# CHAPTER 136

## DOLOS-ARMORED BREAKWATERS: SPECIAL CONSIDERATIONS

By

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## INTRODUCTION

Rubble-mound breakwaters are used extensively throughout the world to provide protection from the destructive forces of storm waves for harbor and port facilities. In some locations, a proposed rubble-mound breakwater may be subject to attack by waves of such magnitude that quarrystone of adequate size to provide economic construction of a stable breakwater is not available. Under these circumstances, it is required that the protective cover layer consist of specially shaped concrete armor units.

In 1966, Merrifield and Zwamborn (1) introduced a new shape of armor unit, the dolos (Figure 1) which was acclaimed to have much higher stability characteristics than any existing armor unit. Site-specific model tests conducted at the U. S. Army Engineer Waterways Experiment Station (WES) by Davidson (2); Carver (3); Bottin, Chatham, and Carver (4); and Carver and Davidson (5) have shown dolos to exhibit an excellent stability response when exposed to breaking wave conditions.

Comprehensive stability tests of dolos also have been conducted at WES by Carver and Davidson (6) for a wide range of nonbreaking wave conditions. These tests used randomly placed dolosse with a first underlayer stone weight of $W_r/5$ and a density of units per given area (N/A) equal to $0.83\ V^{-2/3}$, i.e., n=2, $k_\Delta$=0.94, and P=56 percent. It was concluded from this study that the stability response of dolos can be adequately predicted by the Hudson Stability Equation for the range of wave conditions investigated. Their data indicated an average stability coefficient (K) of 33 for dolosse use in a nonbreaking nonovertopping wave environment. Based on the lower limit scatter of their data, a K of 31 was approved for design.

## OBJECTIVE

The objective of this paper is to investigate the effects on stability of (1) varying the first underlayer stone weight from 1/5 to 1/20 of the armor weight ($W_r$); (2) placing the dolosse in selected geometric patterns; and (3) reducing the number of dolosse used in the cover layer. As a basis for comparison, K=33 will be used.

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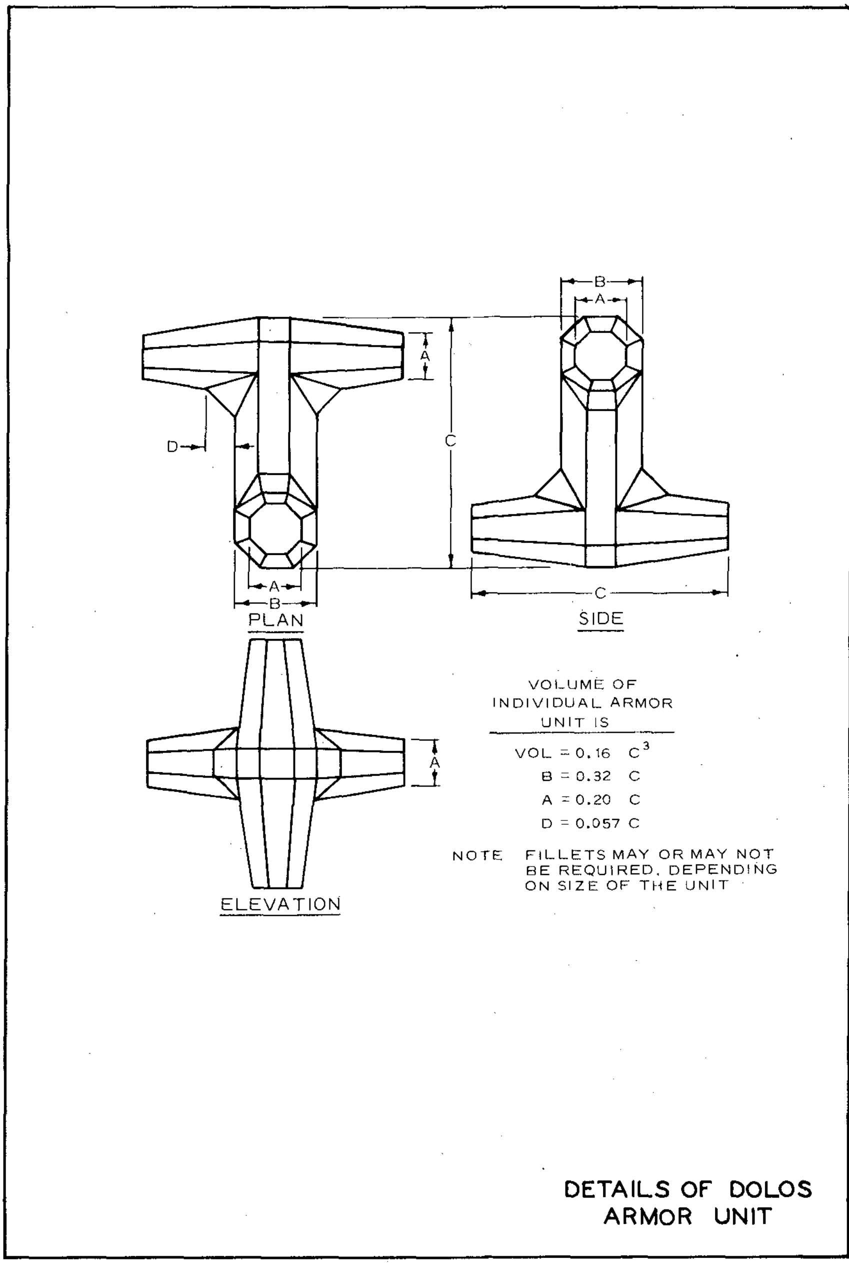

B
A
A
C
D
A
B
PLAN
SIDE
C
A
ELEVATION
VOLUME OF
INDIVIDUAL ARMOR
UNIT IS
VOL = 0.16 C³
B = 0.32 C
A = 0.20 C
D = 0.057 C
NOTE FILLETS MAY OR MAY NOT
BE REQUIRED, DEPENDING
ON SIZE OF THE UNIT
DETAILS OF DOLOS
ARMOR UNIT

FIGURE 1

## TEST EQUIPMENT AND MATERIALS

All wave action tests were conducted in a flat-bottomed, 1.5-m-wide, 1.2-m-deep, and 36-m-long concrete wave flume with test sections installed in the flume about 27 m from a vertical dispalcement wave generator. The generator is 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 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.

The dolos armor units weighed 138 g and had a specific weight of 2.26 g/cm$^3$. Sieve-sized limestone ($\gamma$ = 2.64 g/cm$^3$) of angular shape was used for the underlayers ($W_1$ and $W_2$) and the core ($W_4$). Rough granite armor stone ($W_3$) having an average length of approximately two times its width and an average weight of 172 g was used to armor those areas of the structures not protected by dolosse.

## SCALE EFFECT CONSIDERATIONS

Hudson (7) has presented a detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater models (critical $R_N = 3x10^4$). For all tests reported herein the sizes of model armor units and wave dimensions were selected such that scale effects were insignificant (i.e., $R_N$ was greater than $3x10^4$).

## METHOD OF CONSTRUCTING TEST SECTIONS

All model breakwater sections were constructed to simulate as nearly as possible prototype breakwater characteristics obtained by usual prototype methods of construction. Typical sections of the breakwater tested (Figure 2) were built as follows. The core material, dampened as it was dumped by bucket or shovel into the flume, 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, i.e., laid down in such a way that no intential interlocking of the units was obtained (except for the pattern-placement tests). After each test, the dolosse were removed from the breakwater, all of the underlayer stones and the stones in the cover layer below that portion of the cover layer comprised of dolosse were replaced to the grade of the original test section, and the dolosse were replaced.

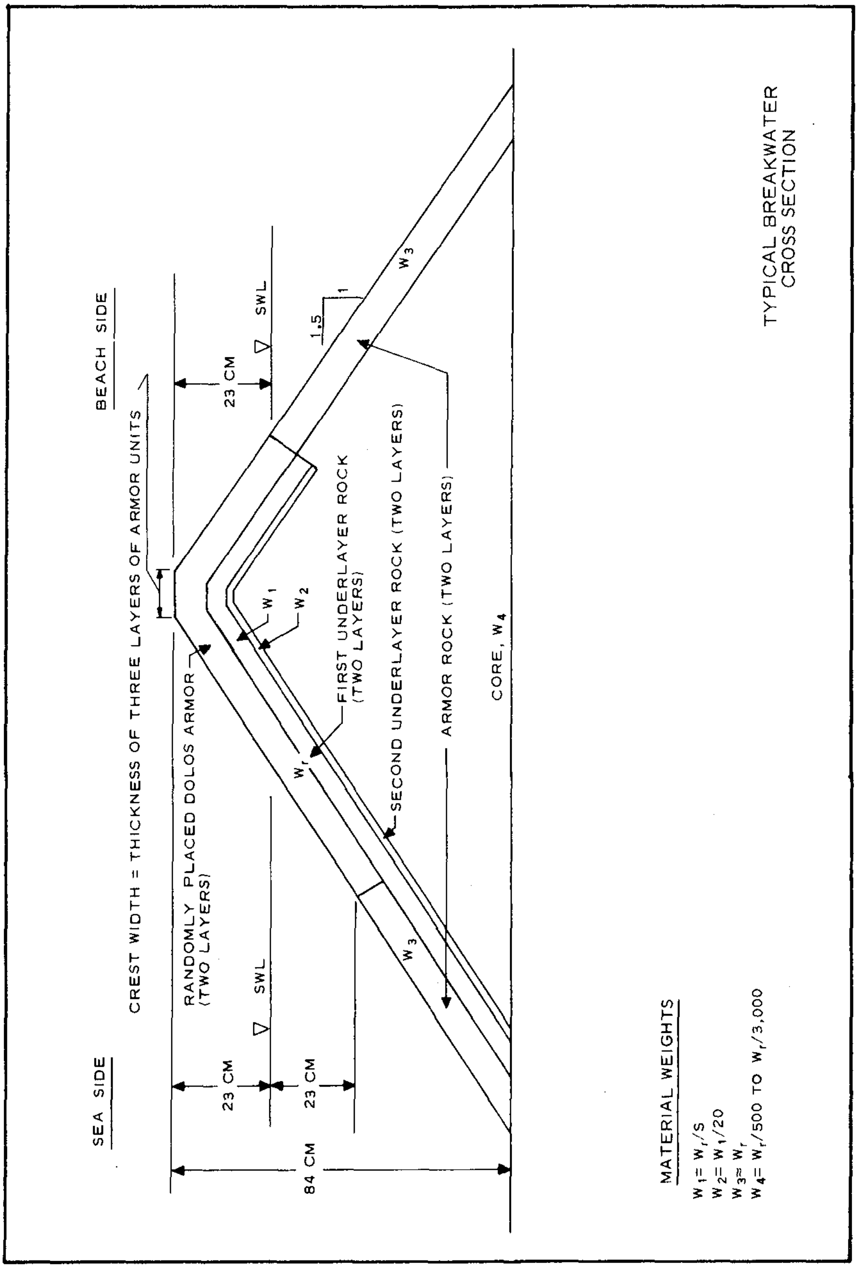

TYPICAL BREAKWATER CROSS SECTION
BEACH SIDE
SEA SIDE
SWL
SWL
23 CM
23 CM
23 CM
84 CM
1.5
1
CREST WIDTH = THICKNESS OF THREE LAYERS OF ARMOR UNITS
RANDOMLY PLACED DOLOS ARMOR (TWO LAYERS)
FIRST UNDERLAYER ROCK (TWO LAYERS)
SECOND UNDERLAYER ROCK (TWO LAYERS)
ARMOR ROCK (TWO LAYERS)
CORE, $W_4$
$W_1$
$W_2$
$W_3$
$W_3$
$W_r$
MATERIAL WEIGHTS
$W_1 = W_r/S$
$W_2 = W_1/20$
$W_3 \approx W_r$
$W_4 = W_r/500$ TO $W_r/3,000$

FIGURE 2

## METHOD OF DETERMINING DAMAGE

In order to evaluate and compare breakwater stability test results, it is necessary to quantify the changes that have taken place in a given structure during attack by waves of specified characteristics. The WES damage-measurement technique requires that the cross-sectional area occupied by armor units be determined for each stability test section. Armor unit area is computed from elevations (soundings) taken at predetermined locations over the seaward face of the structure before the armor is placed on the underlayer, after the armor has been placed but before the section has been subjected to wave attack, and finally after wave attack. Elevations are obtained with a sounding rod equipped with a circular spirit level for plumbing, a scale graduated in thousandths of a foot, and a ball-and-socket foot for adjustment to the irregular surface of the breakwater slope.

Sounding data for each test section were obtained as follows: after the first underlayer was in place, soundings were taken on the sea-side slope of the structure along rows beginning at and parallel to the longitudinal center line of the structure and extending in 7.5-cm horizontal increments to the junction with the secondary cover layer of armor stone. On each parallel row, 13 sounding points, spaced at 7.5-cm increments, were measured. This distance represented the middle 90 cm of a 152-cm-wide test section; the 31 cm of structure next to each wall was not considered because of the possibility of discontinuity effects between the armor units and the flume walls. Soundings were taken at the same points once the armor was in place and again after the structure had been subjected to wave attack.

Sounding data from each stability test were reduced in the following manner. The individual sounding points obtained on each parallel row were averaged to yield an average elevation at the bottom of the armor layer before the dolosse were placed and then at the top of the armor layer before and after testing. From these values, the cross-sectional armor area before testing and the area from which armor units were displaced (either downslope or off the section) were calculated. Damage was then determined from the following relation:

$$\text{Percent damage} = \frac{A_2}{A_1}\ (100)$$

where

$A_1$ = area before testing, $cm^2$

$A_2$ = area from which units have been displaced, $cm^2$

The percentage given by the WES sounding technique is, therefore, a measurement of an end area which converts to an average volume of armor material that has been moved from its original location (either downslope of off the structure). This particular method of measuring damage does not consider the rocking of individual armor units as exercised by some researchers. However, WES visual definition of no-damage from which the less than 5 percent displaced volume criterion determined by the sounding technique was developed is defined such that no significant movement of individual units is allowed after the initial movement of unnested armor units (which are generally present on any newly constructed structure, but whose displacement does not significantly affect the composite cover layer) occurs, thus the rocking criterion does not play as important a part in our evaluation as those of other researchers.

## SELECTION OF DESIGN WAVE HEIGHTS

Design wave heights for the no-damage criterion were determined by subjecting the test sections to monochromatic waves successively larger in height in 0.5-cm increments, until the maximum wave height was found that would produce no more than 5 percent damage. Each test wave was allowed to attack the breakwater for a cumulative period of 30 minutes, then the test sections were rebuilt prior to attack by the next added increment wave. This 30-minute interval allowed sufficient time for the test sections to stabilize, i.e., time for all significant movement of armor material to abate. During the tests, the wave generator was stopped as soon as reflected waves from the breakwater reached it, and the waves were allowed to decay to zero height before restarting the generator in order to prevent the test section from being exposed to uncontrolled wave groups and/or an undefined wave spectrum.

## CORRELATION OF TEST RESULTS

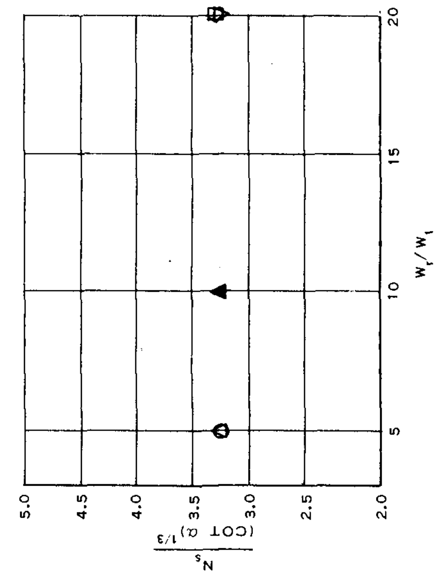
Hudson (8) has presented the results of stability tests for the no-damage and no-overtopping criteria on rubble-mound breakwaters in which that part of the breakwater subjected to the most intense wave action was protected by smooth, randomly placed quarry-stone armor units. Based on those data, dimensional analysis and other analytical considerations, the following empirical stability equation (Hudson formula) was derived:

$$W_r = \frac{\gamma_r H^3}{K(S_r - 1)^3 \cot \alpha}$$

This equation is used to correlate the stability test data presented herein.

## UNDERLAYER WEIGHT EFFECT TESTS

Underlayer weight effect tests were conducted with randomly placed armor and slopes of 1:2 and 1:3. The number of dolos units per given surface area, A , was $N = 0.83V^{-2/3}$ (n=2, $k_\Delta$=0.94, P=56 percent). Initially, the structure was build with a 1:2 slope and $W_1 = W_r/5$, and the design wave height for T = 1.52 sec was determined to be H = 20.5 cm. The breakwater was then reconstructed on the same 1:2 slope and tested for the same wave condition with $W_1 = W_r/10$ and $W_1 = W_r/20$. The stability response of the structure was almost identical in all 3 cases. The structure was then rebuilt at a 1:3 slope with $W_1 = W_r/5$ and the design wave height for T = 1.52 sec was determined to be H = 22.5 cm. The structure was then rebuilt and tested for the same wave condition with $W_1 = W_r/20$. Test results for the 1:3 slope were almost identical Figure 3 shows a plot of relative first-underlayer weight $(W_r/W_1)$ versus the primary coverlayer stability number normalized for slope effects $N_s/(\cot \alpha)^{1/3}$. Thus, considering these




LEGEND

$W_r$ = WEIGHT OF INDIVIDUAL DOLOSSE, G

$W_1$ = WEIGHT OF 1ST UNDERLAYER STONE, G

$\gamma_r$ = SPECIFIC WEIGHT OF ARMOR UNIT, G/CM$^3$

H = HEIGHT OF DESIGN WAVE, CM

K = EXPERIMENTAL COEFFICIENT

$S_r$ = SPECIFIC GRAVITY OF ARMOR UNIT, RELATIVE TO WATER IN WHICH PLACED $(\gamma_r/\gamma_w)$

$\alpha$ = ANGLE OF BREAKWATER SLOPE, MEASURED FROM HORIZONTAL, DEG

$N_s$ = STABILITY NUMBER = $\dfrac{\gamma_r^{1/3} H}{W_r^{1/3}(S_r - 1)} = K (\cot \alpha)^{1/3}$

| | $W_1$ | COT $\alpha$ |
|---|---|---|
| ○ | $W_r/5$ | 2 |
| ▲ | $W_r/10$ | 2 |
| ▽ | $W_r/20$ | 2 |
| △ | $W_r/5$ | 3 |
| □ | $W_r/20$ | 3 |

EFFECT OF FIRST UNDERLAYER STONE WEIGHT ON PRIMARY ARMOR STABILITY

$N_s/(\text{COT } \alpha)^{1/3}$ VS $W_r/W_1$

FIGURE 3

two structure slopes, it is concluded that if first underlayer weights in the range of $W_r/5$ to $W_r/20$ have an effect on stability, it is minimal. These data are not presented to recommend changes in the existing underlayer sizing but they are of particular importance when quarry yield is not satisfactory for normal design requirements.

## PATTERN-PLACEMENT TESTS

Tests also were conducted to determine if the stability of the dolosse could be increased by placing them in a geometric pattern. It is reasonable to assume that pattern placement will increase prototype placement costs to some extent; however, it was not thought inconceivable that some pattern could be found that would increase stability (reduce the armor weight required for a given design wave height) to the extent that the increased placement costs would be more than compensated for in material savings.

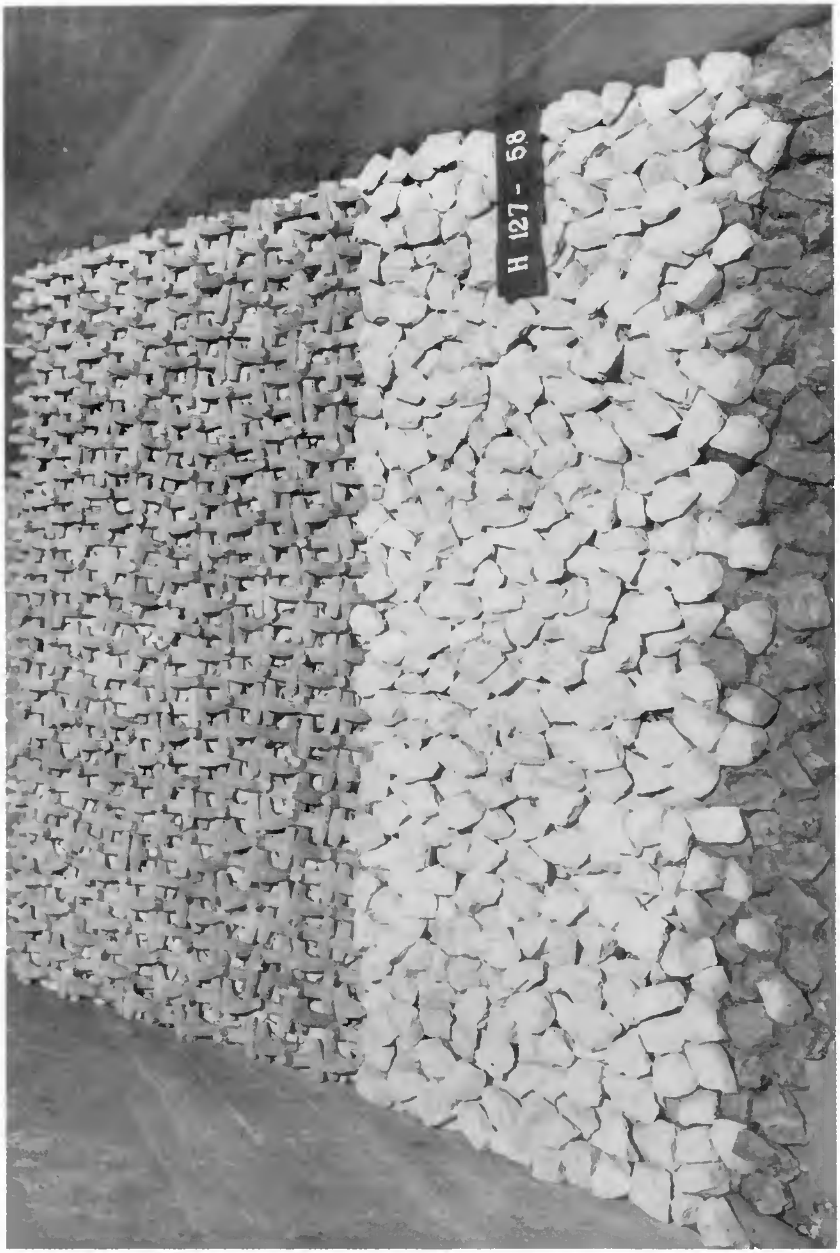
Three patterns were investigated at a 1:1.5 slope. Initially, the structure was built with randomly placed units and the design wave height for wave periods of 1.31 and 2.65 secs was determined to be H = 18.5 cm. Patterns were then tested with the design wave height determined for randomly placed units and their stability responses were classed: better, the same, or worse than the stability response of randomly placed units. Details of the patterns tested and general results were as follows:

a. Pattern 1 had the first layer of units placed with the shanks parallel to the slope and the vertical legs alternately upslope and downslope (Photograph 1). The second layer was placed in the horizontal plane of the slope with the shanks perpendicular to those of the first layer (Photograph 2). Attack of 2.65-sec, 18.5-cm, waves produced extensive damage (Photograph 3) with the first underlayer being exposed near the crown. Pattern 1 was less stable then random placement.

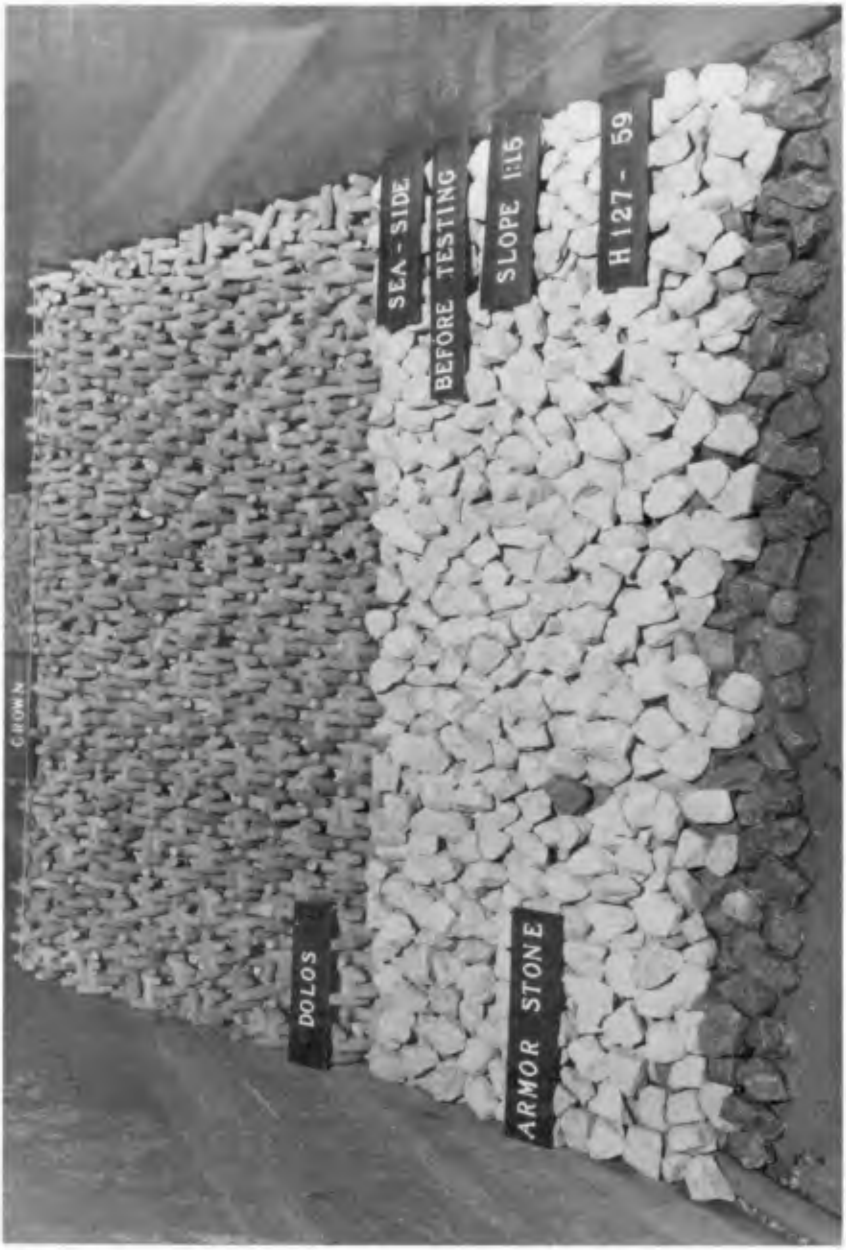
b. Pattern 2 was constructed with the shanks of all units parallel to the slope and the vertical leg downslope. Photograph 4 shows one layer of units in place while Photograph 5 shows the completed structure. Extensive damage was produced by 1.31-sec, 18.5-cm waves (Photograph 6). Pattern 2 was less stable than random placement.

c. Pattern 3 had the first layer of units placed with the shanks parallel to the slope and the vertical legs all upslope or downslope on alternating upslope rows (Photograph 7). The second layer of units was placed in the same manner to yield the complete structure (Photograph 8). Attack of 2.65-sec, 18.5-cm waves produced no damage (Photograph 9). Pattern 3 was more stable than random placement.

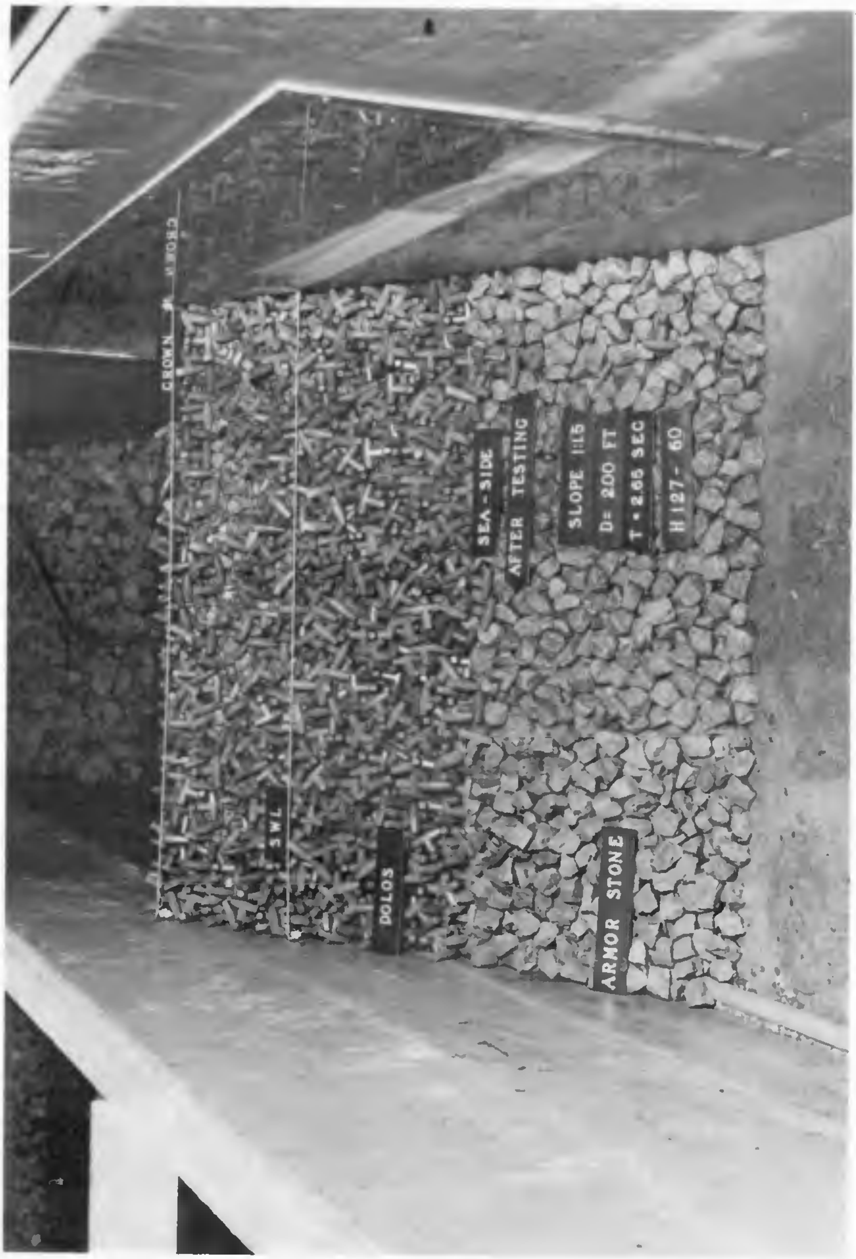
The pattern tests described above proved enlightening in that they showed that of the three geometric patterns selected for testing, two proved to be less stable than random placement. Based on these results, designers and construction supervisors are cautioned not to assume that any geometric pattern will increase stability.



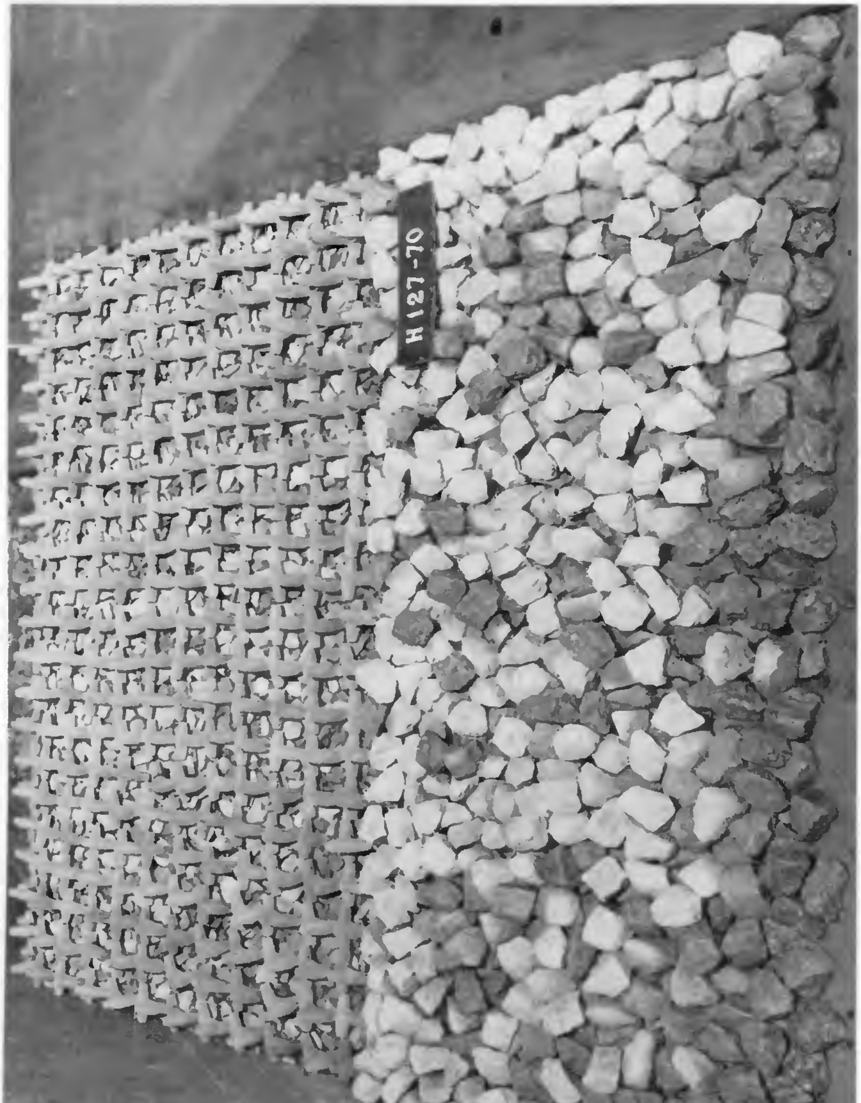

Photograph 1. Pattern 1 with one layer of armor units in place



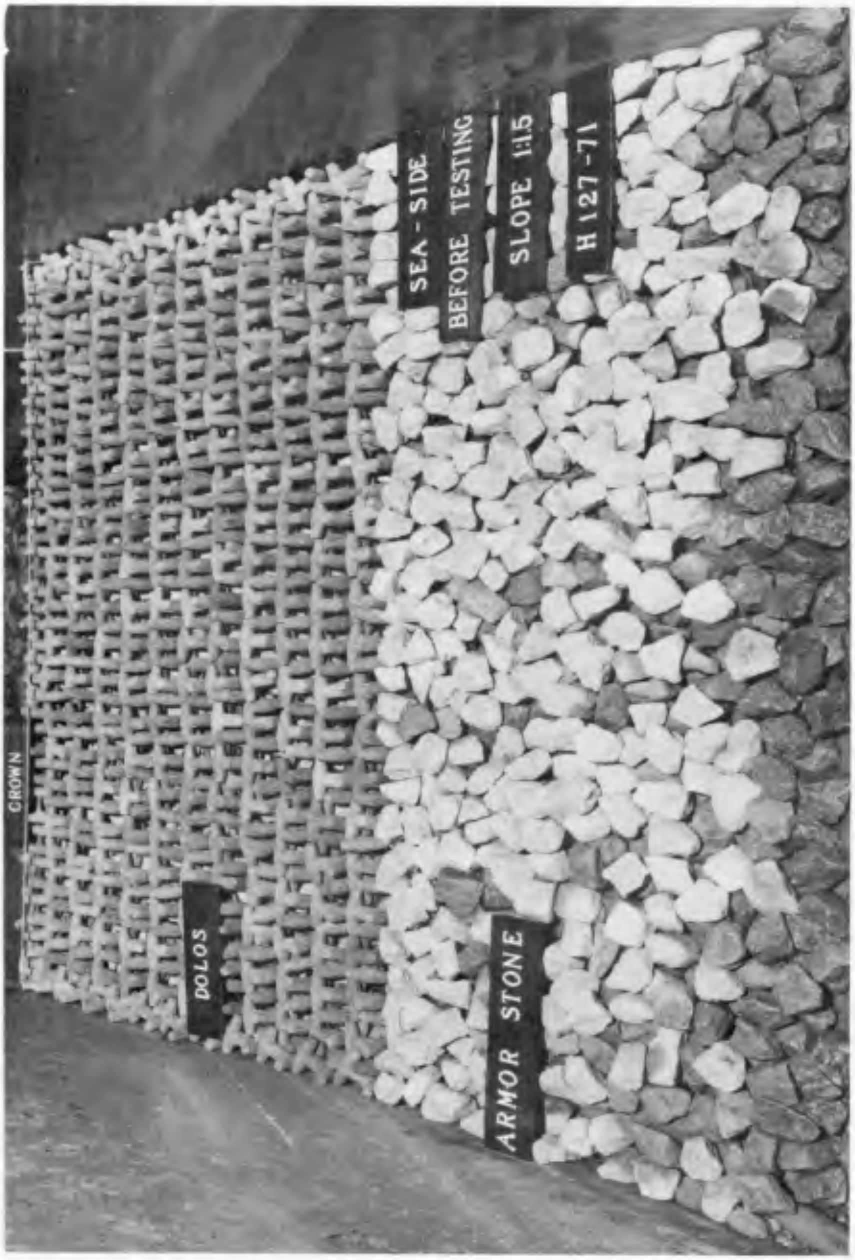

Photograph 2. Pattern 1 with two layers of armor units in place



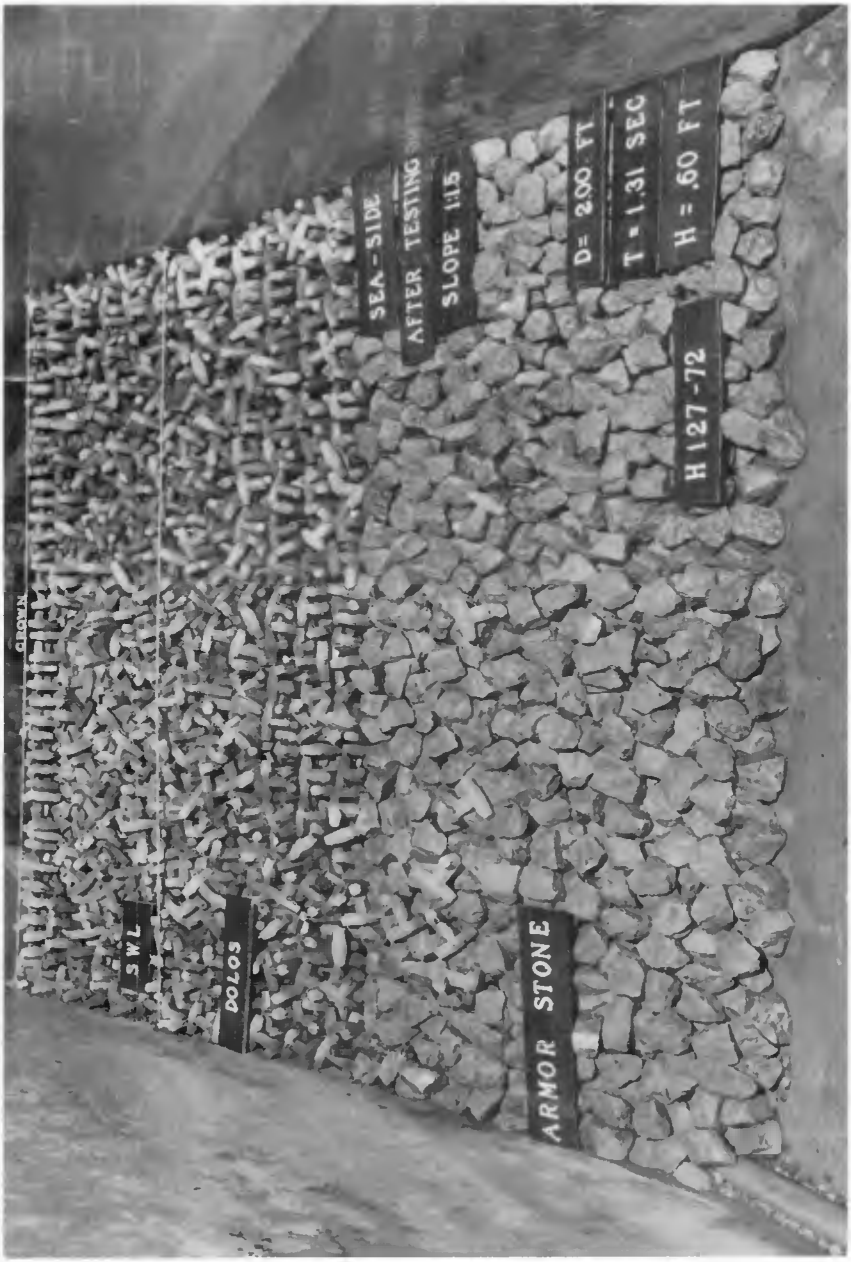

Photograph 3. Pattern 1 after attack of 2.65-sec, 18.5-cm waves




Photograph 4. Pattern 2 with one layer of armor units in place




Photograph 5. Pattern 2 with two layers of armor units in place




Photograph 6. Pattern 2 after attack of 1.31-sec, 18.5-cm waves


Photograph 7. Pattern 3 with one layer of armor units in place


Photograph 8. Pattern 3 with two layers of armor units in place


Photograph 9. Pattern 3 after attack of 2.65-sec, 18.5-cm waves

Subsequent stability tests showed Pattern 3 to meet the no-damage criterion for wave heights up to 20 cm at the 1:1.5 slope. This was a substantial enough increase over random placement that it was decided to test Pattern 3 at slopes of 1:2 and 1:3. Results of these tests are summarized as follows:

| Sea-Side Slope | $H_{D=0}$, cm | K |
|---|---|---|
| 1:1.5 | 20.0 | 42 |
| 1:2.0 | 22.0 | 43 |
| 1:3.0 | 25.0 | 44 |

Recalling that Carver and Davidson's (6) earlier tests yielded an average stability coefficient of 33 for random placed dolosse, the values of K presented above are quite impressive. Considering Pattern 3 as a two-layer system, values of $k_\Delta$ and P were determined to be 0.92 and 50 percent, respectively, or $N/A = 0.92\ V^{-2/3}$.

## THE EFFECT THE NUMBER OF DOLOS UNITS IN THE COVERLAYER HAS ON STABILITY

Limited tests were conducted using a 1:1.5 slope to determine the effect on stability of using a decreased number of armor units in the cover layers. For these tests, the structures were built using the random placement technique with approximately 25 percent fewer armor units than were used by Carver and Davidson (6) in the stability tests that yielded an average stability coefficient of 33. This armor unit coverage was sparse but could still be considered a two-layer system. Values of $k_\Delta$ and P were 0.62 and 50 percent, or $N/A = 0.62\ V^{-2/3}$. These tests yielded a design wave height of 15 cm and thus a stability coefficient of 17, showing that reducing the number of armor units by approximately 25 percent reduced the stability coefficient by approximately 50 percent.

Similar results were found by Vonk (9) for dolos tests where model units represening 4.7 metric ton dolosse were reduced from 0.70 units per square meter ($N/A = 1.07\ V^{-2/3}$) to 0.56 units per square meter ($N/A = 0.86\ V^{-2/3}$). His data show that for 9-18 sec period waves, the stability coefficient at 2 percent damage dropped approximately 58 and 31 percent for breakwater slopes of 1:1.5 and 1:2, respectively. All these data illustrate the important role the number of armor units play in determining the stability coefficients that are being used today and emphasize the fact that prototype designs should never use less dolosse per given area than recommended by the particular data upon which the stability coefficient is based.

Although the data is limited and it is difficult to relate equivalent stability from different laboratories, Figure 4 indicates the general increase in K as the packing density coefficient (C) increase for dolosse. The data presented in Figure 4 are taken from Carver and Davidson (6), Shore Protection Manual (10); Merrifield and Zwamborn (1), and personal correspondence between Davidson and Zwamborn (11). Reference (6) and (10), K factors are based on the no-damage criteria of less than 5 percent damage by the sounding method previously described, whereas data in

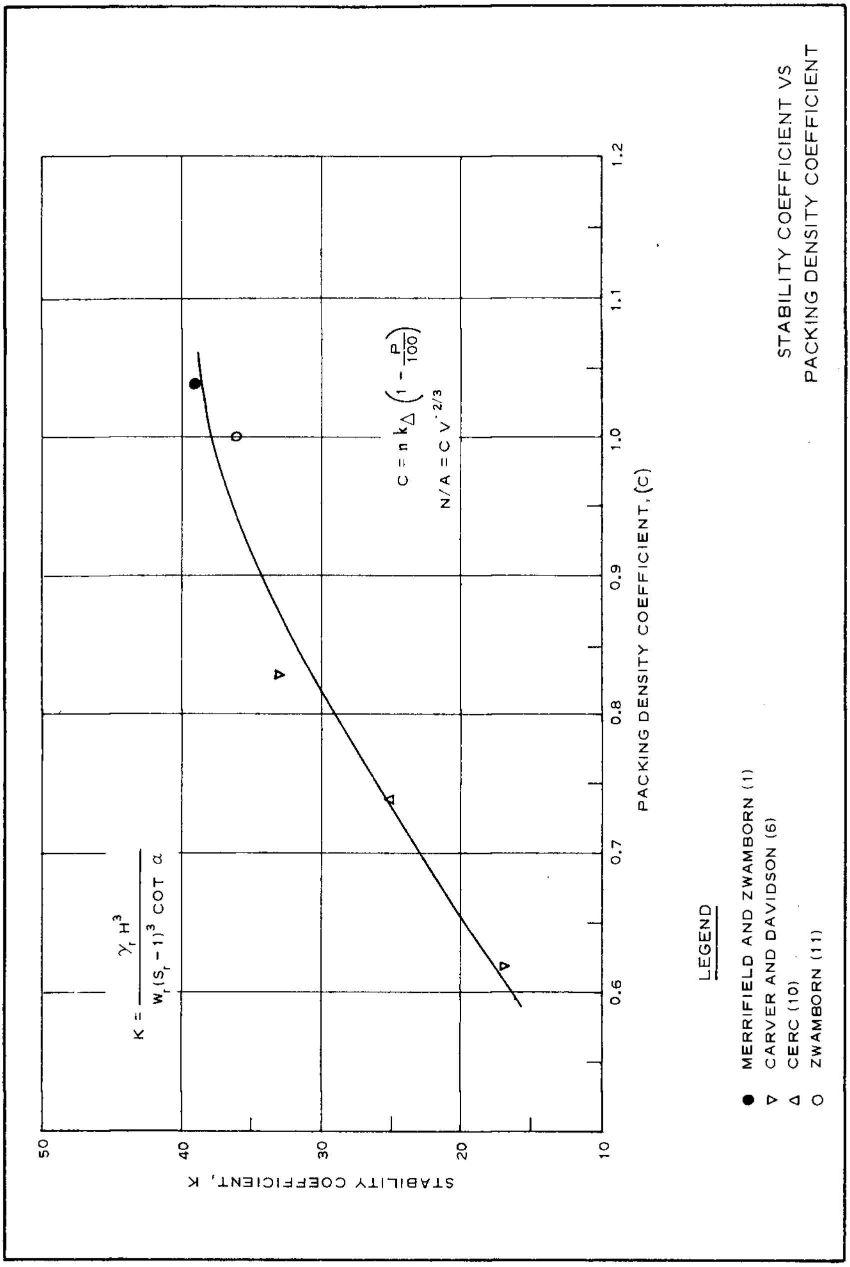

STABILITY COEFFICIENT VS
PACKING DENSITY COEFFICIENT
STABILITY COEFFICIENT, K
PACKING DENSITY COEFFICIENT, (C)
K = $\frac{\gamma_r H^3}{W_r (S_r - 1)^3 \text{ COT } \alpha}$
C = n $k_\Delta \left(1 - \frac{P}{100}\right)$
N/A = C $V^{-2/3}$
LEGEND
● MERRIFIELD AND ZWAMBORN (1)
▽ CARVER AND DAVIDSON (6)
△ CERC (10)
○ ZWAMBORN (11)
50
40
30
20
10
0.6
0.7
0.8
0.9
1.0
1.1
1.2

FIGURE 4

References (1) and (11) are based on 2 percent damage by number of displaced units. These data do not necessarily recommmend an optimum number of dolosse to use per given area because the safety and economics of each prototype project should be considered on its own merits. They do show, however, that the number of dolosse used per given area is critical to the selection of the stability coefficient and should be considered accordingly.

## CONCLUSIONS

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

_a_. For sea-side slopes in the range of 1:2 to 1:3, variations in first-underlayer weights ($W_1$) from $W_r/5$ to $W_r/20$ do not have a significant effect on stability.

_b_. Placement of dolosse in geometric patterns may or may not increase stability over that obtained by random placement, depending on the selected pattern; thus caution should be taken not to assume that every geometric pattern will increase stability.

_c_. The number of dolosse in the cover layer definitely affects the stability coefficient; thus a designer should take precaution to assure that a given stability coefficient is commensurate with the number of dolos units per given area upon which that stability coefficient was developed.

## ACKNOWLEDGEMENTS

The data presented in this paper were extracted from part of the model tests described in the Waterways Experiment Station (WES), Technical Report H-77-19, entitled, "Dolos Armor Units Used on Rubble-Mound Breakwater Trunks Subject to Nonbreaking Waves with No Overtopping," which was published for public release in November 1977. The comprehensive study was conducted at WES for the office, Chief of Engineers under the Corps of Engineers Civil Works Research and Development Program. The tests were conducted in the Wave Dynamics Division (Dr. Robert W. Whalin, Chief) of the Hydraulics Laboratory (Mr. H. B. Simmons, Chief); by Mr. R. D. Carver, Research Hydraulics Engineer; and Mr. W. G. Dubose, Engineering Technician, under the immediate supervision of Mr. D. D. Davidson, Chief of the Wave Research Branch.

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

## NOTATION

Variables

| | |
|---|---|
| $A$ | Surface area, $m^2$ |
| $C$ | Packing density coefficient, $C=nk_\Delta(1-\frac{P}{100})$ |
| $D$ | Damage parameter |
| $g$ | Acceleration due to gravity, m/sec |
| $H$ | Wave height, cm |
| $k_\Delta$ | Coefficient of layer thickness |
| $K$ | Stability coefficient, Hudson formula |
| $\ell$ | Characteristic linear dimension of armor unit, cm |
| $n$ | number of armor layers |
| $N$ | Number of armor units |
| $P$ | Porosity of breakwater material, percent |
| $R_N$ | Reynolds stability number = $\frac{g^{\frac{1}{2}}H^{\frac{1}{2}}\ell}{\nu}$ |
| $S_r$ | Specific gravity ($S_r=\gamma_r/\gamma_w$) |
| $T$ | Wave period, sec |
| $V$ | Volume of an individual dolos, $cm^3$ |
| $W$ | Weight, gm |
| $\alpha$ | Angle of breakwater slope, measured from horizontal, degree |
| $\cot\alpha$ | Reciprocal of breakwater slope |
| $\gamma$ | Specific weight, $g/cm^3$ |
| $\nu$ | kinematic viscosity |

Subscripts

| | |
|---|---|
| $D$ | Refers to damage |
| $r$ | Refers to armor unit |
| $\Delta$ | Refers to shape factor |

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