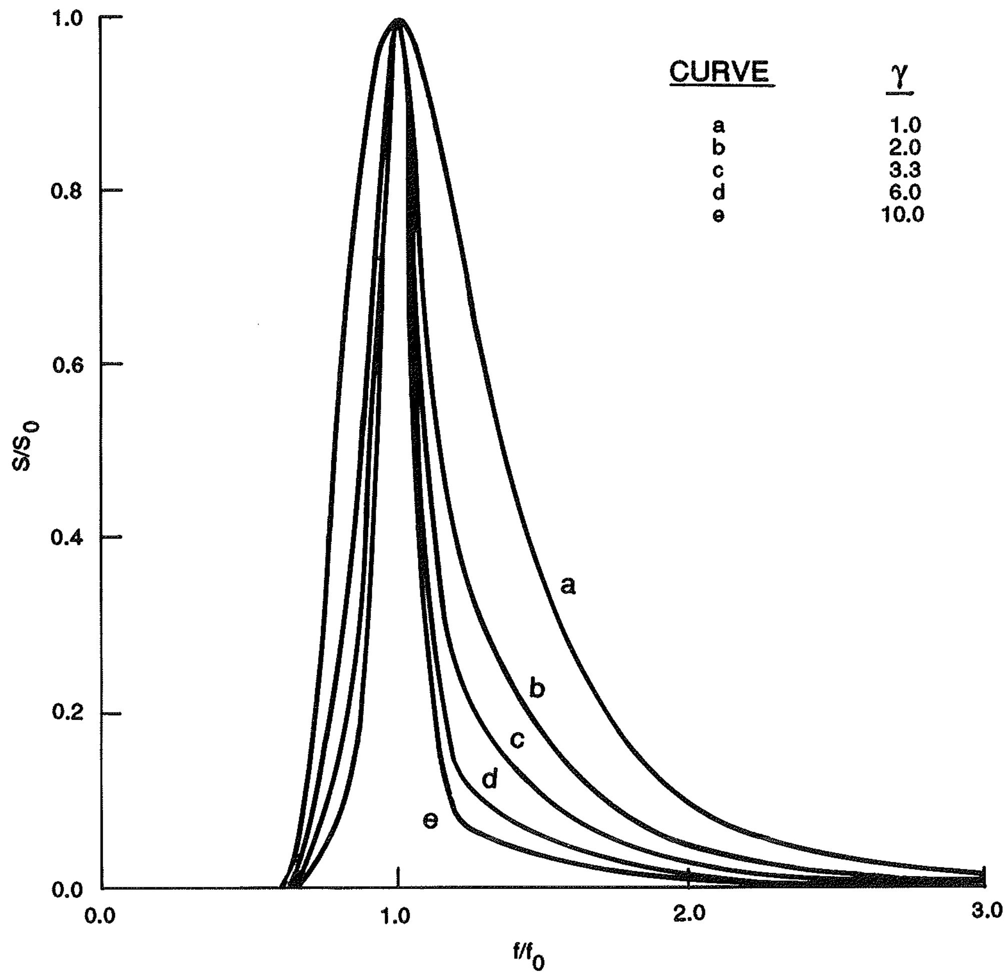
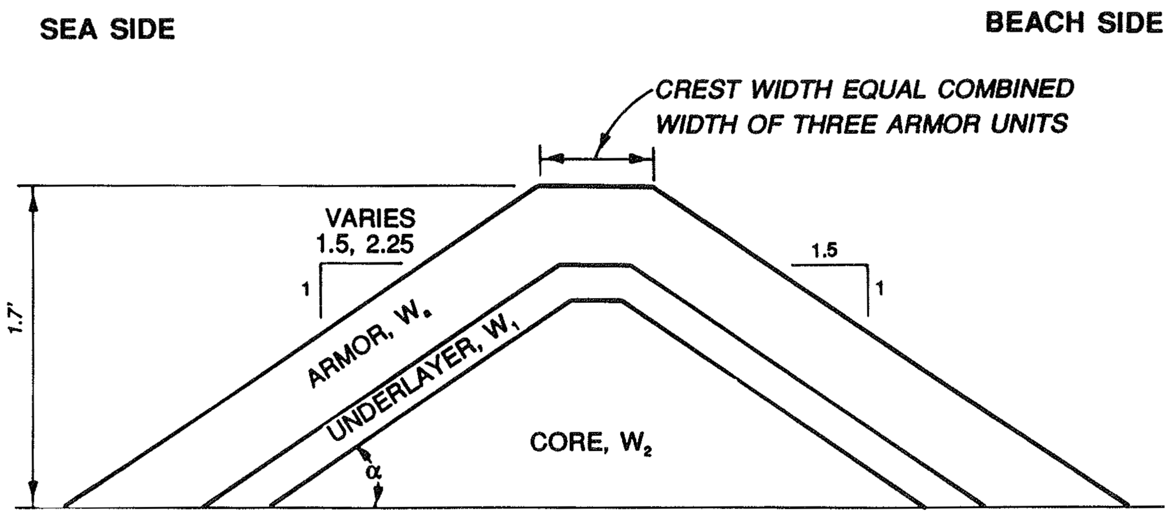


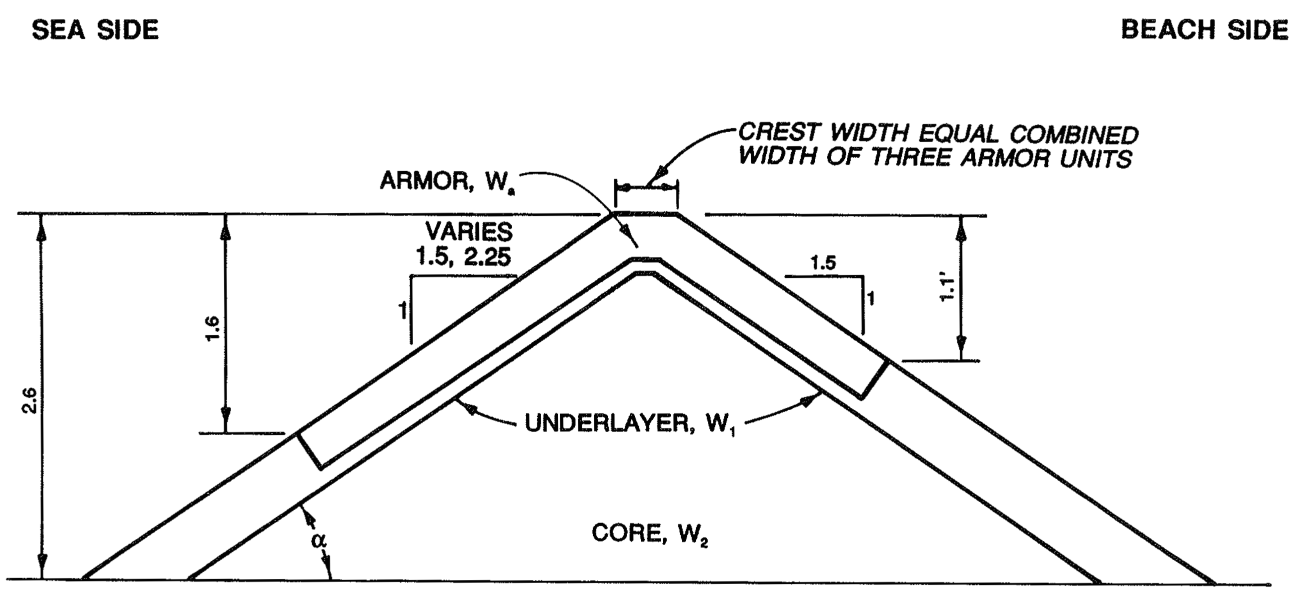
Figure 1. Five examples of JONSWAP spectra in dimensionless form (curve a is a Pierson-Moskowitz spectrum; curve c is the result of the JONSWAP experiment)



MATERIALS WEIGHTS, LB

W_a	W_1	W_2	ARMOR TYPE
0.38	0.038	0.00095 TO 0.0019	STONE
0.276	0.055	0.00069 TO 0.0014	DOLOS

Figure 2. Typical breakwater cross section, depth = 1.0 ft



MATERIALS WEIGHTS, LB

W_a	W_1	W_2	ARMOR TYPE
0.38	0.038	0.00095 TO 0.0019	STONE
0.276	0.055	0.00069 TO 0.0014	DOLOS

Figure 3. Typical breakwater cross section, depth = 2.0 ft

PART III: TEST RESULTS

12. Experience with the stability of rubble-mound breakwaters to monochromatic waves suggests that one of the most important variables to correlate the stability response might be one similar to the stability number used by Hudson and Davidson (1975). The following definition is used for this stability number as applied to tests with irregular waves:

$$N_{mono} = \frac{H_{mo}\gamma_a^{1/3}}{(S_a - 1)W_a^{1/3}} \tag{2}$$

where

γ_a = specific weight of armor unit, pcf

S_a = specific gravity of armor unit, dimensionless

W_a = weight of armor unit, lb

As tests described herein progressed, it became apparent that effects of wave period were important and needed to be included in the stability analysis; thus, a new spectral stability number was derived. It is defined as

$$N_{spec} = \frac{\gamma_a^{1/3}(H_{mo}^2 L_p)^{1/3}}{(S_a - 1)W_a^{1/3}} \tag{3}$$

where L_p is the Airy wave length calculated using T_p and the water depth d at the toe of the breakwater. A stability number of this form is logical in that by including the effects of wave period it becomes proportionate to incident wave energy. Also, this finding is consistent with results of a study conducted by Gravesen, Jensen, and Sorensen (1980).

Water Depth = 2.0 Ft

13. Stability test results (d = 2.0 ft) for stone and dolos armor are summarized in Tables 1 and 2, respectively. Presented therein are experimentally determined design wave heights and corresponding stability numbers as functions of wave period, relative depth, relative wave height, and breakwater slope. All tests were repeated once. Breakwater slopes of 1V on 1.5H and 1V

on 2.25H were used for both armor types. Photos 9-16 show typical after-testing views of the structures. As evidenced in these photos, the design wave conditions allowed occasional displacement of a few random armor units; however, movement was never extensive enough to jeopardize the stability of the test section.

14. Figure 4 presents N_{mono} as a function of wave period and breakwater slope for stone armor. These data show stability to be influenced by both wave period and slope with minimum stability occurring at the 1.80-sec wave period. Model observations indicated that flow velocities parallel to the armor slope tended to peak at the 1.80-sec wave period. Thus, a corresponding peak in the drag force and the associated minimum stability would be expected. It is interesting to note that these data show the influence of wave period to be as significant as the influence of breakwater slope.

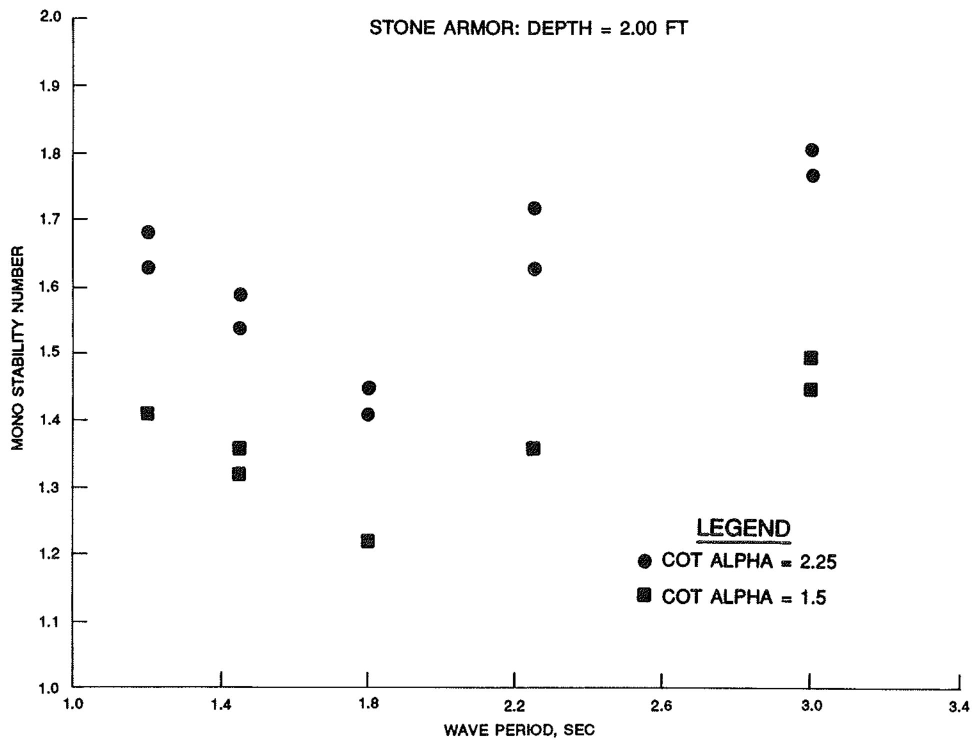


Figure 4. Monochromatic stability number versus wave period

15. Figure 5 presents N_{spec} as a function of wave period and breakwater slope. These data show that the maximum energy level at which the armor is stable tends to increase in an almost linear fashion with increasing wave period.

16. Previous breakwater stability work has shown relative depth d/L to be an important dimensionless variable associated with changes in stability

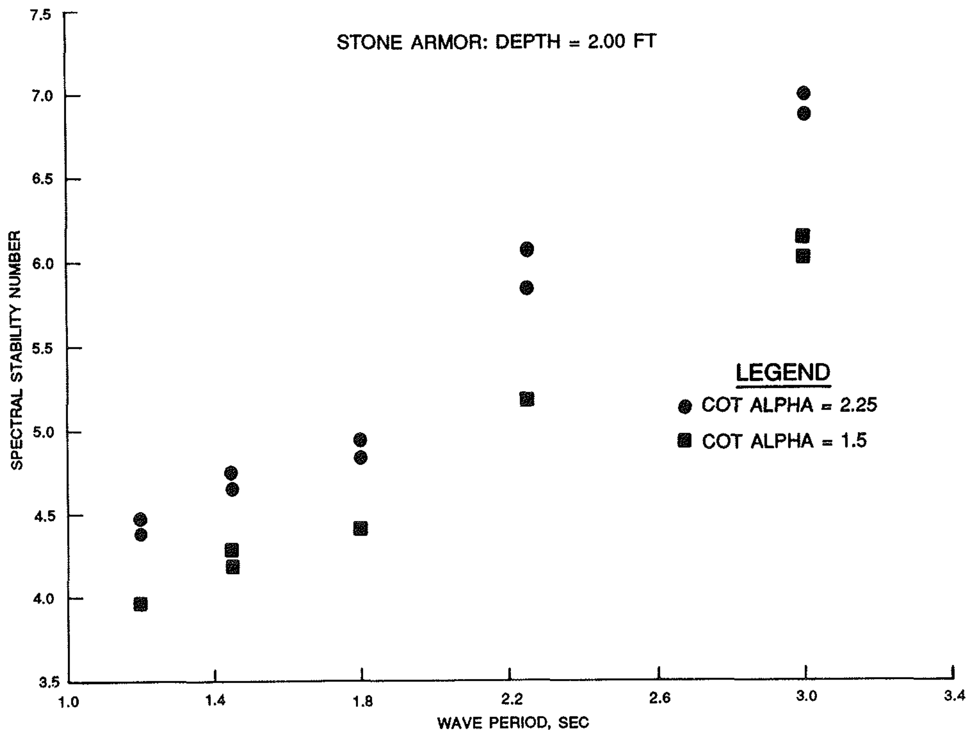


Figure 5. Spectral stability number versus period

response. Therefore, N_{spec} is plotted as a function of d/L in Figure 6, and a strong correlation is observed.

17. The monochromatic stability number is depicted as a function of wave

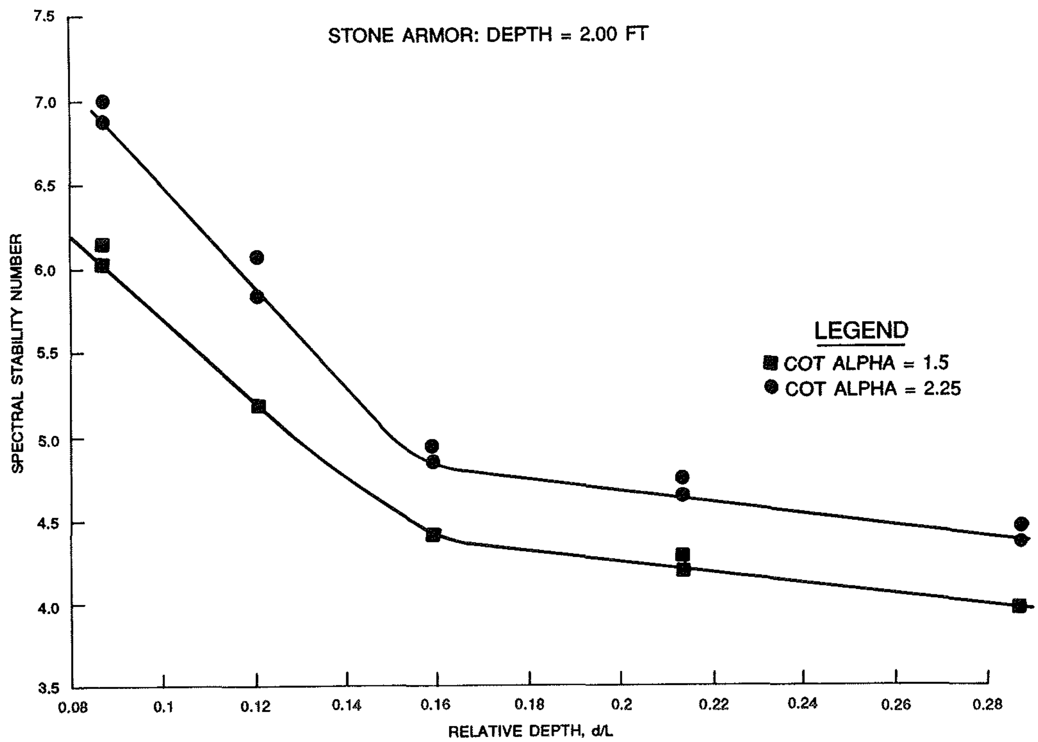


Figure 6. Spectral stability number versus d/L

period and breakwater slope for dolos armor in Figure 7. Similar to stone armor, these data show stability to be influenced by both wave period and armor slope with minimum stability occurring at the 1.80-sec wave period. It is interesting that the relative influence of slope is not as significant as was observed for stone armor. Only a small increase in stability is observed at the 1.80-sec period when the slope is flattened from 1V on 1.5H to 1V on 2.25H. Since stone achieves most of its resistance to movement from inertia and dolos from interlocking, it is reasonable that the stability response of stone would be more influenced by changes in breakwater slope.

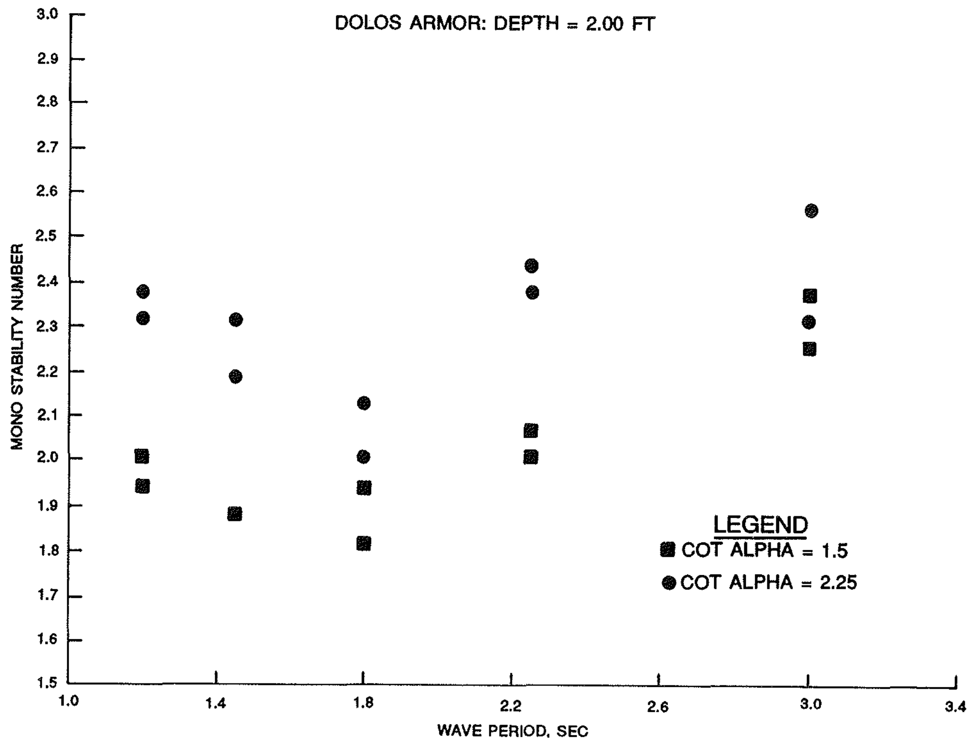


Figure 7. Monochromatic stability number versus wave period

18. Figure 8 presents the spectral stability number as a function of the wave period and breakwater slope. As with stone armor, these data show that the maximum energy level at which the armor is stable tends to increase in a generally linear fashion with increasing wave period. Finally, the spectral stability number is presented as a function of d/L in Figure 9, and again a strong correlation is observed.

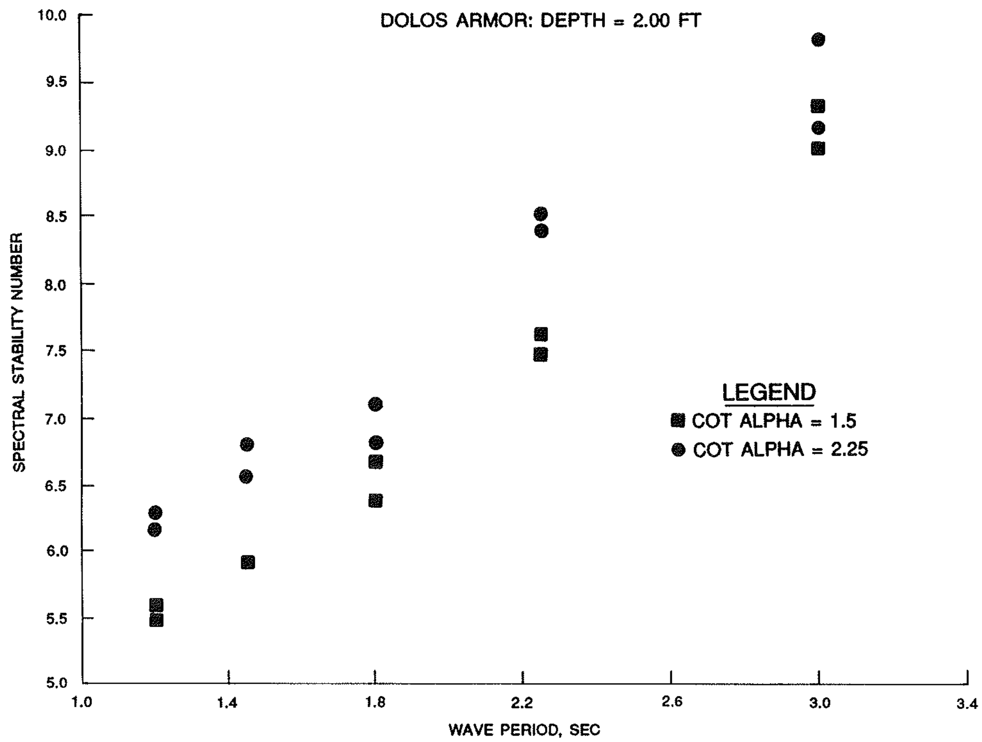


Figure 8. Spectral stability number versus period

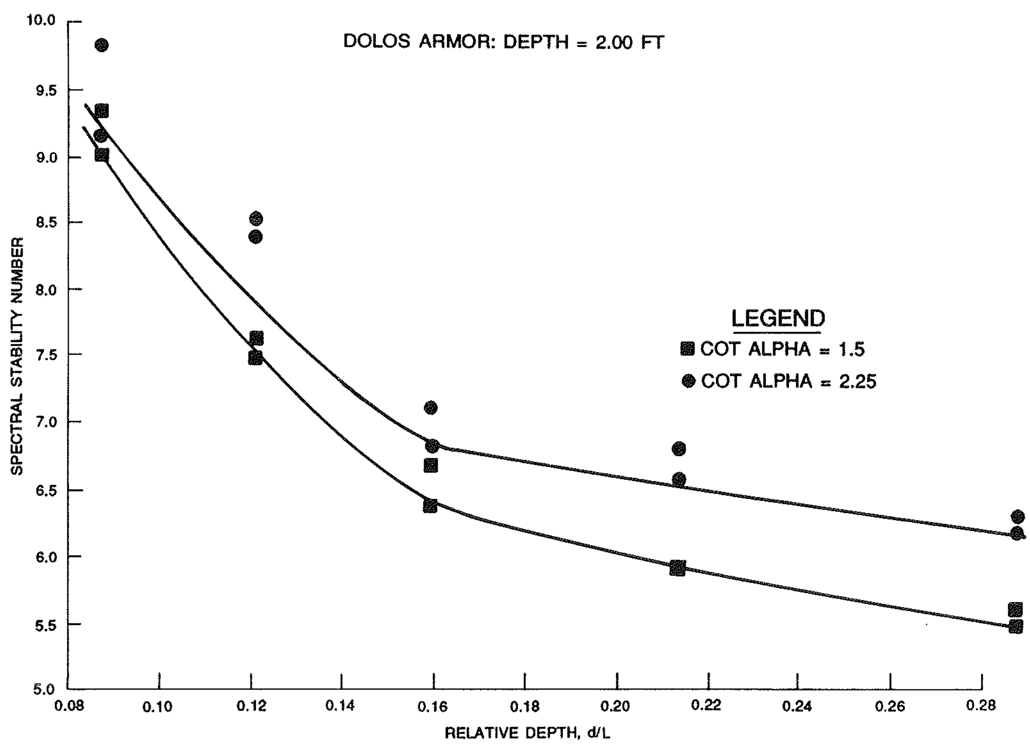


Figure 9. Spectral stability number versus d/L

Water Depth = 1.0 Ft

19. An indication of relative wave height effects (i.e., influence of water depth in which the breakwater is sited relative to the design wave heights) was obtained by conducting additional tests in a 1.0-ft model water depth. Results of these tests are summarized in Table 3. Presented therein are the experimentally determined design wave heights and corresponding stability numbers as functions of wave period, relative depth, relative wave height, and armor type. All tests were repeated once. As evidenced in Photos 17-20, the design wave conditions allowed occasional displacement of a few random armor units; however, movement was never extensive enough to jeopardize stability of the test section.

20. Figure 10 presents the monochromatic stability number as a function of wave period. Similar to results obtained in the 2.0-ft water depth, these data show stability to be influenced by wave period with minimum stability occurring at the 1.80-sec period.

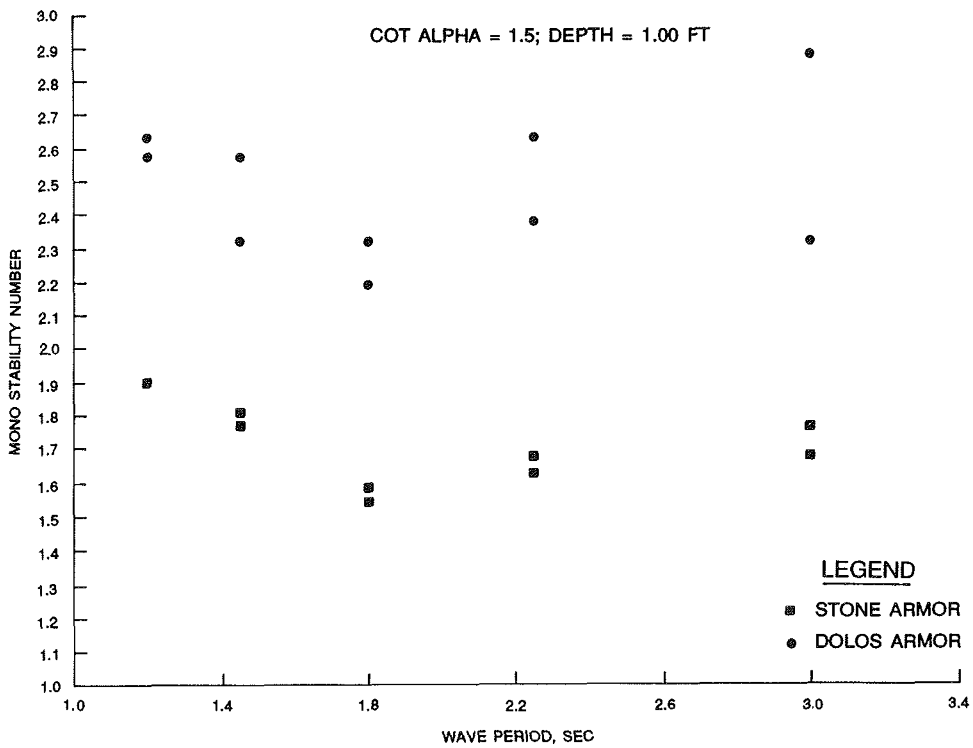


Figure 10. Monochromatic stability number versus wave period

21. A plot of the spectral stability number as a function of wave period (Figure 11) shows the maximum energy level at which the armor is stable tends

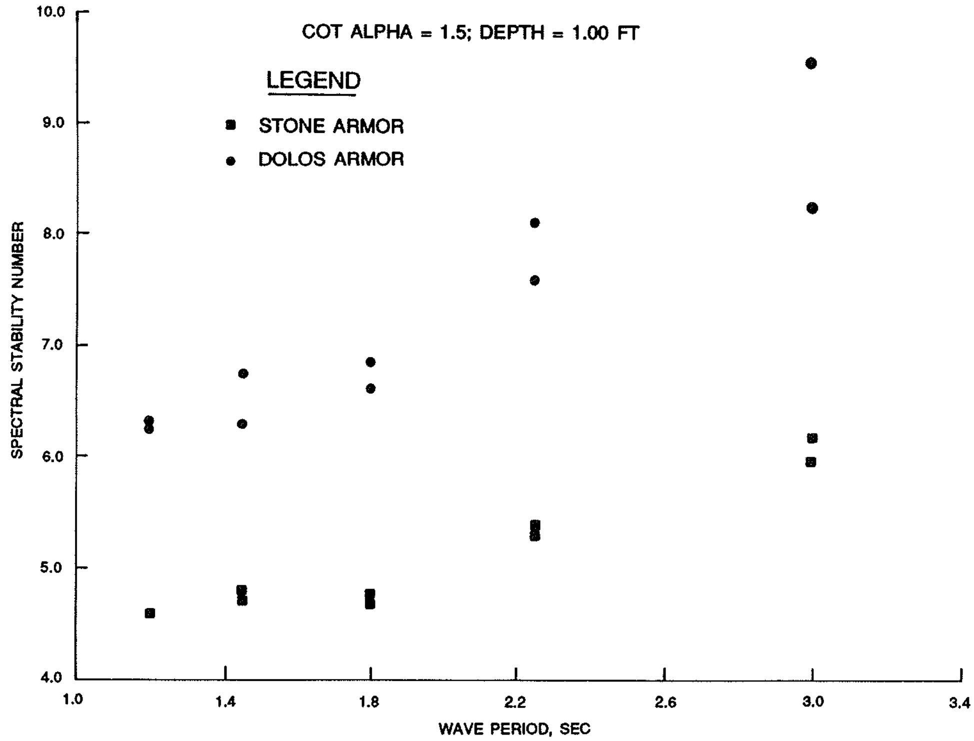


Figure 11. Spectral stability number versus period

to increase in a fairly linear manner with increasing wave period. Also, repeat test results for dolos armor tend to diverge as the wave period is increased. This divergence was not observed at the 2.0-ft depth, and a precise explanation of why it occurred is unknown.

22. Figure 12 presents the spectral stability number as a function of d/L . As with the 2.0-ft depth, a strong correlation is observed.

Discussion

23. A comparison of Tables 1-3 and Figures 6, 9, and 12 shows that decreasing the depth to 1.0 ft resulted in slightly higher design wave heights and some shift of the stability numbers; however all data trends are very similar. This occurrence probably results from the maximum waves (relative to H_{mo}) being more limited in the lower water depth.

24. The lower limit curves presented in Figures 6, 9, and 12, when used with Equation 3, should provide an improved methodology for selection of stable stone and dolos weights. The two water depths tested herein were not sufficient to develop a functional relationship between the spectral stability

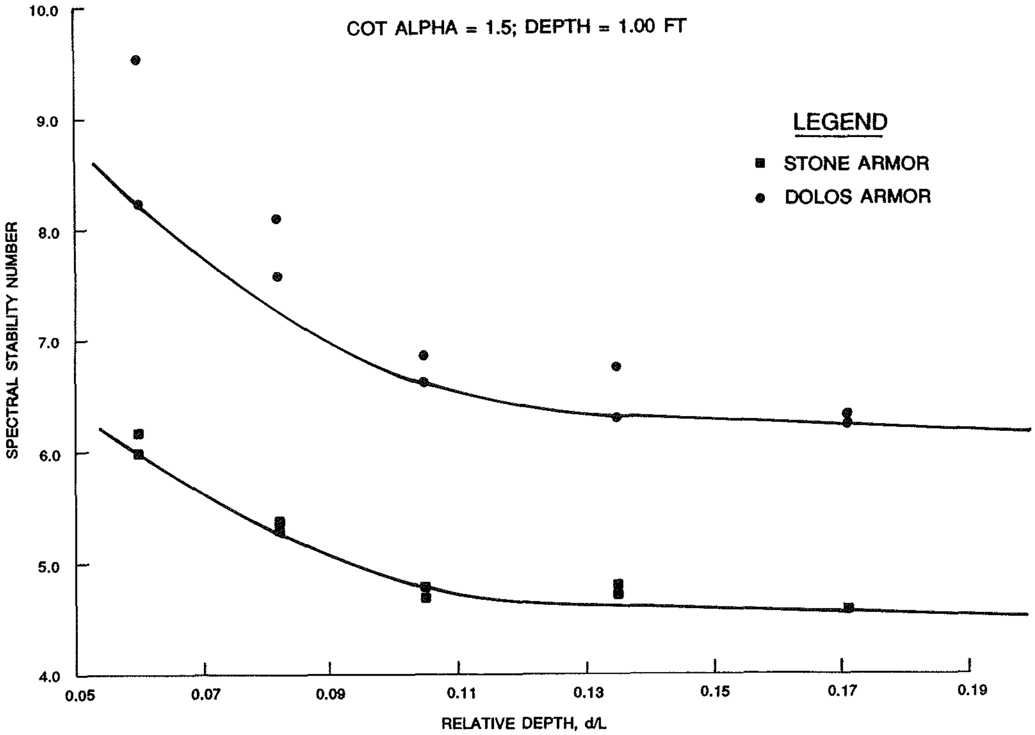


Figure 12. Spectral stability number versus d/L

number and relative wave height. However, effects of this variable appear to be minor relative to the influences of wave period and breakwater slope. Influences of H_{mo}/d can be accounted for by using Figures 6 and 9 when H_{mo}/d is less than 0.21, and Figure 12 may be applied if H_{mo}/d is greater than 0.34. If $0.21 < H_{mo}/d < 0.34$, both curves should be checked and the stability number yielding the larger armor weight used.

PART IV: DESIGN CURVE USE

Example Problem 1

Description

25. The selected structure is a breakwater trunk with stone armor having a unit weight of 165 pcf. Water depth at the toe is 50 ft, the design H_{mo} is 10 ft, and the wave period is 12 sec. The armor slope is 1V on 2.25H.

Design Curve Use

26. Calculate L_o, d/L_o, and d/L:

$$L_o = \frac{gT^2}{2\pi} = \frac{(32.17)(12)^2}{2\pi} = 737 \text{ ft}$$

$$\frac{d}{L_o} = \frac{50}{737} = 0.068$$

Thus,

$$\frac{d}{L} = 0.112$$

Since H_{mo}/d is less than 0.21, use Figure 6 with d/L = 0.112 and determine that the appropriate spectral stability number is 6.2. Solving for W_a in Equation 3, we have

$$W_a = \frac{\gamma_a H_{mo}^2 L}{N_{spec}^3 (S_a - 1)^3}$$

$$W_a = \frac{(165)(10)^2(446)}{(6.2)^3 \left(\frac{165}{64} - 1\right)^3}$$

$$W_a = 7{,}856 \text{ lb} \approx 4 \text{ tons}$$

Example Problem 2

Description

27. The selected structure is a breakwater trunk with dolos armor having a unit weight of 155 pcf. Water depth at the toe is 45 ft, the design H_{mo} is 24 ft, and the wave period is 14 sec. The armor slope is 1V on 1.5H.

Design Curve Use

28. Calculate L_o, d/L_o, and d/L:

$$L_o = \frac{gT^2}{2\pi} = \frac{(32.17)(14)^2}{2\pi} = 1{,}004 \text{ ft}$$

$$\frac{d}{L_o} = \frac{45}{1{,}004} = 0.0448$$

Thus,

$$\frac{d}{L} = 0.0886$$

Since H_{mo}/d is greater than 0.34, use Figure 12 with $d/L = 0.0886$ and determine that the appropriate spectral stability number is 7.1. Solving for W_a in Equation 3, we have

$$W_a = \frac{\gamma_a H_{mo}^2 L}{N_{spec}^3 (S_a - 1)^3}$$

$$W_a = \frac{(155)(24)^2(508)}{(7.1)^3 \left(\frac{155}{64} - 1\right)^3}$$

$$W_a = 44{,}082 \text{ lb} \approx 22 \text{ tons}$$

PART V: CONCLUSION

29. Based on tests and results described herein, in which stone and dolos armor are used on breakwater trunks and subjected to spectral wave attack, it is concluded that:

- a. Stability of both armor types is influenced by wave height, wave period, breakwater slope, and, to a lesser extent, water depth.
- b. A new energy based stability number (Equation 3) has been developed.
- c. Equation 3 correlates strongly with the relative depth (d/L).
- d. Stone stability is more strongly influenced by changes in breakwater slope than is dolos stability. This result seems reasonable in that stone achieves most of its stability through inertia; whereas interlocking is critical to dolos stability.
- e. Dolos test results show more variability (i. e., less repeatable than the stone stability tests).
- f. The lower-limit curves presented in Figures 6, 9, and 12, when used with Equation 3, should provide an improved method for selection of stable stone and dolos sizes.

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Table 1

Monochromatic and Spectral Stability Numbers for Stone Armor Randomly Placed on Breakwater Trunks

Cot α = 1.50 and 2.25; d = 2.0 ft

Cot α	T_p, sec	H_{mo}, ft	H_{mo}/d	d/L	Stability Number Monochromatic	Stability Number Spectral
1.50	1.20	0.31	0.16	0.287	1.41	3.97
1.50	1.20	0.31	0.16	0.287	1.41	3.97
1.50	1.45	0.30	0.15	0.213	1.36	4.29
1.50	1.45	0.29	0.15	0.213	1.32	4.19
1.50	1.80	0.27	0.14	0.159	1.22	4.41
1.50	1.80	0.27	0.14	0.159	1.22	4.41
1.50	2.25	0.30	0.15	0.121	1.36	5.18
1.50	2.25	0.30	0.15	0.121	1.36	5.18
1.50	3.00	0.32	0.16	0.087	1.45	6.03
1.50	3.00	0.33	0.17	0.087	1.50	6.16
2.25	1.20	0.36	0.18	0.287	1.63	4.39
2.25	1.20	0.37	0.19	0.287	1.68	4.47
2.25	1.45	0.34	0.17	0.213	1.54	4.66
2.25	1.45	0.35	0.18	0.213	1.59	4.75
2.25	1.80	0.31	0.16	0.159	1.41	4.84
2.25	1.80	0.32	0.16	0.159	1.45	4.94
2.25	2.25	0.36	0.18	0.121	1.63	5.85
2.25	2.25	0.38	0.19	0.121	1.72	6.07
2.25	3.00	0.39	0.20	0.087	1.77	6.88
2.25	3.00	0.40	0.20	0.087	1.81	7.00

Table 2

Monochromatic and Spectral Stability Numbers for Dolos Armor Randomly Placed on Breakwater Trunks

Cot α = 1.50 and 2.25; d = 2.0 ft

Cot α	T_p, sec	H_{mo}, ft	H_{mo}/d	d/L	Stability Number: Monochromatic	Stability Number: Spectral
1.50	1.20	0.32	0.16	0.287	2.01	5.60
1.50	1.20	0.31	0.16	0.287	1.94	5.49
1.50	1.45	0.30	0.15	0.213	1.88	5.92
1.50	1.45	0.30	0.15	0.213	1.88	5.92
1.50	1.80	0.29	0.15	0.159	1.82	6.39
1.50	1.80	0.31	0.16	0.159	1.94	6.68
1.50	2.25	0.32	0.16	0.121	2.01	7.48
1.50	2.25	0.33	0.17	0.121	2.07	7.63
1.50	3.00	0.36	0.18	0.087	2.26	9.02
1.50	3.00	0.38	0.19	0.087	2.38	9.35
2.25	1.20	0.38	0.19	0.287	2.38	6.29
2.25	1.20	0.37	0.19	0.287	2.32	6.17
2.25	1.45	0.35	0.18	0.213	2.19	6.57
2.25	1.45	0.37	0.19	0.213	2.32	6.81
2.25	1.80	0.32	0.16	0.159	2.01	6.83
2.25	1.80	0.34	0.17	0.159	2.13	7.11
2.25	2.25	0.39	0.20	0.121	2.44	8.53
2.25	2.25	0.38	0.19	0.121	2.38	8.39
2.25	3.00	0.41	0.21	0.087	2.57	9.83
2.25	3.00	0.37	0.19	0.087	2.32	9.18

Table 3

Monochromatic and Spectral Stability Numbers for Stone and Dolos Armor Randomly Placed on Breakwater Trunks

Cot $\alpha = 1.5$; $d = 1.0$ ft

Armor type	T_p, sec	H_{mo}, ft	H_{mo}/d	d/L	Stability Number Monochromatic	Stability Number Spectral
stone	1.20	0.42	0.42	0.171	1.90	4.58
stone	1.20	0.42	0.42	0.171	1.90	4.58
stone	1.45	0.39	0.39	0.135	1.77	4.72
stone	1.45	0.40	0.40	0.135	1.81	4.80
stone	1.80	0.34	0.34	0.105	1.54	4.69
stone	1.80	0.35	0.35	0.105	1.59	4.78
stone	2.25	0.36	0.36	0.082	1.63	5.29
stone	2.25	0.37	0.37	0.082	1.68	5.39
stone	3.00	0.37	0.37	0.060	1.68	5.97
stone	3.00	0.39	0.39	0.060	1.77	6.18
dolos	1.20	0.41	0.41	0.171	2.57	6.23
dolos	1.20	0.42	0.42	0.171	2.63	6.33
dolos	1.45	0.37	0.37	0.135	2.32	6.30
dolos	1.45	0.41	0.41	0.135	2.57	6.75
dolos	1.80	0.35	0.35	0.105	2.19	6.61
dolos	1.80	0.37	0.37	0.105	2.32	6.86
dolos	2.25	0.38	0.38	0.082	2.38	7.58
dolos	2.25	0.42	0.42	0.082	2.63	8.10
dolos	3.00	0.37	0.37	0.060	2.32	8.25
dolos	3.00	0.46	0.46	0.060	2.88	9.54

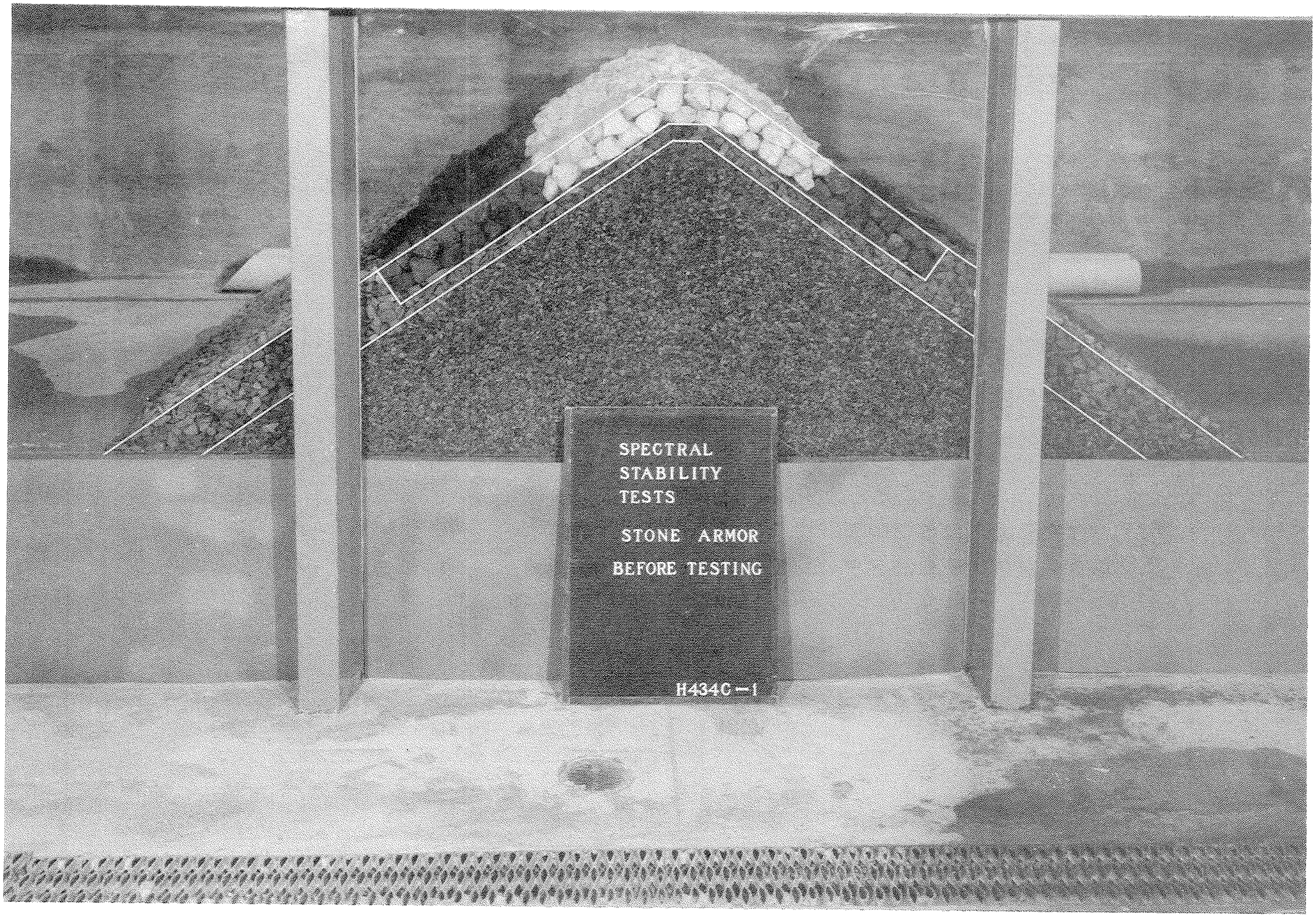

Photo 1. End view of a typical stone section before wave attack at a 1V on 1.5H seaside structure slope; d = 2.0ft

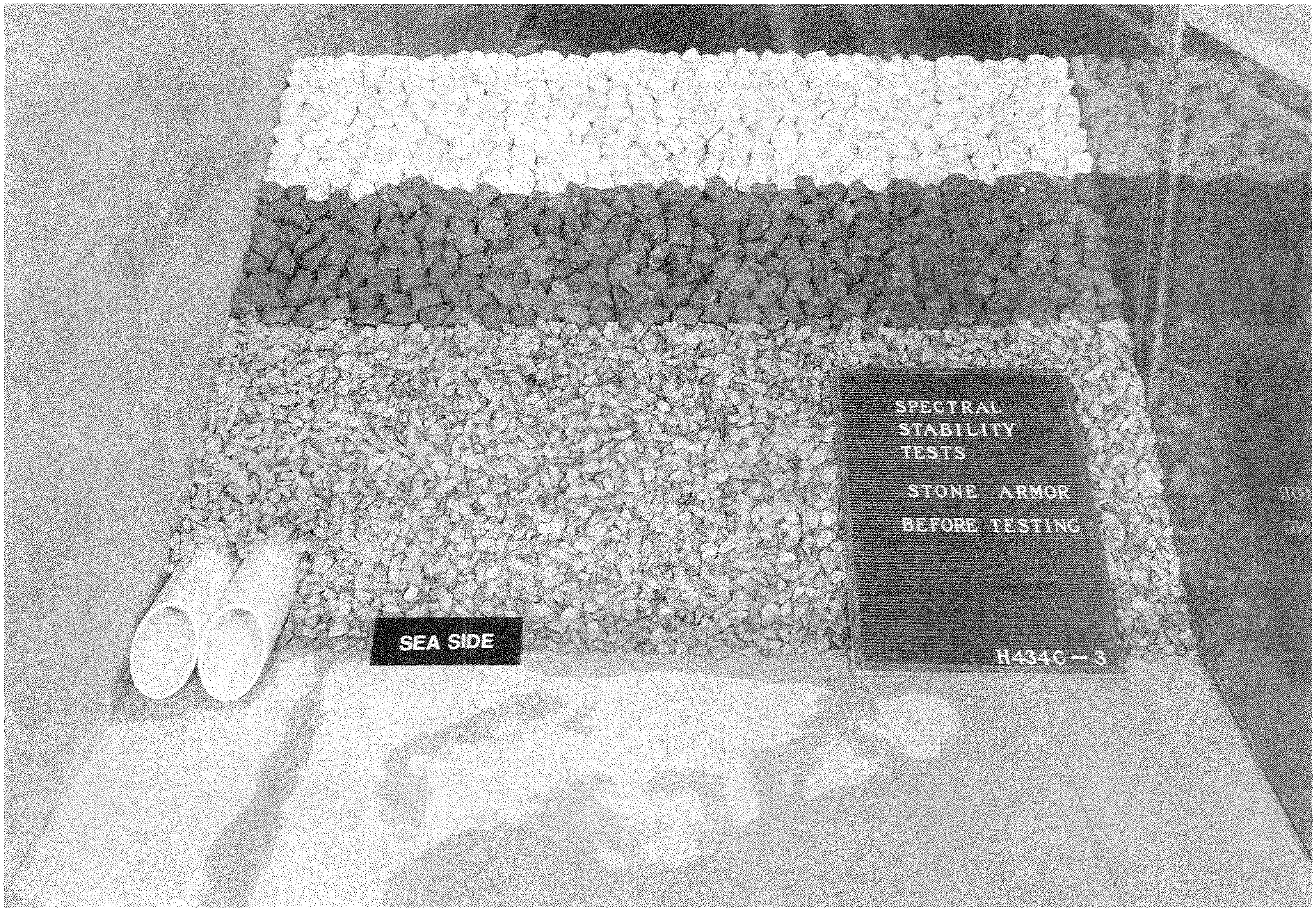

Photo 2. Seaside view of a typical stone section before wave attack at a 1V on 1.5H seaside structure slope; d = 2.0 ft

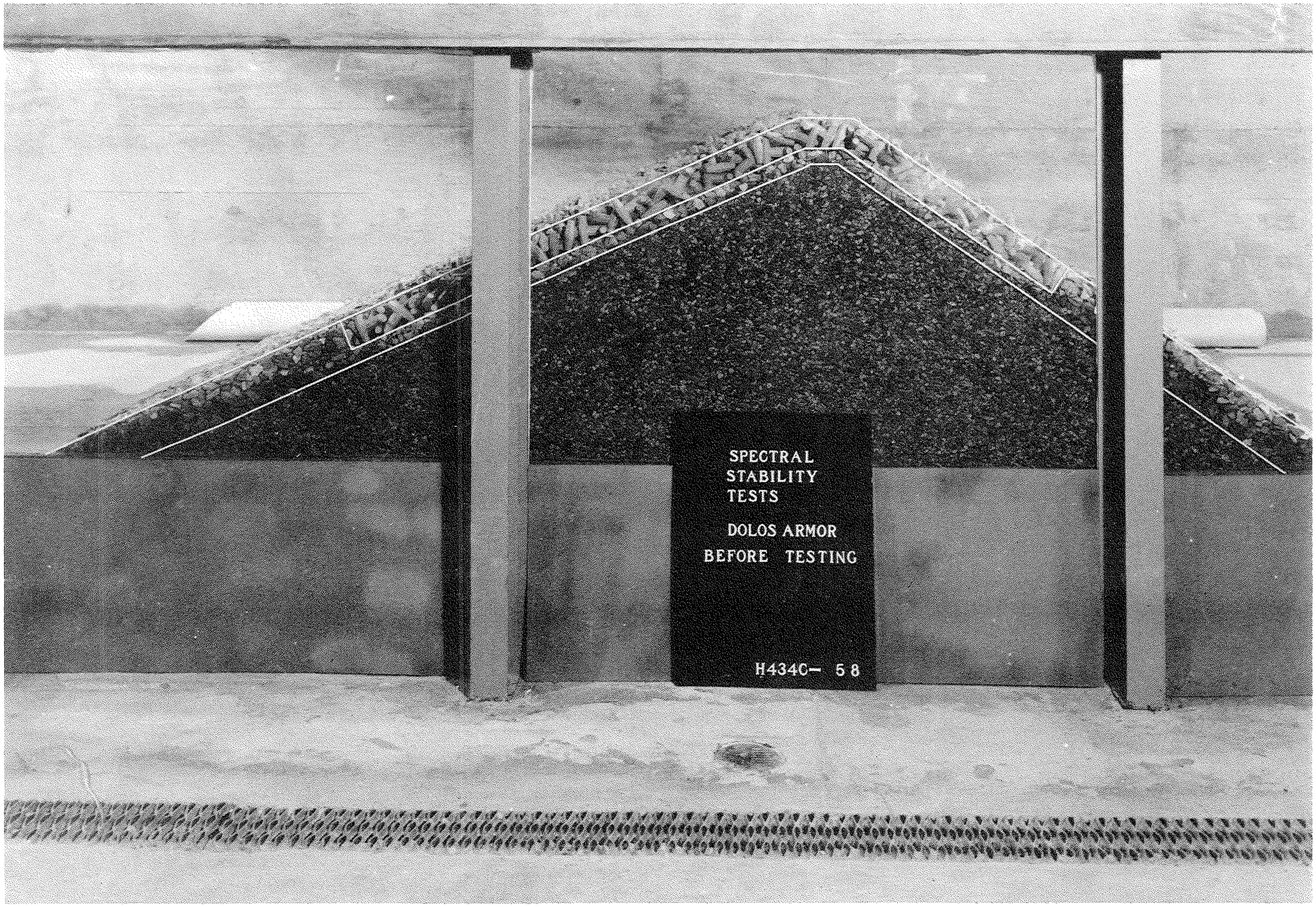

Photo 3. End view of a typical dolos section before wave attack at a 1V on 2.25H seaside structure slope; d = 2.0 ft

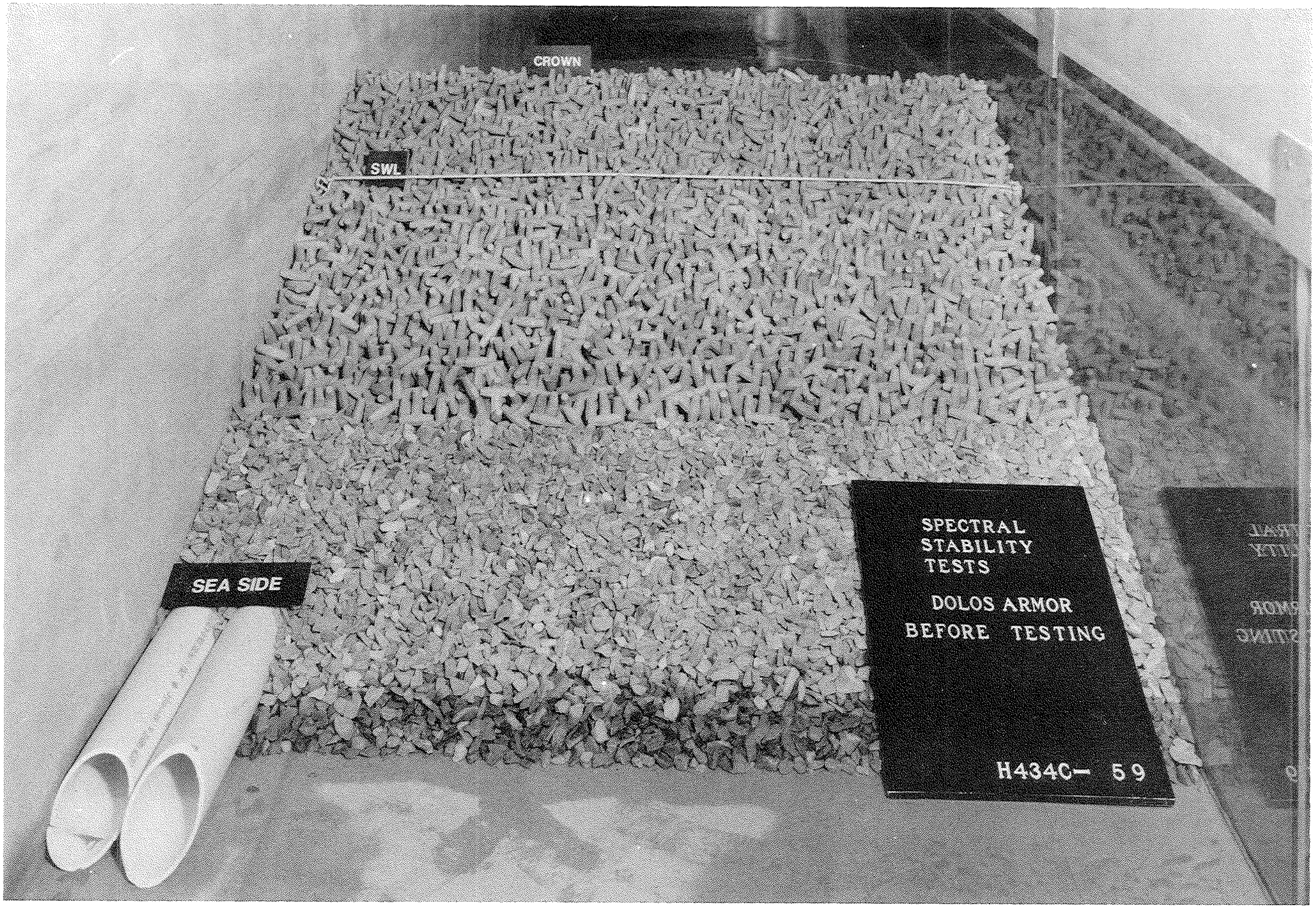

Photo 4. Seaside view of a typical dolos section before wave attack at a 1V on 2.25H seaside structure slope; d = 2.0 ft

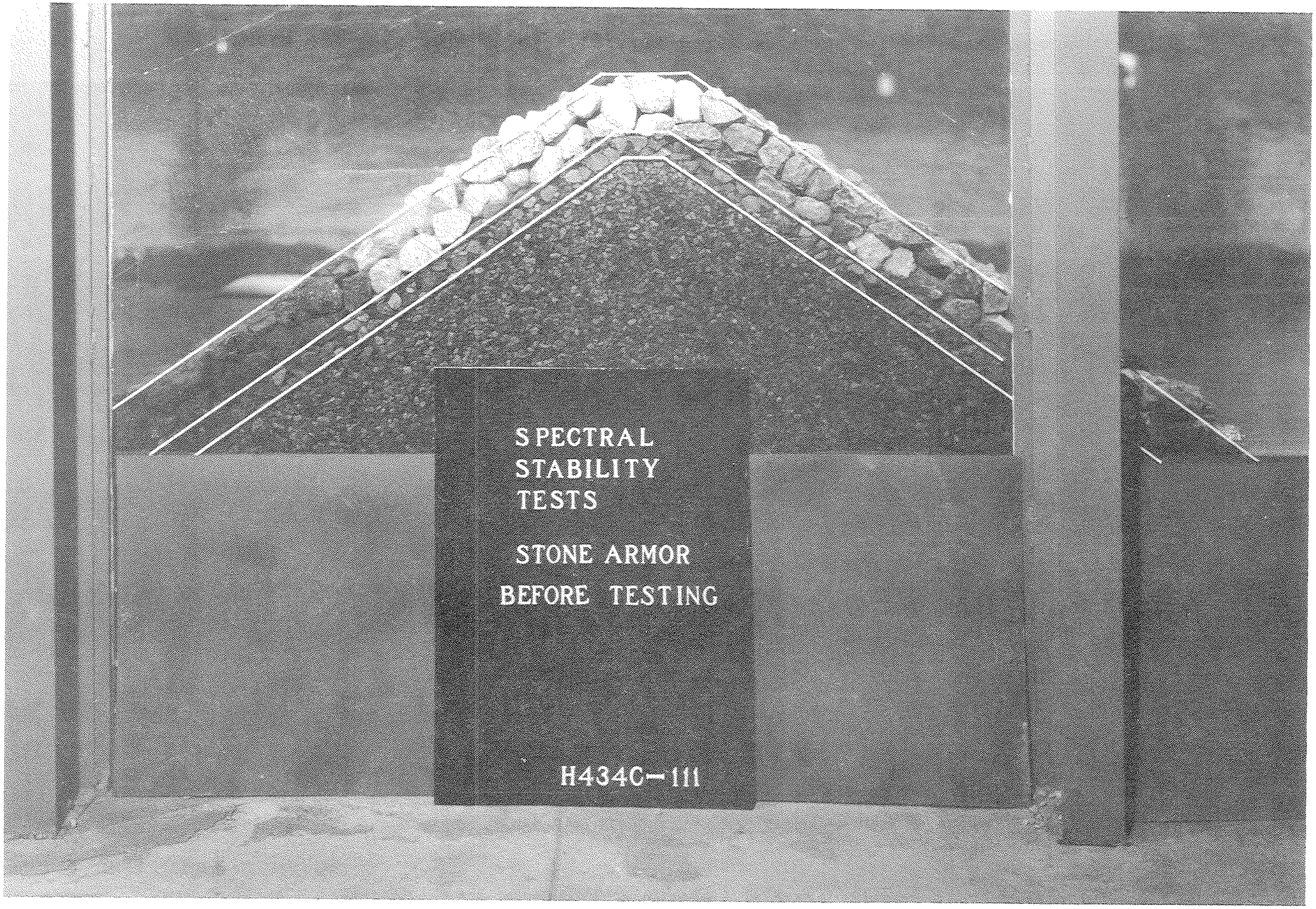

Photo 5. End view of a typical stone section before wave attack at a 1V on 1.5H seaside structure slope; d = 1.0 ft

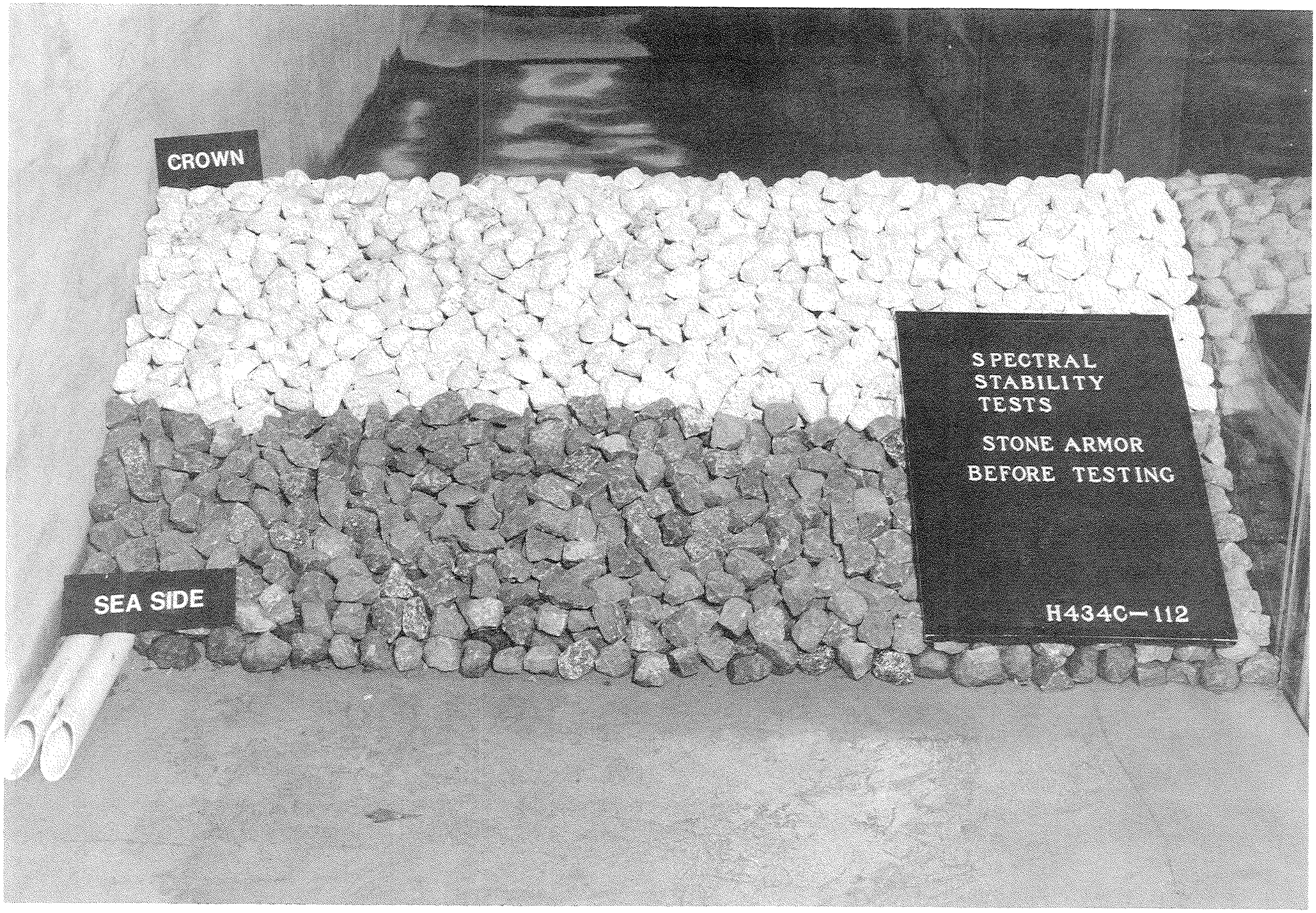

Photo 6. Seaside view of a typical stone section before wave attack at a 1V on 1.5H seaside structure slope; d = 1.0 ft

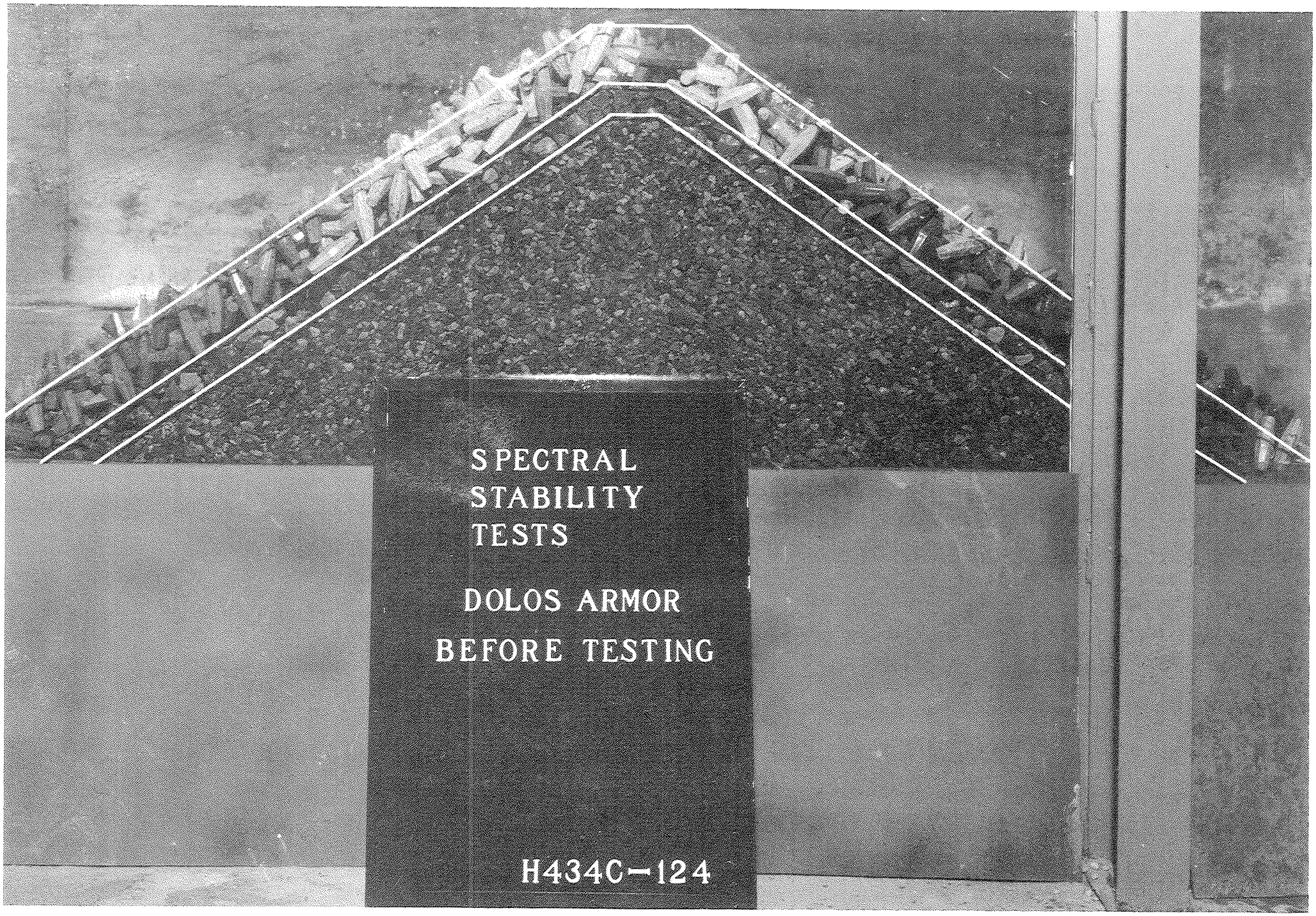

Photo 7. End view of a typical dolos section before wave attack at a 1V on 1.5H seaside structure slope; d = 1.0 ft

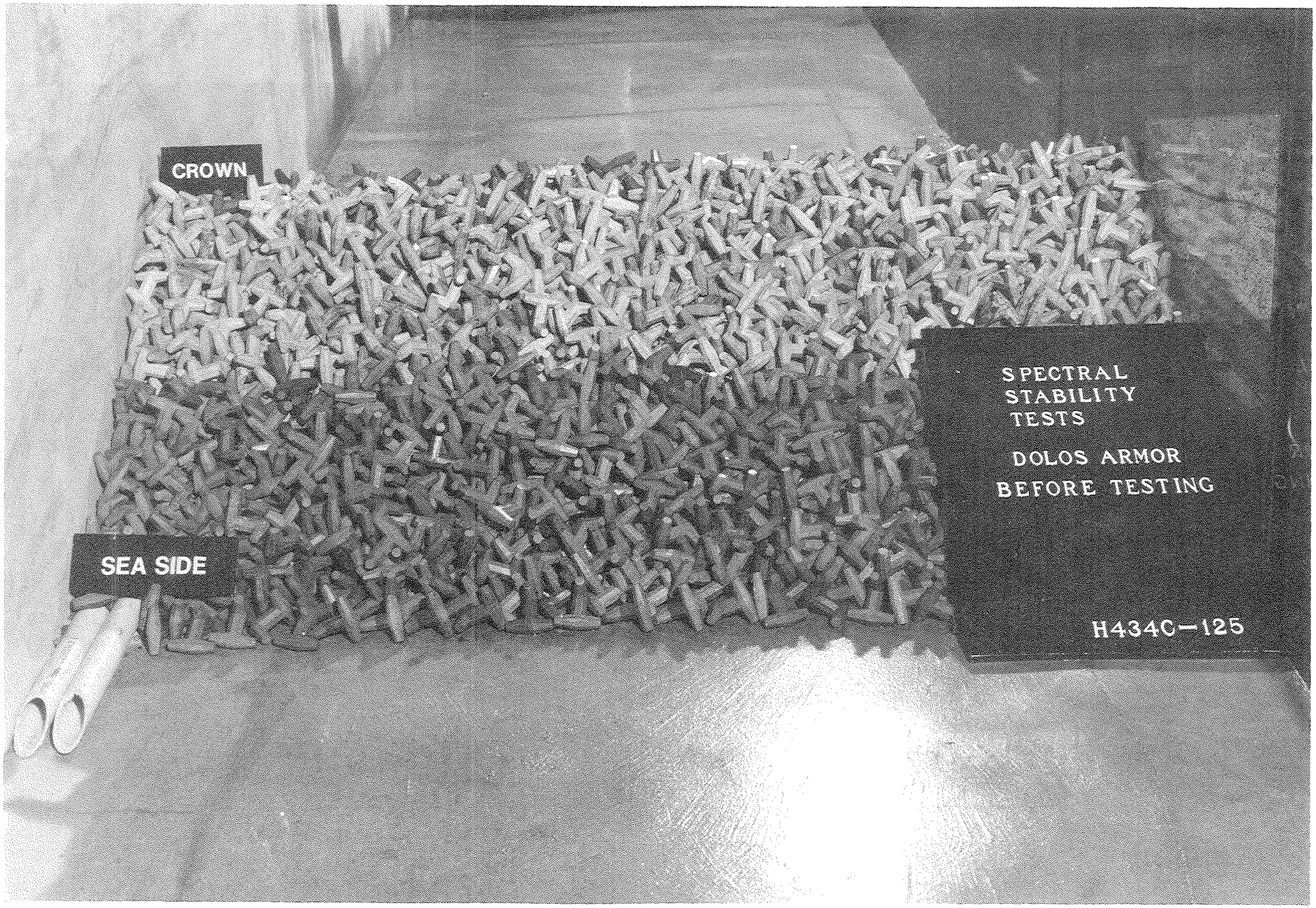

Photo 8. Seaside view of a typical dolos section before wave attack at a 1V on 1.5H seaside structure slope; d = 1.0 ft

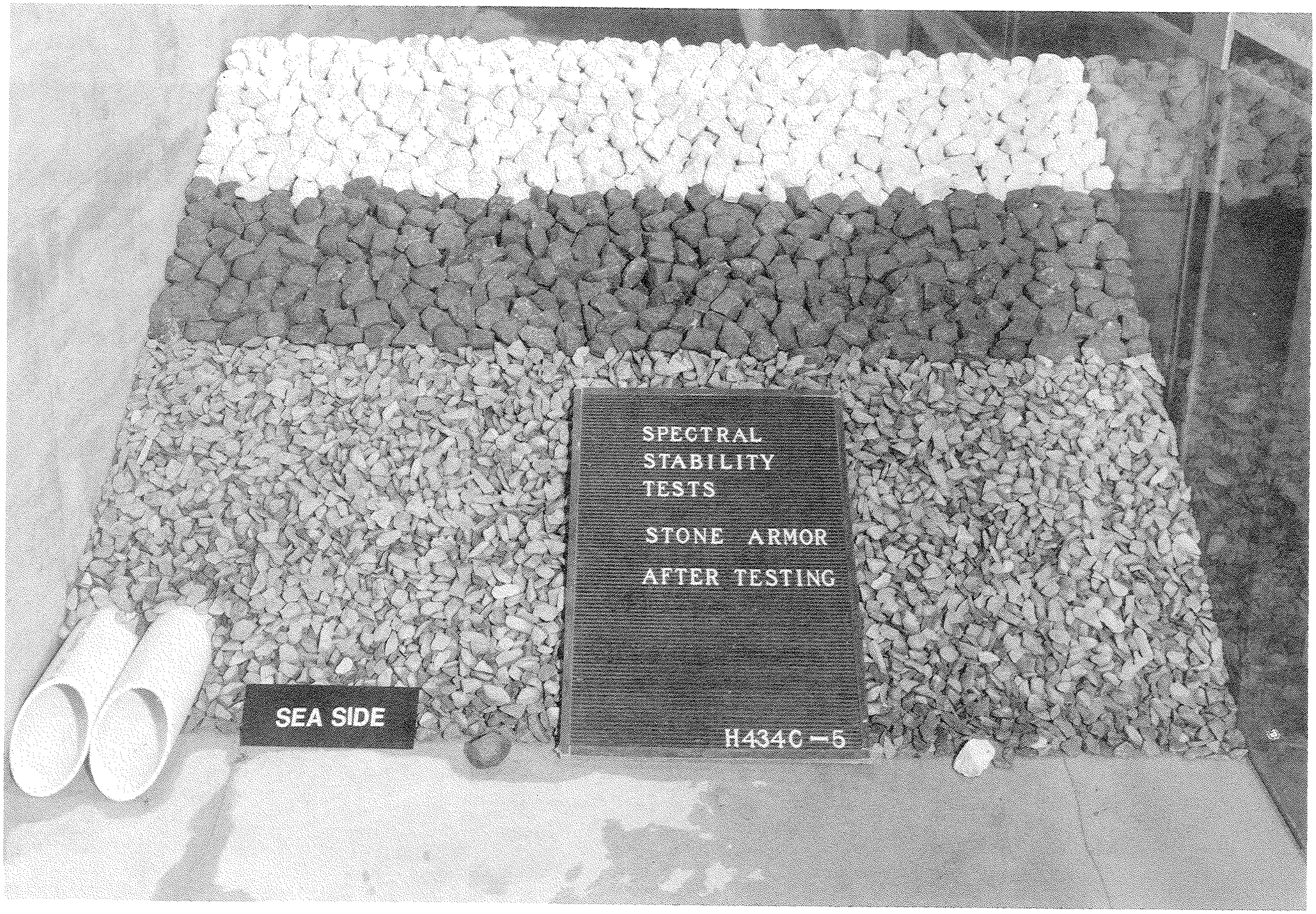

Photo 9. Seaside view after attack of 1.2-sec waves; d = 2.0 ft; 1V on 1.5H structure slope; stone armor

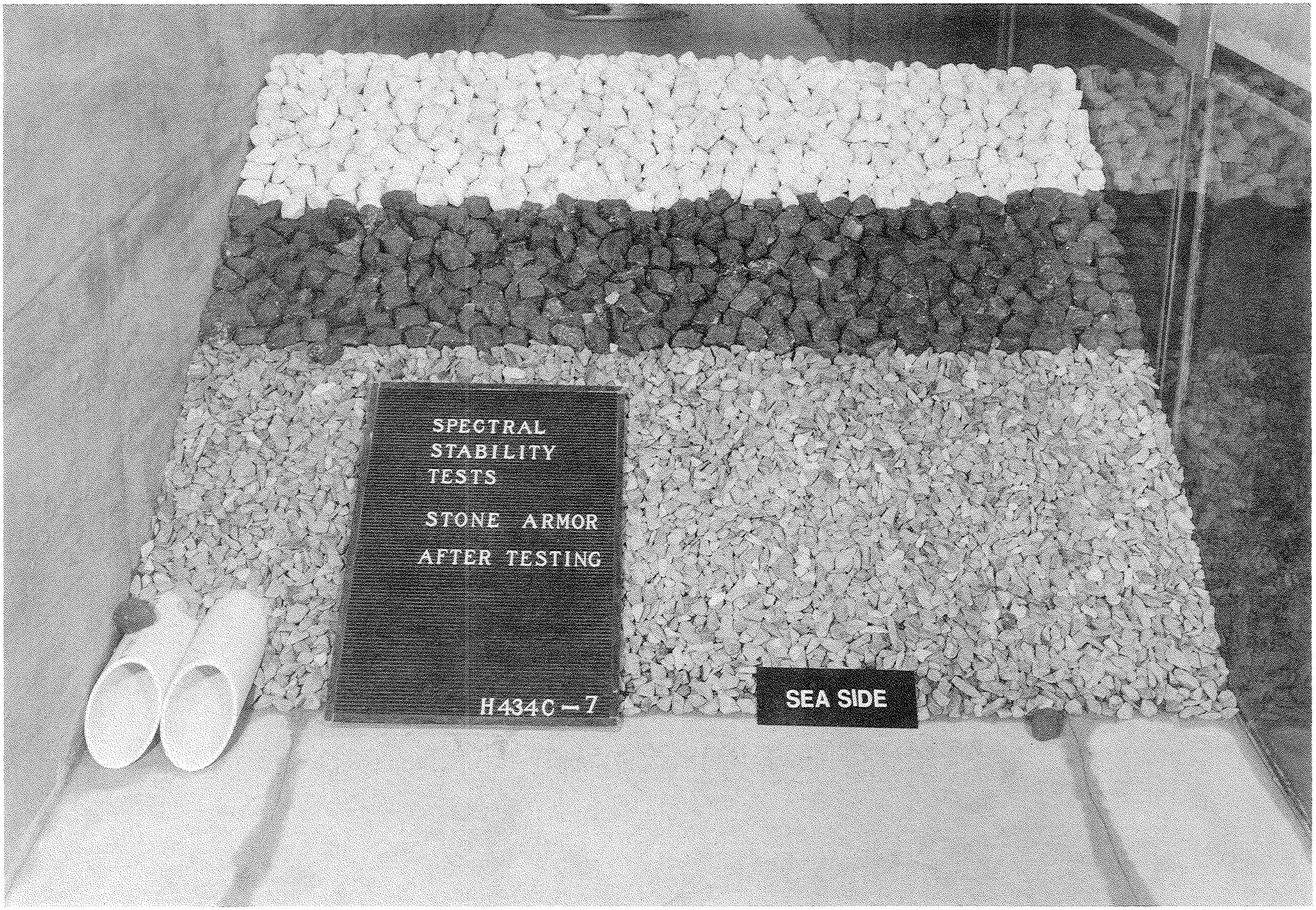

Photo 10. Seaside view after attack of 1.45-sec waves; d = 2.0 ft; 1V on 1.5H structure slope; stone armor

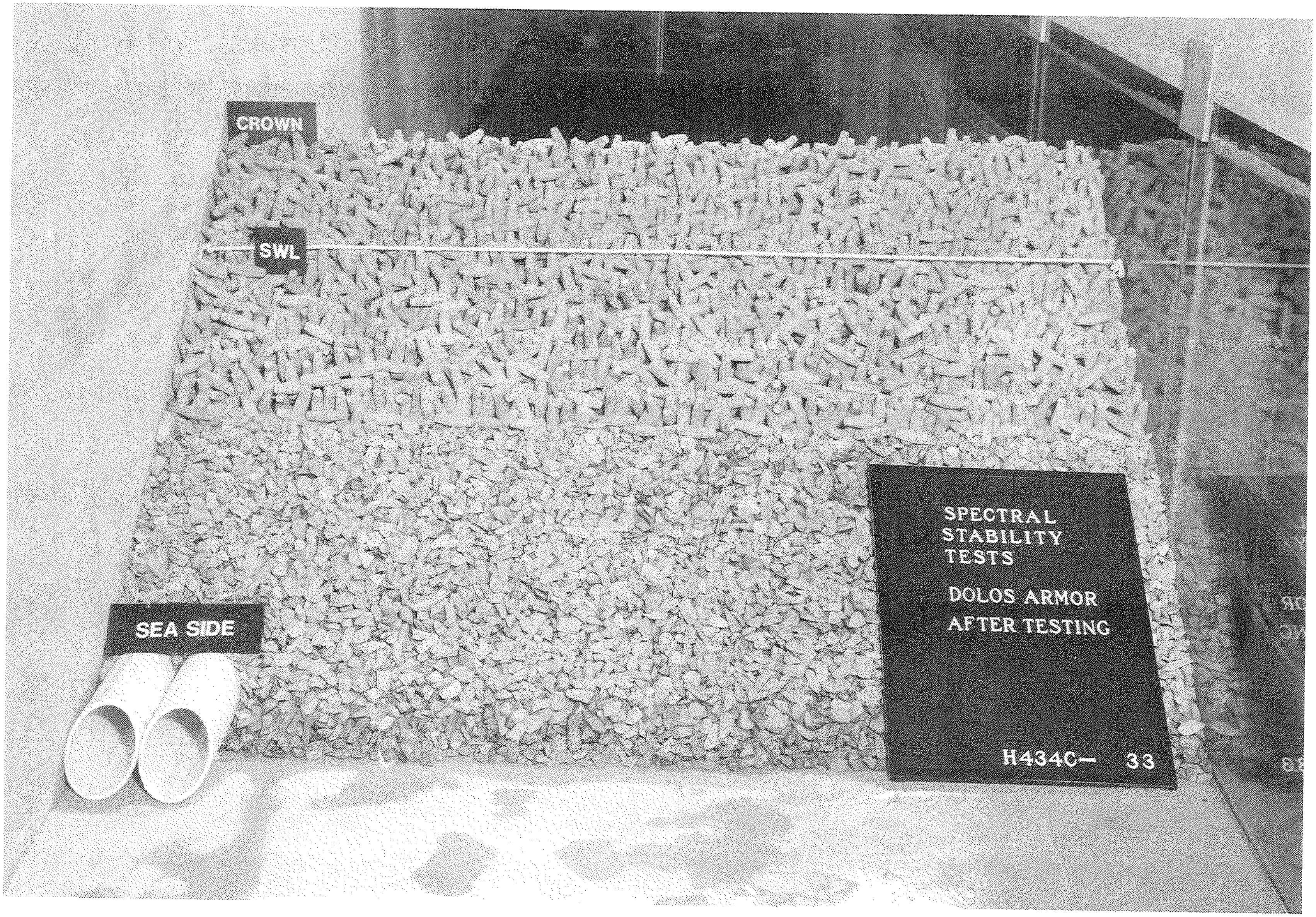

Photo 11. Seaside view after attack of 1.8-sec waves; d = 2.0 ft; 1V on 1.5H structure slope; dolos armor

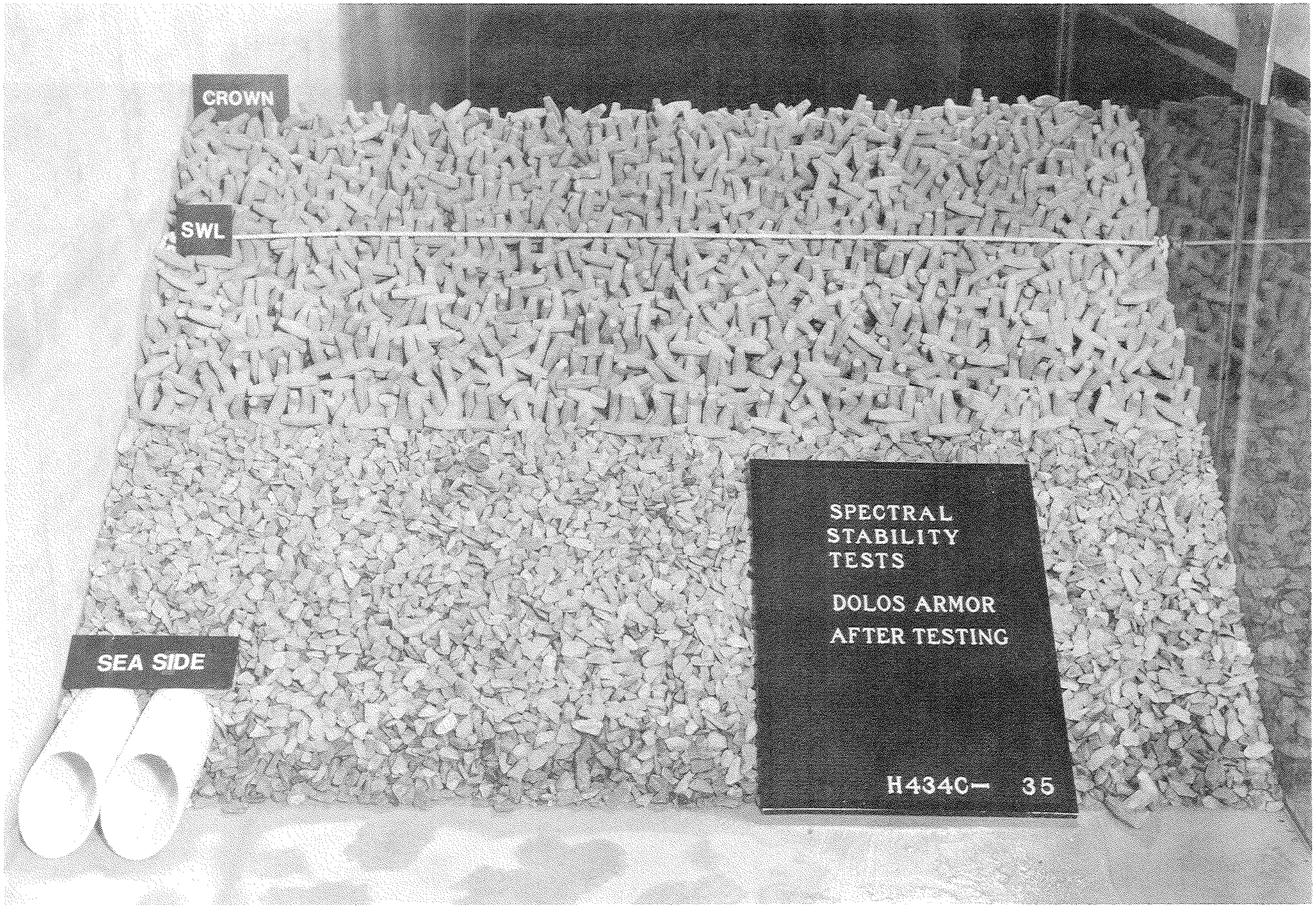

Photo 12. Seaside view after attack of 2.25-sec waves; d = 2.0 ft; 1V on 1.5H structure slope; dolos armor

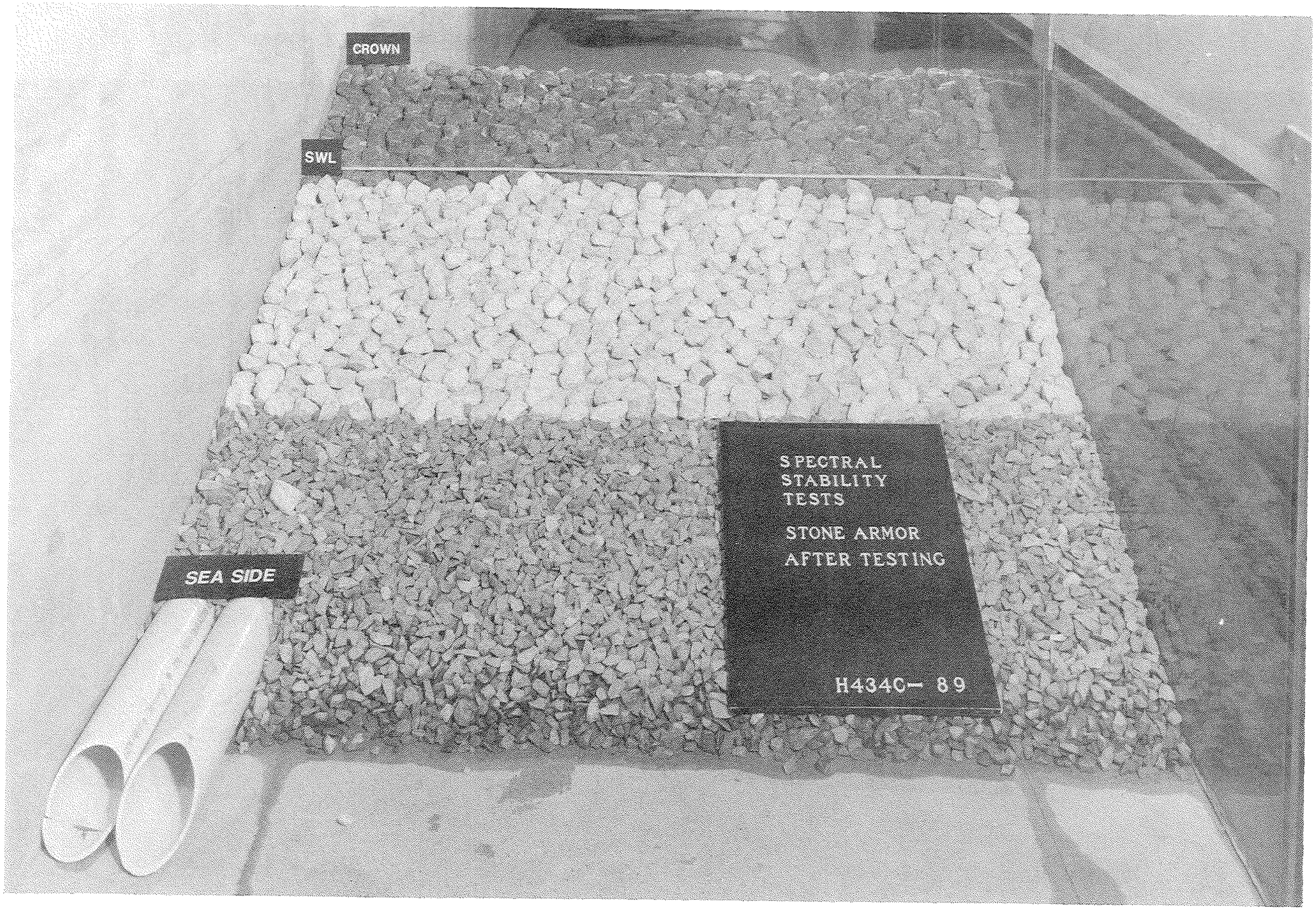

Photo 13. Seaside view after attack of 3.0-sec waves; d = 2.0 ft; 1V on 2.25H structure slope; stone armor

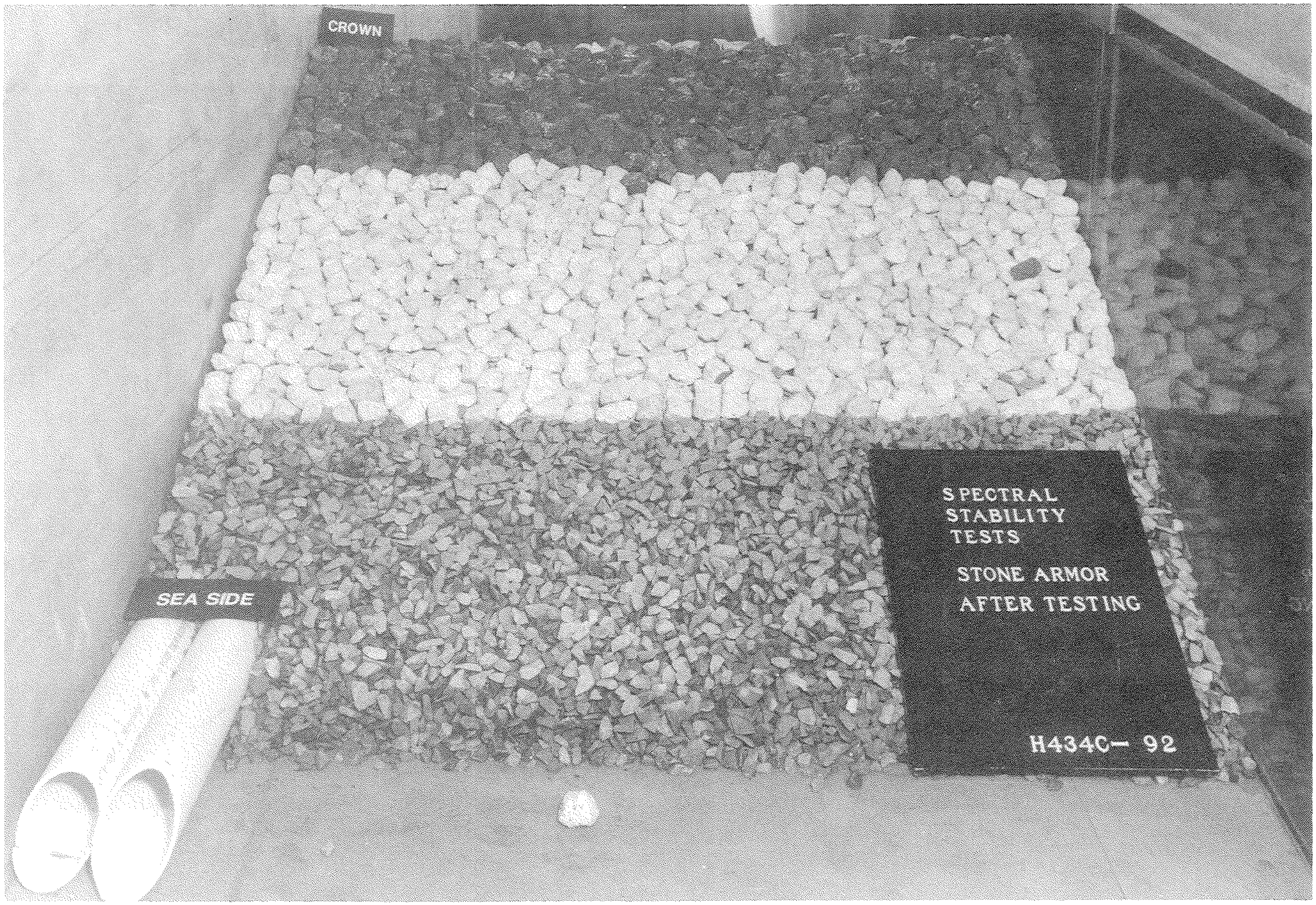

Photo 14. Seaside view after attack of 1.2-sec waves; d = 2.0 ft; 1V on 2.25H structure slope; stone armor

Photo 15. Seaside view after attack of 1.45-sec waves; d = 2.0 ft; 1V on 2.25H structure slope; dolos armor

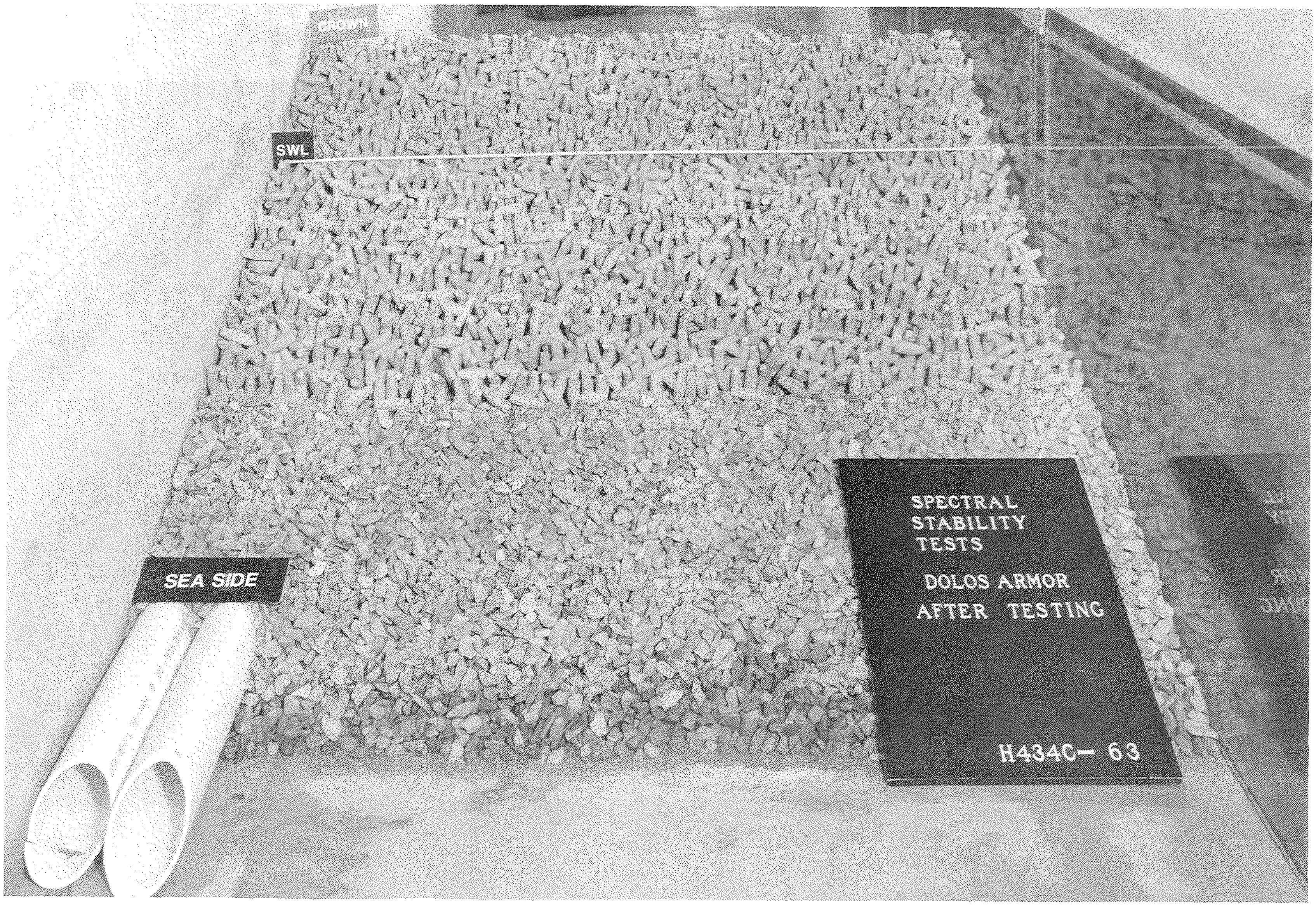

Photo 16. Seaside view after attack of 1.8-sec waves; d = 2.0 ft; 1V on 2.25H structure slope; dolos armor

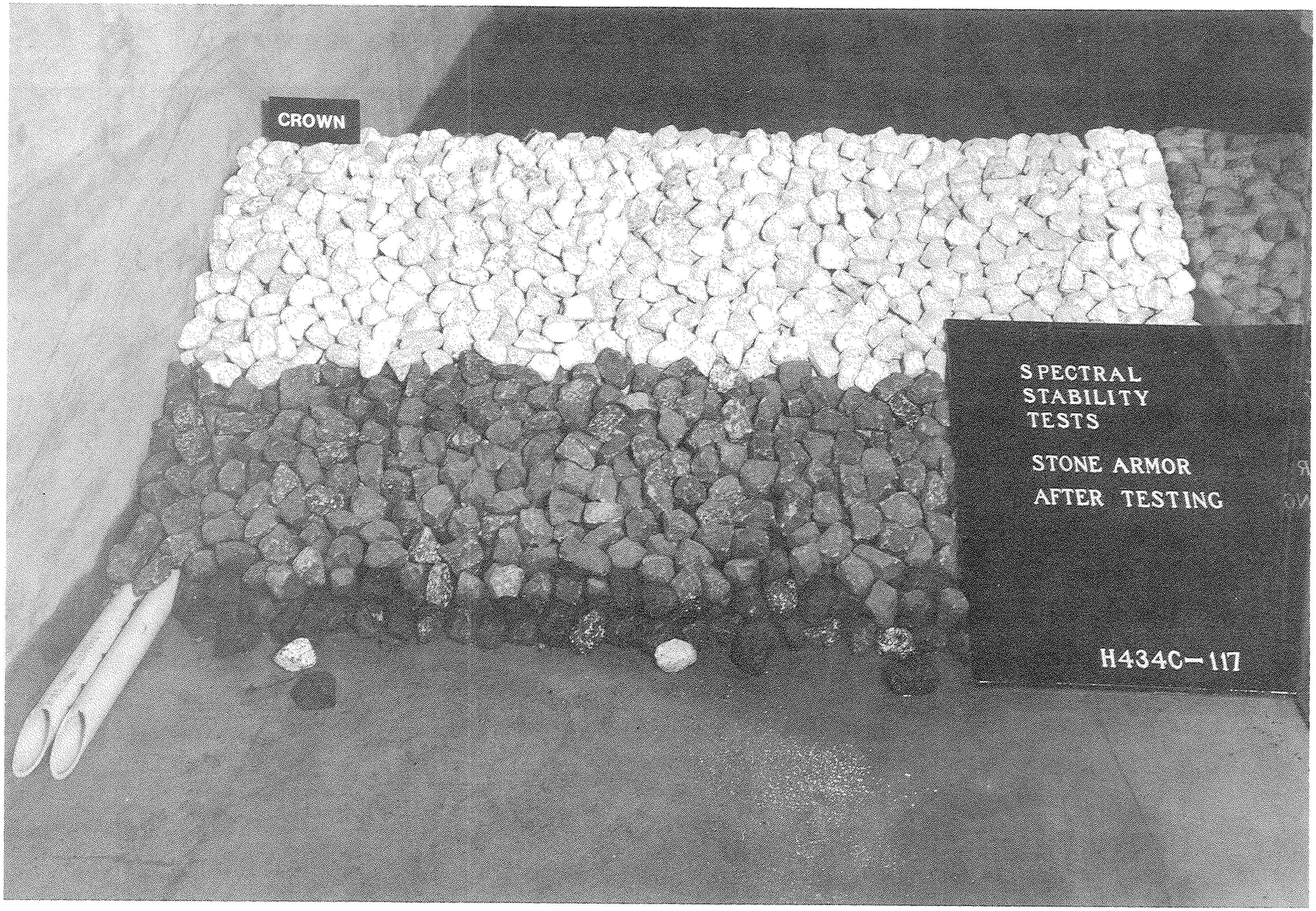

Photo 17. Seaside view after attack of 2.25-sec waves; d = 1.0 ft; 1V on 1.5H structure slope; stone armor

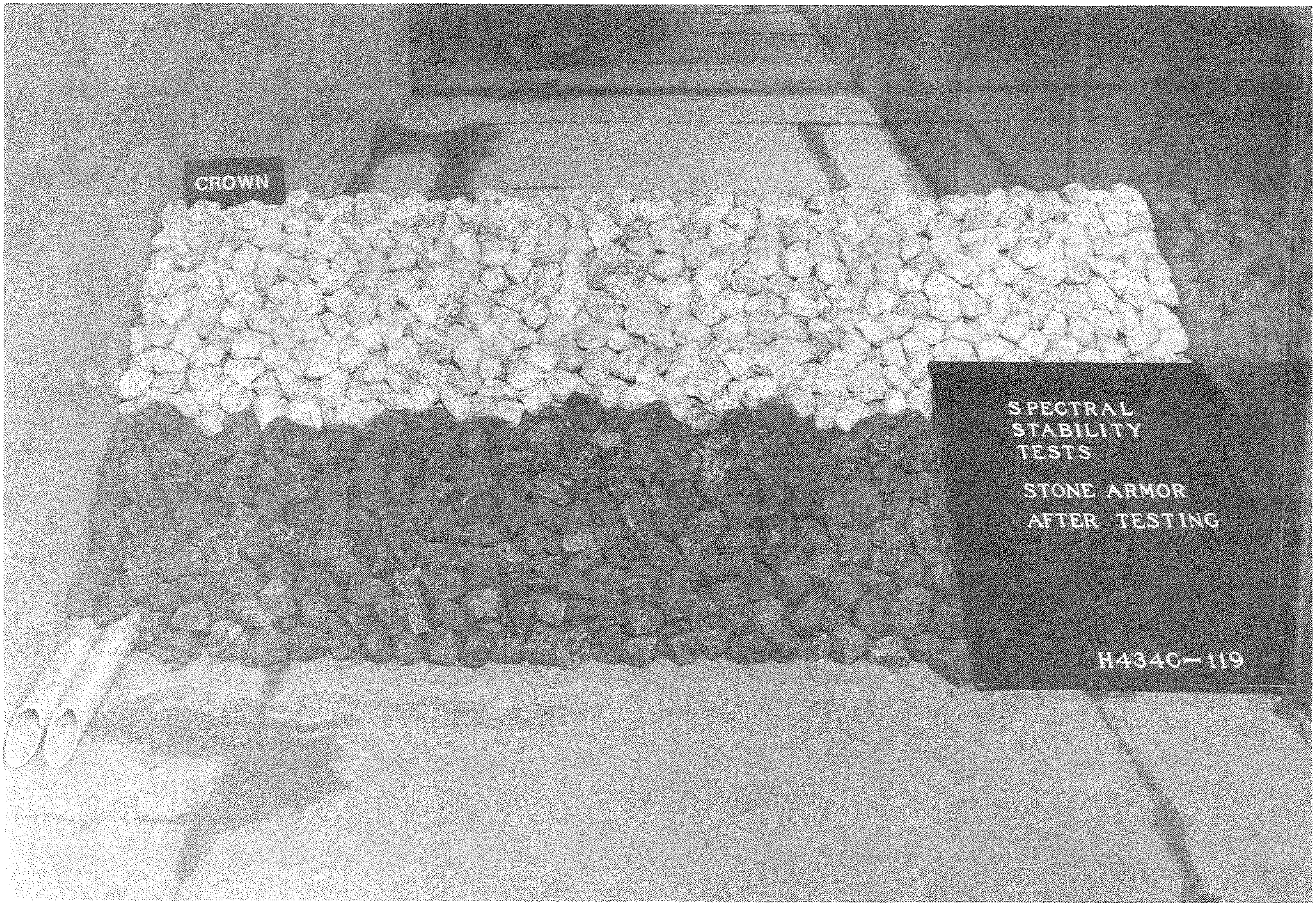

Photo 18. Seaside view after attack of 3.0-sec waves; d = 1.0 ft; 1V on 1.5H structure slope; stone armor

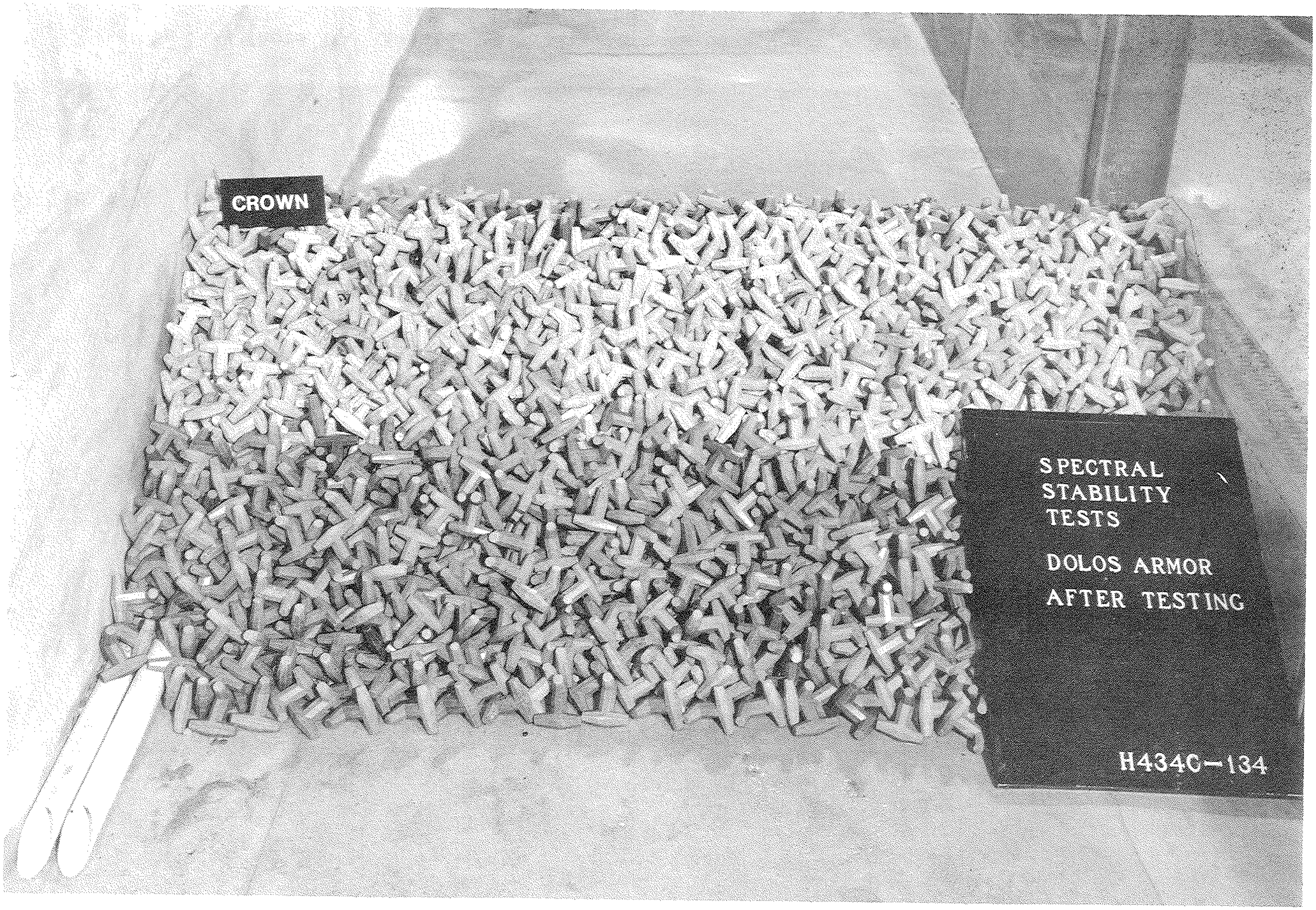

Photo 19. Seaside view after attack of 1.45-sec waves; d = 1.0 ft; 1V on 1.5H structure slope; dolos armor

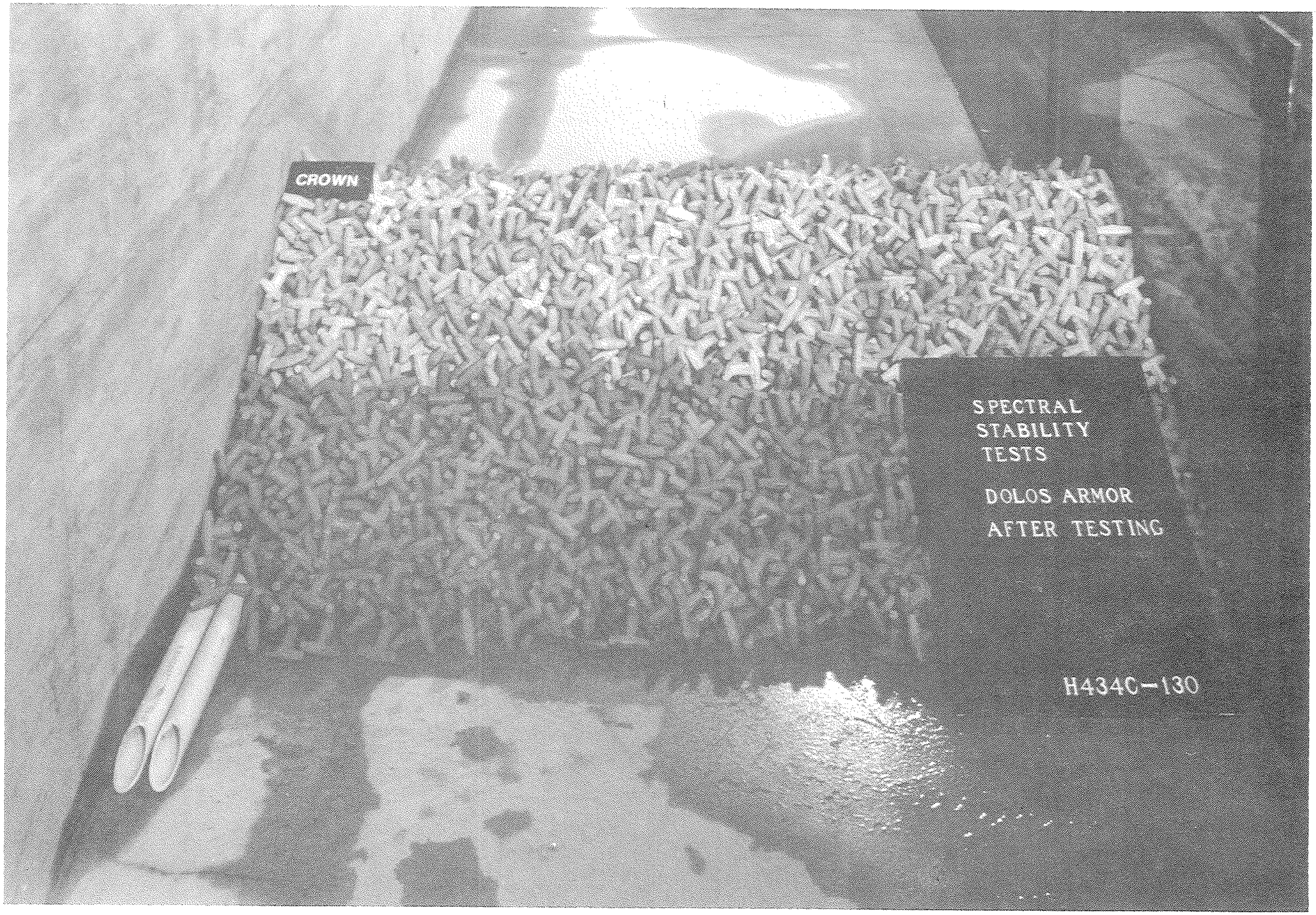

Photo 20. Seaside view after attack of 2.25-sec waves; d = 1.0 ft; 1V on 1.5H structure slope; dolos armor

APPENDIX A: NOTATION

A	Acceleration due to gravity, ft/sec^2
d	Water depth, ft
d/L	Relative depth, dimensionless
H_{mo}	Zero-moment wave height, ft
H_{mo}/d	Relative wave height, dimensionless
l_a	Characteristic length of armor unit, ft
L_p	Airy wave length, ft
N_{mono}	Monochromatic stability number, defined by Equation 2
N_{spec}	Spectral stability number, defined by Equation 3
R_N	Reynolds stability number, defined by Equation 1
T_p	Wave period of peak energy density of spectrum, sec
W	Weight, lb
α	Angle of breakwater slope, measured from horizontal, deg
cot α	Reciprocal of breakwater slope
γ	Specific weight, pcf
γ_a	Specific weight of armor unit, pcf
υ	Kinematic viscosity of experimental fluid medium, ft^2/sec