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Tests of Low-Density Marine Limestone for Use in Breakwaters

by

Daniel M. Allison and R. P. Savage

TECHNICAL PAPER NO. 76-4

MAY 1976

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U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

Kingman Building
Fort Belvoir, Va. 22060

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TP 76-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TESTS OF LOW-DENSITY MARINE LIMESTONE FOR USE IN BREAKWATERS		5. TYPE OF REPORT & PERIOD COVERED Technical Paper 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Daniel M. Allison R.P. Savage		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CERRE-SP) Kingman Building, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS F31236
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, Virginia 22060		12. REPORT DATE May 1976 13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Breakwaters	Marine limestone
Coastal structures	New Bern, North Carolina
Cover layer	Rubble-mound armor unit

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

A porous, low-density limestone (cemented shell stone) available from a quarry in New Bern, North Carolina, was suggested for use as a cover layer in coastal structures. The stability of the New Bern stone as a rubble-mound armor unit was tested in the large wave tank at CERC. Fourteen tests were conducted with 3.75-, 5.60-, and 7.87-second wave periods and wave heights ranging from 2.5 to 4.2 feet. The armor stones were also numbered and weighed at the beginning and end of testing to evaluate the durability of the stone.

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Results of the stability test showed armor unit stability coefficients (K_D) of 2.8, 3.5, and 7.8 for the 3.75-, 5.60-, and 7.87-second wave periods, respectively. The stones still identifiable at the end of testing lost an average of 5.5 percent of their original weight. As a result of the stone weight losses experienced in the laboratory tests, 13 stones were placed on or near a jetty in Fort Macon, North Carolina, by the U.S. Army Engineer District, Wilmington. The stones were periodically removed, weighed, and replaced for about 18 months. Results showed that the stones considered to be of the best quality had lost from 5 to 20 percent of their original weight after 6 months. Additional heavy weight losses (45 to 65 percent) to those stones still located at the end of testing indicated that excessive weight loss would continue.

The use of New Bern stone as a cover or underlayers of rubble-mound coastal structures is not recommended.

PREFACE

The work reported in this publication was originally prepared at the request of the U.S. Army Engineer District, Wilmington to determine the stability of a marine limestone available from a quarry near New Bern, North Carolina. The stone was tested in the large wave tank at the Coastal Engineering Research Center (CERC), and in the ocean environment near the jetties at the harbor entrance at Morehead City, North Carolina. The work was carried out under the coastal processes program of CERC.

The report was prepared by Daniel M. Allison, formerly of CERC, and R.P. Savage, Chief, Research Division, CERC.

The stability testing at CERC was conducted by George Simmons, Senior Engineering Technician, under the general supervision of Mr. Savage. Field testing was conducted under the supervision of C.J. Frazelle, U.S. Army Engineer District, Wilmington, who, along with W.T. Robins III of the District, developed basic procedures for determining relative changes in weight of solids. Stone for the tests was supplied by the Superior Stone Company of New Bern, North Carolina.

The authors acknowledge the assistance of John Ahrens, Coastal Structures Branch, CERC, and Bruce McCartney, Formerly of CERC. Special acknowledgment is entended to George Simmons for his critical review of the final report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Wilson P. Andrews

WILSON P. ANDREWS
LTC, Corps of Engineers
Commander and Director

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Symbols and Definitions

		Dimension
A_1	volume of damage per unit	ft^3/ft
A_2	base volume per unit length for damage calculations	ft^3/ft
$D_{H=0}$	depth equal to zero-damage wave height	ft
E	void ratio	
e_c	calculated void ratio	
e_a	assumed void ratio	
$H_{D=0}$	zero-damage wave height	ft
K_D	dimensionless armor unit stability coefficient	
n	armor and underlayer thickness (average number of stones)	
S	degree (percent) of saturation of a stone	
S_{max}	maximum degree of saturation of a stone	
V_S	volume of stone, solids only	ft^3
V_T	total volume of stone, solids plus voids	ft^3
V_V	volume of voids in stone	ft^3
W_{DA}	air-dried weight of stone	lb
W_S	weight of stone (solids only) in air	lb
W_{TA}	"wet" weight of stone (solids plus absorbed water) in air	lb
W_{TW}	weight of stone submerged	lb
W_W	weight of water absorbed by stone	lb
W_{50}	air-dried weight of the 50th percentile of armor stone weights	lb
γ_S	specific weight of stone, solids only	lb/ft^3
γ_T	"wet" specific weight of stone (solids plus absorbed water and voids)	lb/ft^3

		Dimension
$\overline{\gamma}_T$	mean "wet" specific weight of stones (solids plus absorbed water and voids)	lb/ft^3
γ_W	specific weight of water	lb/ft^3
σ	standard deviation	
α	angle between the seaward slope of the breakwater and the horizontal	degrees

TESTS OF LOW-DENSITY MARINE LIMESTONE FOR USE IN BREAKWATERS

by
Daniel M. Allison and R.P. Savage

I. INTRODUCTION

This report describes laboratory and field testing of a porous, low-density, limestone (cemented shell stone) available from a quarry near New Bern, North Carolina. Testing was requested by the Superior Stone Company of New Bern for approval in using the stone in coastal structures constructed by the Corps of Engineers.

The quarry and minor coastal structures using the stone as a cover layer were inspected by the Coastal Engineering and Research Center (CERC) in June 1965. General conclusions at that time indicated that the stone durability appeared satisfactory, and that the roughness of the stone could give interlocking characteristics to compensate for its low density, making the stone suitable for use as rubble-mound armor layer units.

A series of wave tank tests was conducted at CERC later in 1965 to determine the stability of the stone as a cover layer for major coastal structures subjected to wave attack. Rubble-mound sections were tested to determine stability coefficients, K_D, (Hudson, 1957) for use in field design. The results of the wave tank tests showed that individual stones lost weight during the testing interval.

Field tests to verify weight losses under field conditions were carried out by the U.S. Army Engineer District, Wilmington, from November 1967 to June 1969 at Fort Macon, North Carolina. Thirteen stones were placed in voids in the sand or on the sand near an existing jetty (the wave action zone) to determine if a weight loss occurred, and if so, was the loss caused by solution, abrasion, or breaking of the stones.

II. PHYSICAL AND CHEMICAL PROPERTIES OF THE LIMESTONE

1. Physical Properties.

a. General Appearance. The New Bern quarry contains low-density, porous, shelly limestone. The stone is usually gray in color, consists mainly of consolidated colloidal lime particles, and has a moderately rough-textured surface with numerous shells. It contains no significant continuous voids but has many small discontinuous voids. Occasionally, the stone has brown parts that contain pockets of poorly cemented sand and silt-size particles which can be easily removed, and has one or more extensive continuous voids.

b. Specific Weight. The specific weight varies from stone to stone. The average "wet" (stone plus abosrbed water) specific weight is about 125 pounds per cubic foot. The wet specific weight increases significantly with time when immersed in water. The grain specific weight (specific weight of solids) of the rock is about 160 pounds per cubic foot.

c. Absorption. The stone absorbs water because it is porous. The average amount of water absorbed by a stone immersed in water for 24 hours is 2 to 6 percent of the dry weight of the stone. The rate and amount of absorption depend on the porosity, size, and shape of the stone. Surface area to volume ratio is proportional to rate and amount of absorption.

2. Chemical Properties.

a. Chemical Composition. Laboratory tests (Turner, 1965) show the average chemical composition of the stone to be about 71 percent calcium carbonate, 23 percent quartz, and 6 percent silt or clay. The chemical properties of the stone appear to be less variable than the physical properties.

b. Dissolution of Stone. The weight of individual stones is reduced by the stone entering solution and increased by water absorption by the stone. Therefore, these processes mask each other and, in reweighing the stones after immersion in water, only the net effect of the two processes can be measured. However, because of the stone's chemical composition (71 percent calcium carbonate), stone solution losses do not appear to be significant.

III. WAVE TANK TESTS

1. Test Setup.

a. The Wave Tank. Tests were conducted at CERC in a large wave tank, 635 feet long, 15 feet wide, and 20 feet deep (U.S. Army, Corps of Engineers, 1968). Two instrument carriages ride on rails mounted on the walls of the tank. Waves are generated by a vertical bulkhead, 15 feet wide and 23 feet high, mounted on a carriage and driven by an 800-horsepower, variable speed motor. The wave generator is capable of generating monochromatic waves from 2.6 to 24.5 seconds, and heights of up to 6 feet.

b. Breakwater Construction. The location and construction of the breakwater in the wave tank are shown in Figure 1. The layer thicknesses and underlayer stone weights used in this study were determined in accordance with the EM 1110-2-2904 (U.S. Army, Corps of Engineers, 1963) and Turner (1965) (Fig. 1). The armor and first underlayer stone came from the New Bern Quarry. Armor stone weights ranged from 230 to 450 pounds with a mean weight of 320 pounds.

Both the armor layer and the first underlayer were about two units (stones) thick (n = 2). The core and the second underlayer were not compacted. Each of the armor stones was weighed, painted with a reference number, and placed on the breakwater with a crane one stone at a time.

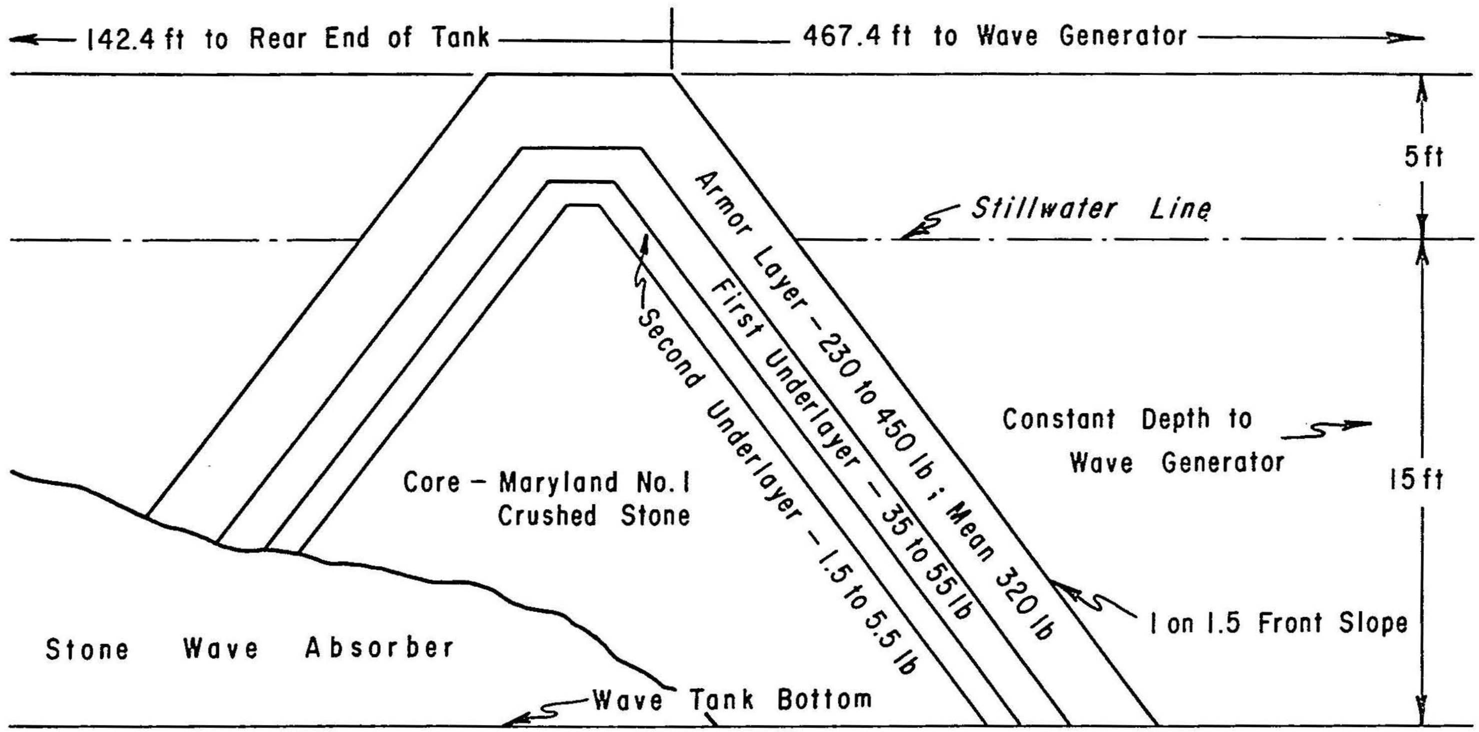

Figure 1. Breakwater location and construction.

Although no effort was made to interlock the stones, they were fitted to keep the surface approximately parallel to the gradeline painted on the tank wall (Fig. 2).

c. Wave Generator Calibration. Since the wave generator had been calibrated during previous tests, it could be set to generate waves of desired height and period. In previous calibration tests, wave heights were measured at the same location as the intersection of the stillwater line with the seaward slope of the breakwater test section. These calibrations were made at a water depth of 15 feet. Wave gage and wave heights were measured visually by a scale on the tank wall. Checks were made during these tests to ensure that previous calibration results were reproduced. The heights reported in Table 1 are from the generator calibration.

Table 1. Results of wave tank breakwater stability tests[1]

Test	Wave period (s)	Wave height (ft)	Run time (min)	Damage (pct)
A[2]	3.75	2.5	78.6	2.15
B	3.75	3.2	81.8	9.42
C[2]	3.75	2.8	81.8	5.13
D[2]	7.87	2.9	81.8	1.90
E	7.87	3.4	81.8	2.36
F	7.87	3.75	85.8	1.97
G[2]	7.87	3.75	81.8	3.19
H[2]	7.87	3.85	81.8	4.87
I[3]	7.87	4.0	81.8	9.53
J[2]	5.60	2.8	48.5	2.44
K	5.60	3.6	78.4	3.45
L[2]	5.60	4.2	3.7	29.24
M[2]	5.60	4.2	78.4	12.75
N[2]	5.60	2.8	72.4	4.77

1. Water depth = 15 feet.
2. Breakwater built or rebuilt before testing.
3. Water depth was 14.5 feet, structure rebuilt.

Figure 2. Completed breakwater, forward slope.

2. Test Procedures.

a. Beginning. After the breakwater section was constructed and surveyed, water was added to bring the water depth to 15 feet. Test I (see Table 1) which was run with a water depth of 14.5 feet was the only exception. Three wave periods were used in a total of 14 tests. The waves were run in bursts of short duration to minimize complications due to reflections from the structure. The wave generator was shut off just before the wave energy reflected from the structure returned to the wave blade. For the 3.75-, 5.60-, and 7.87-second wave periods, the number of waves in each burst was 17, 8, and 6, respectively. Figure 3 shows the runup of a test wave on the breakwater section.

b. Run Termination and Structure Reconditioning. A *test* is defined as a series of monochromatic wave trains generated in bursts. After a set number of bursts was run or significant damage had occurred to the breakwater, a test was terminated. A maximum number of bursts was set to assure a standard run time (about 80 minutes) for all tests. The number of waves for each test was arrived at by dividing the wave period into 80 minutes. The first test at each wave period was run with a wave height not expected to damage the breakwater; however, this was not achieved (see Table 1).

The succeeding tests were generally run at the same wave period with successively higher waves. A survey was made of the seaward face of the structure after the termination of a test; if the survey showed significant damage, the armor layer was removed and replaced to grade. Usually, the removal of the armor stones was limited to about 5 feet (vertically) below the stillwater line to the breakwater crest (Table 1). Before the next test was run, the seaward face of the rebuilt breakwater was resurveyed.

c. Surveys. Survey soundings were made from a movable carriage with a 1-inch diameter aluminum sounding rod equipped with a 6-inch diameter footplate at the bottom end. The footplate was mounted to the rod with a ball joint so it could adjust to the rock surface of the breakwater. Each survey consisted of two sets of soundings made at the same points on a horizontal grid. Grid points were at 2-foot intervals along the tank axis (station) and across the width of the tank (range). There were 18 stations and 6 ranges for a total of 108 survey points. A single profile was obtained by averaging the soundings at each station. The resulting profile and the procedure for establishing the percent damage to the armor layer are shown in Figure 4.

d. Stone Characteristic Tests. Each stone in the armor layer of the breakwater was weighed during construction of the test section and painted with a number. Three stones from the seaward face of the test section, one at the stillwater level, one about 4 feet above the stillwater level, and one about 3 feet below the stillwater level, were chosen as test stones. These stones were weighed during the reconstruction of the breakwater, between some of the tests and at the completion of the tests.

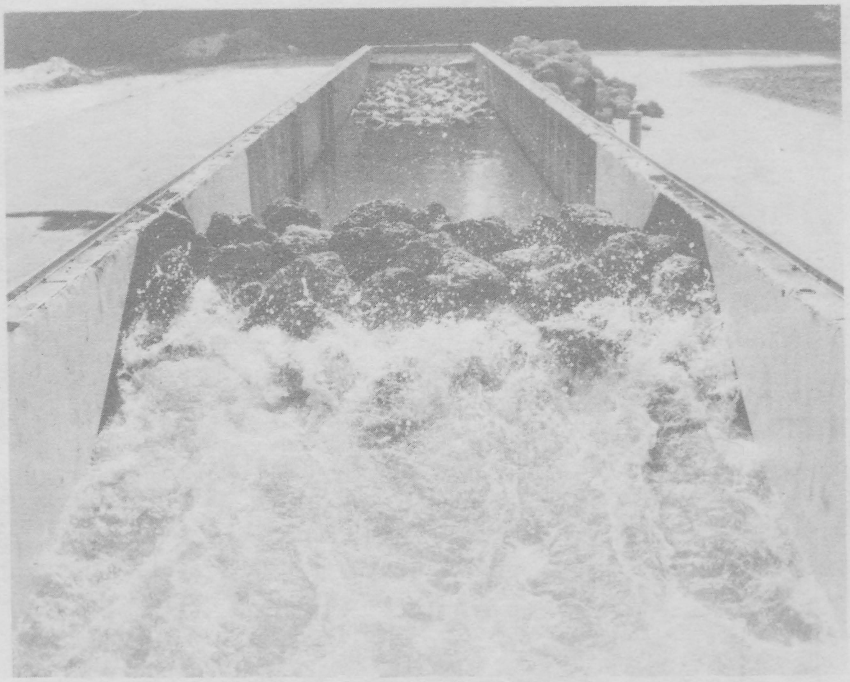

Figure 3. Wave runup on breakwater section.

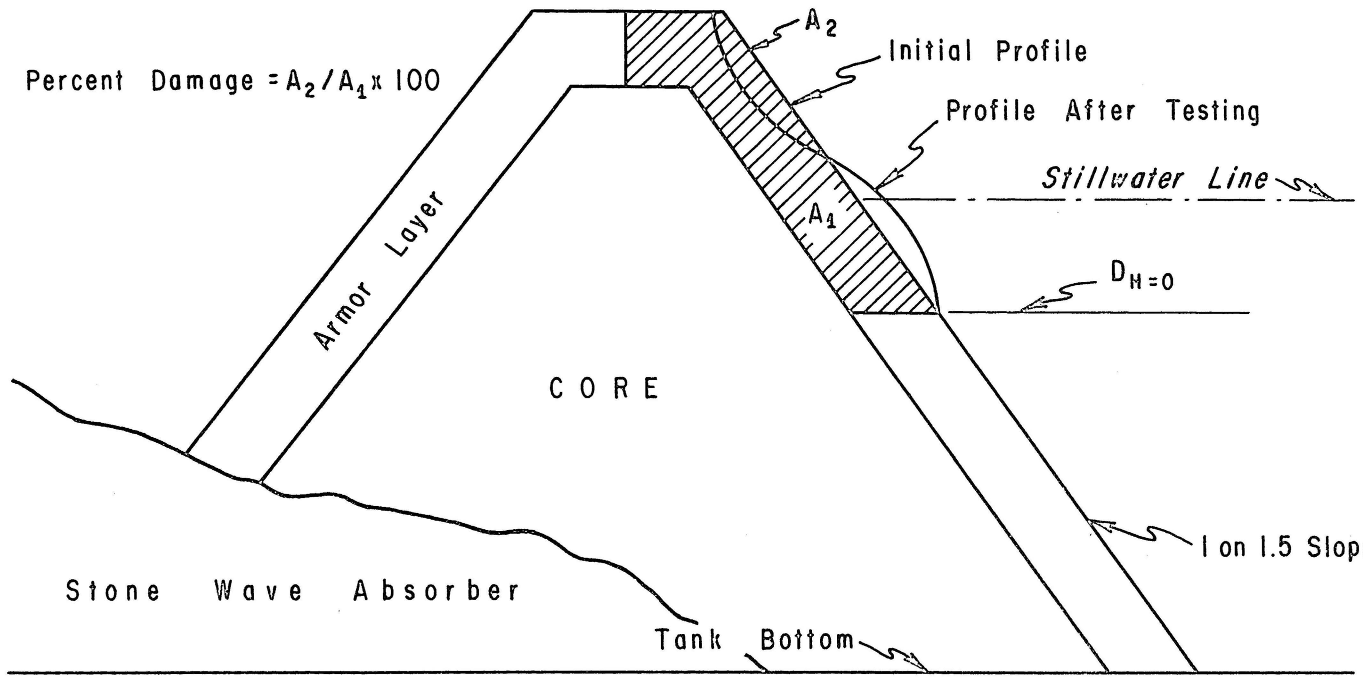

Figure 4. Percent damage of New Bern stone.

3. Breakwater Damage Criteria and Results.

The Hudson (1957) formula for breakwater stability gives the minimum stable weight for rubble-mound armor units as a function of the incident wave height, the seaward slope of the structure, and the characteristics of the armor unit. The equation is:

$$W_{50} = \frac{\gamma_T \, H^3_{D=0}}{K_D \left(\gamma_T / \gamma_W - 1 \right)^3 \cot \alpha}$$

where,

K_D = an empirical coefficient that varies primarily with the shape of the armor units, roughness of the surface, sharpness of edges, and degree of interlocking obtained in placement,

$H_{D=0}$ = the zero-damage wave height, in feet, (maximum wave height with less than 1-percent volumetric damage),

W_{50} = the weight of the 50^{th} percentile of armor stone weights, in pounds,

γ_T = the wet specific weight of stone,

γ_W = the specific weight of water (62.4 pounds per cubic foot),

and

α = the angle between the seaward slope of the breakwater and the horizontal.

Breakwater stability tests were made to determine the stability coefficient (K_D). With the exception of the zero-damage wave height, all of the parameters necessary to compute K_D are available from the stone and water characteristics, and the seaward slope of the breakwater. The zero-damage wave height, $H_{D=0}$, taken in this study as the maximum wave height at which no more than 1-percent volumetric damage occurs on the face of the structure, must be determined experimentally. Determination of percent volumetric damage is made by surveying the breakwater before it is subjected to wave action, and again after the breakwater has been subjected to wave action for a period long enough to ensure that the seaward slope has reached a condition of equilibrium. This period of wave action is denoted as a *test*.

The percent volumetric damage is then determined from the "before" and "after" surveys as shown in Figure 4. Table 1 summarizes the conditions and damage percentages for each of the 14 tests. Using the percent volumetric damage and corresponding wave heights, the wave height causing 1-percent damage ($H_{D=0}$) was determined as shown in Figure 5. These values were then used with Hudson's (1957) equation to compute values of K_D. The resulting $H_{D=0}$ and K_D values are listed in Table 2.

Table 2. Summary of damage data K-Δ results.

Wave period (s)	"Fit-by-eye"		Regression analysis			
	Y = ax + b		Y = ax + b		$Y = ax^b$	
	$H_{D=0}$ (ft)	K_D	$H_{D=0}$ (ft)	K_D	$H_{D=0}$ (ft)	K_D
3.75	2.4	3.7	2.4	3.7	2.2	2.8
5.60	2.6	4.8	2.8	6.3	2.3	3.5
7.87	3.2	8.8	3.3	9.6	3.1	7.8

4. Analysis and Discussion of Breakwater Damage Results.

Difficulty in obtaining accurate K_D values arise from the need to determine zero-damage wave height values. Since the stability coefficient is directly proportional to the third power of the zero-damage wave height, a small error in wave height produces a comparatively large error in K_D. Three methods were tested to best curve-fit the data in Table 1: (a) a linear fit-by-eye curve; (b) a least square regression curve of the form, $y = ax + b$ (linear); and (c) a least square regression curve of the form $y = ax^b$ (logarithmic). The zero-damage wave height values obtained from each of the three methods and the resulting K_D values are presented in Table 2.

The third method of curve fitting, $y = ax^b$, is the best for the following reasons: (a) It gives the most conservative results (Table 2); (b) the data appear to fit the form $y = ax^b$ better than the form $y = ax + b$; and (c) data collected in riprap stability studies performed at CERC (personal communication, J. Ahrens, oceanographer, CERC, 1974) were best fit by a logarithmic curve. Data and resulting curves using method (c) are shown in Figure 5. The K_D values from this figure are 2.8, 3.5, and 7.8, for the 3.75-, 5.60-, and 7.87-second period waves, respectively. The zero-damage wave breaker types were "collapsing" for the 3.75-second period and "surging" for the 5.60- and 7.87-second periods.

The zero-damage wave height and related stability coefficient results are complicated by the "last wave effect" associated with generator-created waves. When the wave generator is stopped at the end of a burst, the last wave is usually larger than the waves preceding it in the wave train. Calculations for K_D are based on the model wave height of a wave train; however, the last large wave may be the dominant cause of the

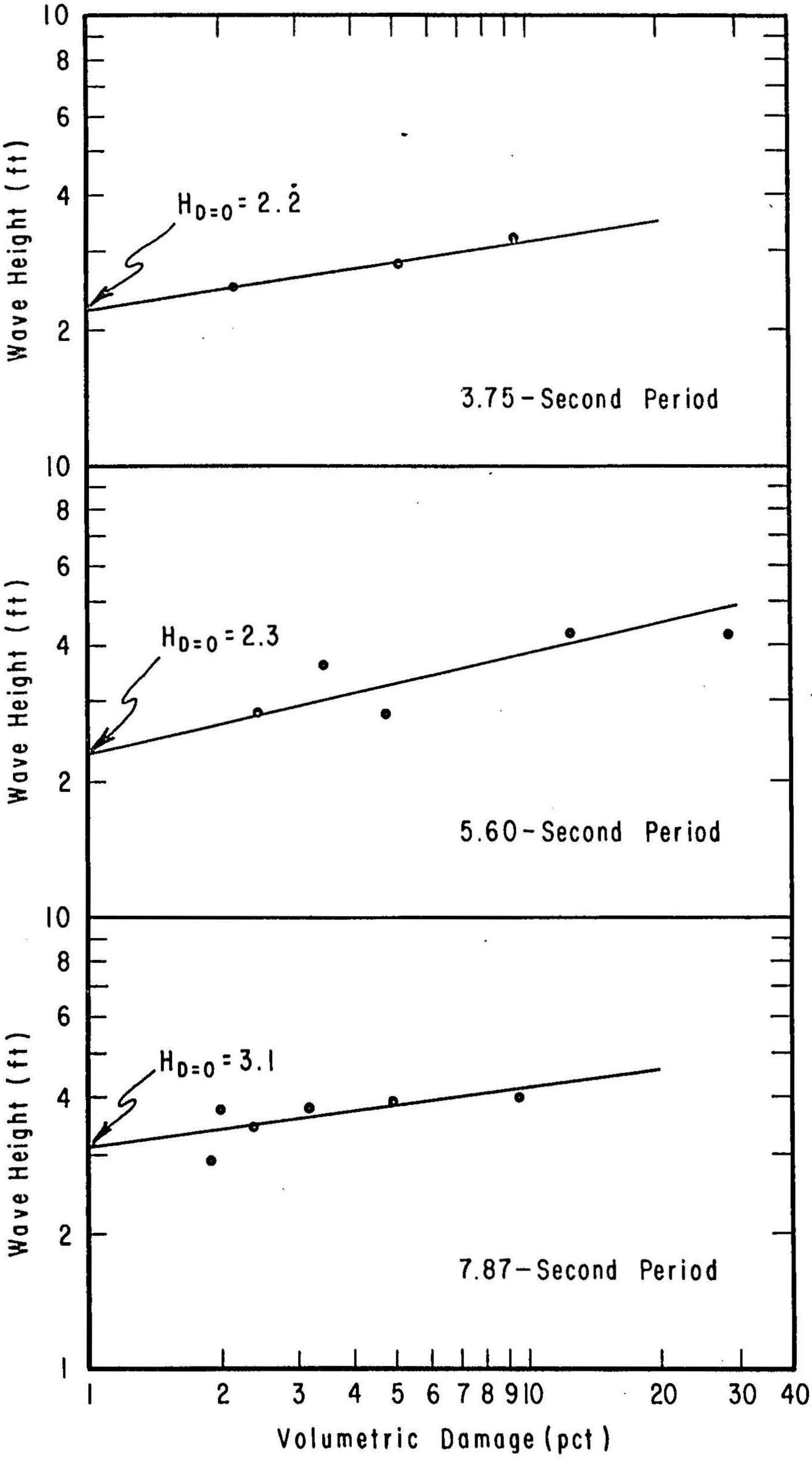

Figure 5. Damage curves for 3.75-, 5.60-, and 7.87-second periods.

damage experienced. Therefore, the values computed may be conservative. The last wave effect is greater for short waves than for long waves.

5. Stone Characteristic Test Results.

a. Weight Losses. The results of the initial and final weighings of the armor stone are shown in Tables 3 and 4. The armor stones on the top and seaward face of the structure were divided into five groups (Fig. 6) to determine the relationship between the stone's weight loss and location on the structure. The factors which cause weight loss to an individual stone during testing are a function of the stone's location on the structure. If the relative importance of these factors as a function of stone location is known, the factors could be separated and individually evaluated. A second division of the stones was made with the previously divided groups 1, 2, and 3 designated as group A, and groups 4A and 4B designated as group B. The second division of the stones was based on location to compare the relative effect of the tests on stones located in the generally active upper zone on the face of the breakwater and those in the lower zone which were generally not subjected to the turbulence associated with breaking waves. The stones in group B (lower zone) were not removed after each test.

After completion of all of the tests, final weighing was done by lowering the water in the wave tank to a level of about 4 feet above the bottom of the tank. Each stone was weighed while submerged, and reweighed wet, immediately after removal. The painted numbers had worn off the stones to such an extent that only 147 of the 299 armor stones in groups 1 to 4 could be identified.

Weighing time, the stone weights, and the gain or loss for each of the three preselected stones are shown in Table 4. If these stones had been tested continuously for 1 week under the same conditions as the testing (including being intermittently removed and replaced), extrapolation of weight data indicates that stones 364, 269, and 79 would lose 13, 63, and 47 percent of their original weights, respectively.

b. Specific Weight Measurements. The individual values of wet specific weight (γ_S) of the stones were determined from the equation:

$$\gamma_S = \frac{W_W \; W_{TA}}{W_{TA} - W_{TW}}$$

where,

W_{TA} = the stone weight in air, and

W_{TW} = the weight of the stone submerged.

The average of the wet specific weight values of the 270 stones at the final weighing was 124.4 pounds per cubic foot (specific gravity = 1.99),

Table 3. Stone weight loss by group at end of testing.

Group		Unidentified (no.)	(no.)	Identified				
				Totals			Average weight loss	
				Identified (pct)	Weight (lb)	Loss (lb)	Per stone[1] (lb)	Stones (pct)
1	Crest of structure	13	22	37.1	4,348	270	20.8	6.2
2	Just above SWL	17	18	48.6	5,802	603	35.5	10.4
3	Just below SWL	38	74	33.9	12,768	1,005	26.4	7.9
4A	Middepth	24	10	70.6	8,012	325	13.5	4.1
4B	Next to tank bottom	55	28	66.3	18,365	527	9.6	2.9
Total		147	155	48.7	49,295	2,730	18.6	5.5

1. This loss is conservative since it is a *net* loss, not the loss of solids. It does not include any consideration of weight gain by water uptake, and does not include unidentified stones. If unidentified stones were included, the loss would probably be greater.

Table 4. Weight history of three stones on the seaward slope of the test breakwater.

Number	Weight (lb)	Gain or loss: Since previous weighing (lb)	Gain or loss: Total (lb)	Weighing after tests
364[1]	365			
79[2]	247			before tests
269[3]	329			
364	358	-7	-7	
79	237	-10	-10	B
269	313	-16	-16	
364	358	0	-7	
79	237	0	-10	C
269	313	0	-16	
364	356	-2	-9	
79	235	-2	-12	E
269	305	-8	-24	
364	354	-2	-11	
79	232	-3	-15	G
269	301	-4	-28	
364	356	+2	-9	
79	235	+3	-12	H
269	---[4]			
364	355	-1	-10	
79	---			I
269	297	-4	-32	
364	353	-2	-12	
79	233	-2	-14	K
269	294	-3	-35	
364	---			
79	230	-3	-17	L
269	---			
364	---			
79	229	-1	-18	M
269	---			

1. Stone 364 located at SWL on face of breakwater.
2. Stone 79 located about 4 feet above SWL on face of breakwater.
3. Stone 269 located about 3 feet below SWL on face of breakwater.
4. Not weighed.

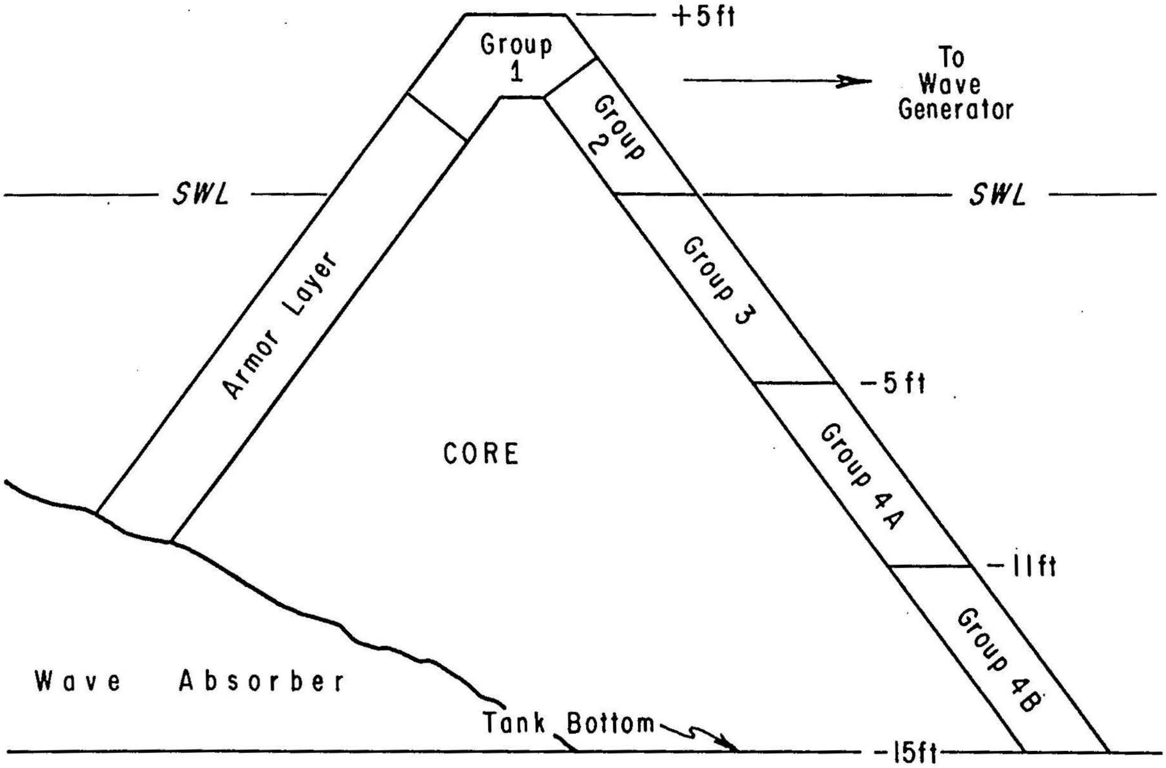

Figure 6. The division of armor layer into five groups.

which was used in Hudson's (1957) equation to compute the K_D values shown in Table 2. The standard deviation of the population of wet specific weights was 11.3 pounds per cubic foot.

c. Water Absorption. Although water intake was not directly measured, the net effect of the two opposing processes, stone breakdown and water intake, was measured. Water intake determinations were made on a single stone in the large wave tank with no waves running, after the completion of the breakwater stability tests. The stone was weighed, lowered to approximately 3 feet below the surface of the water, removed, reweighed, and replaced periodically.

6. Analysis and Discussion of Results of Stone Characteristic Tests.

a. Water Absorption and Stone Solution. The results of water intake for a single stone are shown in Table 5. Note that while the stone was submerged for 144 hours (6 days), a total of 12 pounds was gained which is almost 4 percent of its original weight.

b. Stone Weight Losses. The final weight losses of the final grouping of stones in the breakwater division are shown in Table 3. The *net* average weight loss for the 147 identified stones was 5.5 percent of the original stone weight. The *gross* weight loss (net stone weight loss plus absorbed water) is 2 to 6 percent higher, or about 7 to 12 percent of the original weight.

Causes of weight loss were: (a) abrasion caused by the flow of water and suspended particles past the stone; (b) movement, chipping and crushing from tumbling or rocking by waves; (c) handling, chipping and crushing during placing, removal, and weighing; and (d) solution of solids. Weight gain was caused by water absorption. Table 3 does not provide exact quantitative relationships of the relative strengths of the causes of stone weight change; however, a qualitative evaluation of stone weight changes was made (see App. A).

7. Conclusions Resulting from Laboratory Tests.

a. The physical properties of stone from the New Bern quarry varied from stone to stone.

b. The wet specific weight of the individual stones was variable. A total of 270 stones averaged 124.4 pounds per cubic foot with a standard deviation of 11.3 pounds per cubic foot. The wet specific weight changes were due primairly to the amount of water absorbed, and increased with time of immersion.

c. The water intake of the individual stones varied considerably, ranging from 2 to 6 percent of their original weight during a 2-month period of immersion.

d. The stone lost weight from handling, rubbing, rolling against other stones, small surface particles being washed away by wave action,

Table 5. Water absorption of one New Bern stone with dry weight of 314 pounds.

Weighing number	1965	Cumulative time in water		Net weight	Gain
		(h)	(min)	(lb)	(lb)
1	8 Dec.	0	1	317	3
2	8 Dec.	0	31	322	8
3	8 Dec.	1	1	322	8
4	8 Dec.	2	1	322	8
5	8 Dec.	3	1	322	8
6	8 Dec.	20	30	322	8
7	9 Dec.	26	43	322	8
8[1]	9 Dec.	44	38	326	12
9[1]	10 Dec.	45	8	327	13
10[1]	10 Dec.	50	19	327	13
11	13 Dec.	115	51	326	12
12	13 Dec.	122	4	326	12
13	13 Dec.	139	27	326	12
14	14 Dec.	144	0	326	12

1. Waves were running in the wave tank before weighing.
Water depth in the wave tank was 15 feet.
Stone was suspended about 3 feet below water surface.

and from entering solution. Quantitative and qualitative evaluation of the relative effects of the factors causing stone weight change was not possible with the measurements made.

e. The breakwater stability coefficients for use in Hudson's (1957) equation were 2.8, 3.5, and 7.8 for the 3.75-, 5.60-, and 7.87-second periods, respectively.

IV. FIELD TESTS

1. Purpose.

As a result of the wave tank breakwater stability tests, arrangements were made with the U.S. Army Engineer District, Wilmington, for field tests of the New Bern stone. The stone was placed in an ocean environment to determine the magnitude of weight losses.

2. Test Procedure.

Thirteen stones with individual weights ranging from 150 to 688 pounds were numbered and placed on or near the west jetty at Fort Macon, North Carolina. The stones were weighed dry then submerged in water for 3 to 5 minutes, reweighed submerged, and then reweighed wet in air.

Due to the size of the voids between the 12- to 20-ton granite jetty armor stones, the test stones could not be "keyed in" with the armor stones. Instead, they were placed with their bases at about +1 foot to +1.5 feet, mean low water (MLW) on the sand ridge formed within the armor stone voids. This was done by a crane stationed on the top of the jetty.

The test procedure called for periodic removal, reweighing, and subsequent replacement of the stones. The stones were reweighed while submerged in a seawater-filled tank, and then in the air with a wet surface. This procedure is similar to that used to determine wet specific weights in the wave tank tests.

3. Test Results.

Stone weight, date of weighing, and the number of days elapsed since the initial immersion are shown in Table 6. The wet specific weights and dates of weighing are given in Table 7.

4. Analysis and Discussion of Results.

a. Grouping of Stones. Based on visual observation before testing, and the results from testing by CERC and the U.S. Army Engineer District, Wilmington, stones 1, 3, 5, 6, 7, 11, 12, and 13 (referred to here as group A) were considered to be of acceptable quality and durability for use as underlayer stone at jetties with low wave forces. These stones represented most of the material available in the quarry. Stones 4 and 10 were considered unacceptable; stones 2, 8, and 9 were considered question-

Table 6. Weights of field test stones in pounds.

Date	Stone number (W_{DA})[1] 1 (149)		2 (708)		3 (677)		4 (542)		5 (554)		6 (308)		7 (448)		8 (341)		9 (646)		10 (490)		11 (344)		12 (474)		13 (267)	
	W_{TA}[2]	W_{TW}[3]	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}	W_{TA}	W_{TW}
1967 13 Nov. (0)[4]	153	70	770	398	688	316	585	254	563	262	312	145	460	217	366	161	686	365	535	244	347	158	479	222	271	126
14 Nov. (+1)	155	72	771	404	694	322	580	256	568	269	316	150	458	220	364	161	683	359	527	240	349	161	481	229	272	129
17 Nov. (+4)	155	73	762	410	694	324	571	264	568	271	317	152	458	223	362	167	693	371	524	243	353	166	483	232	273	130
20 Nov. (+7)	151	72	761	414	694	327	558	256	565	271	310	149	443	217	362	166	690	373	520	248	348	163	483	233	273	130
5 Dec. (+22)	145	70	582	322	690	332	---	---	559	271	310	151	---	---	351	165	530	290	512	248	338	161	481	235	268	130
1968 12 Feb. (+91)	142	71	404	227	686	331	361	173	557	272	305	150	---	---	---	---	---	---	---	---	323	156	482	240	267	131
10 May (+179)	119	59	432	238	629	307	354	175	535	262	285	139	---	---	---	---	---	---	---	---	301	145	---	---	206	103
20 Sept. (+312)	---	--	378	202	---	---	292	143	---	---	---	---	---	---	---	---	---	---	---	---	302	147	---	---	202	103
1969 27 June (+592)	---	--	263	143	---	---	262	127	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	150	74

1. Air-dried weight.
2. Wet weight in air.
3. Wet weight in seawater
4. Number of days since initial immersion.

(from U.S. Army Engineer District, Wilmington)

Table 7. Wet specific weights of test stones.

Date	Stone number (lb/ft³)[1]												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1967 13 Nov. (0)[2]	118.0	132.5	118.4	113.1	120.0	119.6	121.2	114.3	136.8	117.7	117.5	119.3	119.6
14 Nov. (1)	119.5	134.5	119.4	114.6	122.0	121.8	123.2	114.8	135.0	117.5	119.0	122.2	121.7
17 Nov. (4)	121.0	138.6	120.0	119.1	122.4	123.0	124.7	118.8	138.0	119.3	120.8	123.2	122.2
20 Nov. (7)	122.3	140.4	121.0	118.3	123.0	123.2	125.5	118.2	139.3	122.4	120.4	123.7	122.2
5 Dec. (22)	123.7	143.3	123.4	-----	124.2	124.8	-----	120.8	141.3	124.1	122.2	125.1	124.3
1968 12 Feb. (91)	128.0	146.1	123.7	122.9	125.1	125.9	-----	-----	-----	-----	123.8	127.5	125.6
10 May (179)	126.9	142.5	125.0	126.6	125.4	124.9	-----	-----	-----	-----	123.5	-----	128.0
20 Sept. (312)	-----	137.4	-----	125.4	-----	-----	-----	-----	-----	-----	124.7	-----	130.6
1969 27 June (592)	-----	140.3	-----	124.2	-----	-----	-----	-----	-----	-----	-----	-----	126.3

1. Air-dried weight.
2. Number of days since initial immersion.

(from the U.S. Army Engineer District, Wilmington) able. These stones (2, 4, 8, 9, and 10) are designated here as group B. Grouping of the stones permitted investigation of whether acceptable stones could be identifiable by a brief visual examination.

b. Analysis Based on Directly Measurable Paramenters.

(1) Net Weight Loss. The date of weighing and the original air-dried weight are shown in Table 6. Although only three of the test stones were located for the final weighing, there were sufficient data to indicate serious weight loss over the test period. Weight loss in group B was more prevalent, occurring sooner on the average and at a faster rate than group A. Note that the original air-dried weights of the 13 stones before initial immersion were less than the wet weights after initial immersion.

(2) Water Absorption Upon Initial Immersion. The percentage by weight of water absorbed by the stones upon initial immersion is shown in Figure 7. Note that there is a distinct difference in the magnitude of initial water absorption between groups A and B. Based on air-dried stone weights before initial immersion, the water intake for group A ranged from 0.9 to 2.7 percent of their original weight with an average of 1.7 percent; for group B, the intake ranged from 6.2 to 9.2 percent of their original weight, with an average of 7.9 percent. If group A is assumed to be of superior durability, low initial water absorption may be a good criterion for high stone durability.

(3) Wet Specific Weight After 7 Days Immersion. Wet specific weights were calculated by equation (2) and are listed in Table 7. The wet specific weights used in this analysis are those after 7 days of immersion because none of the stones had been lost at that time.

Group A had a mean wet specific weight of 122.7 pounds per cubic foot. Group B had a mean wet specific weight of 127.7 pounds per cubic foot with a sample standard deviation of 11.2 pounds per cubic foot. Using the variance ratio test (Kenney and Keeping, 1954), it appears unlikely (much less than 1 percent) that the two groups are from the same population. This is a supportive argument for the importance of visual observation in acquiring stones of desired durability.

(4) Stability of Stone to Movement. According to Hudson's (1957) formula, a stone with a wet specific weight of 130 pounds per cubic foot must be 3.2 times heavier than a stone (e.g., granite) with a wet specific weight of 170 pounds per cubic foot to have equal stability on a similar structure.

c. Analysis Based on Indirectly Measurable Parameters.

(1) Relative Changes in Weight of Solids for Group A. Although direct measurements showed that the total weight (solids plus absorbed water) of each stone decreased considerably, the absolute values for loss of weight of solids could not be determined since measurements of water

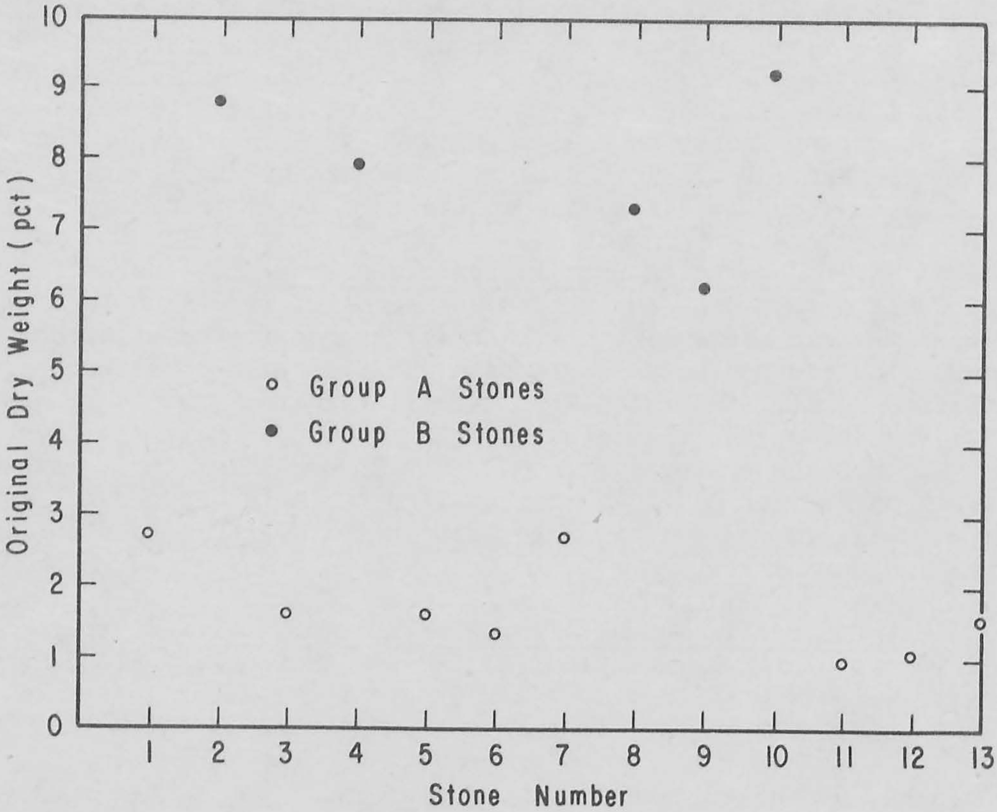

Figure 7. Water absorption by test stones upon initial immersion.

content and apparent specific gravity of solids were not attempted. However, an attempt was made to approximate the changes in weight of solids for group A (Table 8). The procedures used in arriving at the values in Table 8 are explained in Appendix B. The following assumptions are necessary to follow the procedures explained in the Appendix:

(a) All stones have a constant specific gravity of solids;

(b) all stones have a constant void ratio, e, (ratio of volume of voids to volume of solids ($e = V_V/V_S$);

(c) the water displacement method and procedures used are sufficiently accurate for the material being tested; and

(d) the degree of saturation, S, on any given stone, at any given time, is proportional to the calculated wet specific weight of that stone at that time.

The percent weight loss of solids is shown in Table 8. These data indicate loss as a function of time alone, eliminating the factor of initial weight which is important since stones used in coastal structure cover layers may not have weights in the same range as the test stones. Table 8 also suggests that the weight losses would have continued if testing had lasted longer. The loss of solids for the six stones of group A, which were retained for 179 days, ranged from 9 to 29 percent, averaging 18 percent. Stone 13 lost about 47 percent of its initial weight in 592 days.

(2) Relative Changes in Weight of Solids for Group B. The procedure for determining changes in solids with group A cannot be used for group B. Assuming that the calculated wet specific weights for individual stones in group B are correct, no reasonable assumed values of S and γ_S will yield logical results for all weight data for any stone. This is further evidence that group A and group B are different. Based on initial weight, stones 2 and 4 of group B sustained losses in excess of 50 percent in 592 days.

(3) Water Absorption During Testing. The percent of water absorption during testing of group A is shown in Table 8. Water absorbed by the stones before testing is considered part of the original dry stone weight. In determining absorption percentages, it is assumed that as the stone loses volume it also loses a proportional amount of original water. This was taken into account in calculating the values in Table 8.

In the earlier analysis of the CERC wave tank tests, it was speculated that, with respect to time, the net effect of the two opposing processes of absorption of water and weight loss is dominated first by the process of water absorption, and later by the processes which cause weight loss. Figures 8 and 9 which show the difference between weight of solids lost and weight of water absorbed (Table 8), as a function of test time, confirm this theory.

Table 8. Analysis of group A stone weight changes.

Day[1]	W_{TA}[2] (lb)	W_{TW}[3] (lb)	γ_T[4] (lb/ft^3)	W_S[5] (lb)	W_W[6] (lb)	V_T[7] (ft^3)	V_S[8] (ft^3)	V_V[9] (ft^3)	S[10] (pct)	A[11] (pct)	e[12]	W_{LS}[13] (pct)
Stone 1												
Pretest	149	--	114.9	147	2	----	----	----	8	----	-----	---
0	153	70	118.0	147	6	1.30	0.92	0.38	25	2.68	0.405	---
1	155	72	119.5	147	8	1.30	0.92	0.38	33	4.03	-----	---
4	155	73	121.0	145	10	1.28	0.91	0.37	42	5.44	-----	1.4
7	151	72	122.3	140	11	1.24	0.88	0.36	48	6.34	-----	4.8
22	145	70	123.7	133	12	1.17	0.83	0.34	55	7.41	-----	9.5
91	142	71	128.0[14]	126	16	1.11	0.79	0.32	78	10.94	-----	14.3
179	119	59	126.9	106	13	0.94	0.67	0.27	74	11.21	-----	27.9
Stone 3												
Pretest	677	---	116.5	609	68	----	----	----	53	----	-----	---
0	688	316	118.4	609	79	5.80	3.81	1.99	62	1.62	0.524	---
1	694	322	119.4	609	85	5.80	3.81	1.99	67	2.51	-----	---
4	694	324	120.0	605	89	5.77	3.79	1.98	70	3.12	-----	0.7
7	694	327	121.0	600	94	5.73	3.76	1.97	75	4.05	-----	1.5
22	690	332	123.4	586	104	5.58	3.66	1.92	85	5.85	-----	3.8
91	686	331	123.7	581	105	5.53	3.63	1.90	87	6.19	-----	4.6
179	629	307	125.0	528	101	5.03	3.30	1.73	91	7.16	-----	13.3
Stone 5												
Pretest	554	---	117.8	492	62	----	----	----	60	----	-----	---
0	563	262	120.0	492	71	4.69	3.08	1.61	69	1.62	0.524	---
1	568	269	122.0	489	79	4.66	3.06	1.60	77	3.09	-----	0.6
4	568	271	122.4	486	82	4.63	3.04	1.59	81	3.84	-----	1.2
7	565	271	123.0	481	84	4.59	3.01	1.58	83	4.24	-----	2.2
22	559	271	124.2	471	88	4.49	2.95	1.54	89	5.47	-----	4.3
91	557	272	125.1	466	91	4.48	2.91	1.57	90	6.10	-----	5.3
179	535	262	125.4	448	87	4.25	2.79	1.46	93	6.18	-----	8.9
Stone 6												
Pretest	308	---	118.0	274	34	----	----	----	59	----	-----	-----
0	312	145	119.6	274	38	2.61	1.71	0.90	67	1.32	0.522	-----
1	316	150	121.8	272	44	2.59	1.70	0.89	77	3.27	-----	0.7
4	317	152	123.0	270	47	2.57	1.69	0.88	83	4.62	-----	1.1
7	310	149	123.2	264	46	2.51	1.65	0.86	84	4.38	-----	2.7
22	310	151	124.8	260	50	2.48	1.63	0.85	92	6.16	-----	5.1
91	305	150	125.9	254	51	2.42	1.59	0.83	95	6.62	-----	7.3
179	285	139	124.9	239	46	2.27	1.49	0.78	92	5.95	-----	12.8
Stone 7												
Pretest	448	---	118.0	428	20	----	----	----	28	----	-----	---
0	460	217	121.2	428	32	3.79	2.68	1.11	45	2.68	0.416	---
1	458	220	123.2	419	39	3.71	2.62	1.09	56	4.43	-----	2.1
4	458	223	124.7	415	43	3.67	2.59	1.08	62	5.53	-----	3.0
7	443	217	125.5	400	43	3.54	2.50	1.04	64	5.73	-----	6.5

See end of table for footnotes.

Table 8. Analysis of group A stone weight changes-Continued.

Day[1]	W_{TA}[2] (lb)	W_{TW}[3] (lb)	γ_T[4] (lb/ft^3)	W_S[5] (lb)	W_W[6] (lb)	V_T[7] (ft^3)	V_S[8] (ft^3)	V_V[9] (ft^3)	S[10] (pct)	A[11] (pct)	e[12]	W_{LS}[13] (pct)
						Stone 11						
Pretest	344	---	116.5	304	40	----	----	----	60	----	-----	---
0	347	158	117.5	304	43	2.95	1.90	1.05	64	0.87	0.550	---
1	349	161	119.0	302	47	2.93	1.89	1.04	71	2.05	-----	0.7
4	353	166	120.8	301	52	2.91	1.88	1.03	79	3.82	-----	1.0
7	348	163	120.4	297	51	2.88	1.86	1.02	78	3.57	-----	2.3
22	338	166	122.2	285	53	2.76	1.78	0.98	85	4.97	-----	6.7
91	323	156	123.8	269	54	2.60	1.68	0.92	91	6.25	-----	11.5
179	301	145	123.5	251	50	2.42	1.57	0.85	92	5.99	-----	17.4
312	302	147	124.7	250	52	2.42	1.56	0.86	95	6.71	-----	17.8
						Stone 12						
Pretest	474	---	118.0	446	28	----	----	----	36	----	-----	---
0	479	222	119.3	446	33	4.01	2.79	1.22	42	1.05	0.438	---
1	481	229	122.2	437	44	3.93	2.73	1.20	57	3.66	-----	2.0
4	483	232	123.2	435	48	3.93	2.73	1.19	63	4.55	-----	2.5
7	483	233	123.7	434	49	3.90	2.71	1.19	64	4.77	-----	2.7
22	481	235	125.1	426	55	3.84	2.67	1.17	73	6.18	-----	4.5
91	482	240	127.5	421	61	3.78	2.63	1.15	83	7.83	-----	5.6
						Stone 13						
Pretest	267	---	117.8	254	13	----	----	----	32	----	-----	---
0	271	126	119.6	254	17	2.27	1.60	0.67	39	1.50	0.442	---
1	272	129	121.7	251	21	2.23	1.57	0.66	50	3.03	-----	1.2
4	273	130	122.2	251	22	2.23	1.57	0.66	52	3.41	-----	1.2
7	273	130	122.2	251	22	2.23	1.57	0.66	52	3.41	-----	1.2
22	268	130	124.3	242	26	2.15	1.51	0.64	64	5.51	-----	4.7
91	267	131	125.6	238	29	2.12	1.49	0.63	71	6.80	-----	6.3
179	206	103	128.0	181	25	1.61	1.13	0.48	81	8.42	-----	28.8
312	202	103	130.6	174	28	1.55	1.09	0.46	95	10.38	-----	31.5
592	150	74	126.3	133	17	1.18	0.83	0.35	76	7.91	-----	47.6

1. Number of days since initial immersion
2. Wet weight in air
3. Bouy weight.
4. Wet specific weight.
5. Weight of solids.
6. Weight of water.
7. Total volume.
8. Solids volume.
9. Volume of voids.
10. Saturation.
11. Absorption.
12. Void ratio.
13. Weight loss of solids.
14. Maximum.

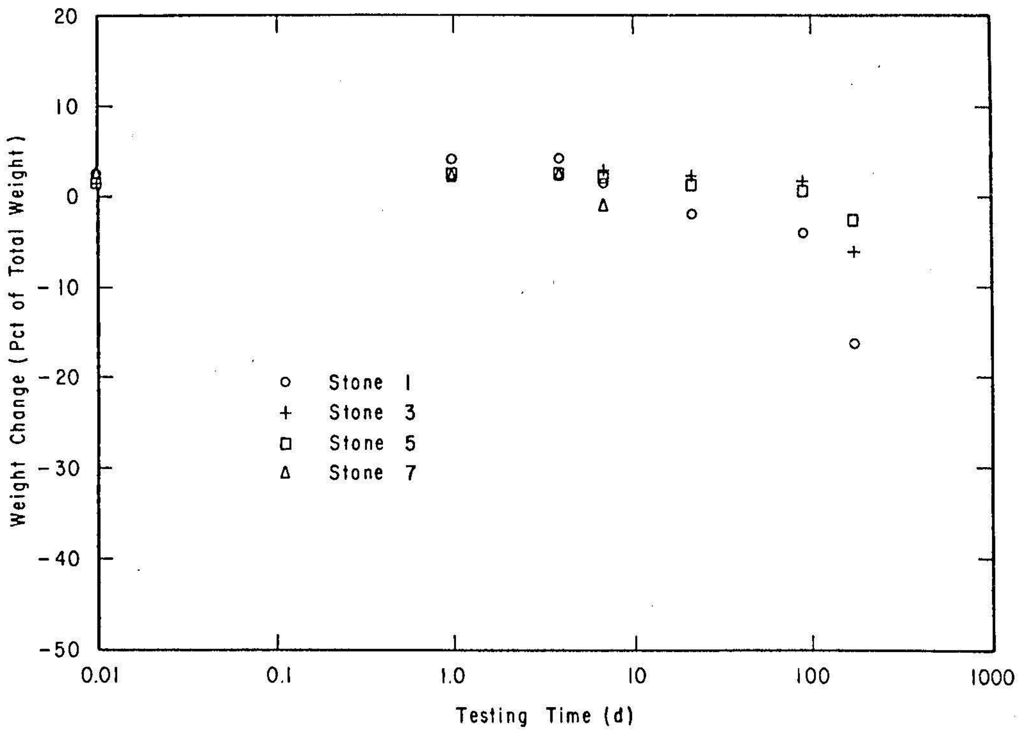

Figure 8. Net weight change of group A stones (absorption minus solid losses).

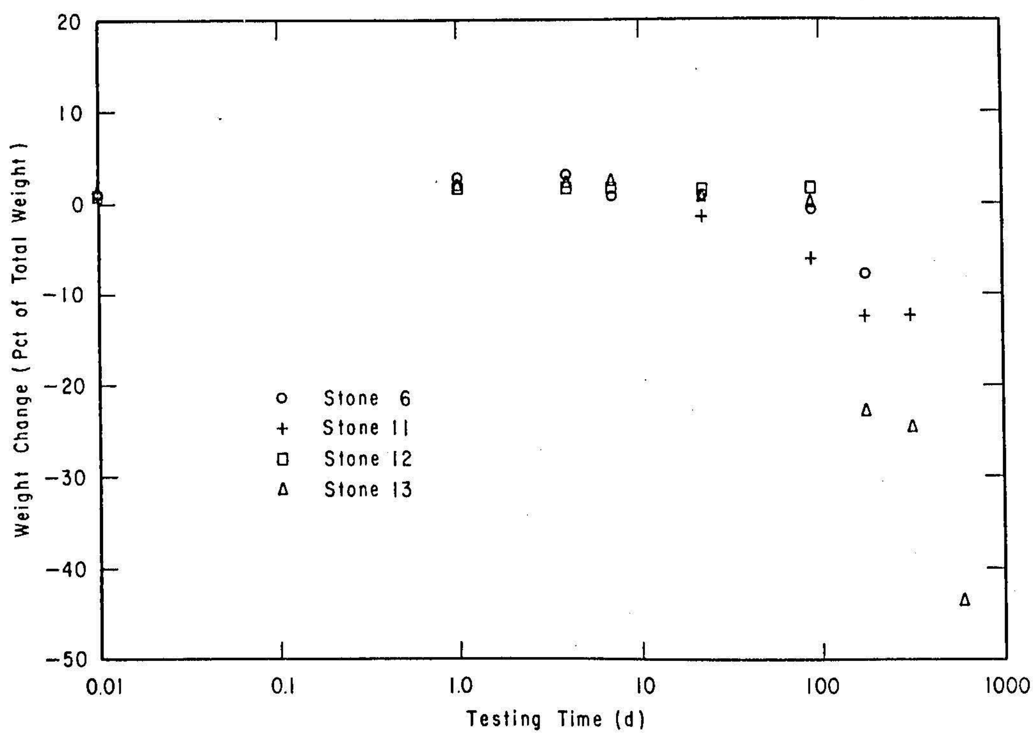

Figure 9. Net weight change of group A stones (absorption minus solid losses).

(4) Abrasion and Solution of Solids. Although the processes by which the stones lost weight are not quantitatively evaluated, some conclusions were made. Observations during the weighings for 179 days indicated that stones 1, 5, 6, 11, and 13 of group A had not moved between weighings from 12 February to 10 May 1968. Yet, these stones lost considerable weight during this interval, indicating that abrasion (loss of surface particles due to water movement and suspended sand resulting from waves and tides), and solution of solids contributed significantly to stone weight losses. Abrasion and solution of solids are the two weight loss causes which cannot be controlled when the stone is being used in the cover layer of a coastal structure.

5. Conclusions.

a. Visual examination and evaluation can be an important aid in the selection of stones of acceptable quality and durability for use in cover and undercover layers in coastal structures when the physical characteristics of the stone supply vary.

b. When immersed in seawater, New Bern stone of good quality and durability (group A) initially gains weight due to water absorption. As time passes, the stone continues to absorb water but at a decreasing rate; the factors which cause stone breakdown begin to dominate and the stone begins to lose weight.

c. The water intake of the New Bern stone varies considerably from stone to stone. The maximum amount of water absorbed (saturation) by group A of the New Bern stones ranges from about 4 to 13 percent of the stone's original air-dried weight. None of group A reached saturation for the duration of testing. Generally, stones with high initial water absorption tend to be more prone to weight loss than stones with low initial water absorption.

d. All New Bern stone exposed to ocean wave action lose weight. The evidence indicates that weight loss would continue indefinitely.

e. A combination of abrasion and, to a lesser extent, solution of solids apparently contributed significantly to the stone's loss of weight. These are the only two causes of weight loss which cannot be eliminated in the prototype situation.

6. Recommendations.

a. Due to excessive weight losses, particularly because of abrasion and a lesser extent solution of solids, the use of the New Bern stone in cover or underlayers of coastal structures is not recommended.

b. The following are general recommendations concerning the testing of the quality of stone for use in cover layers of coastal structures:

(1) Where practical, granites or granitic-type stone (stone with a high specific gravity and low porosity) should be used as cover stone for coastal structures.

(2) Testing and examination of the source stone or rock is essential before the use of any stone for coastal structures.

(3) According to a survey of case histories on inland rubble-mound protective structures by Esmiol (1967), most failures of the structures surveyed were due to disintegration of stone. Specific gravity, absorption, and petrographic examination are recommended as the most valuable methods currently being used to identify sound durable rock. EM 1110-2-2904 (U.S. Army Corps of Engineers, 1963) suggests that "any testing program for the determination of the quality of rock for use as breakwater and jetty stone, should include a petrographic examination, determination of specific gravity, an abrasion test, a slaking or wetting-and-drying test, and a freeze-thaw test. The best data for use in evaluating stone for use in breakwaters and jetties are service records."

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APPENDIX A

A QUALITATIVE EVALUATION OF STONE WEIGHT CHANGE FOR GROUPED STONES DURING LABORATORY TESTING

A consideration of the test conditions and the way the tests were conducted lead to the following thoughts about the five groups of stone from the laboratory tests (Fig. 6):

(a) Groups 1 and 2 were exposed to the same handling and submersion conditions. The primary difference in the exposure of these two groups was the greater agitation (abrasion and movement) experienced by group 2, due to breaking waves (particularly for the 3.75-second period). This is consistent with the larger average weight loss for group 2 (10.4 percent) compared to the loss for group 1 (6.2 percent).

(b) Groups 2 and 3 were exposed to essentially the same abrasion and handling; however, group 3 was submerged most of the time while group 2 was wet only during wave action. Therefore, it would be expected that group 3 stones would absorb more water than group 2 stones. Group 3 weight losses averaged 7.9 percent of their original weight compared to 10.4 percent average losses by group 2. This is consistent with the initial hypothesis.

(c) Group 4A stones were above water when the water level in the wave tank was lowered to 4 feet above the bottom for the final stone weighing. Group 4A was not moved during the tests or handled during rebuilding of the breakwater. In addition, group 4A was agitated less by wave action during the tests. Therefore, less weight loss due to movement, handling, and abrasion should be expected in group 4A when compared to group 3. Water absorption should have been similar. Thus, group 3 losses should have been larger than those of group 4A. This was the case--a 7.9-percent loss for group 3 compared to a 4.1-percent loss for group 4A.

(d) Group 4B consists of those stones in group 4 which remained immersed in water after the water level was lowered to 4 feet above the bottom of the tank for the final stone weighing. The stones in group 4B lost 3.0 percent of their original weight as opposed to 4.1 percent for the stones in group 4A. The 1.1 percent greater weight loss for group 4A was probably the direct result of greater water absorption by group 4B.

The relative effects of handling and abrasion were investigated by dividing the stones into two groups--group A in the upper, active zone handled after each test, and group B in the lower inactive zone not removed after each test. This division combined the armor stones in groups 1, 2, and 3 from the first division, redesignating them as group A. Groups 4A and 4B were combined and redesignated as part of group B.

Group A had an average net weight loss of 8.2 percent of the original weight of the 68 stones with identifiable numbers at the end of testing. Group B had an average net weight loss of 3.2 percent of the original weight of the 79 stones with identifiable numbers at the end of testing. These results support the idea that the handling and agitation in the upper zone, combined with a smaller opportunity to absorb water, led to greater overall weight loss.

APPENDIX B

PROCEDURES FOR DETERMINING THE RELATIVE CHANGES IN WEIGHT OF SOLIDS FOR GROUP A FIELD TEST STONES

The value for the degree of saturation S on the day of maximum calculated wet specific weight (Table 8) is assumed to yield logical results for all sets of weight data for the stone and not violate the four assumptions listed in Section IV. Data fitting and the number of days the individual stone attained its maximum wet specific weight influenced the value of S. The values of S on the day of maximum wet specific weight may vary. The relationships (equations) used in this analysis are:

$$W_{TA} = W_S + W_W, \qquad \text{(B-1)}$$

$$W_{TA} = \gamma TV_T, \qquad \text{(B-2)}$$

$$W_S = \gamma_S V_S, \qquad \text{(B-3)}$$

$$W_W = S\gamma_W V_V, \qquad \text{(B-4)}$$

$$V_T = V_S + V_V, \qquad \text{(B-5)}$$

where,

W_{TA} = wet weight in air of stone (solids and water), pounds,

W_S = weight of solids, pounds,

W_W = weight of absorbed water, pounds,

γ_T = wet specific weight of stone (solids and water), pounds per cubic foot,

V_T = volume of stone, cubic foot,

γ_S = specific weight of solids = 159.7 pounds per cubic foot (average value from laboratory report for quarry),

S = degree (percent) of saturation, or percentage of available void space filled with water,

γ_W = specific weight of seawater = 64 pounds per cubic foot,

V_S = volume of solids (stone minus voids), cubic foot,

V_V = volume of voids, cubic foot.

These five relationships can be combined to yield:

$$W_{TA} = \gamma_S V_S + S\gamma_W(V_T - V_S) \ . \qquad \text{(B-6)}$$

Equation (B-6) is used to determine the amount of stone (solid material) and absorbed water which, when combined, equal the weights measured (Table 6).

As an example, the values of the wet weight in air, W_{TA}, and the buoyant wet weight in seawater, W_{TW}, of stone 1 (Table 8) were measured from these values, the wet specific weight, γ_T, is calculated:

$$\gamma_T = \frac{(W_{TA})(W_W)}{(W_{TA} - W_{TW})} \ .$$

The total volume, V_T, is calculated from the wet weight in air and the wet specific weight: $V_T = W_{TA}/\gamma_T$. The remaining values in Table 8 are unknown. The first step in determining the unknown values is to locate the maximum value of γ_T in the wet specific weight of Table 8. For stone 1 the maximum wet specific weight occurred on the 91st day and equaled 128 pounds per cubic foot. According to assumption (d), the maximum degree of saturation, S, also occurred on the 91st day. By considering equation (B-6) and filling in the knowns from Table 9, stone 1 on the 91st day becomes: $142.1 = 159.7\ V_S + S(64)(1.11 - V_S)$. Thus, there are two unknowns, S and V_S, and only one equation which cannot be solved explicitly. By trial and error, a value of S must be selected which gives the most logical results and is most consistent with the limiting assumptions.

First, try $S_{max} = 1.0$ (100 percent). From equation (B-6), $V_S = 0.742$ cubic foot. Using this value in equation (B-5), $V_V = 0.368$ cubic foot and $e = V_V/V_S = 0.496$. From equations (B-3) and (B-4), respectively, $W_S = 118.4$ pounds and $W_W = 23.6$ pounds. Next, using the value of e = 0.496, determined from the data for the 91st day, the corresponding values for the 22nd day are determined. From equation (B-5), $V_S = 0.782$ cubic foot, and $V_V = 0.388$ cubic foot. From equation (B-3), $W_S = 124.9$ pounds; from equation (B-1), W_W must equal 20.1 pounds. Hence from equation (B-4), the degree of saturation, S, equals 0.81 (81 percent) for the 22nd day. By using the value of S(0.81) in equation (B-6) the void ratio, e, is calculated to see if it remains constant and equals to 0.496 (assumption (b) in Section IV). This results in a calculated e of 0.504. The difference in e assumed (0.496) and e calculated (0.504) is recorded. Repeating the procedure, i.e., assuming e = 0.496 and using equations (B-5), (B-3), (B-1), and the knowns, the values V_S, V_W, W_S, and W_W are calculated for each day. Then, using equation (B-4), values of S are calculated for each day. Using equation (B-6) and the calculated values of S, the void ratios, e, are calculated. The difference between the assumed constant void ratio (0.496), and the calculated void ratio is recorded for each day of weighing. After the differences between the calculated and assumed void ratios (e_c and e_a, respectively) for all test days have been determined, the sum of their squares is calculated and recorded. For S_{max} = 100 percent of stone 1, $(e_c - e_a)^2 = 492 \times 10^{-6}$. Other values of S_{max} are used to to arrange them by elevation groups, in order to have the data in a form useful to project considerations; (d) when mixed samples are used, analysis of duplicates from the mixtures can provide a way to evaluate variability in the results due to analysis procedure; and (e) the original unmixed samples should be retained should additional size analysis be required because of errors or because the original mixtures chosen do not provide the appropriate information needed to solve problems later in the investigation.

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43 p. : ill. (Technical paper - U.S. Coastal Engineering Research Center ; no. 76-4)
Bibliography: p. 37.
A porous, low-density limestone (cemented shell stone) available from a quarry in New Bern, North Carolina, was tested for stability as a rubble-mound armor unit, in the large wave tank at CERC. The use of New Bern stone as a cover or underlayers of rubble-mound coastal structures is not recommended.

1. Breakwaters. 2. Structures. 3. New Bern, North Carolina. 4. Rubble mound armor unit. I. Title. II. Savage, R.P., joint author. Series: U.S. Coastal Engineering Research Center. Technical paper no. 76-4.

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