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

by

Robert D. Carver, C. Ray Herrington, Brenda J. Wright
Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

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Washington, DC 20314-1000
under Work Unit 31269
The purpose of the investigation herein was to obtain design information for stone and dolos armor used on breakwater heads and subjected to nonbreaking 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:

- Type of armor unit,
- Sea-side slope of the structure,
- Angle of wave attack,
- Wave period,
- Wave height.

The abstract (continued)
Based on tests and results described herein, in which stone and doloe armor are used on conical breakwater heads and subjected to nonbreaking waves with angles of wave attack of 0, 45, 90, and 135 deg, it is concluded that:

a. The longer wave periods (2.00 and 2.75 sec) generally produce the lower stabilities;
b. Angles of wave attack of 45 and 90 deg are the most critical;
c. Flattening the slope from 1V on 1.5H to 1V on 2H does not improve stability of the stone armor.
PREFACE

Authority for the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), to conduct this study was granted by the Office, Chief of Engineers (OCE), US Army Corps of Engineers, under Work Unit 31269, "Stability of Breakwaters," Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development. OCE Technical Monitors for this research were Messrs. John H. Lockhart, Jr., and John G. Housley. 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, Wave Research Branch (CW-R). This report was prepared by Mr. Robert D. Carver, Project Engineer, and Ms. Brenda J. Wright and Mr. C. Ray Herrington, Engineering Technicians, CW-R. The model was operated by Ms. Wright and Messrs. Herrington and Marshall P. Thomas, Engineering Technicians, with Mr. Herrington serving as lead technician. 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, CE, was Commander and Director of WES during report publication. Dr. Robert W. Whalin was Technical Director.
Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<table>
<thead>
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<tr>
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STABILITY OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND BREAKWATER HEADS SUBJECTED TO NONBREAKING WAVES WITH NO OVERTOPPING

PART I: INTRODUCTION

Background

1. The experimental investigation described herein constitutes a portion of a research effort to provide engineering data 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. However, a systematic investigation of the stability response of breakwater heads has not been undertaken.

3. A proposed structure may necessarily be designed for either non-breaking 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 in order 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 non-breaking waves.

Purpose of Study

4. The purpose of the present investigation was to obtain as much design information for stone and dolos armor used on breakwater heads and
subjected to nonbreaking waves as possible. 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.
5. If the absolute sizes of experimental breakwater materials and wave
dimensions become too small, flow around the armor units enters the laminar
regime; and the induced drag forces become a direct function of the Reynolds
number. Under these circumstances, prototype phenomena are not properly
simulated, and stability scale effects are induced. Hudson (1975) presents a
detailed discussion of the design requirements necessary to ensure the
preclusion of stability scale effects in small-scale breakwater tests and
concludes that scale effects will be negligible if the Reynolds stability
number

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

where

- $g$ = acceleration due to gravity, ft/sec$^2$
- $H$ = wave height, ft
- $l_a$ = characteristic length of armor unit, ft
- $u$ = kinematic viscosity of experimental fluid medium, ft$^2$/sec

is equal to or greater than $3 \times 10^4$. 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 $3 \times 10^4$).

**Method of Constructing Test Sections**

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

* For convenience, symbols and abbreviations are listed in the Notation
(Appendix A).
structure. Once the core material was in place, it was sprayed with a low-
velocity water hose to ensure adequate compaction of the material. Then the
underlayer stone was 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 were individually placed but were laid down without special orien-
tation or fitting. After each test series 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 an L-shaped concrete flume
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 flume is equipped with a paddle wave genera-
tor capable of producing sinusoidal waves of various periods and heights. For
all tests, waves of the required characteristics were generated by varying the
frequency and amplitude of the paddle motion. Changes in water surface eleva-
tion 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 and recorded on chart paper by an electrically operated oscillograph.
The electrical output of the wave gages was directly proportional to their
submergence depth. Test sections were constructed on the flat bottom portion
of the flume, about 130 ft from the wave generator.

Material
8. Rough, hand-shaped granitic stone W with an average length of
approximately two times its width, average weight of 0.55 lb, and a specific
weight of 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 ($\gamma_a = 165.0$ pcf) was used for the underlayers and core.

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

9. Tests were conducted on stone and dolos conical head sections of the type shown in Figures 2-5 and Photos 6-12. Sea-side slopes of 1V on 1.5H and 1V on 2H were investigated, while the beach-side slope was held constant at 1V on 1.5H. Wave periods of 1.25, 1.5, 2.0, and 2.75 sec were simulated, thus assuring a wide range of wave steepness H/L. The water depth was 1.5 ft. Angles of wave attack \( \theta \) were 0, 45, 90, and 135 deg (Figures 6 and 7).

10. Design wave heights for the no-damage criterion were determined by subjecting the test sections to monochromatic waves successively larger in height in 0.01- to 0.02-ft increments until the maximum heights for which the armor was stable were reached. Each 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 added increment wave. This 30-min
Figure 2. Typical breakwater cross section, 1V-on-1.5H structure slope

Figure 3. Typical breakwater cross section, 1V-on-2H structure slope
Figure 4. Typical plan view, 1V-on-1.5H structure slope

Figure 5. Typical plan view, 1V-on-2H structure slope
Figure 6. Test section orientations for 0°- and 90-deg wave attack

Figure 7. Test section orientations for 45°- and 135-deg wave attack
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 restart-
ing the generator in order to prevent the test sections from being exposed to
uncontrolled wave groups and/or an undefined wave spectrum.
PART III: TEST RESULTS

11. Stability test results for stone and dolos armor are summarized in Tables 1 and 2, respectively. Presented therein are experimentally determined design wave heights and corresponding stability numbers as functions of wave period, wave steepness, and breakwater slope. Breakwater slopes of 1V on 1.5H and 1V on 2H were used for both armor types. The number of armor units per given surface area $A$ was $N = 1.26 V^{2/3}$, with $n = 2$, $k_A = 1.00$, and $P = 37$ percent for stone armor, and $N = 0.83 V^{2/3}$ with $n = 2$, $k_A = 0.94$, and $P = 56$ percent of dolos armor. The variable $V$ is defined as the volume of an individual armor unit. Photos 13-54 show the after-testing stability conditions of the structures.

12. Tests were initially conducted on a 1V-on-2H breakwater slope with 1.25-, 1.50-, 2.00-, and 2.75-sec waves for 0-, 45-, 90-, and 135-deg angles of wave attack. Results of these tests showed the 45- and 90-deg wave directions and the longer wave periods to be the most critical to stability. Therefore, tests on the 1V-on-1.5H slope were conducted with 1.50-, 2.00-, and 2.75-sec waves at 45- and 90-deg angles of wave attack.

13. Figures 8-11 and 12-15 present stability number $N_S$ as a function of wave period and direction for stone and dolos, respectively. Figures 16 and 17 summarize the data by armor type. These data show that the longer wave periods (2.00 and 2.75 sec) generally produce the lower stabilities, and angles of wave attack of 45 and 90 deg are the most critical. Also, it is important to note that flattening the slope to 1V on 2H does not improve stability of the stone armor. Effects of wave direction on dolos stability are consistent with trends previously observed by Willock (1977).

14. Assuming a Hudson stability relationship is applicable to the present data (i.e., the stability coefficient $K_D$ equals $N_S^3/cot\alpha$ and using the critical (minimum) values of $N_S$ determined herein), the following is obtained:

<table>
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<th>Armor Type</th>
<th>$cot\alpha$</th>
<th>$N_S$</th>
<th>$K_D$</th>
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<tr>
<td>Stone</td>
<td>1.5</td>
<td>1.60</td>
<td>2.7</td>
</tr>
<tr>
<td>Stone</td>
<td>2.0</td>
<td>1.60</td>
<td>2.0</td>
</tr>
<tr>
<td>Dolos</td>
<td>1.5</td>
<td>2.26</td>
<td>7.7</td>
</tr>
<tr>
<td>Dolos</td>
<td>2.0</td>
<td>2.63</td>
<td>9.1</td>
</tr>
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</table>
Figure 8. Stone armor stability number $N_s$ versus wave period $T$, 0-deg wave attack

Figure 9. Stone armor stability number $N_s$ versus wave period $T$, 45-deg wave attack
Figure 10. Stone armor stability number $N_s$ versus wave period $T$, 90-deg wave attack

Figure 11. Stone armor stability number $N_s$ versus wave period $T$, 135-deg wave attack
Figure 12. Dolos armor stability number $N$ versus wave period $T$, 0-deg wave attack.

Figure 13. Dolos armor stability number $N$ versus wave period $T$, 45-deg wave attack.
Figure 14. Dolos armor stability number $N_s$ versus wave period $T$, 90-deg wave attack.

Figure 15. Dolos armor stability number $N_s$ versus wave period $T$, 135-deg wave attack.
Figure 16. Stone armor stability number $N_s$ versus angle of wave attack $\phi$.

Figure 17. Dolos armor stability number $N_s$ versus angle of wave attack $\phi$.
These results are extremely significant in that minimum stability coefficients are considerably less than those presented in the Shore Protection Manual (SPM) (1984) and EM 1110-2-2904 (Headquarters, Department of the Army, US Army Corps of Engineers (USACE) 1986).
PART IV: CONCLUSIONS

15. Based on tests and results described herein, in which stone and dolos armor are used on conical breakwater heads and subjected to nonbreaking waves with angles of wave attack of 0, 45, 90, and 135 deg, it is concluded that:

a. The longer wave periods (2.00 and 2.75 sec) generally produce the lower stabilities.

b. Angles of wave attack of 45 and 90 deg are the most critical.

c. Flattening the slope from IV on 1.5H to IV on 2H does not improve stability of the stone armor.

d. Assuming a multiplicity of wave directions, the following values of the stability coefficient $K_p$ are recommended:

<table>
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<tr>
<th>Armor Type</th>
<th>Structure Slope</th>
<th>$K_p$</th>
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<td>Stone</td>
<td>IV on 1.5H</td>
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</tr>
<tr>
<td>Stone</td>
<td>IV on 2H</td>
<td>2.0</td>
</tr>
<tr>
<td>Dolos</td>
<td>IV on 1.5H</td>
<td>7.7</td>
</tr>
<tr>
<td>Dolos</td>
<td>IV on 2H</td>
<td>9.1</td>
</tr>
</tbody>
</table>

It should be noted that the $K_p$ values presented in item d are significantly lower than those presently recommended in the SPM (1984) and FM 1110-2-2404 (USACE 1986).
REFERENCES


Table I
Values of $H$, $H/L$, and $N_s$ for Two Layer of Stone Armor Randomly Placed on Breakwater Heads and Subjected to Nonbreaking Waves with No Overtopping: $W_a = 0.55$ lb; $\gamma_a = 167$ pcf

<table>
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<th>$T$, sec</th>
<th>$H$, ft</th>
<th>$H/L$</th>
<th>$N_s$</th>
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<td>Cot $\alpha = 2.0$</td>
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</tr>
<tr>
<td>0</td>
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<td>0.025</td>
<td>2.82</td>
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*Table 2: Values of \( H \), \( H/L \), and \( N/\eta \) for Two Layers of Dolos Armor Randomly Placed on Breakwater Heads and Subjected to Nonbreaking Waves with No Overtopping: \( \bar{w}_a = 0.276 \) lb; \( \cot \alpha = 1.5 \) and 2; \( d = 1.50 \) ft.*
Photo 2. Sea-side view of a typical stone section before wave attack at a 1V–on-2H-structure slope; angle of wave attack = 45 deg
Photo 3. End view of a typical stone section before wave attack at a 14- on-2H-structure slope; angle of wave attack = 90 deg
Photo 4. End view of a typical stone section before wave attack at a 1V- on-2H-structure slope; angle of wave attack = 135 deg
Photo 5. End view of a typical stone section before wave attack at a 1V-on-1.5H-structure slope; angle of wave attack = 45 deg.
Photo 6. End view of a typical stone section before wave attack at a 1V-on-1.5H-structure slope; angle of wave attack = 90 deg.
Photo 7. End view of a typical dolos section before wave attack at a 1V-on-2H-structure slope; angle of wave attack = 0 deg
Photo 9. End view of a typical dolos section before wave attack at a 1V- on-2H-structure slope; angle of wave attack = 90 deg.
Photo 10. End view of a typical dolos section before wave attack at a 1V-on-2H-structure slope; angle of wave attack = 135 deg
Photo II. End view of a typical dolos section before wave attack at a 1W-on-1.5H-structure slope; angle of wave attack = 45 deg
Photo 12. End view of a typical dolos section before wave attack at a 1V- on-1.5H-structure slope; angle of wave attack = 90 deg
Photo 13. End view after attack of 1.25-sec, 0.50-ft waves; angle of wave attack = 0 deg; LV = on-ZH-structure slope; stone armor
Photo 14. End view after attack of 1.50-sec, 0.52-ft waves; angle of wave attack = 0 deg; IV- on-2H-structure slope; stone armor
Photo 16. End view after attack of 2.75-sec, 0.53-ft waves; angle of wave attack = 0 deg; 4V- on-2H-structure slope; stone armor
Photo 17. Sea-side view after attack of 1.25-sec, 0.47-ft waves; angle of wave attack = 45 deg; IV- on-2H-structure slope; stone armor
Photo 18. Sea-side view after attack of 1.50-sec, 0.42-ft waves; angle of wave attack = 45 deg; IV- on-2H-structure slope; stone armor
Photo 19. Sea-side view after attack of 2.00-mec, 0.42-ft waves; angle of wave attack = 45 deg; V-on-2H structure slope; stone armor.
Photo 20. Sea-side view after attack of 2.75-sec, 0.40-ft waves; angle of wave attack = 45 deg; IV- on-2H-structure slope; stone armor.
Photo 22. End view after attack of 1.50-sec, 0.52-ft waves; angle of wave attack = 90 deg; 1V- on-2H-structure slope; stone armor
Photo 23. End view after attack of 2.00-sec, 0.40-ft waves; angle of wave attack = 90 deg; 1V on-2H-structure slope; stone armor
Photo 24. End view after attack of 2.75-sec, 0.48-ft waves; angle of wave attack = 90 deg; IV- on-2H-structure slope; stone armor
Photo 25. End view after attack of 1.25-sec, 0.56-ft waves; angle of wave attack = 135 deg; IV- on-2H-structure slope; stone armor
Photo 26. End view after attack of 1.50-sec, 0.52-ft waves; angle of wave attack = 135 deg; 1V-on-2H-structure slope; stone armor
Photo 27. End view after attack of 2.00-sec, 0.51-ft waves; angle of wave attack = 135 deg; 1V-on-2H-structure slope; stone armor
Photo 28. End view after attack of 2.75-sec, 0.48-ft waves; angle of wave attack = 135 deg; IV- on-2H-structure slope; stone armor
Photo 29. End view after attack of 1.50-sec, 0.40-ft waves; angle of wave attack = 45 deg; IV- on-1.5H-structure slope; stone armor
Photo 31. End view after attack of 2.75-sec, 0.53-ft waves; angle of wave attack = 45 deg; 1V- on-1.5H-structure slope; stone armor
Photo 32. End view after attack of 1.50-sec, 0.45-ft waves; angle of wave attack = 90 deg; IV-on-1.5H-structure slope; stone armor
Photo 35. End view after attack of 1.25-sec, 0.57-ft waves; angle of wave attack = 0 deg; W- on-2H-structure slope; dolos armor
Photo 36. End view after attack of 1.50-sec, 0.52-ft waves; angle of wave attack = 0 deg; 1V- on-2H-structure slope; dolos armor
Photo 37. End view after attack of 2.00-sec, 0.47-ft waves; angle of wave attack = 0 deg; 1W- on-2H-structure slope; dolos armor
Photo 38. End view after attack of 2.75-sec, 0.54-ft waves; angle of wave attack = 0 deg; 1V- on-2H-structure slope; dolos armor
Photo 35. Sea-side view after attack of 1.25 sec, 0.50-ft waves; angle of wave attack 45 deg; 10 ft on-structure slope; Dalton armor
Photo 40. Sea-side view after attack of 1.50-sec, 0.42-ft waves; angle of wave attack = 45 deg; IV- on-2H-structure slope; dolos armor
Photo 41. Sea-side view after attack of 2.00-sec, 0.45-ft waves; angle of wave attack = 45 deg; IV- on-7M-structure slope; does armor
Photo 42. Sea-side view after attack of 2.75-sec, 0.45-ft waves; angle of wave attack = 45 deg; TV- on-2H-structure slope; dolom armor
Photo 44. End view after attack of 1.50-sec, 0.52-ft waves; angle of wave attack = 90 deg; 1V- on-ZH-structure slope; dolos armor
Photo 46. End view after attack of 2.75-sec, 0.50-ft waves; angle of wave attack = 90 deg; IV- on-2H-structure slope; dolos armor
Photo 47. End view after attack of 1.25-sec, 0.56-ft waves; angle of wave attack = 175 deg; IV+ on-2H-structure slope; dolos armor
Photo 48. End view after attack of 1.50-sec, 0.50-ft waves; angle of wave attack = 135 deg; IV- on-2H-structure slope; dolos armor
Photo 49. End view after attack of 2.00-sec, 0.45-ft waves; angle of wave attack = 135 deg; IV- on-2H-structure slope; dolos armor
Photo 30. End view after attack of 2.75-sec., 0.42-ft waves; angle of wave attack = 135 deg; 15'-on-28'-structure slope; dolerite armor
Photo 51. End view after attack of 2.00-sec, 0.38-ft waves; angle of wave attack = 45 deg; IV on-1.5H-structure slope; dolos armor
Photo 54. End view after attack of 2.75-sec, 0.45-ft waves; angle of wave attack = 90 deg; TV on 1.5H-structure slope; dolos armor
APPENDIX A: NOTATION

A  Surface area, ft$^2$
C  Coefficient
G  Acceleration due to gravity, ft/sec$^2$
H  Wave height, ft
H/L  Wave steepness
k  Shape coefficient
K  Stability coefficient
L$_a$  Characteristic length of armor unit, ft
L  Length, wavelength, ft
n  Number of layers of armor units
N  Number of armor units
P  Porosity of breakwater material, percent
R  Reynolds stability number = $g^{1/2}H^{1/2}L_a/U$
T  Wave period, sec; time
V  Volume, ft$^3$
W  Weight, lb
X  Angle of breakwater slope, measured from horizontal, deg
$\cot X$  Reciprocal of breakwater slope
$\rho$  Angle of wave attack, deg
$\gamma$  Specific weight, pcf
$\gamma_a$  Specific weight of armor unit, pcf
$\Delta$  Shape of armor unit or underlayer material
v  Kinematic viscosity of experimental fluid medium, ft$^2$/sec

Subscripts
a  Refers to armor unit
s  Refers to stability
w  Refers to water in which the structure is located