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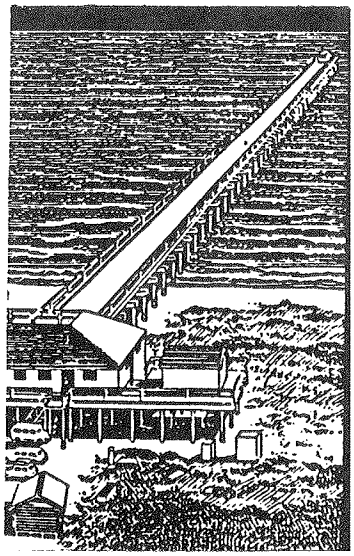

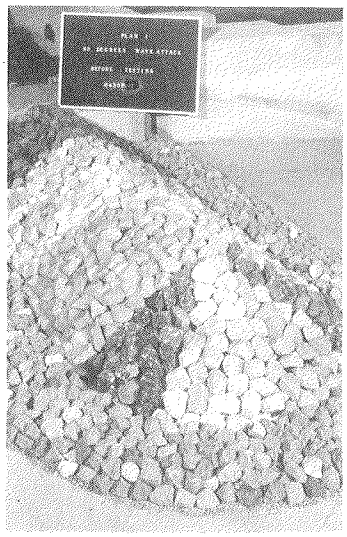

TECHNICAL REPORT CERC-89-4

STABILITY OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND BREAKWATER HEADS SUBJECTED TO BREAKING AND NONBREAKING WAVES WITH NO OVERTOPPING

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 heads and subjected to breaking waves. More specifically, it was desired to determine the minimum weight of individual armor units (with given specific weights) required for stability as a function of sea-side slope of the structure, angle of wave attack, wave period, and wave height.

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PREFACE

Authority for the US Army Engineer Waterways Experiment Station's (WES's) 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, CERC, 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 Mrs. Martha S. Heimbaugh, Hydraulic Engineer, CW-R. The models were operated by Messrs. C. Ray Herrington and Marshall P. Thomas, Engineering Technicians. This report was typed by Ms. Myra Willis, CW-R, and edited by Ms. Shirley A. J. Hanshaw, Information Products Division, Information Technology Laboratory, WES.

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

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

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

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745329	radians
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 OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND BREAKWATER HEADS SUBJECTED TO BREAKING AND NONBREAKING WAVES WITH NO OVERTOPPING

PART I: INTRODUCTION

Background

1. The experimental investigation described herein constitutes a portion of a research effort to provide guidance for the safe and economical design of rubble-mound breakwaters. In this study, a rubble-mound breakwater is defined as a protective structure constructed with a core of quarry-run stone, sand, or slag and protected from wave action by one or more stone underlayers and a cover layer composed of selected quarrystone or specially shaped concrete armor units.

2. Previous investigations have yielded a significant quantity of design information for (a) quarrystone (Hudson 1958 and Carver 1980, 1983); (b) quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson 1968); (c) dolosse (Carver and Davidson 1977 and Carver 1983); and (d) toskane (Carver 1978) which allow selection of armor type and weight for use on structure trunks. The stability of stone- and dolos-armored rubble-mound breakwater heads has been investigated for nonbreaking waves (Carver, Herrington, and Wright 1987). However, a systematic investigation of the stability response of breakwater heads has not been undertaken for breaking wave attack.

3. A proposed structure may necessarily be designed for either nonbreaking or breaking waves depending upon positioning of the breakwater and severity of anticipated wave action during its economic life. Some local wave conditions may be of such magnitude that the protective cover layer must consist of specially shaped concrete armor units to provide economic construction of a stable breakwater; however, many local design requirements are most advantageously met by quarrystone armor. This particular report addresses the use of stone and dolos armor on breakwater heads subject to breaking and nonbreaking waves.

Purpose of Study

4. The purpose of the present investigation was to obtain design information for stone and dolos armor used on breakwater heads. More specifically, it was desired to determine the minimum weight of individual armor units (with given specific weights) required for stability as a function of:

a. Type of armor unit.

b. Sea-side slope of the structure.

c. Angle of wave attack.

d. Wave period.

e. Wave height.

PART II: TESTS

Stability Scale Effects

5. Laboratory tests of model breakwaters must consider scale effects. 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 requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater tests and concludes that scale effects will be negligible if the Reynolds stability number R_N *

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

where

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

---

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

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

shovel into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype 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.

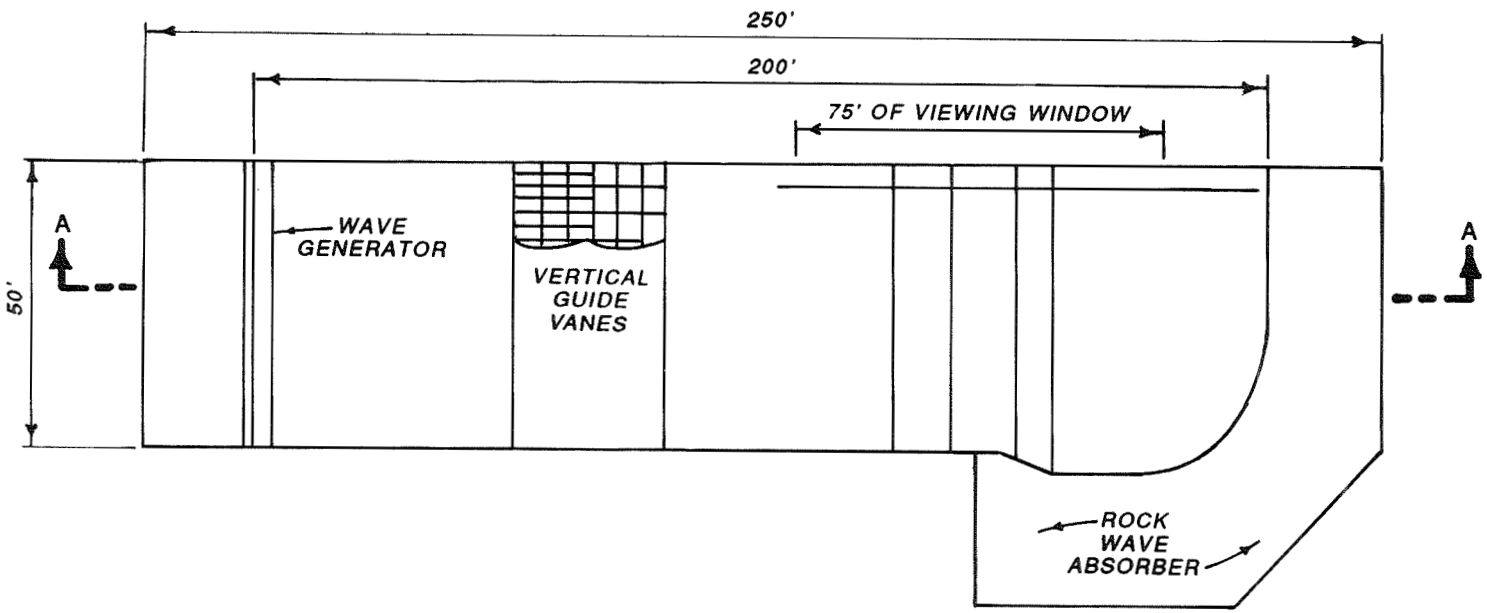
Test Equipment and Materials

Equipment

7. All stability tests were conducted in either an L-shaped or a T-shaped concrete flume. The L-shaped flume is 250 ft long, 50 and 80 ft wide at the top and bottom of the L, respectively, and 4.5 ft deep (Figure 1). The T-shaped flume is 164 ft long, 43 and 15 ft wide at the top and bottom of the T, respectively, and 3.3 ft deep (Figure 2). The L-shaped flume is equipped with a flap wave generator, whereas the T-shaped flume is equipped with a horizontal displacement wave generator. Changes in water surface elevation as a function of time (wave heights) were measured by electrical wave height gages in the vicinity where the toe of the test sections was to be placed. Electrical output of the wave gages was directly proportional to their submergence depth. Test sections constructed in the L-shaped flume were at the top of a 1V:35H bottom slope; whereas, the section tested in the T-shaped flume was at the top of a 1V:10H slope.

Material

8. Rough, hand-shaped granitic stone with an average length of approximately two times its width, average weights of 0.38 and 0.55 lb, and a specific weight of approximately 167 pcf was used to armor the stone sections. Dolos sections were armored with 0.276-lb units that have a specific weight of 142.2 pcf. Sieve-sized limestone (specific weight = 165 pcf) was used for the underlayers and core.



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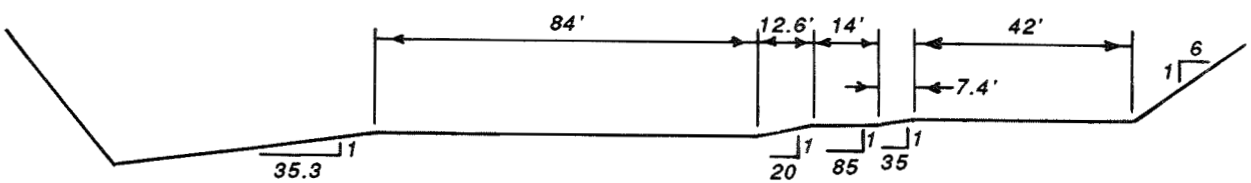
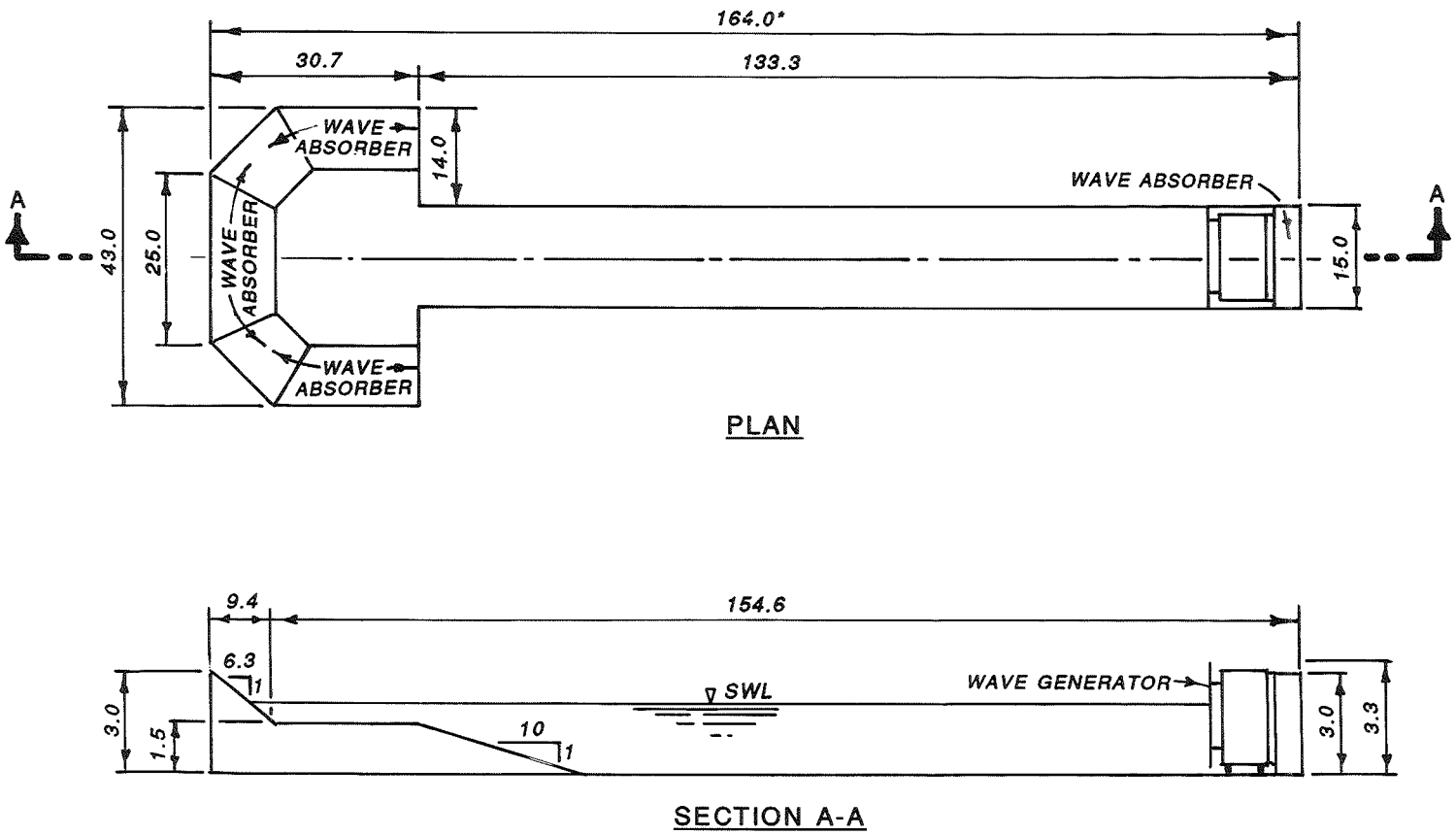


SECTION A-A

Figure 1. Layout of the L-shaped flume



* LINEAR DIMENSIONS ARE IN MODEL FEET

Figure 2. Layout of the T-shaped flume (swl = still-water level)

Selection of Test Conditions

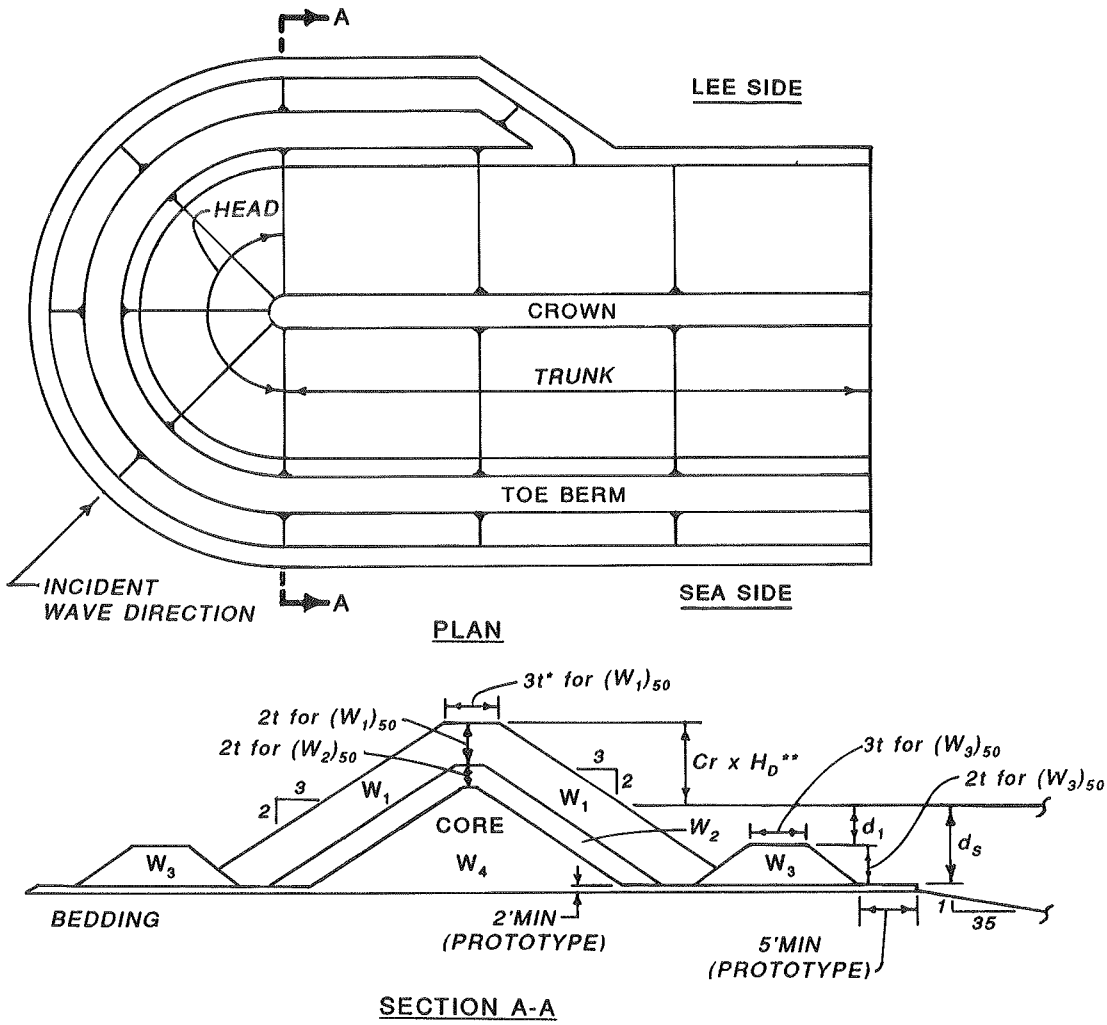
9. By nondimensionalizing design conditions from site-specific projects, it was found that a d/L range of 0.04 to 0.14 should include most prototype conditions encountered in breaking-wave stability designs. A review of capabilities of the available wave flumes and generators showed that this range of d/L values could be achieved for a reasonable range of testing depths.

10. The wave flumes were calibrated (wave height was determined as a function of paddle strokes) for depths of 0.40, 0.50, and 0.60 ft at d/L values of 0.04, 0.06, 0.08, 0.10, 0.12, and 0.14. This range of depths and, consequently, breaking wave heights proved to be compatible with the selected armor weights and breakwater slopes. Model periods ranged from 1.10 to 2.82 sec.

11. Previous breaking wave tests have been conducted with the most severe condition obtainable for a particular combination of wave period and water depth. Armor weight would then be adjusted until stability was achieved. Because of time constraints on the tests described herein, a limited number of tests were conducted with a predetermined stone weight, and the breaking wave height was adjusted until the armor was stable for that combination of wave period and water depth. These tests are noted in Appendix A with an asterisk. Results fit the trends established by previous data when they are nondimensionalized.

12. Each monochromatic test wave was allowed to attack the breakwater for a cumulative period of 30 min, then the test sections were rebuilt prior to attack by the next wave condition. This 30-min interval allowed sufficient time for the test sections to stabilize, i.e., time for all significant movement of armor material to abate. During tests, the wave generator was stopped as soon as reflected waves from the breakwater reached it, and the waves were allowed to decay to zero height before restarting the generator in order to prevent the test sections from being exposed to uncontrolled wave groups and/or an undefined wave spectrum.

13. All tests were conducted on stone and dolos conical head sections of the type shown in Figure 3 and Photos 1 and 2. Results of previously conducted nonbreaking wave head tests (Carver, Herrington, and Wright 1987) are graphically summarized in Figure 4. These data show angles of wave attack



W_1 = PRIMARY ARMOR ($(W_1)_{50}$ = (0.38 OR 0.55 LB STONE OR 0.276 LB DOLOS, VARIED FROM PLAN TO PLAN)

W_2 = UNDERLAYER STONE ($(W_2)_{50} = 1/10(W_1)_{50}$ FOR STONE ARMOR AND $(W_2)_{50} = 1/5(W_1)_{50}$ FOR DOLOS ARMOR)

W_3 = TOE BERM STONE $(W_3)_{50}$ RANGED FROM 0.55 TO 0.055 LB; (WEIGHT VARIED WITH d_s AND H_D)

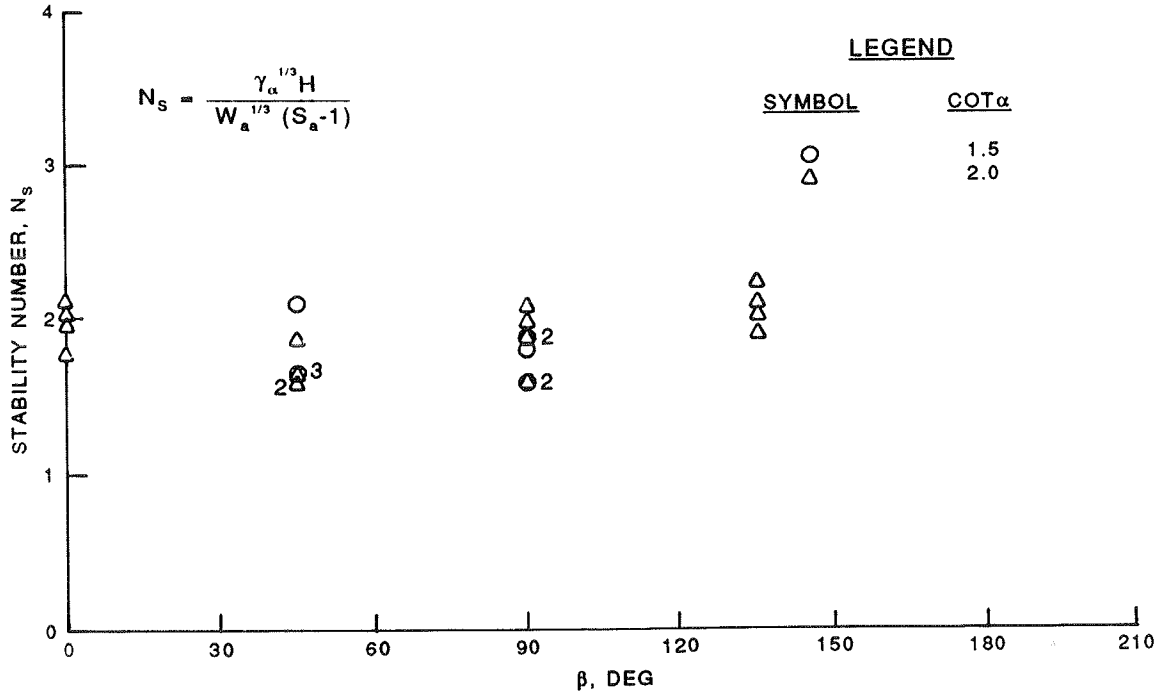
W_4 = CORE AND BEDDING STONE ($W_4 = W_1/200$ TO $W_1/4000$)

---

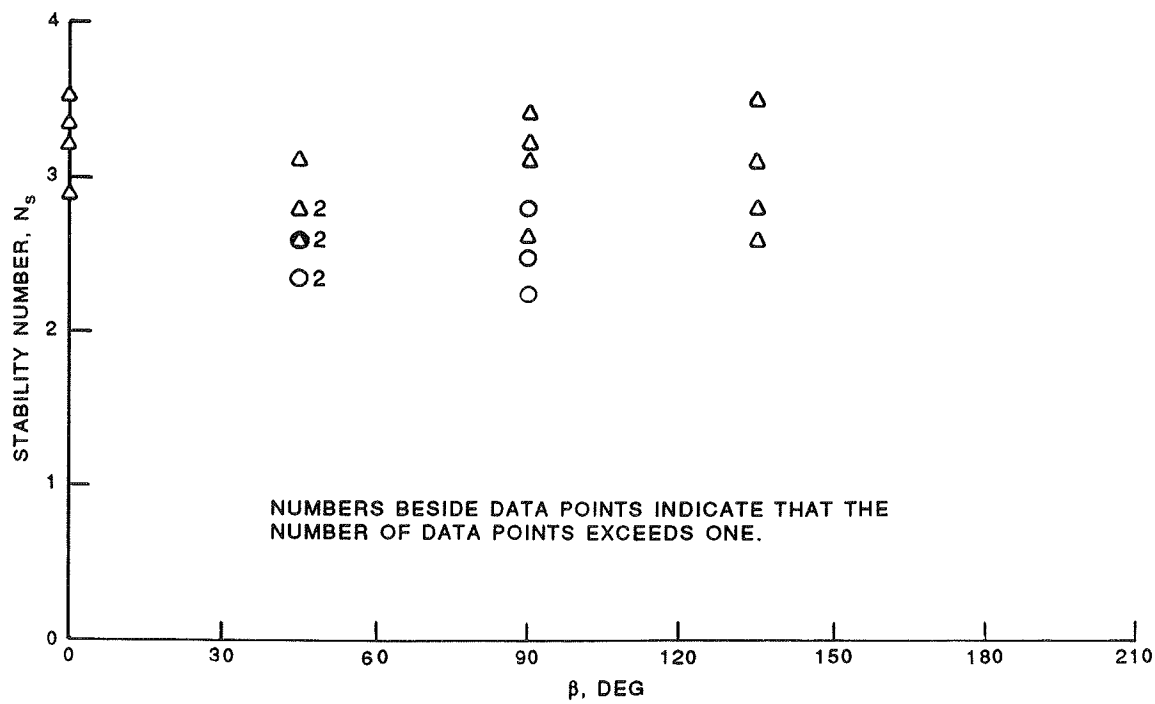
* $t = k^{\Delta}(W/\gamma)^{1/3}$, WHERE k^{Δ} = 1.0 FOR ROUGH ANGULAR STONE AND 0.94 FOR DOLOSSE AND $W = W_{50}$

** CREST HEIGHT SET AT $C_r X H_D$ ABOVE MAXIMUM SWL, WHERE H_D IS DESIGN WAVE HEIGHT ASSOCIATED WITH MAXIMUM SWL AND C_r IS MAXIMUM RUNUP COEFFICIENT FOR MAXIMUM SWL DESIGN CONDITIONS. C_r = 0.80 FOR DOLOSSE AND C_r = 1.0 FOR STONE ARMOR.

Figure 3. Typical test section



a. Stone armor stability number N_s versus angle of wave attack β



b. Dolos armor stability number N_s versus angle of wave attack β

Figure 4. Nonbreaking wave head test results

of 45 and 90 deg to be the most critical for nonbreaking waves. Therefore, these wave directions were selected for use in the present investigation. Monochromatic data for breaking waves collected in the present investigation were combined with the above mentioned nonbreaking wave data to generalize and expand the present data analysis.

PART III: DATA ANALYSIS AND TEST RESULTS

Monochromatic Tests

14. As previously mentioned, data in this report come from current breaking wave tests and previous monochromatic nonbreaking wave tests (Carver, Herrington, and Wright 1987). Appendix A summarizes all data showing the experimentally determined design wave heights and corresponding stability numbers as functions of wave period, water depth, surf parameter, foreslope, and structure slope. Combining data taken for the 45- and 90-deg angles of wave attack for breaking and nonbreaking wave conditions provides sufficient data to present a new method to calculate armor unit weight. Photos 3-14 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.

15. The stability number N_s provides a way to correlate stability test results. The Shore Protection Manual (SPM 1984) defines N_s as

$$N_s = \frac{\gamma_a^{1/3} H}{\left(S_a - 1\right) W_a^{1/3}} \tag{2}$$

where γ_a is the specific weight of an armor unit in pcf, H is the wave height at the structure toe in feet, S_a is the specific gravity of an armor unit relative to the water in which it is placed, and W_a is the weight in pounds of an acceptably stable armor unit. A more detailed discussion of N_s can be found in Carver (1983).

16. An effort was made to consolidate the data into a definable trend by plotting N_s versus several dimensionless variables. The dimensionless variable that provided the best correlation was the surf similarity parameter, ξ, defined as

$$\xi = \frac{\tan \theta}{\left(\frac{H}{L}\right)^{1/2}} \tag{3}$$

where

θ = angle between structure's front slope and the horizontal, in degrees

H = wave height at the toe of the structure in feet

L = calculated wavelength in the water depth at the toe of the structure in feet

Figure 5 is a plot of stability number N_s versus surf parameter ξ for the combined 45- and 90-degree wave attack directions. These data represent breaking and nonbreaking wave conditions for stone and dolos armor units as well as several different fronting slopes. The data clearly fall into four separate trends. The two upper trends represent dolos armor units with structure slopes of 1V on 1.5H and 1V on 2H, while the two lower trends represent stone armor units also with structure slopes of 1V on 1.5H and 1V on 2H. Best fit regression curves in the form of

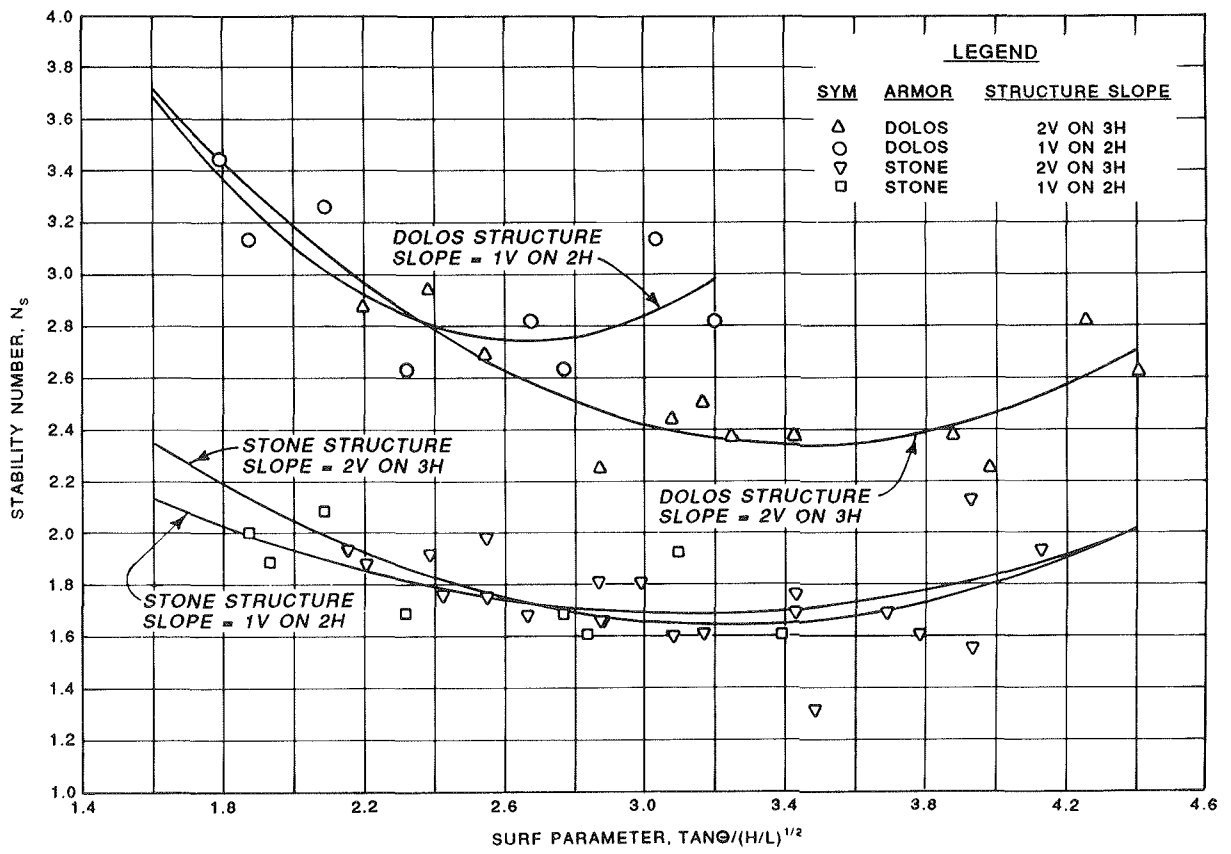


Figure 5. Stability number versus surf parameter (best fit curves for 45- and 90-deg wave attack)

$$N_s = A\xi^2 + B\xi + C \tag{4}$$

where A, B, and C are dimensionless regression coefficients, were fit to the data and are also shown in Figure 5. The successful fit is encouraging and is supported by earlier work (Ahrens and McCartney 1975), where regression curves of the same form were fit to dumped stone riprap stability data with similar success.

17. To use these curves for the design of head sections, it is necessary to make the regression curves more conservative. Using the standard error of estimate, which is the error between the observed data points and the predicted regression curve, provides a logical way to lower the regression curves. By subtracting two standard errors of estimate from the "C" coefficient, a new coefficient, C conservative or simply C_c is produced. This new coefficient can be used in concept with Equation 5 to form lower, more conservative design curves. The design coefficients along with the standard

$$N_s = A\xi^2 + B\xi + C_c \tag{5}$$

errors of estimate for each curve and the approximate tested range of the surf parameter are given in Table 1. Figure 6 shows the recommended design curves which correspond to the data in Table 1. Lowering the curves by two standard errors of estimate should predict safe armor weights for the complete range of wave periods and is consistent with the earlier work of Ahrens and McCartney (1975). Using the design curves outside the tested range of ξ is not recommended. Example Problems 1 and 2 (Part IV) demonstrate the use of these design curves. Figures 7 and 8 show data plots of N_s versus ξ for angles of wave attack of 0 and 135 deg, respectively. Because of the minimum amount of data available for these two wave directions and because the 45- and 90-deg wave directions are more critical for design, no attempt was made at defining design curves for these angles of wave attack.

Spectral Tests

18. Spectral wave capability was added to the L-shaped flume prior to completion of this study; therefore, it was decided to conduct limited comparative spectral tests. As previously discussed, the 0.38-lb stone armor

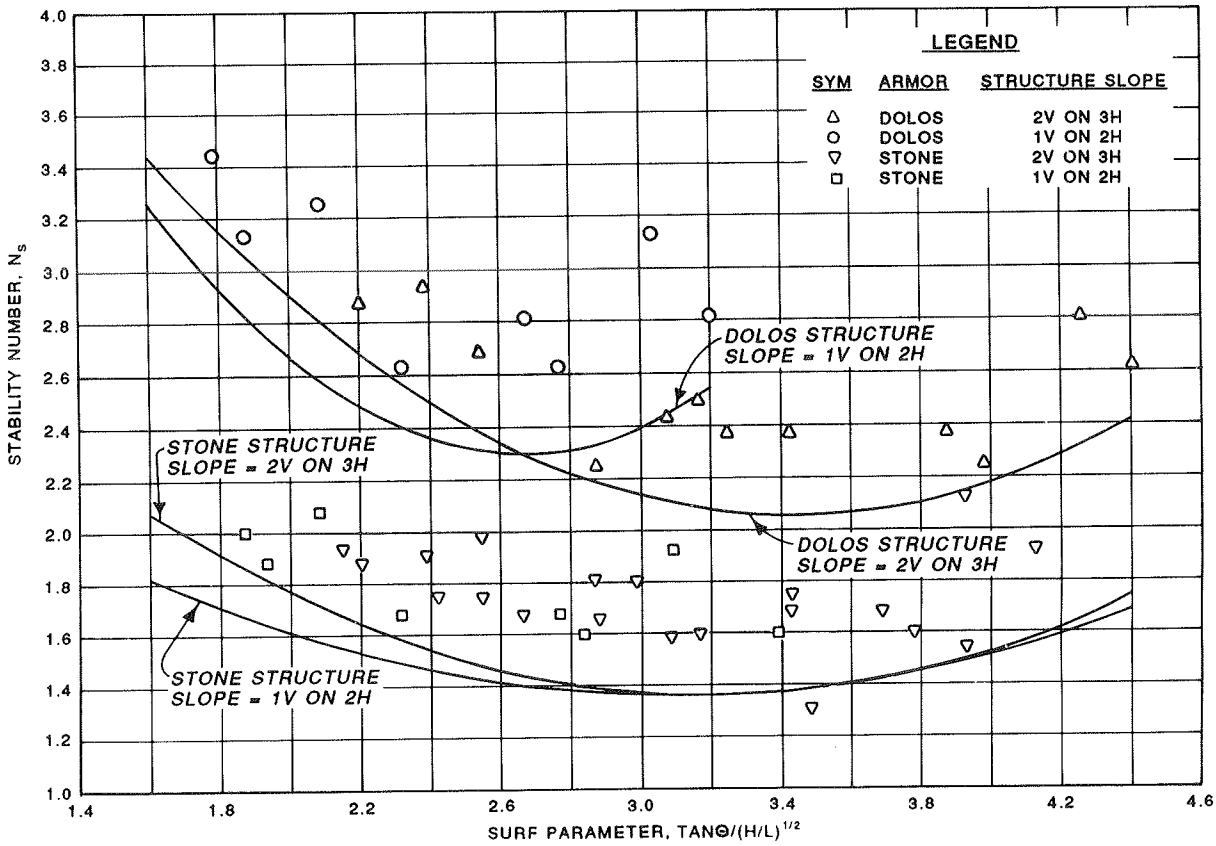


Figure 6. Stability number versus surf parameter (recommended design curves)

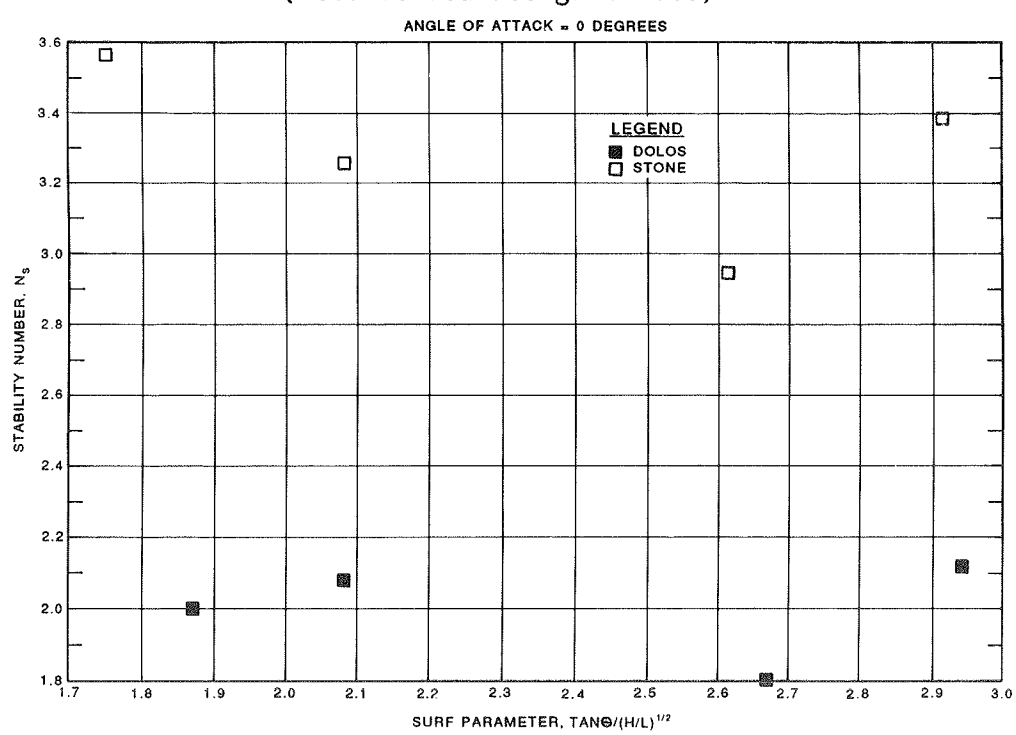


Figure 7. Stability number versus surf parameter for 0-deg wave attack

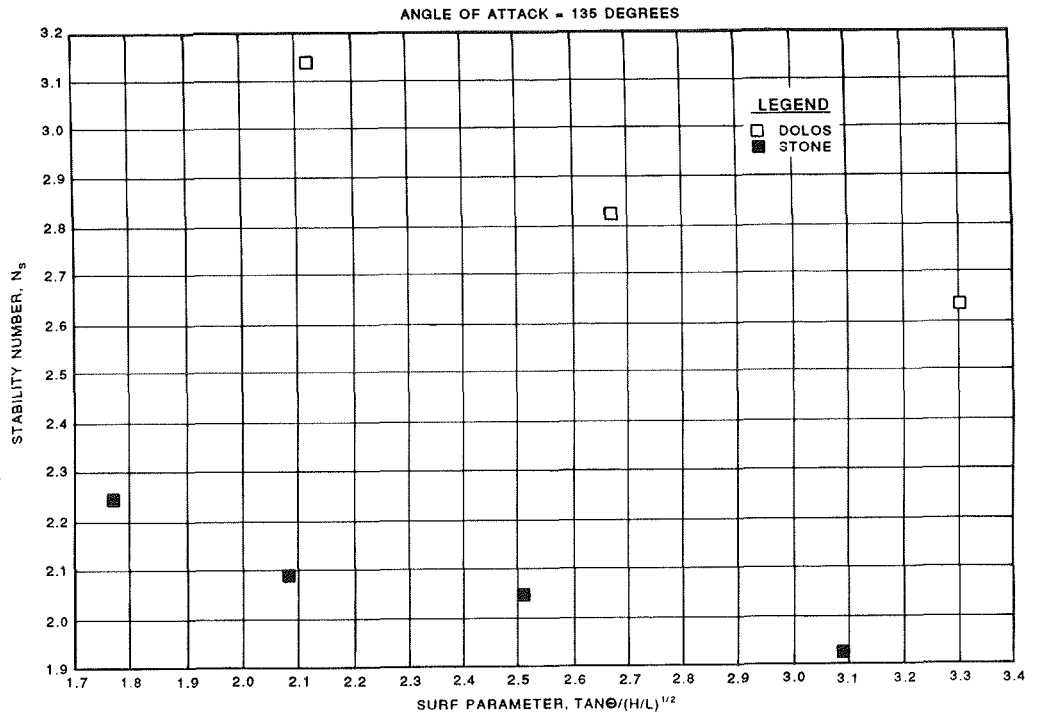


Figure 8. Stability number versus surf parameter for 135-deg wave attack

proved to be stable for the most severe breaking wave conditions obtainable with the following combinations of water depth and wave period for both 45- and 90-deg wave attack.

d, ft	T, sec
0.40	1.90
0.40	2.82
0.50	1.32
0.50	1.62
0.60	1.10

Selection of test conditions

19. Comparable JONSWAP spectra were tested for the above listed combinations of d and T. All spectral signals were developed with a gamma value of 3.3, and the peak period was assumed to be equal to the equivalent monochromatic period. The slope parameter was held constant at 0.07 for f<fp and 0.09 for f>fp (definition sketch in Figure 9). Goda and Suzuki's (1976) method was used to resolve the incident and reflected spectra. Figure 9

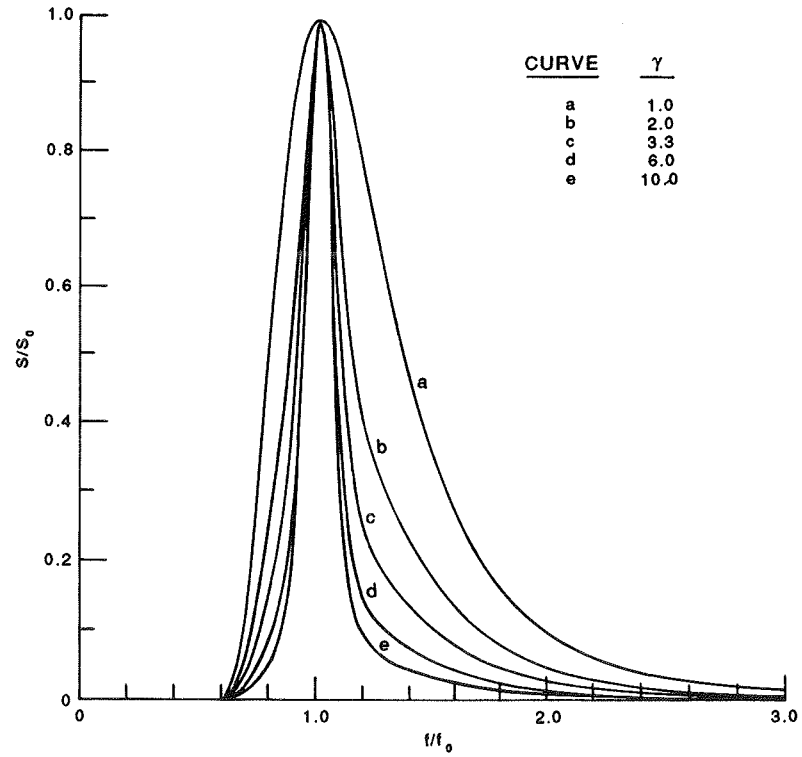


Figure 9. Five examples of JONSWAP spectra in dimensionless form

provides examples of Joint North Sea Wave Project (JONSWAP) spectra. As indicated, 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. Case a is a Pierson-Moskowitz spectrum. Case c is the result of the JONSWAP experiment.

Test results

20. Each spectrum was allowed to attack the test sections for a time equivalent to at least 1,000 peak wave periods. 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. Results of the spectral wave tests were very similar to those obtained in equivalent monochromatic tests; that is, test waves produced occasional displacement of a few random armor units; however, movement was never extensive enough to jeopardize stability of the test sections. Due to the limited number of spectral tests reported herein, results were evaluated based on observations and judged to be similar, more severe, or less severe than previously conducted monochromatic tests.

Discussion

21. The limited spectral stability tests described herein are by no means extensive enough to provide generalized guidance for design of structure heads. Observed similarity to monochromatic test results increases confidence in presently used design procedures which are based primarily on results of regular wave tests.

PART IV: DESIGN CURVE USE

Example Problem 1

Description

22. The selected structure is a rubble-mound breakwater head with quarrystone armor having a unit weight of 165 pcf, subjected to nonbreaking waves. Water depth at the toe, measured from National Geodetic Vertical Datum (NGVD) is 50 ft. The design wave height is 15 ft with a period of 14 sec. The sea-side slope of the structure is 1V on 1.5H.

Design curve use

23. Using Nielsen's Method (Nielsen 1982) calculate L:

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

$$L = (2\pi d L_o)^{1/2}\left(1 - \frac{d}{L_o}\right)$$

$$L = (2\pi)(50)(1{,}004)^{1/2}\left(1 - \frac{50}{1{,}004}\right)$$

$$L = 534 \text{ ft}$$

Then, using Equation 3, calculate the surf parameter,

$$\xi = \frac{\tan\theta}{\left(\frac{H}{L}\right)^{1/2}} = \frac{\frac{1}{1.5}}{\left(\frac{15}{534}\right)^{1/2}}$$

$$\xi = 4.0$$

In Table 1, verify that you are in a tested range of ξ. Using Table 1 and Equation 5, calculate N_s.

$$N_s = 0.272(4)^2 - 1.749(4) + 4.179$$

$$N_s = 1.535$$

Solving for W_a in Equation 2, we have

$$W_a = \frac{\gamma_a H^3}{N_S^3 \left(S_a - 1\right)^3}$$

Thus,

$$W_a = \frac{(165)(15)^3}{(1.535)^3(\frac{165}{64} - 1)^3}$$

$$W_a = 39,175 \text{ lb} \simeq 20 \text{ tons}$$

Example Problem 2

Description

24. The selected structure is a rubble-mound breakwater head with dolos armor having a unit weight of 160 pcf. Water depth at the toe is 40 ft NGVD. The design wave height is 34 ft with a period of 17 sec. The armor slope is 1V on 2H.

Design curve use

25. Begin by calculating L using Neilsen's Method (1982).

$$L_o = \frac{gT^2}{2\pi} = \frac{(32.17)(17)^2}{2\pi} = 1,480 \text{ ft}$$

$$L = (2\pi d\ L_o)^{1/2}\left(1 - \frac{d}{L_o}\right)$$

$$L = [(2\pi)(40)(1,480)]^{1/2}\left(1 - \frac{40}{1,480}\right)$$

$$L = 593 \text{ ft}$$

Using Equation 3, calculate the surf parameter

$$\xi = \frac{\tan\theta}{\left(\frac{H}{L}\right)^{1/2}} = \frac{\frac{1}{2}}{\left(\frac{34}{593}\right)^{1/2}} = 2.088$$

In Table 1, verify that your are in a tested range of ξ . Using Table 1 and Equation 5, calculate N_s .

$$N_s = 0.840(2.088)^2 - 4.466(2.088) + 8.244$$

$$N_s = 2.58$$

Solving for W_a in Equation 2,

$$W_a = \frac{\gamma_a H^3}{N_s^3 \left(S_a - 1\right)^3}$$

Thus

$$W_a = \frac{(160)(34)^3}{(2.58)^3\left(\frac{160}{64} - 1\right)^3}$$

$$W_a = 108{,}499 \text{ lb} \simeq 54 \text{ tons}$$

Table 1

Coefficients for Solution of Equation 5

Armor Type	Structure Slope	A	B	C_c	Valid ξ Range
Stone	1V on 1.5H	0.272	-1.749	4.179	2.1-4.1
Stone	1V on 2.0H	0.198	-1.234	3.289	1.8-3.4
Dolos	1V on 1.5H	0.406	-2.800	6.881	2.2-4.4
Dolos	1V on 2.0H	0.840	-4.466	8.244	1.7-3.2

PART V: CONCLUSIONS

26. Based on tests and results described herein, in which stone and dolos armor are used on conical breakwater heads and subjected to breaking waves with angles of wave attack of 45 and 90 deg and results of similar tests conducted with nonbreaking waves by Carver, Herrington, and Wright (1987), it is concluded that:

- a. Stability is influenced by wave height, wave period, and breakwater slope.
- b. Test results for the 45- and 90-deg wave directions proved to be very similar.
- c. Generally, flattening the slope from 1V on 1.5H to 1V on 2H did not significantly improve stability.
- d. A functional relationship that links breaking and nonbreaking wave test results was developed, and this relationship led to the development of predictive equations for stable stone and dolos weights, including effects of wave height, wave period, and breakwater slope.
- e. Observed results of limited spectral wave tests were very similar to those obtained in equivalent monochromatic tests.

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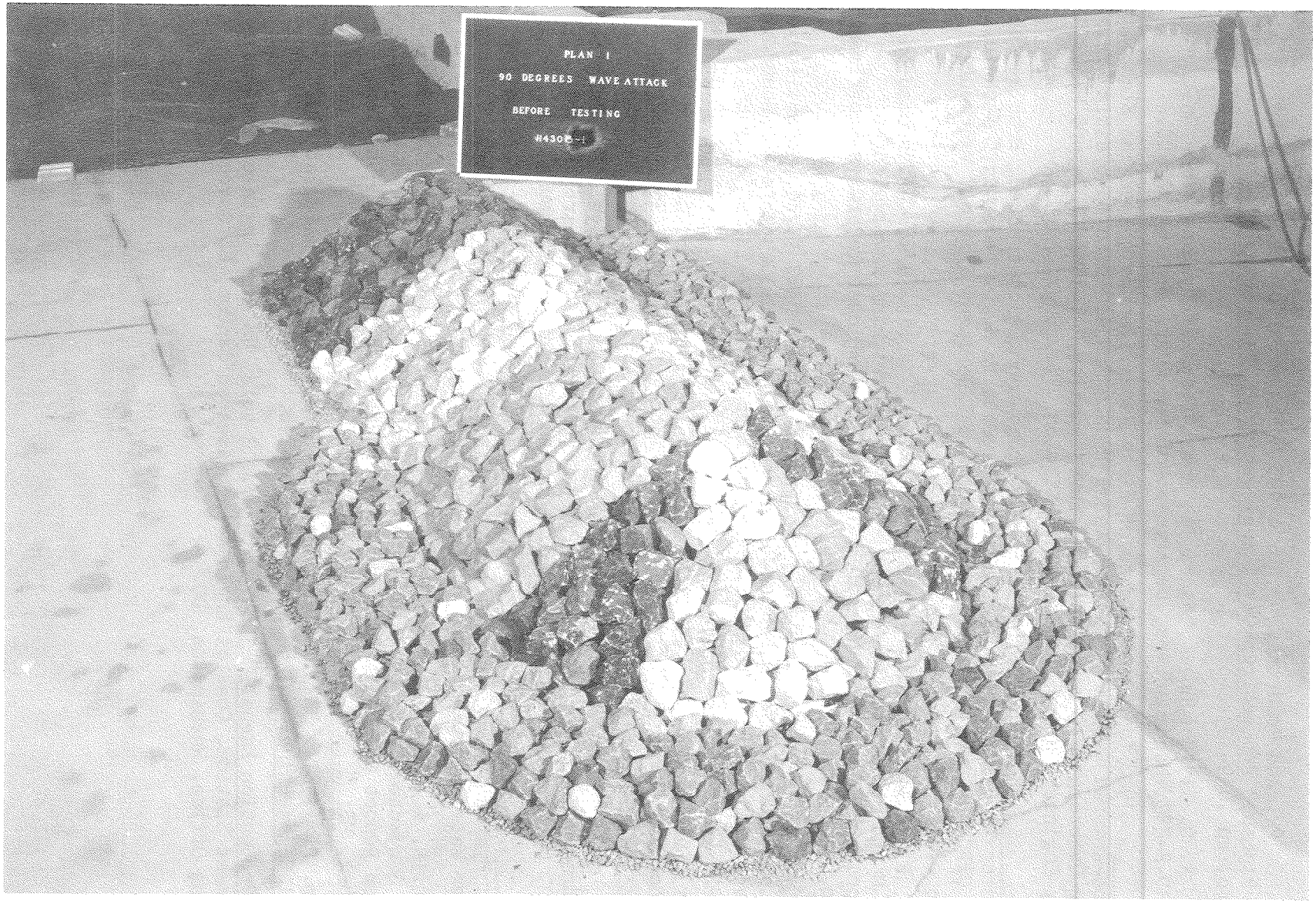

Photo 1. End view of a typical stone section before wave attack; angle of wave attack = 90 deg; W_a = 0.55 lb

Photo 2. Sea-side view of a typical stone section before wave attack; angle of wave attack = 90 deg; W_a = 0.55 lb

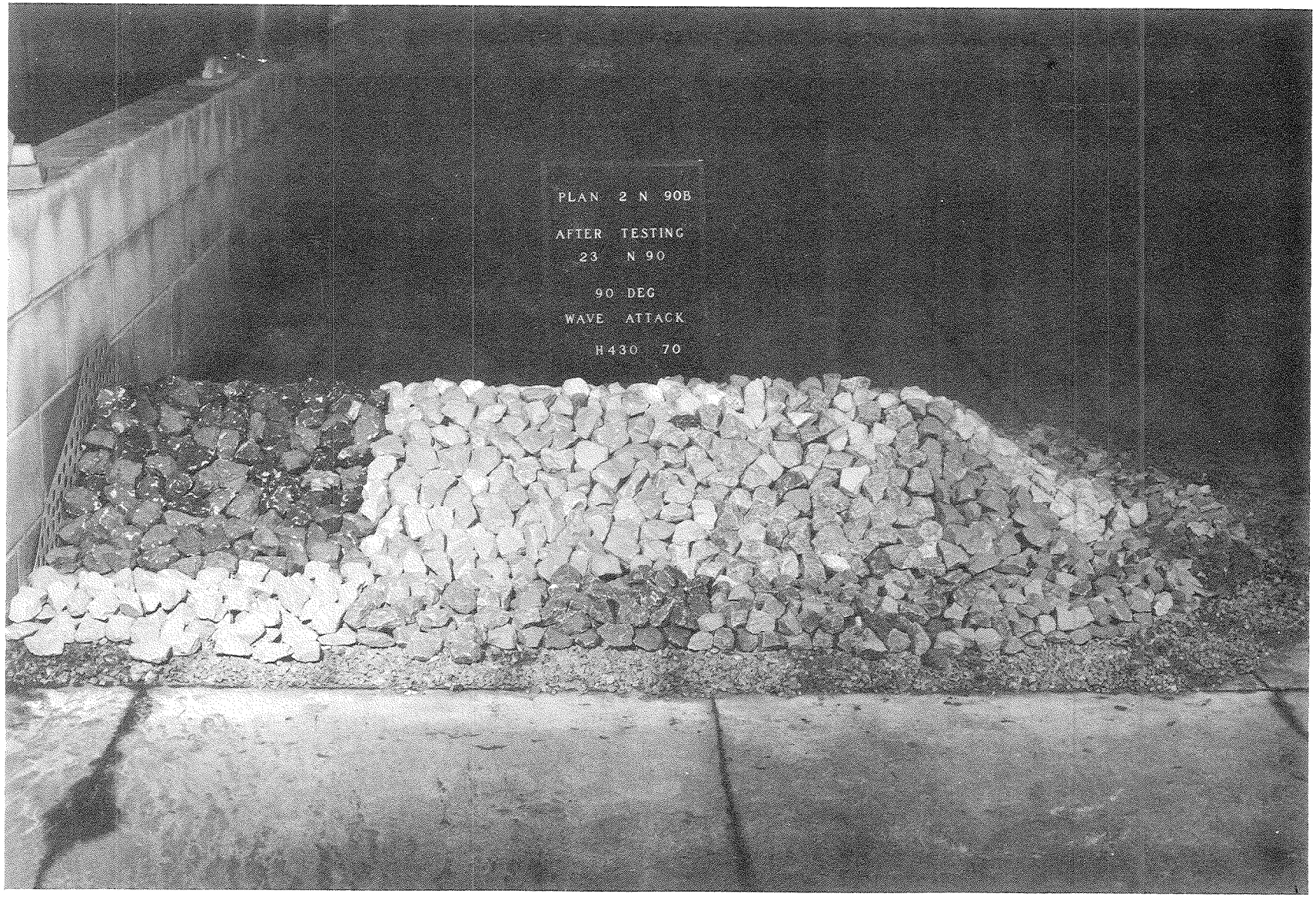

Photo 3. Sea-side view after attack of 1.90-sec, 0.36-ft waves; d = 0.40 ft; angle of wave attack = 90 deg; 0.38-lb stone armor

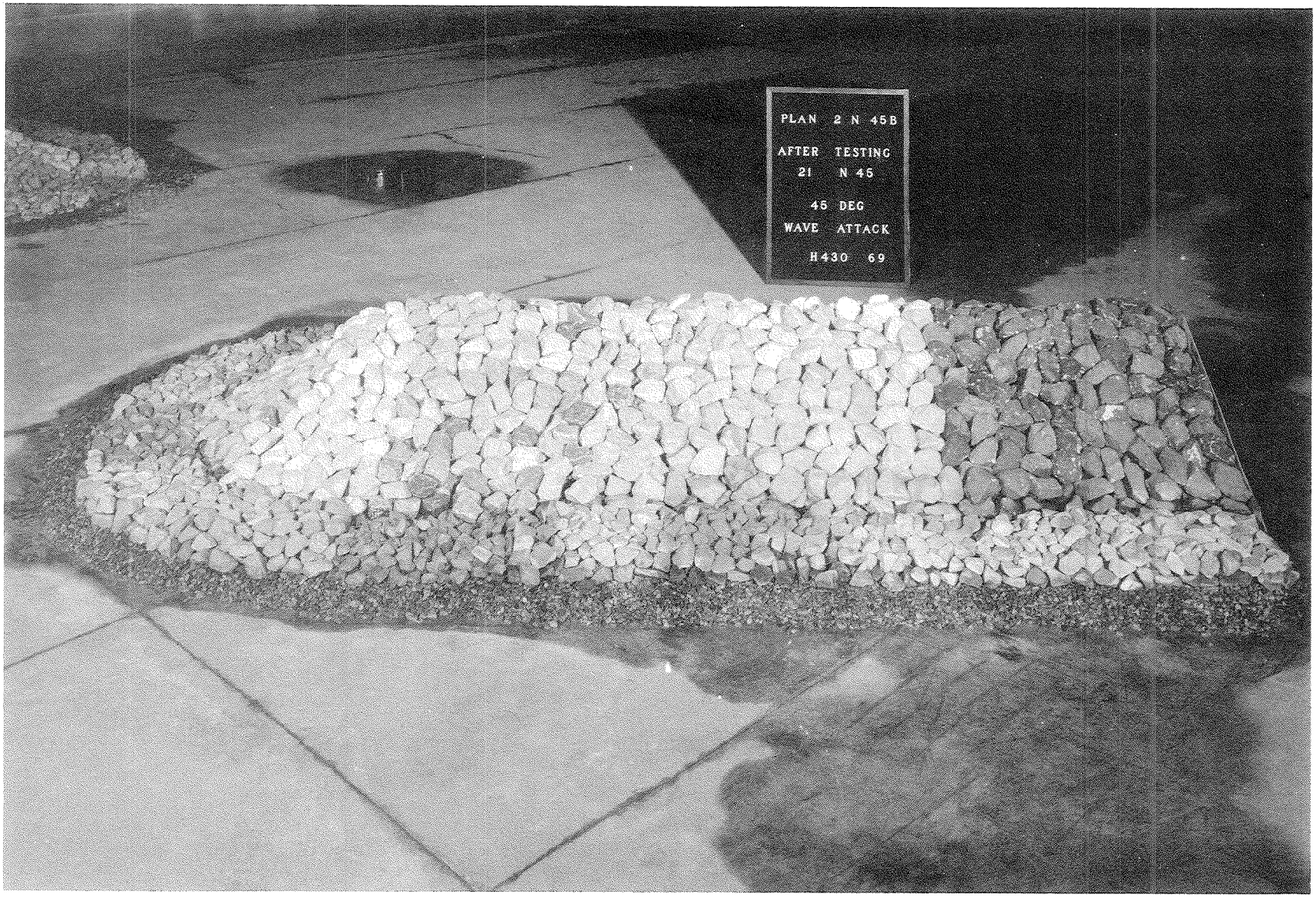

Photo 4. Sea-side view after attack of 2.82-sec, 0.38-ft waves; d = 0.40 ft; angle of wave attack = 45 deg; 0.38-lb stone armor

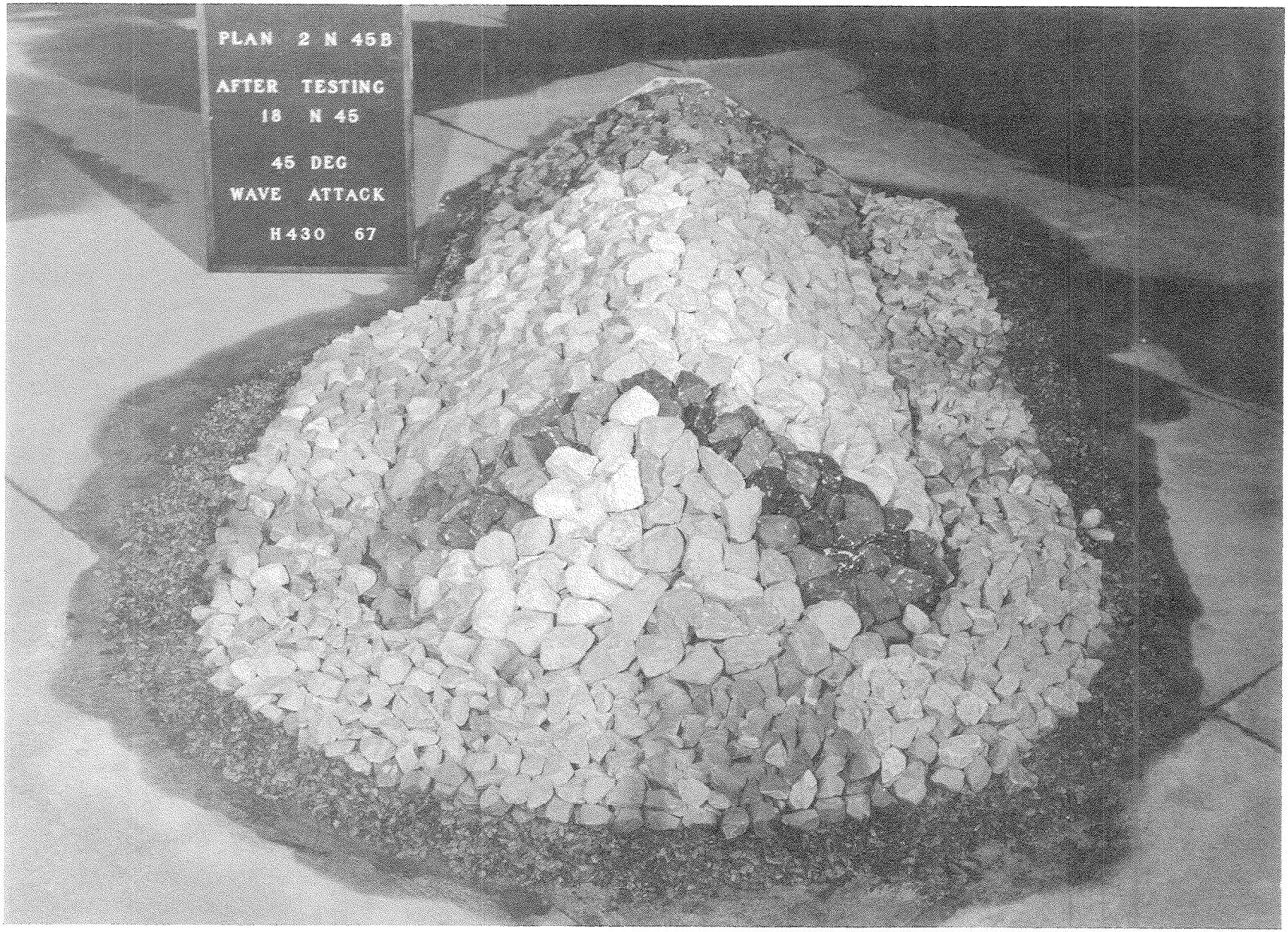

Photo 5. End view after attack of 2.12-sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 45 deg; 0.55-lb stone armor

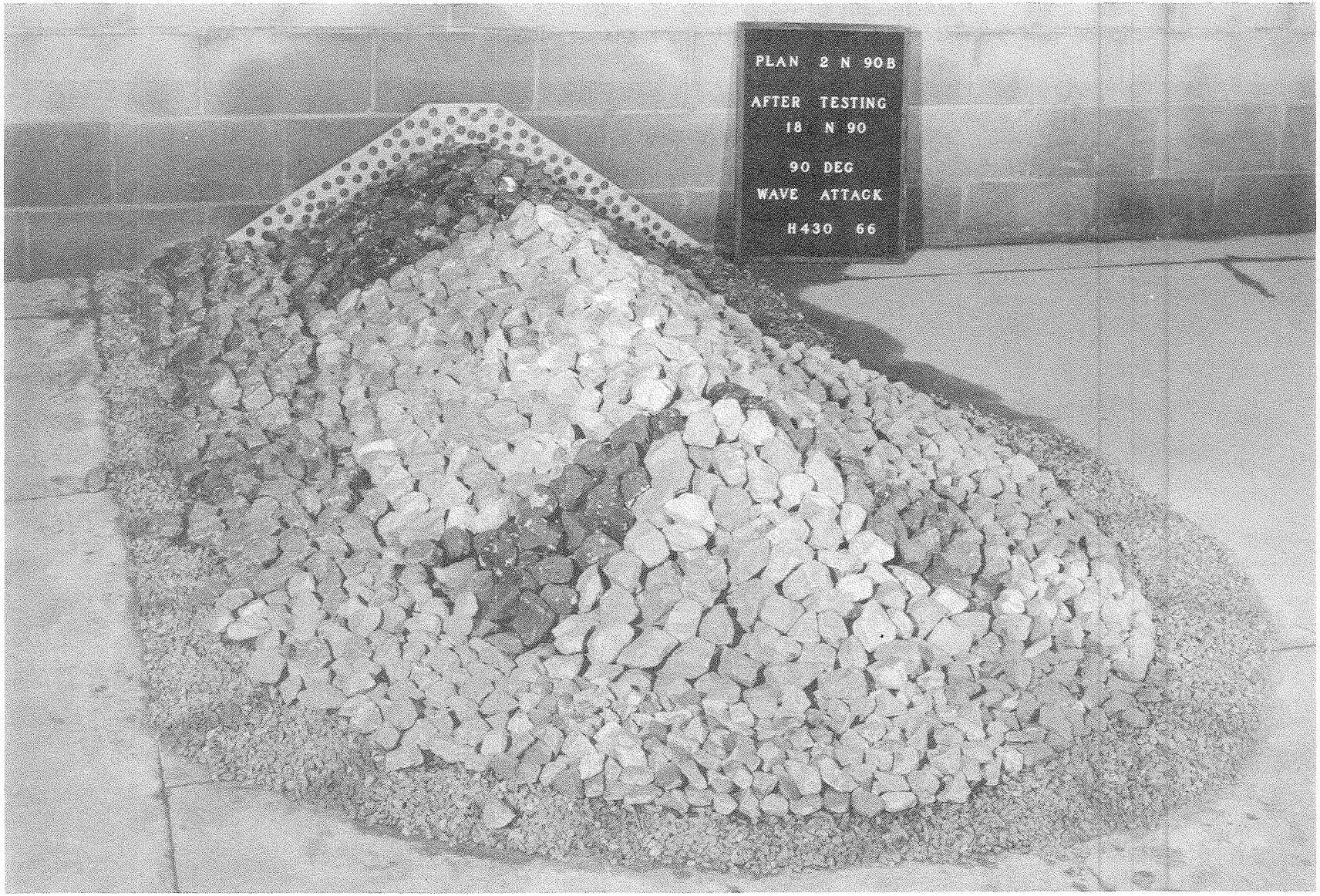

Photo 6. End view after attack of 2.12-sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 90 deg; 0.55-lb stone armor

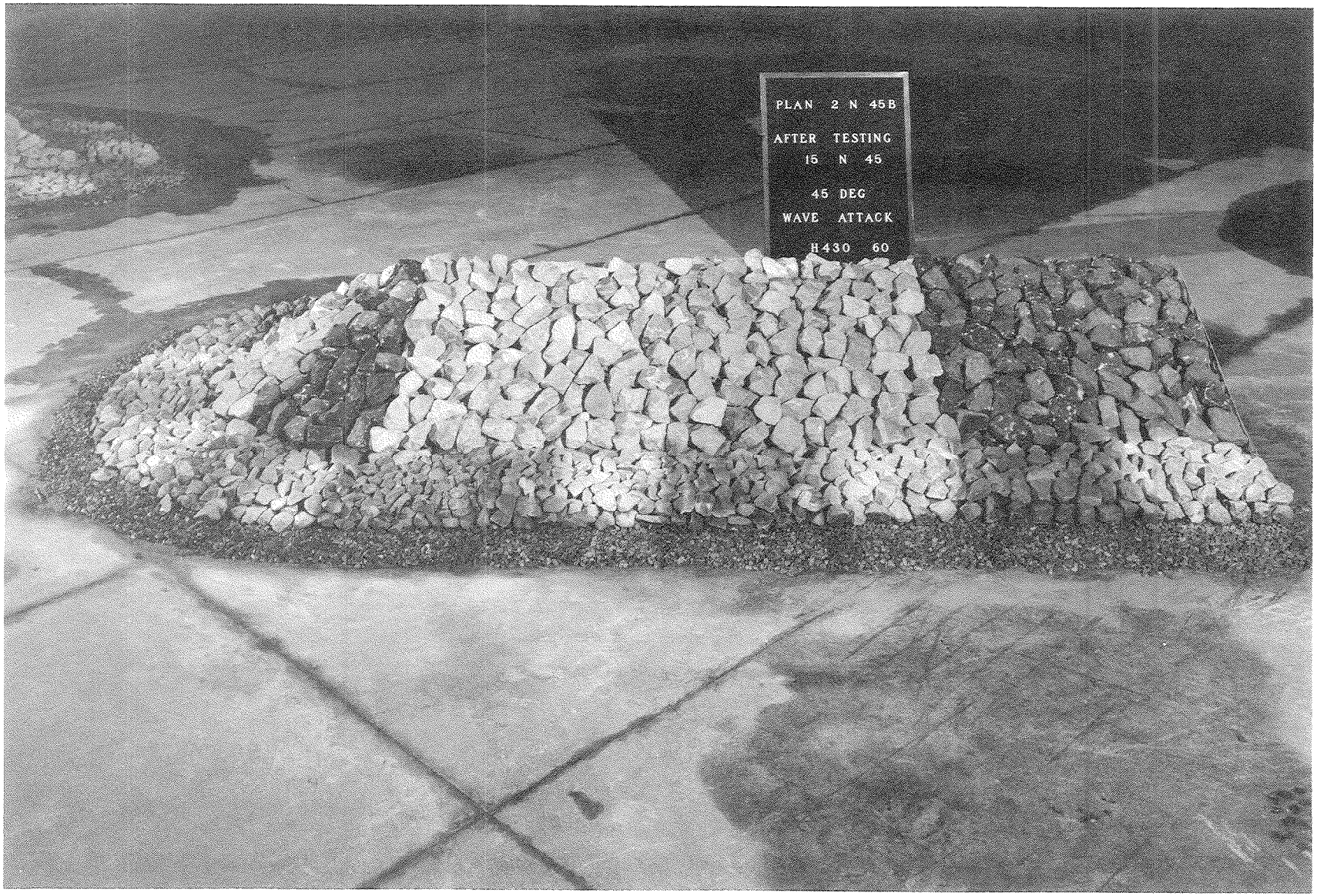

Photo 7. Sea-side view after attack of 1.45-sec, 0.47-ft waves; d = 0.60 ft; angle of wave attack = 45 deg; 0.55-lb stone armor

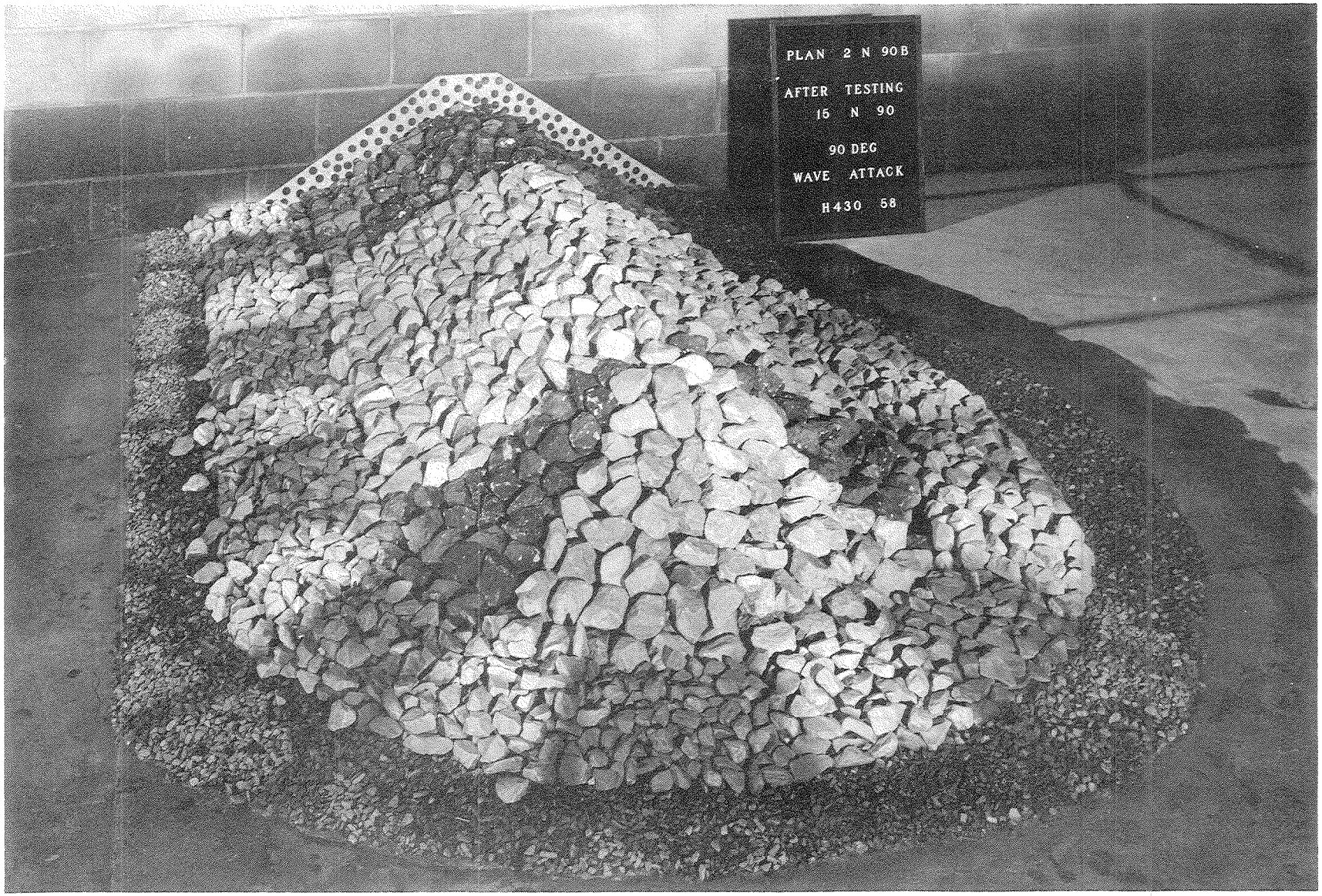

Photo 8. End view after attack of 1.45-sec, 0.47-ft waves; d = 0.60 ft; angle of wave attack = 90 deg; 0.55-lb stone armor

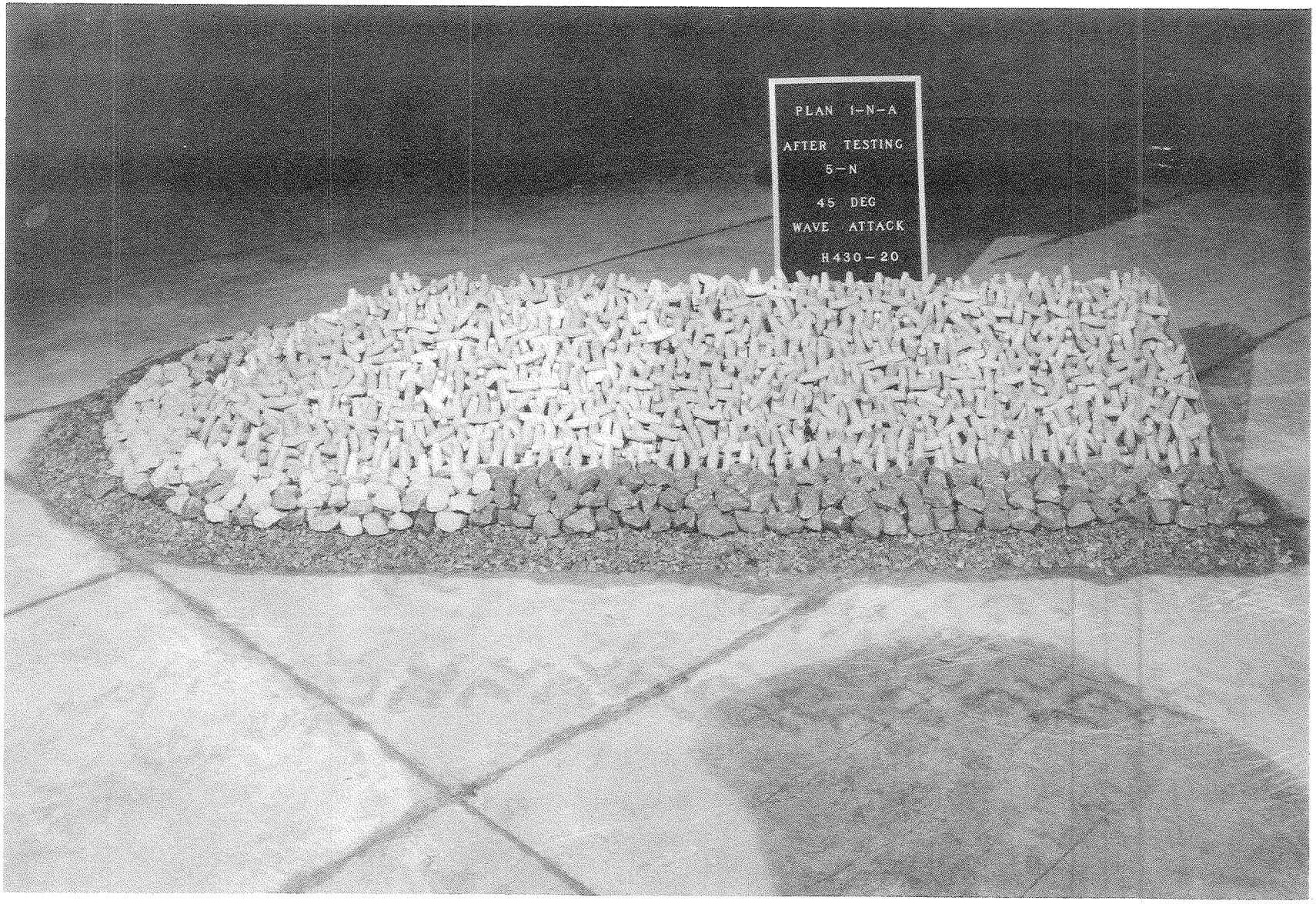

Photo 9. Sea-side view after attack of 2.82-sec, 0.38-ft waves; d = 0.40 ft; angle of wave attack = 45 deg; 0.276-lb dolos armor

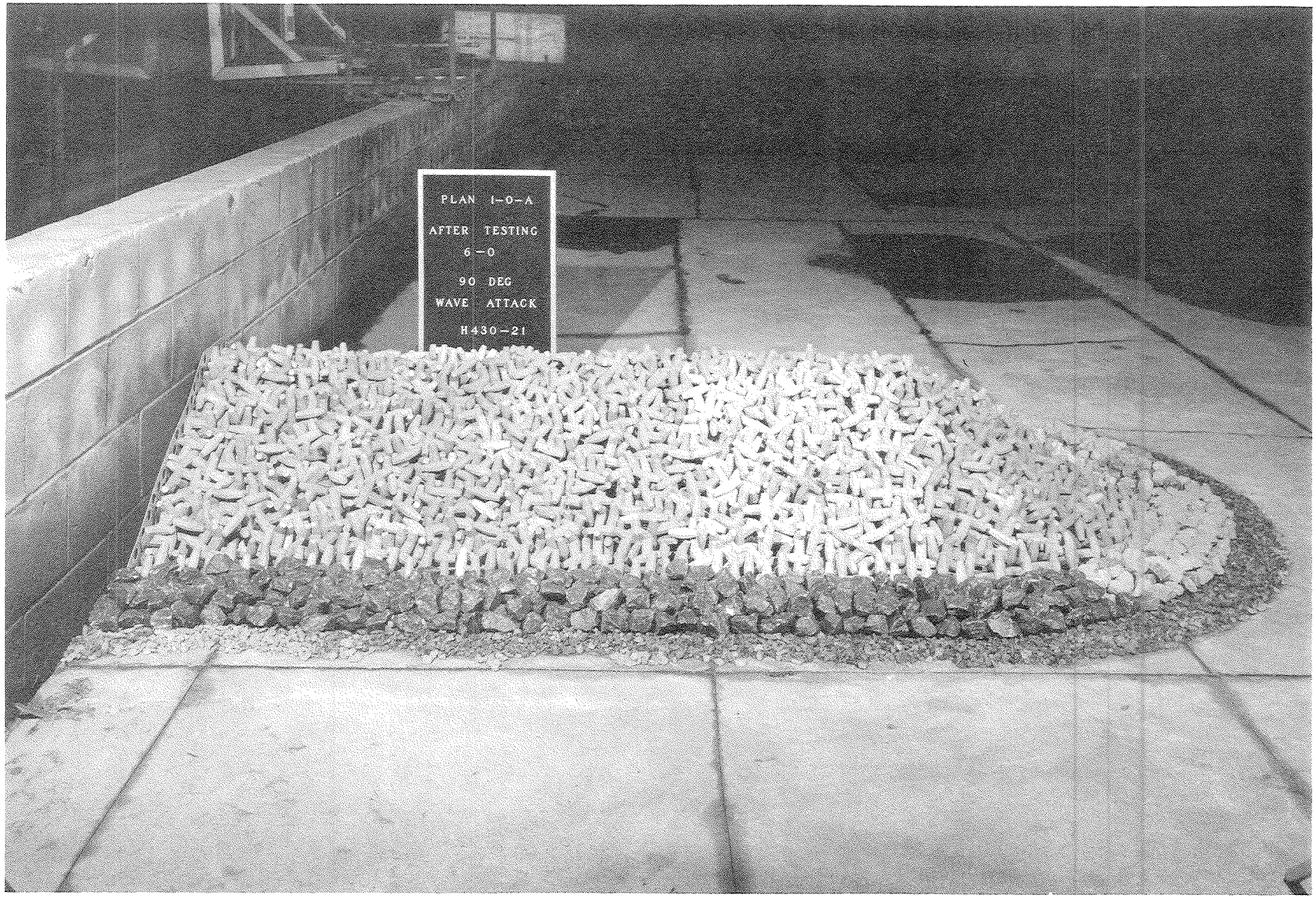

Photo 10. Sea-side view after attack of 2.82-sec, 0.38-ft waves; d = 0.40 ft; angle of wave attack = 90 deg; 0.276-lb dolos armor

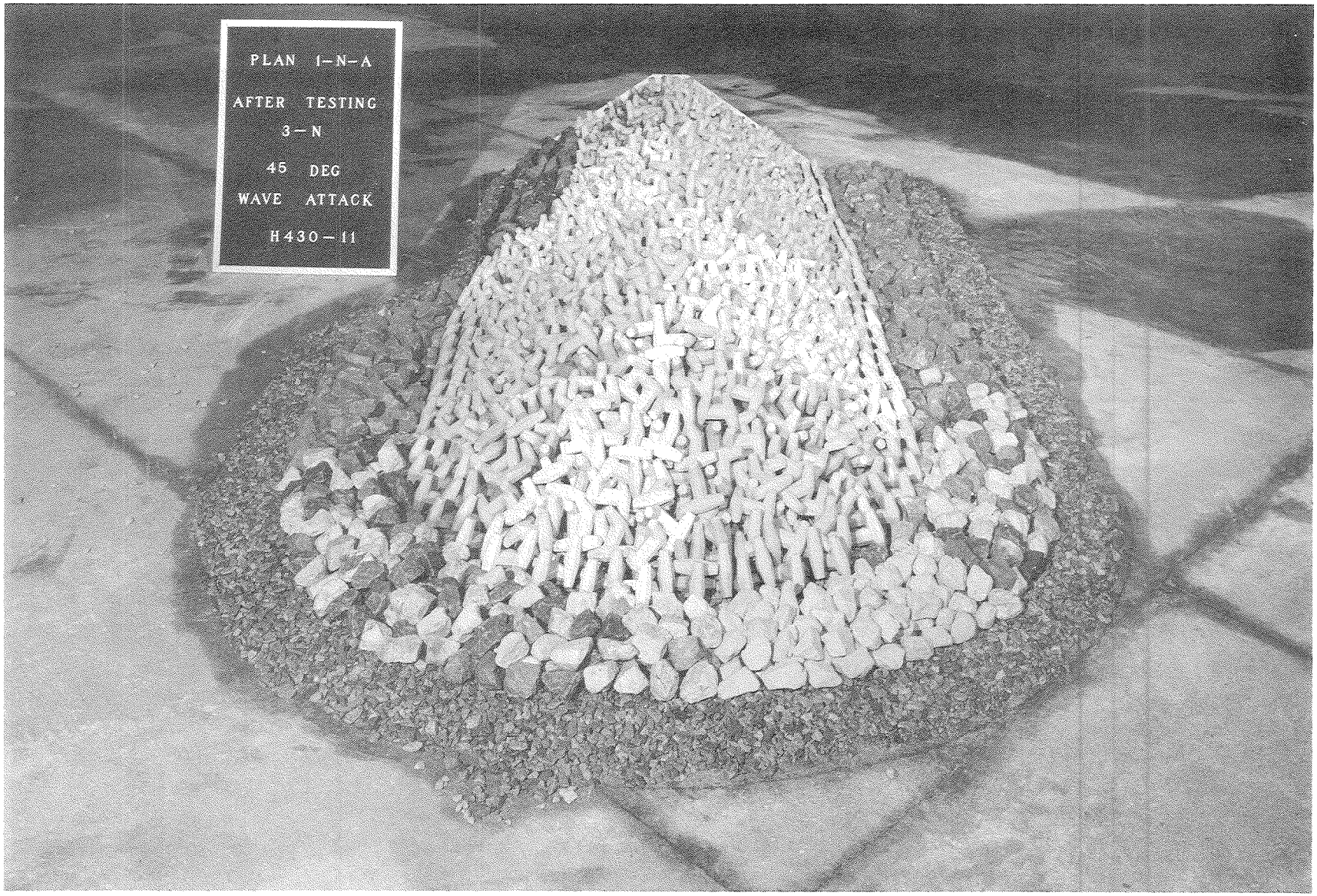

Photo 11. End view after attack of 2.12-sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 45 deg; 0.276-lb dolos armor

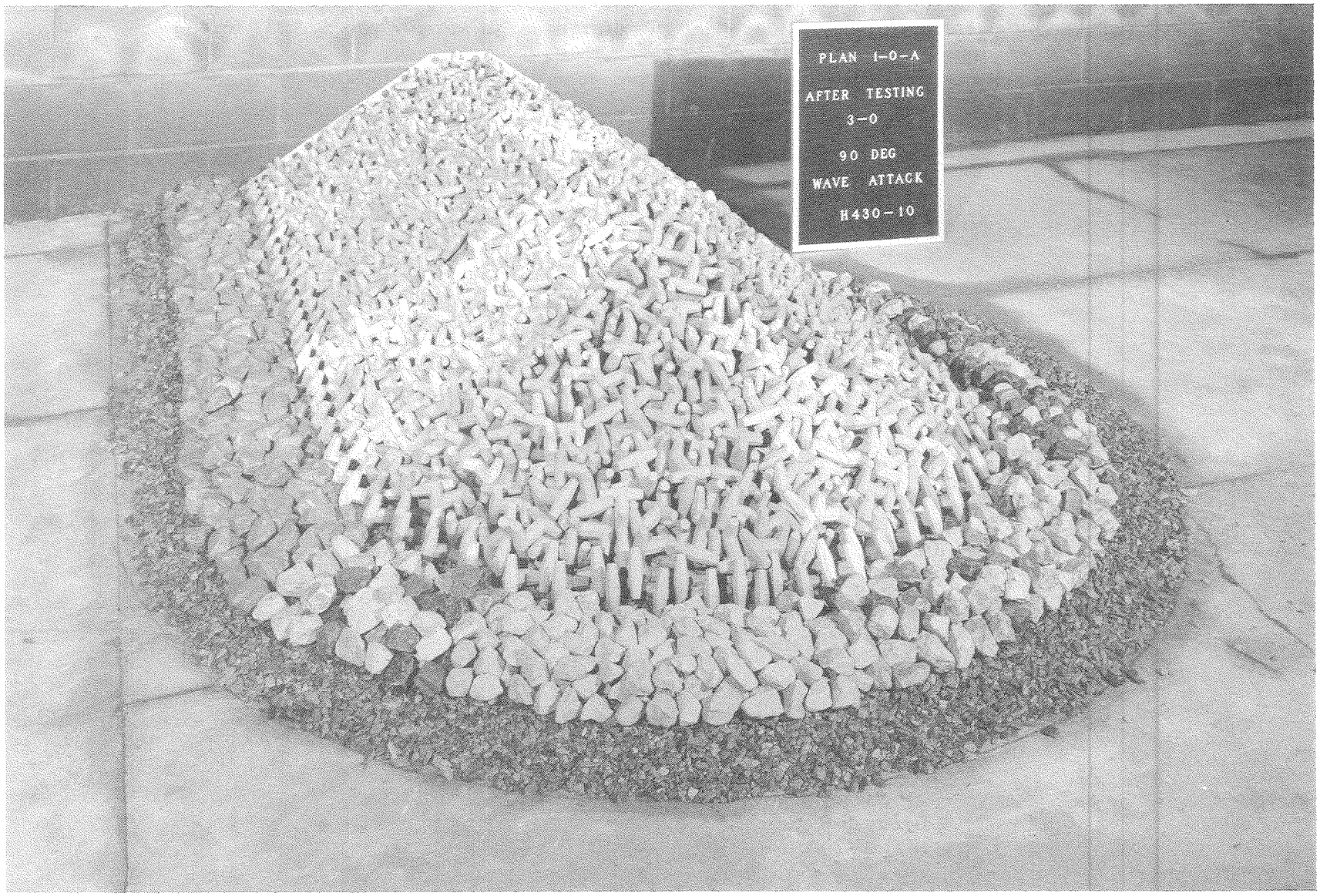

Photo 12. End view after attack of 2.12-sec, 0.39-ft waves; d = 0.50 ft; angle of wave attack = 90 deg; 0.276-lb dolos armor

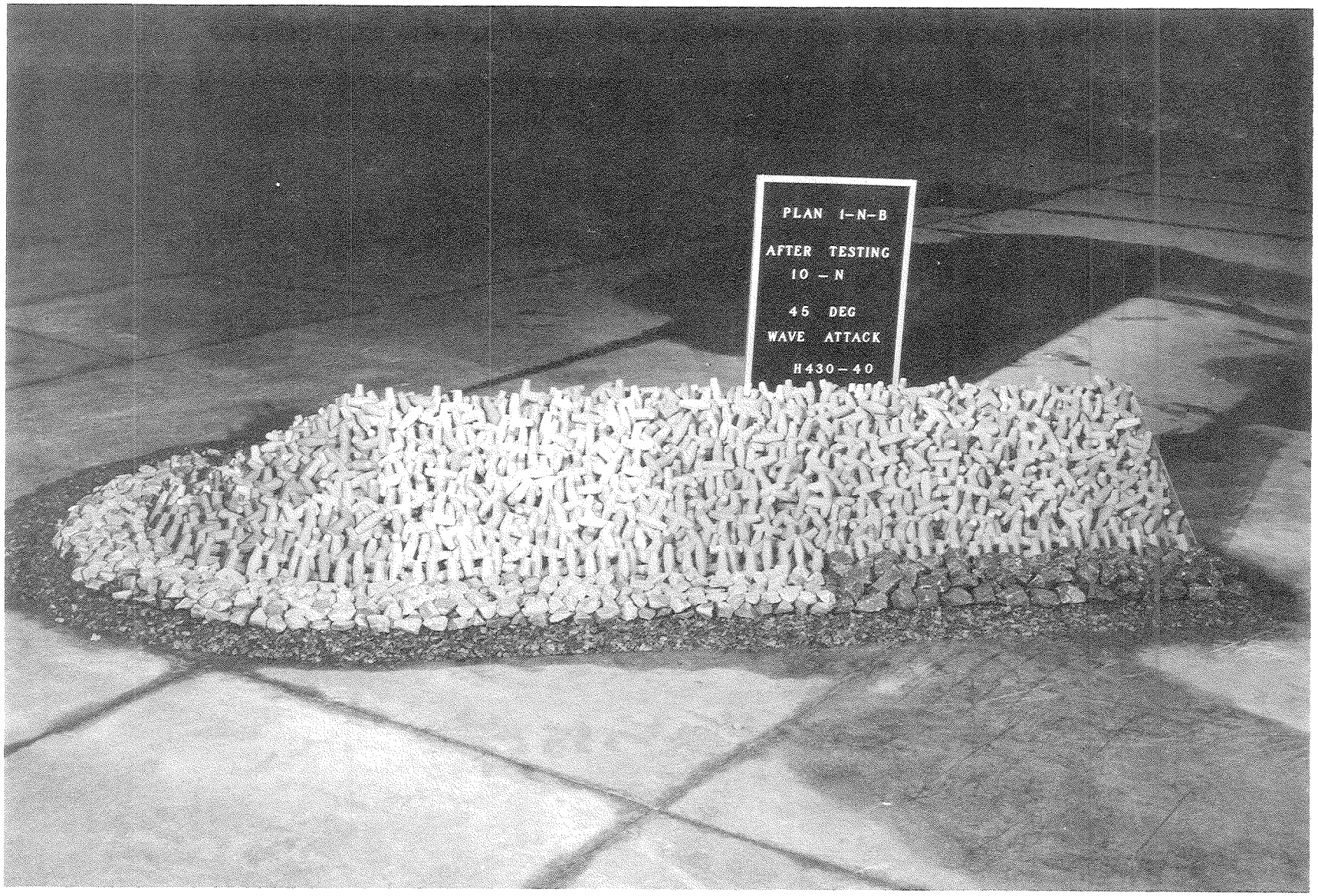

Photo 13. Sea-side view after attack of 1.45-sec, 0.47-ft waves; d = 0.60 ft; angle of wave attack = 45 deg; 0.276-lb dolos armor

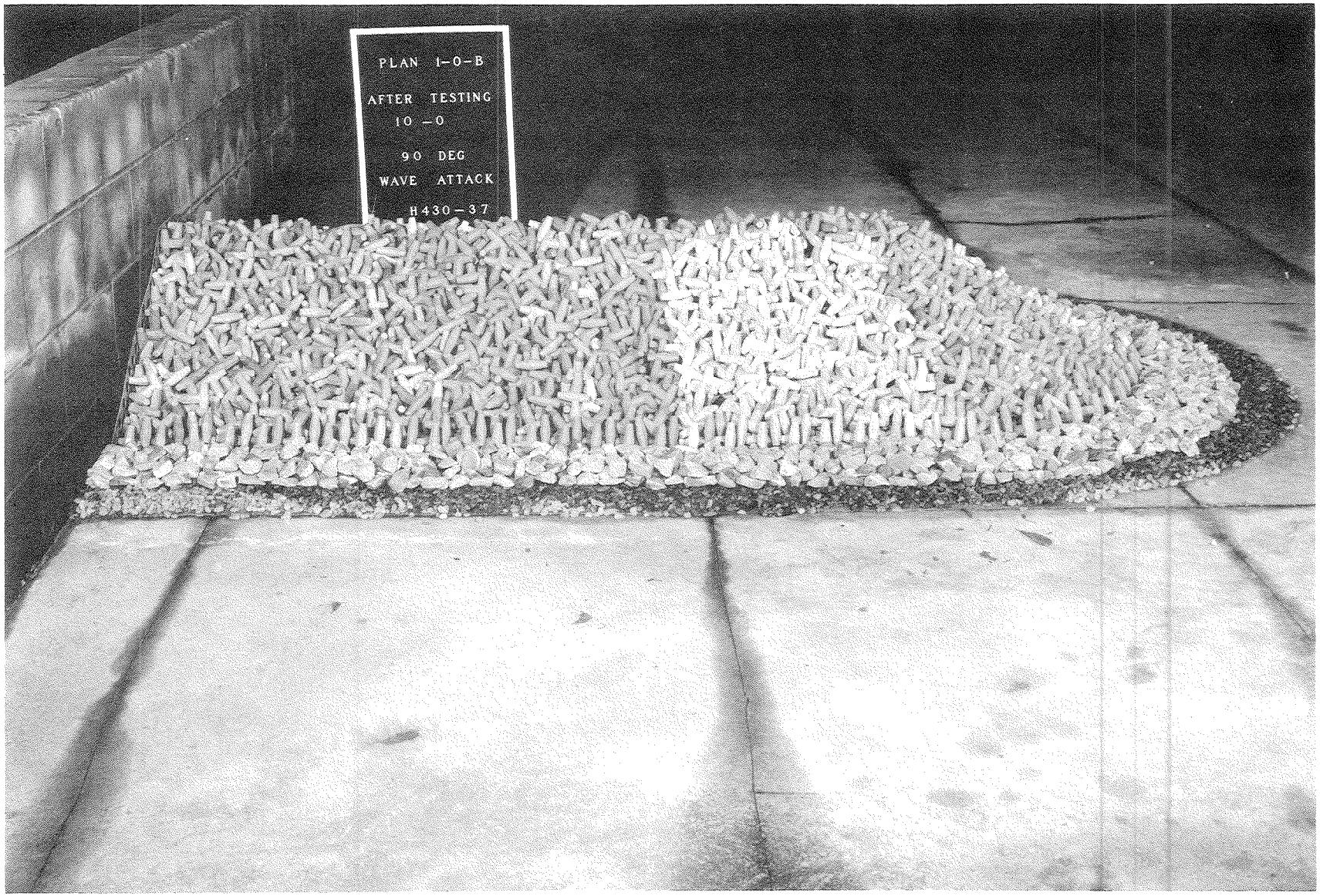

Photo 14. Sea-side view after attack of 1.45-sec, 0.47-ft waves; d = 0.60 ft; angle of wave attack = 90 deg; 0.276-lb dolos armor

APPENDIX A: WAVE TEST DATA SUMMARY

Table A1

Summary of Data from Breaking and Nonbreaking Wave Tests

Armor Type	Wave Type*	No. of Layers n	Armor Weight W_a, lb	Unit Weight pcf	Structure Slope, cot alpha	Seaside Slope, cot p	Angle of Attack beta	d, ft	T, sec	H, ft	L, ft	d/L	Ns	S, Surf Parameter
Stone	NB	2	0.550	167.0	2.0	10	0	1.50	2.75	0.53	18.330	0.08	2.13	2.94
Stone			0.550	167.0					2.00	0.45	12.818	0.12	1.80	2.67
Stone			0.550	167.0					1.50	0.52	8.996	0.17	2.09	2.08
Stone			0.550	167.0					1.25	0.50	6.989	0.21	2.00	1.87
Dolos			0.276	142.2					1.50	0.52	8.999	0.17	3.26	2.08
Dolos			0.276	142.2					2.75	0.54	18.329	0.08	3.39	2.91
Dolos			0.276	142.2					2.00	0.47	12.820	0.12	2.95	2.61
Dolos			0.276	142.2					1.25	0.57	6.989	0.21	3.57	1.75
Stone	B		0.380	165.0	1.5	35	45	0.40	1.90	0.36	6.700	0.06	1.66	2.88
			0.550					0.60	1.45	0.47	5.996	0.10	1.91	2.38
			0.380					0.40	2.82	0.38	10.013	0.04	1.75	3.42
			0.550					0.50	2.12	0.39	8.307	0.06	1.59	3.08
			0.380					0.50	1.32	0.38	4.984	0.10	1.75	2.41
			0.550					0.60	1.24	0.46	5.012	0.12	1.87	2.20
			0.550					0.60	1.45	0.47	5.996	0.10	1.91	2.38
			0.550					0.60	1.24	0.46	5.012	0.12	1.87	2.20
			0.380					0.60	1.10	0.42	4.341	0.14	1.93	2.14
			0.380					0.40	1.90	0.36	6.662	0.06	1.66	2.87
			0.380					0.60	1.10	0.42	4.341	0.14	1.93	2.14
			0.380					0.50	1.32	0.38	4.984	0.10	1.75	2.41
			0.550					0.50	1.62	0.43	6.246	0.08	1.75	2.54
			0.550					0.50	2.12	0.39	8.307	0.06	1.59	3.08
			0.380					0.50	1.62	0.43	6.246	0.08	1.98	2.54
			0.380					0.40	2.82	0.38	10.013	0.04	1.75	3.42
	NB		0.550	167.0	2.0	10		1.50	1.25	0.47	6.989	0.21	1.88	1.93
					2.0			1.50	2.75	0.40	18.329	0.08	1.60	3.38
					2.0			1.50	2.00	0.42	12.820	0.12	1.68	2.76
					2.0			1.50	1.50	0.42	8.994	0.17	1.68	2.31
					1.5			1.50	1.50	0.40	8.999	0.17	1.60	3.16
								1.50	2.00	0.42	12.820	0.12	1.68	3.68
								1.50	2.75	0.53	18.329	0.08	2.13	3.92
Dolos	B		0.276	142.2		35		0.50	1.62	0.43	6.246	0.08	2.70	2.54
						35		0.60	1.45	0.47	5.996	0.10	2.95	2.38
						35		0.60	1.24	0.46	5.012	0.12	2.88	2.20
						35		0.40	1.90	0.36	6.662	0.06	2.26	2.87
						35		0.40	2.82	0.38	10.013	0.04	2.38	3.42
						35		0.50	2.12	0.39	8.307	0.06	2.44	3.08
	NB				2.0	10		1.50	2.00	0.45	12.820	0.12	2.82	2.67
					2.0				1.50	0.42	8.999	0.17	2.63	2.31
					2.0				2.75	0.45	18.329	0.08	2.82	3.19
					2.0				1.25	0.50	6.989	0.21	3.13	1.87
					1.5				2.75	0.42	18.329	0.08	2.63	4.40
					1.5				2.00	0.38	12.820	0.12	2.38	3.87
					1.5				1.50	0.38	8.999	0.17	2.38	3.24
Stone			0.550	167.0	2.0		90		1.25	0.50	6.990	0.21	2.00	1.87
					2.0				1.50	0.52	8.996	0.17	2.09	2.08
					2.0				2.75	0.48	18.330	0.08	1.92	3.09
					2.0				2.00	0.40	12.821	0.12	1.68	2.83
					1.5				1.50	0.45	8.999	0.17	1.80	2.98
Stone**	B							0.40	2.82	0.39	10.011	0.04	1.54	3.40
Stone	NB							1.50	2.00	0.40	12.820	0.12	1.60	3.77
Stone**	B							0.50	2.12	0.42	8.308	0.06	1.68	2.97
Stone**	B							0.40	1.90	0.33	6.662	0.06	1.31	3.01
Stone**	B							0.50	1.32	0.42	4.984	0.10	1.68	2.30
Stone**	B							0.50	1.62	0.45	6.246	0.08	1.81	2.48
Stone	NB							1.50	2.75	0.48	18.329	0.08	1.92	4.12
Dolos	B		0.276	142.2		35		0.40	2.82	0.38	10.013	0.04	2.38	3.42
Dolos	B		0.276	142.2		35		0.40	1.90	0.36	6.662	0.06	2.26	2.87
Dolos	B		0.276	142.2		35		0.60	1.24	0.46	5.012	0.12	2.88	2.20
Dolos	B		0.276	142.2		35		0.60	1.45	0.47	5.996	0.10	2.95	2.38

(Continued)

* NB = nonbreaking; B = breaking.

** Tests conducted with predetermined stone weight.

Table A1 (Concluded)

Armor Type	Wave Type	No. of Layers n	Armor Weight W_a, lb	Unit Weight pcf	Structure Slope, cot alpha	Seaside Slope, cot p	Angle of Attack beta	d, ft	T, sec	H, ft	L, ft	d/L	Ns	S, Surf Parameter
Dolos	B	2	0.276	142.2	1.5	35	90	0.50	1.62	0.43	6.246	0.08	2.70	2.54
	B				1.5	35		0.50	2.12	0.39	8.307	0.06	2.44	3.08
	NB				2.0	10		1.50	1.25	0.55	6.989	0.21	3.45	1.78
					2.0				1.50	0.52	8.999	0.17	3.26	2.08
					2.0				2.75	0.50	18.329	0.08	3.13	3.03
					2.0				2.00	0.42	12.820	0.12	2.63	2.76
					1.5				2.00	0.36	12.820	0.12	2.26	3.98
					1.5				1.50	0.40	8.999	0.17	2.51	3.16
					1.5				2.75	0.45	18.329	0.08	2.82	4.25
Stone			0.550	167.0	2.0		135		2.00	0.51	12.820	0.12	2.04	2.51
Stone			0.550	167.0					1.50	0.52	8.994	0.17	2.09	2.08
Stone			0.550	167.0					1.25	0.56	6.989	0.21	2.25	1.77
Stone			0.550	167.0					2.75	0.48	18.329	0.08	1.92	3.09
Dolos			0.276	142.2					1.50	0.50	8.999	0.17	3.13	2.12
Dolos			0.276	142.2					2.00	0.45	12.820	0.12	2.82	2.67
Dolos			0.276	142.2					2.75	0.42	18.329	0.08	2.63	3.30
Dolos			0.276	142.2					1.25	0.56	6.989	0.21	3.51	1.77

APPENDIX B: NOTATION

A	Dimensionless coefficient in Equations 4 and 5
B	Dimensionless coefficient in Equations 4 and 5
C	Dimensionless coefficient in Equation 4
C_c	Dimensionless coefficient in Equation 5
d	Water depth, ft
g	Acceleration due to gravity, ft/sec^2
H	Wave height, ft
H/L	Wave steepness, dimensionless
l_a	Characteristic length of armor unit, ft
L	Length, wavelength, ft
N_s	Stability number, defined by Equation 2
R_N	Reynolds stability number, defined by Equation 1
T	Wave period, sec; time
W_a	Weight of an armor unit, lb
β	Angle of wave attack, deg
γ	Specific weight, pcf
γ_a	Specific weight of armor unit, pcf
ν	Kinematic viscosity of experimental fluid medium, ft^2/sec
ξ	Surf similarity parameter, defined by Equation 3