BREAKWATER STABILITY - BREAKING WAVE DATA

by

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Abstract

The objective of the research presented is to furnish design information for stone and dolos armor on non-overtopping breakwater trunks that are subjected to severe depth-limited breaking waves. Since it would be a mammoth task to comprehensively investigate all the different types of existing armor, this particular research effort concentrated on stone, which is a natural and economical protection when it is of sufficient size and quality to meet design constraints, and on the dolos, which according to nonbreaking wave data is the best hydraulically stable concrete armor unit.

Introduction

A proposed rubble-mound breakwater may necessarily be designed for either nonbreaking or breaking waves depending on 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 in order to provide economic construction of a stable breakwater; however, many local design requirements are most advantageously met by quarry-stone armor. This paper addresses the use of quarry-stone and dolos armor on breakwater trunks subjected to breaking waves.

Previous investigations have yielded a significant quantity of design information for quarrystone (Hudson, 1958 and Carver, 1980) tetrapods, quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson, 1968), dolos (Carver and Davidson, 1977), and toskane (Carver, 1978). However, the studies conducted by Hudson, Jackson, Davidson, and Carver were limited in that test waves were always nonbreaking and the relative wave height (H/d) varied over a very limited range.

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Purpose of Study

The purpose of the present investigation was to obtain design information for stone and dolos armor used on breakwater trunks 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:

a. Type of armor unit.

b. The sea-side slope of the structure.

c. Wave period.

d. Wave height.

e. Water depth.

f. The sea-bottom slope on which the breakwater is constructed.

Dimensional Analysis

When short-period waves attack rubble-mound breakwaters, the interaction of the dislodging forces induced by the water motion and the resistive action of the armor units produces a complex dynamic phenomenon. Previous attempts to analyze this phenomenon to ascertain the magnitude of the dynamic forces involved by theoretical analyses have not been successful; however, hydraulic scale models of breakwaters can yield accurate design information that relates the required weight of individual armor units to breakwater geometry, local bathymetry, wave characteristics, etc.

An attempt will be made through the use of dimensional analysis to develop functional relationships between the primary variables affecting armor stability. The Buckingham Pi Theorem can be used to determine the number of dimensionless and independent quantities (Pi terms) required to express a relationship among the variables in any phenomenon. Dimensional analysis may then be used to obtain a suitable set of Pi terms.

Definitions and characteristic dimensions in terms of Force (F), Length (L), and Time (T) of the primary variables affecting armor stability are as follows:

γ_a = specific weight of an armor unit, F/L^3

W_a = weight of an armor unit, F

Δ = shape factor of the armor unit, dimensionless

γ_w = specific weight of water, F/L^3

H = wave height, L

L = wave length, L

d = water depth, L

g = acceleration due to gravity, L/T^2

h = height of breakwater crown, L

β = angle of wave attack, dimensionless

ν = kinematic viscosity, L^2/T

α = angle between the horizontal and the seaward face of the breakwater, dimensionless

θ = angle between the horizontal and the sea-bottom on which the breakwater is constructed, dimensionless

PT = technique used to place armor units in the cover layer, dimensionless

D = damage parameter, dimensionless

The present investigation addresses only waves normal to nonovertopping breakwater sections. Therefore, the variables, β and h, are eliminated. Also, since α is directly related to the seaward slope of the breakwater, this variable can be replaced by $\cot \alpha$ where $\cot \alpha$ is the reciprocal of breakwater slope. With these considerations, the list of variables is reduced to 13.

With 13 variables and 3 basic dimensions involved, the Buckingham Pi Theorem predicts that armor stability should be a function of 10 dimensionless Pi terms. One possible set of Pi terms is

$$\pi_1 = \frac{\gamma_a^{1/3} H}{(\frac{\gamma_a}{\gamma_w} - 1) W_a^{1/3}} \tag{1}$$

$$\pi_2 = H/d \tag{2}$$

$$\pi_3 = H/L \tag{3}$$

$$\pi_4 = L^2 H/d^3 \tag{4}$$

$$\pi_5 = \cot \alpha \tag{5}$$

$$\pi_6 = \Delta \tag{6}$$

$$\pi_7 = \theta \tag{7}$$

$$\pi_8 = \frac{(gH)^{1/2}\, \ell_a}{\nu} \tag{8}$$

$$\pi_9 = PT \tag{9}$$

$$\pi_{10} = D \tag{10}$$

Correlation of the test data will be attempted by the functional relationship

$$\pi_1 = f\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}) \tag{11}$$

or

$$\frac{\gamma_a^{1/3} H}{\left(\frac{\gamma_a}{\gamma_w} - 1\right) W_a^{1/3}} = f\,(H/d,\ H/L,\ L^2H/d^3,\ \cot\alpha,\ \theta,\ \Delta,\ (gH)^{1/2}\, \ell_a/\nu,\ PT,\ D) \tag{12}$$

Stability Scale Effects

If the absolute sizes of breakwater materials and wave dimensions become too small, flow around the armor units enters the laminar regime; and the induced drag forces become a direct function of the Reynolds Number. Under these circumstances, prototype phenomena are not properly simulated and stability scale effects are induced. Hudson (1975) presents a detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater models (critical $R_N = 3 \times 10^4$). For all tests reported herein, the sizes of model armor and wave dimensions were selected such that scale effects were insignificant (i.e., R_N was greater than 3×10^4).

Selection of Test Conditions

In planning a stability investigation, it is not possible to preselect exact values of H/L and H/d since the design-wave heights are unknown at the outset of the study. However, the widest possible range of these parameters can be insured by using various armor weights that range from just above the scale-effect regime at the lower limit up to the maximum weights that the test facility is capable of displacing. For the present investigation, armor weights ranged from 106 to 322 grams.

The wave flume was calibrated for depths from 12.2 cm to 29.0 cm in 1.5-cm increments 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 sea-side breakwater slopes.

All stability tests were conducted on sections of the type shown in Figures 1-3. Sea-side slopes of 1:1.5, 1:2, and 1:3 were investigated while the beach-side slope was held constant at 1:1.5. Structure heights of 30 to 50 cm were used. The height necessary to prevent wave overtopping was determined by the combination of structure slope, armor type and weight, and water depth being investigated.

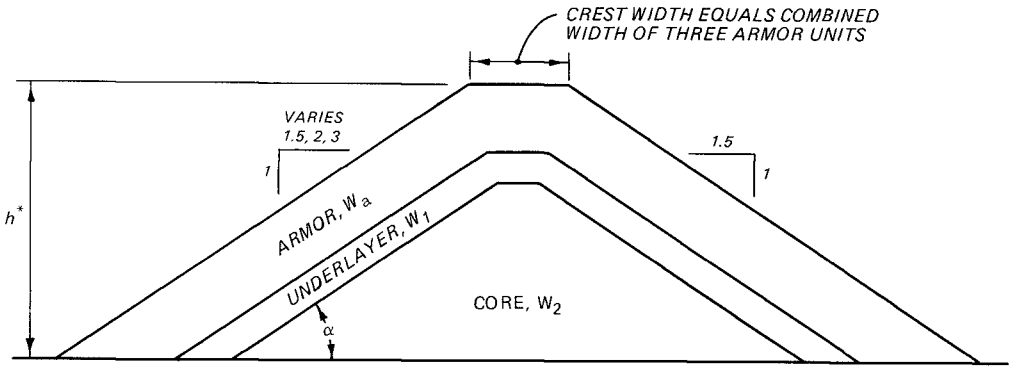
Method of Constructing Test Sections

All model breakwater sections were constructed to reproduce as closely as possible results of the usual methods of constructing prototype breakwaters. The core material was dampened as it was dumped by bucket or shovel into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype 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 was then added by shovel and smoothed to grade by hand or with trowels. No excessive pressure or compaction was applied during placement of the underlayer stone. 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 are individually placed but are laid down without special orientation or fitting. After each test, the armor stones were removed from the breakwater, all of the underlayer stones were replaced to the grade of the original test section, and the armor units were replaced.

Test Equipment and Materials

All wave-action tests were conducted in a 1.5-m-wide, 1.2-m-deep, and 36.3-m-long concrete wave flume with test sections installed about 27.4 m from a vertical displacement wave generator. The first 3.0 m of flume bottom, immediately seaward of the test sections, was molded on a 1:10 slope while the remaining 24.4 m was flat. The generator was capable of producing sinusoidal waves of various periods and heights. Test waves of the required characteristics were generated by varying the frequency and amplitude of the plunger motion. Changes in water-surface elevation as a function of time (wave heights) were measured by electrical wave-height gages in the vicinity of where the toe of the test sections was to be placed and recorded on chart paper by an electrically-operated oscillograph. The electrical output of the wave gages was directly proportional to their submergence depth.

Rough hand shaped granitic stone (W_a) with an average length of approximately two times its width, average weights of 173 gr ($\pm$9 gr), 250 gr ($\pm$11 gr), and 322 gr ($\pm$14 gr), and a specific weight of 2.68 gr/cc was used to armor the stone sections. Dolos sections were armored with the following sizes of units.



MATERIAL WEIGHTS, GRAMS

W_a	W_1	W_2	ARMOR TYPE
173	17	0.04 - 0.86	STONE
250	25	0.06 - 1.27	STONE
322	32	0.08 - 1.63	STONE
106	21	0.02 - 0.54	DOLOS
125	25	0.03 - 0.63	DOLOS
267	53	0.06 - 1.32	DOLOS

* TOTAL STRUCTURE HEIGHT (h) VARIED FROM 0.3 m TO 0.5 m DEPENDING ON THE COMBINATION OF STRUCTURE SLOPE, ARMOR WEIGHT, AND WATER DEPTH BEING INVESTIGATED.

Figure 1. General breakwater cross-section.

Figure 2. Cross-sectional view of typical stone section.

Figure 3. Cross-sectional view of typical dolos section.

W_a, gr	γ_a, gr/cc
106	2.21
125	2.28
267	2.26

Sieve-sized limestone (2.64 gr/cc) was used for the underlayer (W_1) and core (W_2) of both armor types.

Test Procedures

For a given wave period and water depth, the most detrimental breaking wave (i.e., the most damaging wave) was determined by increasing the stroke adjustment on the wave generator in small increments and observing which wave produced the most severe breaking wave condition on the model structures. Wave heights of lower amplitude did not form the critical breaking wave and wave heights of larger amplitude would break seaward of the test structures and dissipate their energy so that they were less damaging than the critically tuned wave.

A typical stability test consisted of subjecting the test section to attack by waves of a given height and period until stability was achieved. Test sections were subjected to wave attack in approximately 30-sec intervals between which the wave generator was stopped and the waves allowed to decay to zero height. This procedure was necessary to prevent the structures from being subjected to an undefined wave system created by reflections from the model breakwater and wave generator. Newly built test sections were subjected to a short duration (five or six 30-sec intervals) of shakedown using a wave equal in height to about one-half of the estimated no-damage wave. This procedure provided a means of allowing consolidation and armor unit seating that would normally occur during prototype construction.

Test Results

Breaking wave stability test results for stone and dolos armor are summarized in Tables 1 and 2, respectively. Presented therein are experimentally determined design wave heights, wave steepness, relative wave height, Ursell Number, and breakwater slope. All stability test results presented in Tables 1 and 2 were verified by at least one repeat test. Sea-side breakwater slopes of 1:1.5, 1:2, and 1:3 were used for both armor types. The following ranges of armor weights, water depths, wave periods and heights, relative depths, wave steepness, Ursell Numbers, and relative wave heights were investigated.

Variable	Range for Indicated Type of Armor	
	Stone	Dolos
armor weight, gr	173-322	106-267
water depth, cm	12.2-22.9	13.7-29.0

(continued)

TABLE 1

Values of $H_{D=0}$, d/L, H/L, H/d, L^2H/d^3, and N_s for Two Layers of Stone Armor Randomly Placed on Breakwater Trunks and Subjected to Breaking Waves with No Overtopping: W_a = 173, 250, and 322 gr; γ_a = 2.68 gr/cc; cot α = 1.5, 2, and 3

W_a, gr	d, cm	T, sec	$H_{D=0}$, cm	d/L	H/L	H/d	L^2H/d^3	N_s
			cot α = 1.5					
173	13.7	1.07	10.1	0.12	0.088	0.73	51.2	1.50
173	16.8	1.04	10.7	0.14	0.089	0.64	32.5	1.59
250	12.2	1.45	11.3	0.08	0.074	0.93	144.7	1.48
250	16.8	1.18	11.6	0.12	0.083	0.69	47.9	1.52
250	18.3	1.09	12.2	0.14	0.093	0.67	34.0	1.60
322	12.2	1.90	12.8	0.06	0.063	1.05	291.4	1.54
322	12.2	2.82	12.8	0.04	0.042	1.05	655.7	1.54
322	15.2	1.32	12.8	0.10	0.084	0.84	84.2	1.54
			cot α = 2.0					
173	15.2	1.13	12.5	0.12	0.098	0.82	57.1	1.86
173	16.8	1.18	11.6	0.12	0.083	0.69	47.9	1.72
173	18.3	1.09	12.2	0.14	0.093	0.67	34.0	1.81
250	12.2	2.82	12.8	0.04	0.042	1.05	655.7	1.68
250	15.2	1.32	12.8	0.10	0.084	0.84	84.2	1.68
250	18.3	1.24	13.7	0.12	0.090	0.75	52.0	1.80
250	19.8	1.13	14.0	0.14	0.099	0.71	36.1	1.84
322	13.7	2.02	14.0	0.06	0.061	1.02	283.9	1.69
322	19.8	1.29	15.5	0.12	0.094	0.78	54.4	1.87
			cot α = 3.0					
173	12.2	2.82	12.8	0.04	0.042	1.05	655.7	1.90
173	18.3	1.24	13.7	0.12	0.090	0.75	52.0	2.03
173	19.8	1.13	14.0	0.14	0.099	0.71	36.1	2.08
250	13.7	2.02	14.0	0.06	0.061	1.02	283.9	1.84
250	18.3	1.45	15.8	0.10	0.087	0.87	86.3	2.07
250	19.8	1.29	15.5	0.12	0.094	0.78	54.4	2.03
250	22.9	1.38	16.8	0.12	0.088	0.73	50.9	2.21

TABLE 2

Values of $H_{D=0}$, d/L, H/L, H/d, L^2H/d^3, and N_s for Two Layers of Dolos Armor Randomly Placed on Breakwater Trunks and Subjected to Breaking Waves with No Overtopping: W_a = 106, 125, and 267 gr; cot α = 1.5, 2, and 3

W_a, gr	d, cm	T, sec	$H_{D=0}$, cm	d/L	H/L	H/d	L^2H/d^3	N_s
			cot α = 1.5					
125	13.7	2.02	14.0	0.06	0.061	1.02	283.9	2.88
125	15.2	1.62	13.7	0.08	0.072	0.90	140.8	2.82
267	19.8	1.85	18.3	0.08	0.074	0.92	144.4	2.96
267	25.9	1.73	21.6	0.10	0.084	0.83	83.4	3.49
267	27.4	1.78	23.5	0.10	0.086	0.86	85.8	3.80
			cot α = 2.0					
106	13.7	2.02	14.0	0.06	0.061	1.02	283.9	3.18
125	16.8	1.70	16.5	0.08	0.079	0.98	153.5	3.39
125	25.9	1.30	17.1	0.14	0.092	0.66	33.7	3.52
125	25.9	1.47	19.2	0.12	0.089	0.74	51.5	3.95
125	29.0	1.37	18.6	0.14	0.090	0.64	32.7	3.83
			cot α = 3.0					
106	21.3	1.34	16.8	0.12	0.094	0.79	54.8	3.82
106	24.4	1.43	16.8	0.12	0.083	0.69	47.8	3.82
106	25.9	1.30	17.1	0.14	0.092	0.66	33.7	3.89
125	18.3	2.32	17.7	0.06	0.058	0.97	268.7	3.64
125	19.8	1.85	18.3	0.08	0.074	0.92	144.4	3.76
125	27.4	1.52	19.5	0.12	0.085	0.71	49.4	4.01
125	29.0	1.56	20.1	0.12	0.083	0.69	48.1	4.13

Variable	Range for Indicated Type of Armor	
	Stone	Dolos
wave period, sec	1.04-2.82	1.30-2.32
wave height, cm	10.1-16.8	13.7-23.5
relative depth	0.04-0.14	0.06-0.14
wave steepness	0.042-0.099	0.058-0.094
relative wave height	0.64-1.05	0.64-1.02
Ursell Number	34.0-655.7	33.7-283.9

The number of armor units per given surface area, A, was $N = 1.45\ \forall^{-2/3}$ and $N = 0.83\ \forall^{-2/3}$ for the stone and dolos, respectively. The variable, $\forall$, is defined as the volume of an individual armor unit. Figures 4 and 5 show typical after testing views of selected test sections.

As previously discussed, it was hoped that stability test results could be analyzed by the following functional relation for the stability number, N_s, where

$$N_s = \frac{\gamma_a^{1/3} H}{(S_a-1) W_a^{1/3}} = f(H/d,\ H/L,\ L^2H/d^3,\ \cot\alpha,\ \theta,\ \Delta,$$

$$(gH)^{1/2}\ell_a/\nu,\ PT,\ D) \qquad (13)$$

For tests described herein θ, PT, and D were held constant; therefore, Equation 13 reduces to

$$N_s = f(H/d,\ H/L,\ L^2H/d^3,\ \cot\alpha,\ \Delta,\ (gH)^{1/2}\ell_a/\nu) \qquad (14)$$

Also, the sizes of model armor units and wave dimensions were selected such that turbulent flow was always obtained: therefore N_s was independent of Reynolds Number $[(gH)^{1/2}\ell_a/\nu]$ and Equation 14 becomes

$$N_s = f(H/d,\ H/L,\ L^2H/d^3,\ \cot\alpha,\ \Delta)$$

Plots of N_s versus H/d, H/L, and L^2H/d^3 are presented in Figures 6, 7, and 8, respectively. These data show a functional dependence of N_s on H/d, H/L, and the Ursell Number (L^2H/d^3) with the dependence being more pronounced for dolos armor. For both armor types it generally appears that minimum stability occurs for the larger values of H/d and L^2H/d^3 and for the intermediate range of H/L ($0.07 \leq H/L \leq 0.085$). Results of previous tests conducted on quarrystone by Hudson (1958) and

Figure 4. Typical sea-side view of stone section after wave attack.

Figure 5. Typical sea-side view of dolos section after wave attack.

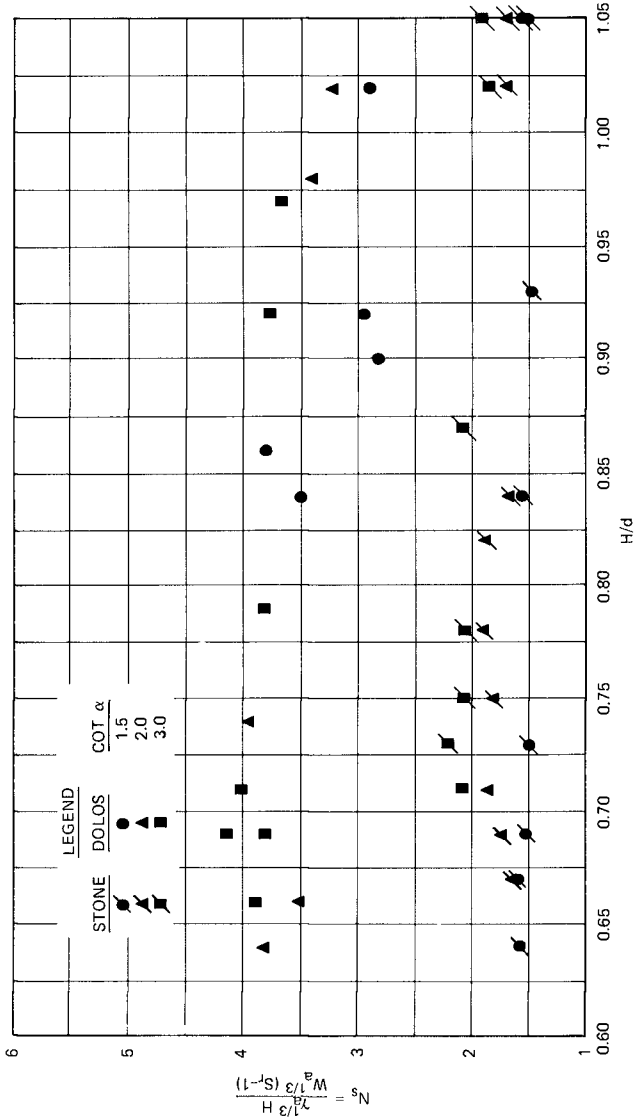


Figure 6. Stability number versus H/d.

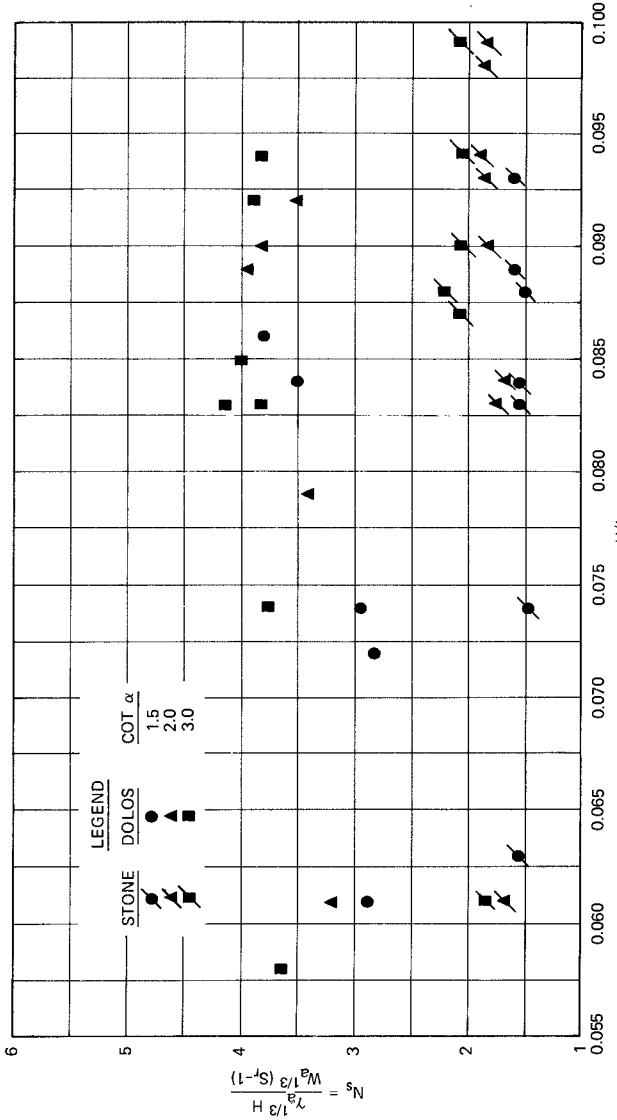


Figure 7. Stability number versus H/L.

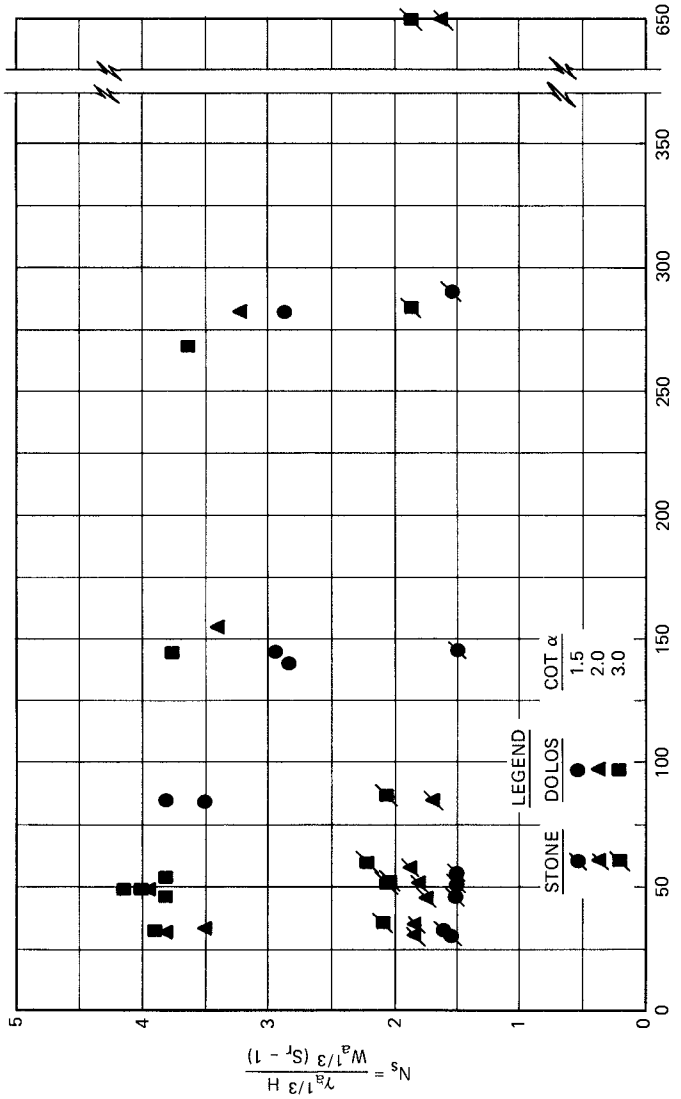


Figure 8. Stability number versus Ursell Number.

Carver (1980) for nonbreaking waves, $H/d \leq 0.32$, and $0.03 \leq H/L \leq 0.08$, do not show these trends. Also the trends are absent from earlier nonbreaking wave tests on dolosse (Carver and Davidson, 1977). The tests of Carver and Davidson were conducted with $H/d \leq 0.37$ and $0.031 \leq H/L \leq 0.083$.

Figure 9 presents a log-log plot of N_s versus cot α. Average and lower limit linear fits of the Hudson type, i.e., 1:3 slope linear fits, are also shown. Even though there is some data spread for each distinct value of cot α (due to variations of H/d, H/L, and L^2H/d^3) the linear fits generally give a reasonable approximation of N_s as a function of cot α, especially for the stone armor.

Conclusions

Based on the tests and results described herein, in which stone and dolos armor are used on breakwater trunks and subjected to breaking waves with a direction of approach of 90 deg, it is concluded that:

a. Armor stability is influenced by wave steepness (H/L), Ursell Number (L^2H/d^3) relative wave height (H/d), and breakwater slope.

b. Effects of H/d, L^2H/d^3, and H/L are more pronounced for dolos armor.

c. In general, minimum stability for each armor type occurred for the larger values of H/d ($H/d > 0.90$), intermediate values of H/L ($0.06 \leq H/L \leq 0.085$), and larger values of L^2H/d^3.

d. Linear Hudson-type data fits generally give a reasonable approximation of N_s as a function of cot α; however, the influences of H/d, H/L, and L^2H/d^3 are strong enough to merit their consideration in final selection of armor unit weight.

Acknowledgements

The data presented in this paper were extracted from model tests described in the Waterways Experiment Station (WES), Technical Report HL-83-____ , entitled "Stability of Stone- and Dolos-Armored, Rubble-mound Breakwater Trunks Subjected to Breaking Waves with No Overtopping," which is being reviewed for publication. The comprehensive study was conducted at WES for the Office, Chief of Engineers under the Corps of Engineers Civil Works Research and Development Program.

Grateful acknowledgement is extended to the Office, Chief of Engineers for granting permission to publish this paper.

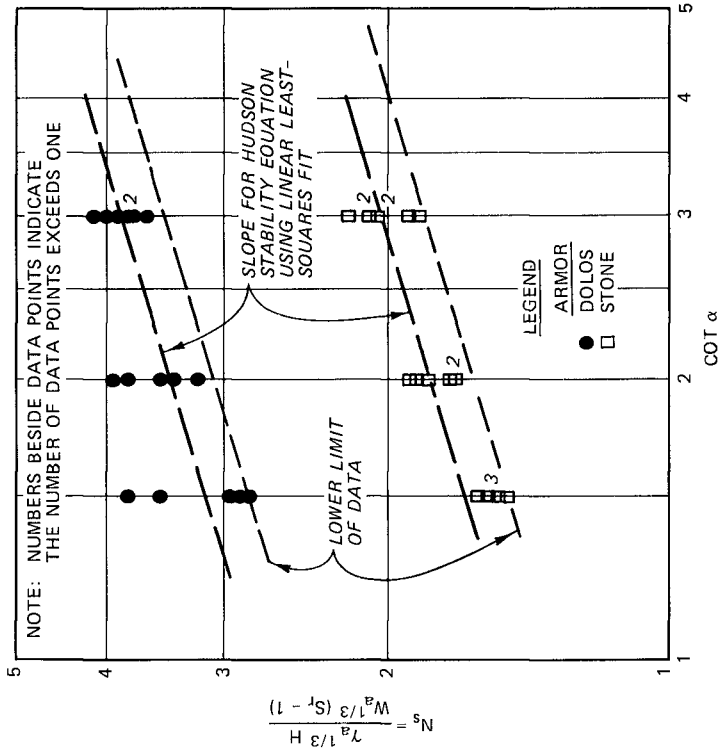


Figure 9. Stability number versus cot α.

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NOTATION

A	Surface area, cm^2
β	Angle of wave attack
d	Water depth, cm
d/L	Relative depth
D	Damage parameter
f	Reads "function of"
g	Acceleration due to gravity, cm/sec^2
h	Height of breakwater crown, cm
H	Wave height, cm
H/d	Relative wave height
H/L	Wave steepness
ℓ_a	Characteristic length of armor unit, cm
L	Length, wavelength, cm
N	Number of armor units per surface area
N_s	Stability Number = $\gamma_a^{1/3} H/(S_a-1) W_a^{1/3}$
PT	Placement technique
R_N	Reynolds stability number = $(gH)^{1/2}\ell_a/\nu$
S_a	Specific gravity of an armor unit relative to water in which the breakwater is constructed
T	Wave period, sec
$\forall$	Volume of individual armor unit, m^3
W	Weight, gr
α	Angle of breakwater slope, measured from horizontal, deg
$\cot \alpha$	Reciprocal of breakwater slope
θ	Angle between the horizontal and the sea bottom on which the breakwater is constructed
γ	Specific weight, gr/cc

γ_a	Specific weight of an armor unit, gr/cc
Δ	Shape of armor unit or underlayer material
ν	Kinematic viscosity, ft^2/sec

Subscripts

a	Refers to armor unit
D	Refers to damage
s	Refers to stability
w	Refers to water in which the structure is located
1 and 2	Refer to underlayer and core, respectively