EFFECT OF UNDERLAYER UNIT WEIGHT ON THE STABILITY OF RUBBLE-MOUND BREAKWATER

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ABSTRACT

Three groups of small-scale model tests on rubble-mound breakwater with different underlayer unit weights were carried out in order to study the effect of underlayer unit weight on the stability of rubble-mound breakwater. Each group of test was run under different wave height and length as well as two different slopes of the cover layer, e.g.:; 1:1.5 and 1:2. Among other findings, the study showed that the variation in underlayer unit weight does not have a significant effect on armor layer stability. However, proper determination of the underlayer unit weight is important in order to prevent finer particles from escaping through the cover layers.

INTRODUCTION

Breakwaters are used extensively throughout the world to provide protection from the destructive forces of storm waves, for harbours, navigation inlets and port facilities.

There are different types of breakwaters; mainly the rubble-mound and upright. The vertical-wall type is usually constructed in shallow or reasonably deep water with some provision, otherwise the width of the structure becomes impractical.

The widely used rubble-mound breakwater is composed of a core of random-shaped and random-placed stones protected by cover layers of natural stones, or concrete armor units. Rubble-mound breakwaters are normally constructed with one or more underlayers between the core material and the main armor layer. The underlayer between core and principal armor layer is of considerable importance for the stability of the entire structure. The purpose of constructing the underlayer is to prevent the core material from being washed out through the main armor layer.

Analysis of rubble-mound breakwater includes two main items. The first is hydraulic to determine the characteristics of the design wave. The second is structural which includes the determination of weights of stones or weights and shapes of concrete units forming the different parts of the section, thickness of different layers, crest width and elevation, inner and outer surface slopes, and stability of the structure.

The relationship between these parameters has been a subject of a large number of emperical or semi-emperical formulae. Among the stability formulae introduced, Hudson expression [1,12,13] has been proven, through a large number of model tests and prototypes, to be the most representive formula.

$$W = \frac{\gamma_r}{(S_r - 1)^3} * \frac{H^3}{K_D . \operatorname{Cot} \alpha} \qquad (1)$$

where:

W = weight of individual armor unit.

γ_r = specific weight of armor unit material.

H = wave height.

S_r = specific gravity of armor unit material.

α = angle of breakwater seaside slope with the horizontal direction.

K_D = stability coefficient that varies with:

1) shape of armor units.
2) degree of interlocking and voids ratio which results from the manner in which the armor units are placed.
3) surface roughness.
4) type of wave attacking the structure (breaking-nonbreaking).
5) part of structure (trunk-head).
6) number of units comprising the thickness of the armor layer.
7) percentage of damage to be allowed.
8) angle of incidence of wave attack.

However, the stability formulae of armor layer do not account for the effect of weight of underlayer unit. Varying the weight of the underlayer unit and the layer slope may alternate the optimum design of rubble-mound breakwater.

In this research, the effect of underlayer unit weight on the stability of cube armor layer of rubble-mound breakwater is studied. Three groups of small-scale model tests on rubble-mound breakwater with different underlayer unit weights were carried out. Each group of tests was run under different wave height and length as well as different slopes of the cover layer, e.g.; 1:1.5 and 1:2.

TEST EQUIPMENTS

1. Wave Flume

A fourty meters long wave flume was used in the experiments. The cross section of the flume, elevation, and plan are shown in Figure(1). The distance between the wave generating machine and the breakwater model was twenty-one meters.

Two water pipes were fitted at the front and the end the wave flume, one of the pipes was connected to the water supply mains, and the other to the drainage. They were used for filling and emptying the wave flume according to the program of study.

2. Wave Generator

The wave generator used in the experiments is illustrated in Figure(2). It consisted of a 9.5 HP motor and a 7.7 HP hydrotitan, and a gear box reduction ratio 1:10.

The discs rotated by the gear box were connected to the wave making plate by two connecting rods that could be adjusted to give an eccentricity varying between 3 and 12 cm.

These rods transformed the rotational motion of the discs into a periodical back and forth movement of the top of the plate and hence to the water.

The characteristics of the generated waves depended on the different conditions of water depth, eccentricity, and machine speed as indicated by the hydrotitan reading. The wave period controlled by the hydrotitan reading, It could be increased or decreased by the decrease or increase of the hydrotitan reading respectively using the handle and the circular gauge of the hydrotitan. The generated wave height increased with the increase of water depth, eccentricity and machine speed.

3. Wave Measuring Devices

The principle of measuring and recording the wave profiles is that the conductivity of the water between two electrodes is measured while water waves pass along the electrode system. The variation of the conductivity with the variation of the submergence of the electrode system serves for measuring and recording the water wavers. The recording equipment consisted of the following components: electrode system, conductivity meter and wave recorder.

EXPERIMENTAL SET-UP AND TEST PROCEDURE

1. General

A series of tests were conducted on a rubble-mound breakwater made of cube armor layer and cube underlayer to determine the effect of underlayer unit weight as a ratio of the main armor unit weight on the stability of the breakwater. Wave heights that caused damage of less than 6% to the armor layer were considered.

The experimental program was divided into three groups of tests A,B and C. In each group, the underlayer unit weight remained unchanged; $w_1 = w_r/5$ for group A, $w_2 = w_r/10$ for group B and $w_3 = w_r/15$ for group C, where w_r is the armor unit weight and w_1, w_2 and w_3 are underlayer unit weights for test group A,B and C respectively.

Each group consisted of 18 tests. Tests were performed under different wave height, H, length, L, as well as two different slopes of the cover layer(1:1.5 and 1:2).

Each test was repeated three times under the same conditions and parameters for assurance. During the run the wave height was consistently increased and readings and observations were recorded for each wave height.

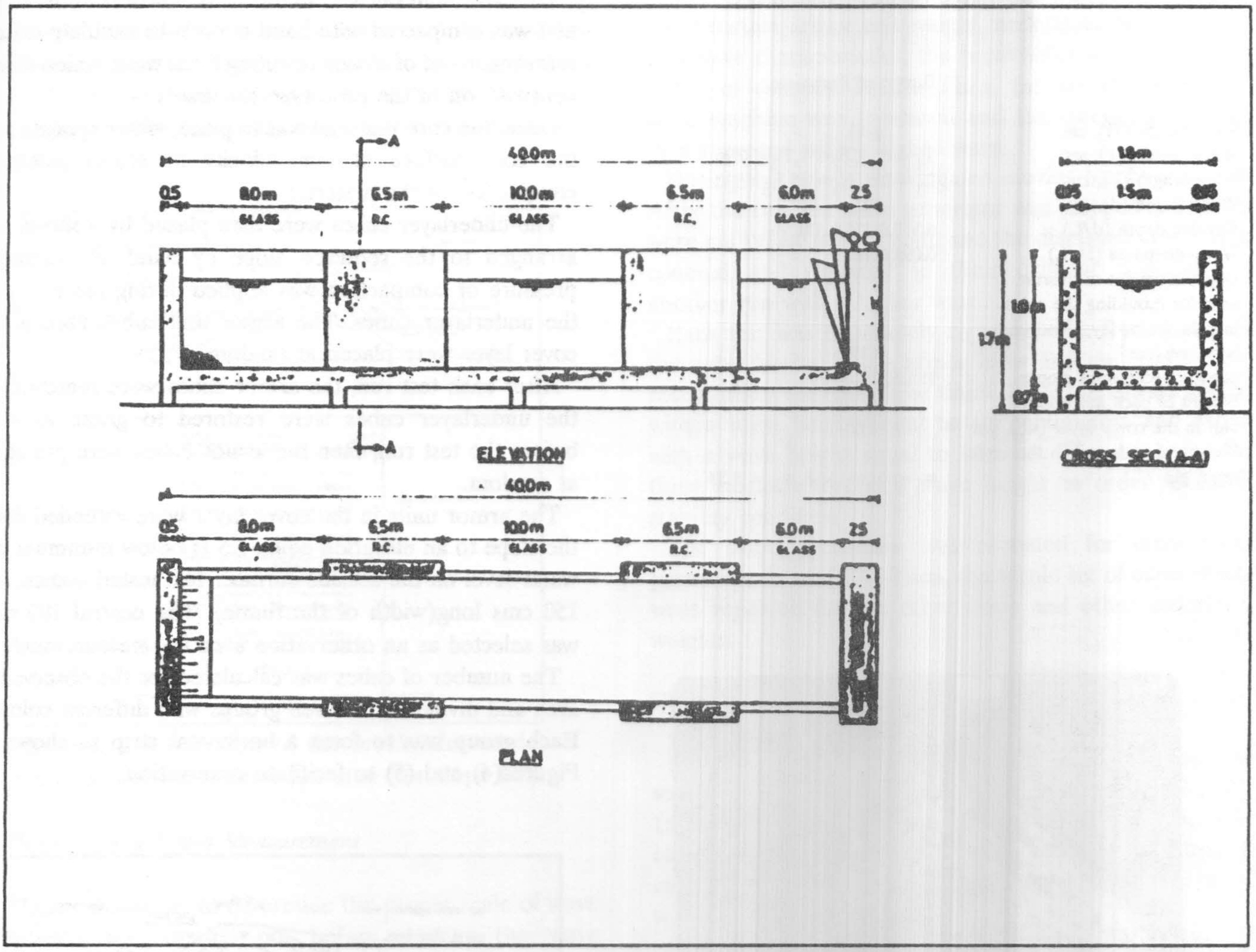


Figure 1. Wave flume.

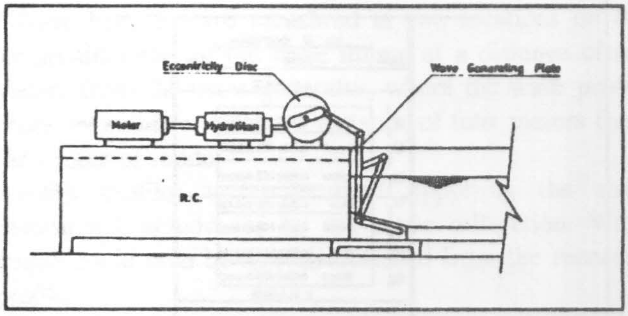


Figure 2. Wave generator.

2. Breakwater Section

The model for these breakwater stability tests was constructed in the wave flume. The cross section of the breakwater model consisted of a core, underlayer, armor layer, Figure (3).

The core of the breakwater was built of crushed quarry stones. The underlayer was made of two sublayers of concrete cubes. The cover layer consisted of two layers of concrete cubes each weighting 80 gms. The cover layer and the underlayer blocks, cubic in shape, were made of moulded cement mortar yielding a dry unit weight $2.19 gm/cm^3$. The crest elevation was high enough to prevent overtopping by the test waves.

Values and ranges of test parameters are listed in Table 1.

Table 1. Values and range of test parameters.

Test Parameter	Range of Parameter
Wave height (H), cm	6-11
Wave period (T), sec	T_1 = 1.3, T_2 = 1, T_3 = 0.96
Wave length (L), cm	L_1 = 63, L_2 = 59, L_3 = 53.5
Water depth (d), cm	20
Relative depth (d/L)	0.317, 0.338, 0.374
Wave steepness (H/L)	0.095-0.182
Dry unit weight of mortar used for moulding the cubes in both armor layer and under layer, gm/cm^3	2.19
Seaside breakwater slopes	1: 1.5, 1:2
Weight of each individual unit in the cover layer (w_r), gm	80
Weight of each unit in the under layer, gm	w_1 = 16, w_2 = 8, w_3 = 5.33

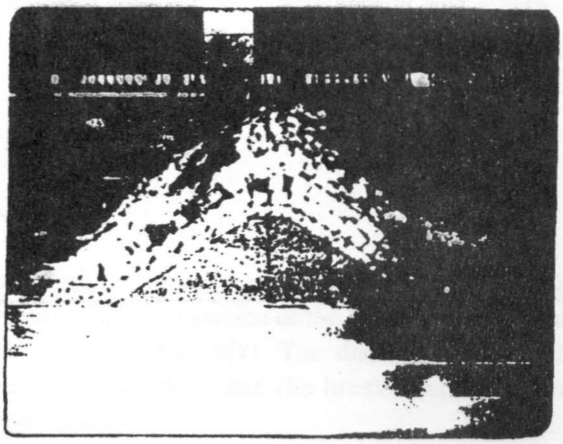


Figure 3. Cross section of the breakwater model.

3. *Formation of The Breakwater Models*

Breakwater models were built-up in the wave flume on a sand base covered by a thin layer of cement mortar. The center section was twenty-one meter away from the wave generator.

The models of breakwater armor unit were designed according to Hudson's formula.

The core material was dumped by a shovel in the flume and was compacted with hand trowels to simulate natural rearrangement of stones resulting from wave action during construction of the prototype breakwaters.

Once, the core material was in place, water sprayed over the core surface at low velocity to ensure adequate compaction of the material.

The underlayer cubes were then placed by a shovel and arranged to the required slope by hand. No excessive pressure or compaction was applied during placement of the underlayer cubes. The armor unit cubes used in the cover layer were placed at random.

After each test run, the armor cubes were removed, all the underlayer cubes were restored to grade as were before the test run, then the armor cubes were put again at random.

The armor units in the cover layer were extended down the slope to an elevation equal 1.5 H below minimum still water level on the seaside surface. The tested section was 150 cms long(width of the flume). The central 100 cms, was selected as an observation area for measurements.

The number of cubes was calculated for the observation area and divided into seven groups with different colours. Each group was to form a horizontal strip as shown in Figures(4) and (5) to facilitate observation.

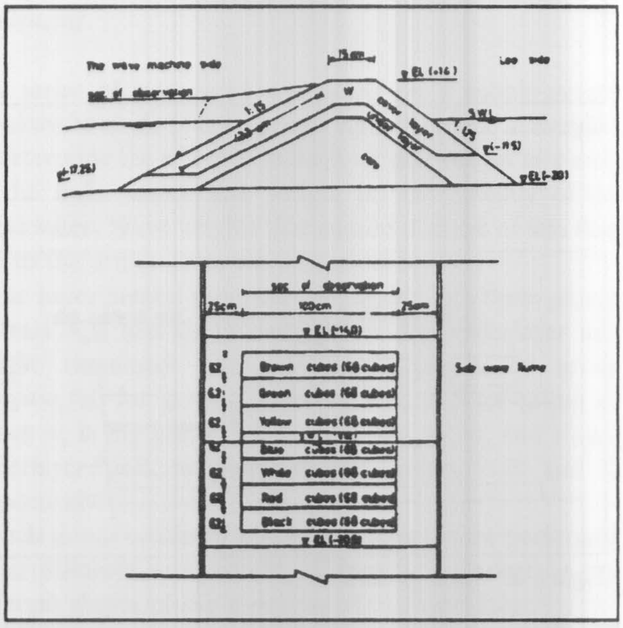


Figure 4. Cross section of the breakwater model and details of the observation area (For slope 1:1.5).

Random placing of cubes commenced at the bottom of the slope. The placement method was to drop the cubes individually by hand from a height of few centimeters, with the wave flume drained out. After finishing the placement of the cubes, the wave flume was filled with water up to the still water level.

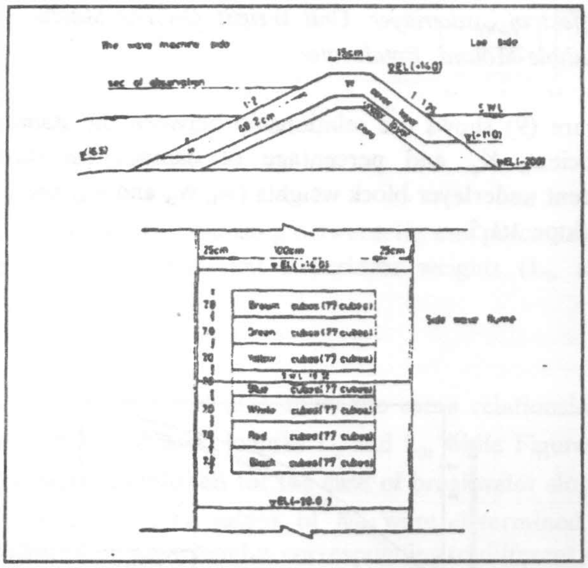


Figure 5. Cross section of the breakwater model and details of the observation area (for slope 1:2).

4. *Wave Applied and Measurement*

Static calibration, to determine the proper scale of wave recorder, was carried out before starting the wave machine. Each test run started with a selected wave height capable of producing damage to the armor layer. Then, the height was increased gradually and measurements were taken corresponding to certain individual wave height.

Wave heights were measured at two locations on the longitudinal axis of the wave flume: at a distance of ten meters from the wave generator, where the wave profile becomes uniform, and at a distance of four meters from the center of model.

Wave profiles were recorded appplying the scale determined in advance by the static calibration. Wave length could then be directly obtained from the recorded profile.

Wave length was taken as the average of ten wave lengths measured at two locations by finding the distance between two consecutive crests using a scale plotted on the side of the flume. Wave period (T) was obtained by measuring the time(t) of ten wave crests passing certain marked position in the wave flume using a stop watch, where $T = t/10$.

For certain armor unit weight, underlayer weight, slope, and wave characteristics, the breakwater was attacked by waves of constant height. Then, the eccentricity of the wave machine was increased and the foregoing run was then repeated with a higher wave.

During this period, rocking and moving blocks observed. After the run, the wave generator was stopped and waves were cut off by a steel plate and the displaced cubes were counted and replaced in their original positions for another run with a higher wave.

Each test was completely repeated with fresh laying of the cubic blocks of the armor layer and underlayer after resmoothing the core three times. Each test always started with a wave height equal to six centimeters and ended with a wave height equal to 11.5 cm. The run lasted for three minutes for each wave height in order to reach stability condition.

The same procedure was repeated for other wave parameter L_2 and $L3$. Then, the whole set of experiments were repeated for the other slope and other underlayer weights.

TEST RESULTS AND ANALYSIS

Series of 54 tests were carried out. In these tests, the seaside slopes of breakwater were adopted as 1:1.5 and 1:2, the depth of water was 20 cms, relative depths, D/L, ranged from 0.317 to 0.377, wave height ranged from 6 cms to 11.5 cms for $w_1 = w_r/5$, $w_2 = w_r/10$ and $w_3 = w_r/15$.

The percentage of damage, defined as the number of displaced blocks divided by the total number of stones included in the (attacked area) times 100, was computed and recorded for each test.. The attacked area was determined as the area between a height equals H above and a depth equals H below the still water level in which H is the incident wave height.

The results were recorded, tabulated and presented in graphical forms in order to study the effect of different parameters on the stability of the breakwater.

1. *Effect of Wave Characteristics on The Stability of Rubble-Mound Breakwater*

For $w_2 = w/10$ and slope 1:1.5, Figures(6-8) show the relationship between the wave height and percentage of damage for different wave lengths.

From these Figures, it can be seen that percentage of damage increases with the wave height, as expected. However, the rate of increase in the percentage of damage is moderate up to a certain wave height (nearly 9 cm) compared to that corresponding to higher waves.

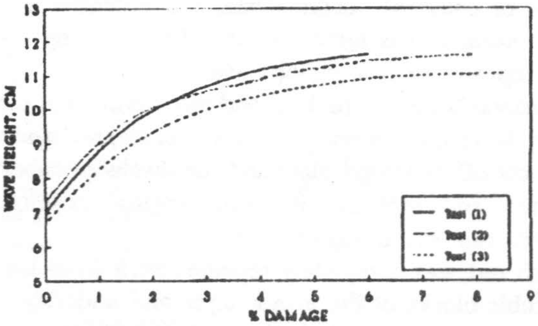


Figure 6. Relationship between wave height and percentage of damage for $w_2 = w_r/10$, $H/L = 0.097$-0.182, and slope 1:1.5.

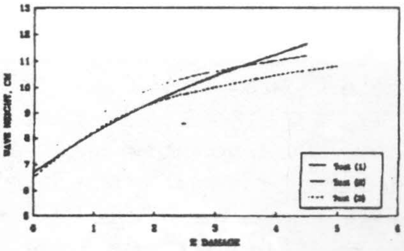


Figure 7. Relationship between wave height and percentage of damage for $w_2 = w_r/10$, $H/L = 0.103$-0.180, and slope 1:1.5.

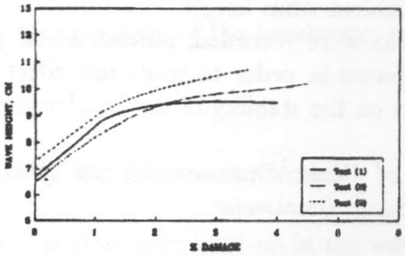


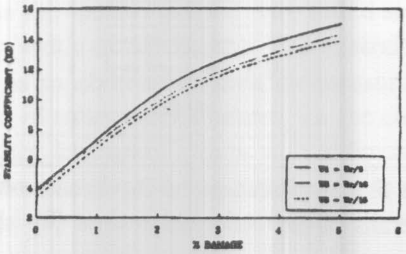
Figure 8. Relationship between wave height and percentage of damage for $w_2 = w_r/10$, $H/L = 0.124$-0.187, and slope 1:1.5.

Three runs were carried out for each case for assurance, so that three curves are plotted in each figure to represent the different runs.

Relationship between wave height and percentage of damage for other underlayer weights (w_1,w_2), as well as slop 1:2 also obtained.

2. *Effect of Underrlayer Unit Weight On The Stability of Rubble-Mound Breakwater*

Figure (9) shows the relationship between the stability coefficient, K_d, and percentage of damage for three different underlayer block weights (w_1, w_2, and w_3) and L1 and slope 1:1.5.



.2**Figure 9.** Relationnship between K_D and percentage of demage for different underlayer weights (L_1, slop 1:1.5).

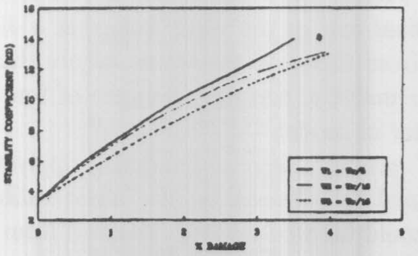


Figure 10. Relationship between K_D and percentage of damage for different underlayer weights (L_2, slope 1:1.5).

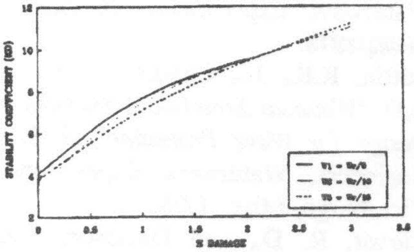


Figure 11. Relationship between K_D and percentage of damage for different underlayer weights (L_3, slope 1:1.5).

Figures (10) and (11) show the same relationship but with different wave lengths L_2 and L_3, while Figures (12-14) were established for the case of breakwater slope 1:2. These different values of K_D were determined from substituting wave heights corresponding to different values of percentage of damage into Hudson's Equation.

From Figures (9-14), it can be seen that, in the zone of no-damage (0-2%) the difference in the percentage of damage of the underlayer units are quite negligible for the same K_D values. However, above the zone of no-damage(0-2%), the percentage of damage may slightly be increased with decreasing w/w_r ratio.

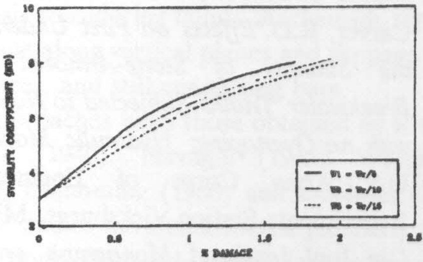


Figure 12. Relationship between K_D and percentage of damage for different underlayer weights (L_1, slope 1:2).

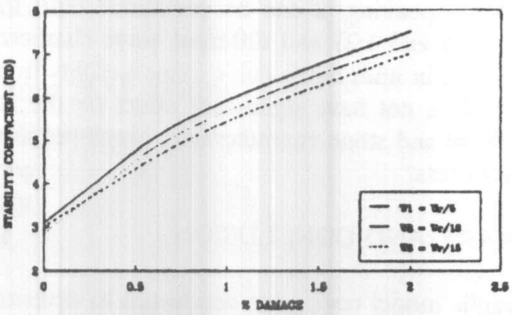


Figure 13. Relationship between K_D and Percentage of damage for different underlayer weights (L_2, slope 1:2).

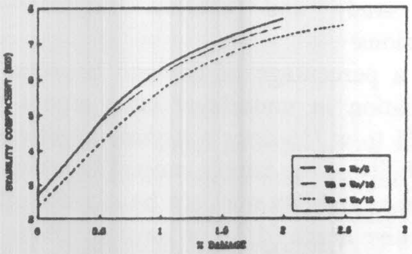


Figure 14. Relationship between K_D and percentage of damage for different underlayer weights (L_2, slope 1:2).

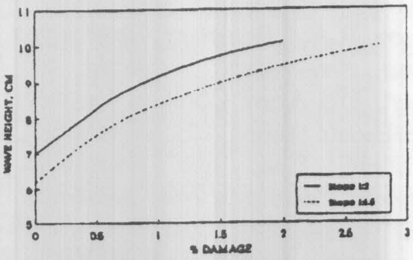


Figure 15. Relationship between wave height and percentage of damage for L_1 and w_2.

Generally speaking, it can be concluded that: for both slopes (1:1.5 and 1:2) and different wave characteristics, the variation in underlayer cubic stone weights from $w_r/5$ to $w_r/15$ does not have significant effect on the stability, for the wave and stone characteristics employed in this set of experiments.

SUMMARY AND CONCLUSIONS

Hydraulic model tests were conducted to determine the effect of underlayer cube stone weight on the stability of rubble-mound breakwater.

A parametric study was carried out to study the effect of other factors as well. This study included the variation of underlayer cube stone weight, breakwater seaside slope, wave height and wave length.

Results of 54 experimental test were recorded and analyzed.

The study and analysis suggests the following conclusions:

1. At a percentage of damage between 0 and 2% the variation in underlayer cube stones weighting from $w_r/5$ to $w_r/15$ does not show significant effect on the stability of the rubble-mound breakwaters.
2. Armor stability may not be significantly influenced by relative depth (d/L) or wave steepness (H/L) over the range of conditions tested ($0.317 \leq d/L \leq 0.374$) and ($0.095 \leq H/L \leq 0.182$).
3. For a percentage of damage greater than 2% a weight of at least $w_r/10$ should be used in order to maintain the stability of the breakwater and to prevent escapement through the cover layer.

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