CHAPTER 157

On the Behavior of Armour Unit in the Coverlayer

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1 INTRODUCTION

As a result of the large-scale failure of the rubblemound breakwater at SINES, Portugal in 1978 a number of research programs were begun. At present, however, very little information is available from technical publications regarding new design criteria, recommendations, or test procedures for model tests of rubblemound breakwaters. The need still exists, therefore, for economically practical model tests and standardized test procedures so that more tests can be conducted and reproducible results from different institutions can be compared.

At the same time, a number of factors related to the stability of rubblemound surface elements, and the interrelationships between those factors, have not been adequately examined or explained. Apparently without extensive model tests, for example, it has been suggested that greater stability can be obtained by using elements with greater unit weights (comparing elements of the same absolute weight), either by adding scrap metal or denser materials, such as granite, to the concrete.

Furthermore, susceptibility to breakage is of major importance to the long-term stability of armour layer units, particularly for dolos and similar less massive element types. This aspect has been generally neglected in laboratory tests, however, and attempts to simulate the lower ultimate strength of elements in reduced-scale model tests appear extremely difficult, as well as costly in terms of time and materials.

Several other factors which can significantly affect the stability of an armour layer include the surface roughness of the individual elements, as well as boundary conditions such as the beach slope.

An attempt will be made in this paper to discuss the various factors mentioned above on the basis of extensive testing of rubblemound breakwaters recently conducted at the Franzius Institute for Hydraulics and Coastal Engineering at the University of Hannover. Standardized procedures, which are independent of the type of element, are introduced for conducting model tests as well as for systematically evaluating and quantifying the results. Results will be presented from tests using both concrete and aluminum dolos with different unit weights, in addition to concrete cubes and tetrapods. K_D-values are proposed for these different element types. The

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characteristic distribution of wave-induced damage over the face of the breakwater and the reasons for this distribution are given. The complex interrelationships between the beach slope, wave period, and water depth, and their influence on the extent and location of damage are also discussed.

2 TEST PROGRAM AND EQUIPMENT

Model tests were carried out in the wave channel at the Franzius Institute (length = 90 m, width = 2.2 m, max. wave height = 0.50 m) with government funding provided by the Federal Republic of Germany. A computer-controlled hydraulic wave generator was used which is capable of generating all types of spectra and third order regular waves.

Tests of rubblemound breakwaters were conducted using three types of armour layer elements (dolos, cubes and tetrapods), all of which are similar in terms of hydraulic stability. Particular emphasis was placed on the investigation of dolos elements.

A model scale as large as practical was chosen in order to minimize scale effects. The wave heights used ranged from about H_s = 10 cm (settlement phase) to H_s = 30 cm. Reynolds Number values varied from $Re = 3.5 * 10^3$ to $Re = 1.1 * 10^5$.

The weights of the various element types used were chosen so as to conform to the equipment and facilities available, with a range of 0.183 - 1.005 kg. The unit weight of the concrete used for all three element types was 2.24 g/cm^3, while the unit weight of the aluminum dolos was 2.7 g/cm^3. The aluminum dolos were purchased from the Waterloopkundig lab in Delft, Holland.

Individual surface elements were not marked with paint so that the test results would not be distorted by the change in surface roughness. Painted elements generally have a smooth surface which can significantly alter test results.

Due to the action of electrolytic corrosion, which attacked the aluminum within a short period of time following its exposure to water, the surface roughness of the aluminum dolos was considered to be comparable to that of the concrete elements.

Breakwaters were built on bed slopes of 1:15 and 1:30 in order to simulate conditions as close to natural as possible. The generated waves broke either on or directly in front of the breakwater. The water depth at the toe of the breakwater varied from 0.05 m to 0.40 m for overall waterdepths of up to 1.20 m in front of the wave generator.

During the construction of the breakwater an attempt was made to closely simulate actual construction practices. As such, elements were randomly placed according to a grid pattern and were allowed to fall into position after initial contact with the surface of the breakwater.

Each test series was begun at 75% of the maximum wave height which the breakwater could theoretically withstand, calculated using the HUDSON equation of C.E.R.C. (1984). This simulates the normal settlement or consolidation phase which normally follows initial

construction. Wave heights were increased in stages until failure in order to monitor damage progression. Each test with a particular wave height was interrupted twice so that photos could be made in order to differentiate between further consolidation and progressive damage.

The wave spectra used included Pierson-Moskowitsch and Jonswap, as well as order regular waves.

3 DEFINITION OF DAMAGE FOR RUBBLEMOUND BREAKWATERS

The following four different methods were used to observe and evaluate the movement of armour layer elements and the extent of damage to the breakwater:

a) direct observations verbally recorded by test personnel equipted with tape recorders;
b) continuous recordings with a high quality video system, also used to support the direct observations of (a);
c) single frame pictures taken using a Super-8 movie camera whenever the receding wave would leave the surface of the breakwater momentarily exposed;
d) positive-negative overlays of photos taken between test runs, with the water drained away.

An addition procedure for defining damage for breakwaters composed of natural stones or rubble was introduced by VAN DER MEER and PILARCZYK (1984). They suggest using the change in the surface profile of the breakwater following a wave attack as a measure of damage to the breakwater. This method is less suitable for breakwaters with concrete armour layers because the comparatively large displacements in the cover layer would lead to breakage of the concrete armour units.

Close analysis of the test results showed that the overlay method of evaluating surface layer movements is considerably better than a system of direct observations supported by video recordings. Even simple movements are easily recognizable in the overlays and at no time were rocking motions observed or recorded which did not also result in some degree of noticeable displacement in the overlays. The theoretical disadvantages that rocking motions and damage progression cannot be recorded with the overlay method therefore appear to be unfounded, particularly when each test is subdivided into three parts so that the damage development sequence associated with a specific wave height can be monitored. Positive-negative overlays therefore still represent the best method - short of installing accelerometers on every element - of recording and evaluating movements in the armour layer.

Each movement visible in the overlay photos was classified as one of 35 different combinations of rotation (7 classes) and displacement (5 classes) in order to establish a distribution diagram (histogram) of all the elements' movements. The system used for dolos to classify a movement in terms of rotation and displacement is shown in Fig. I. The determination of the extent of movement for a single element begins by considering its rotation. The angle (degree) of rotation is estimated after first establishing the point about which an individual element rotates. The second step is then to determine the translation of this point of rotation. Analogous systems were used for the tetrapod and cube elements.

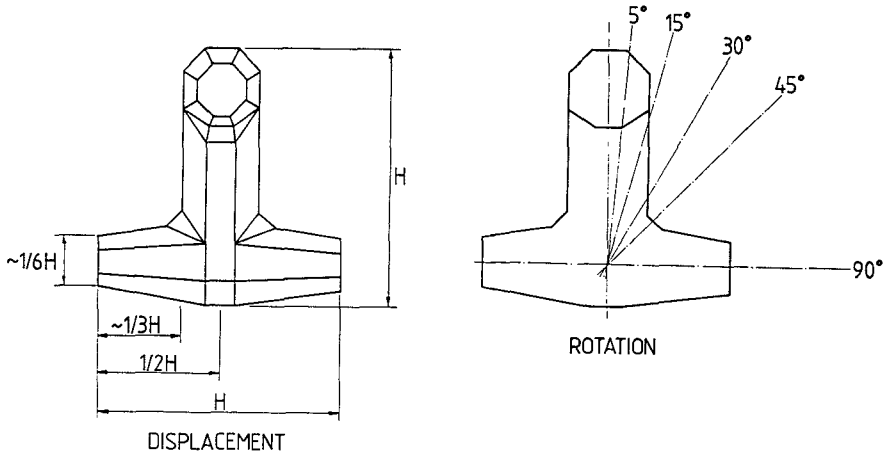

FIGURE I

Classification of Displacement and Rotation for a Dolos Element

A computer was then used to examine various possible groupings of these 35 classes. A meaningful and harmonious distribution was achieved using 6 classes, with the following combinations of rotation : displacement as upper limits:

Class No.	Maximum Rotation	Maximum Displacement	
1	5°	very small	
2	15°	H/6	H = height
3	30°	H/3	of the
4	45°	H/2	element
5	90°	≤ H	
6	90°	roll	

If the rotation and displacement of an element fall into two different classes, only the higher of the two classes is considered. This system is an extension of the method of class division presented by PAUL and BAIRD (1971).

The tests conducted at the Franzius Institut have shown that the damage distributions over large areas were very similar when these 6 general classes were used and the curves normalized, as shown in Fig. II.

This was true for all three types of elements tested, dolos, tetrapod and cube. Likewise, the distribution over a range of loading conditions, from the settlement phase up to the beginning of failure, is almost identical. The number of normalized damage events only first began to increase significantly in classes 4 to 6, with a corresponding decrease in classes 1 to 3, with wave heights which cause greater more progressive damage to the breakwater. This behaviors, which is indicative of unacceptably large damage to the breakwater, was observable in all tests.

A maximum allowable percentage of damage was determined for each of the 6 classes which reflect the susceptibility to breakage of the element type in question. Since the danger of breakage is different for the relatively slender dolos, the more sturdy tetrapods and the rather massive cube elements, these allowable damage limits for each of the 6 classes vary with the type of element. Tests conducted by BURCHARTH (1981) showed that dolos are extremely suspectible to breakage. As such, dolos movements greater than 15° : H/6 should be very strictly limited.

No published information could be found regarding the susceptibility to breakage of cubes or tetrapods. It is known, however, that a relatively high percentage of broken elements have been found in tetrapod breakwaters. The danger of breakage exists even in the case of large concrete cube or block elements as the result of shrinkage cracks caused by temperature changes during curing.

Taking the differing susceptibilities to breakage into consideration, limits on the allowable movements for each of the three types of surface layer elements were set, as shown in Fig. III. As a recommendation, damage curves which exceed these limits in any of the 6 classes should not be considered allowable.

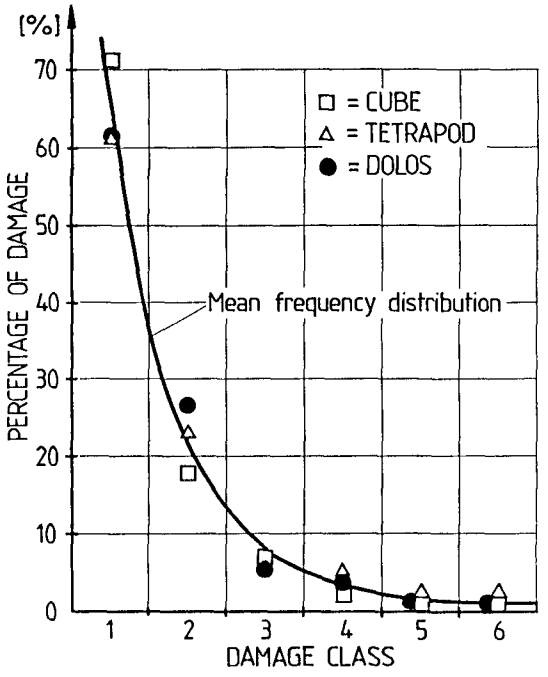

FIGURE II

Normalized Damage Distribution for Dolos, Cube and Tetrapod

(Mean Value)

The percentage of surface layer elements whose movements fall within each of the 6 classes previously described are calculated with reference to the total number of elements within a range extending $1.25 * H_{1/3}$ above and below the still water level (SWL). This is the

region in which almost all of the damage occurs. The percentage of elements experiencing a certain class of movement should always be calculated with reference to the total number of elements within this specified range, not the overall total for the breakwater. Although movements of elements outside of this range were found to be rare, they should also be considered, while still using the same total number of elements as the basis of reference. Only when the breakwater dimensions are smaller than this given range should the total number of surface elements be used.

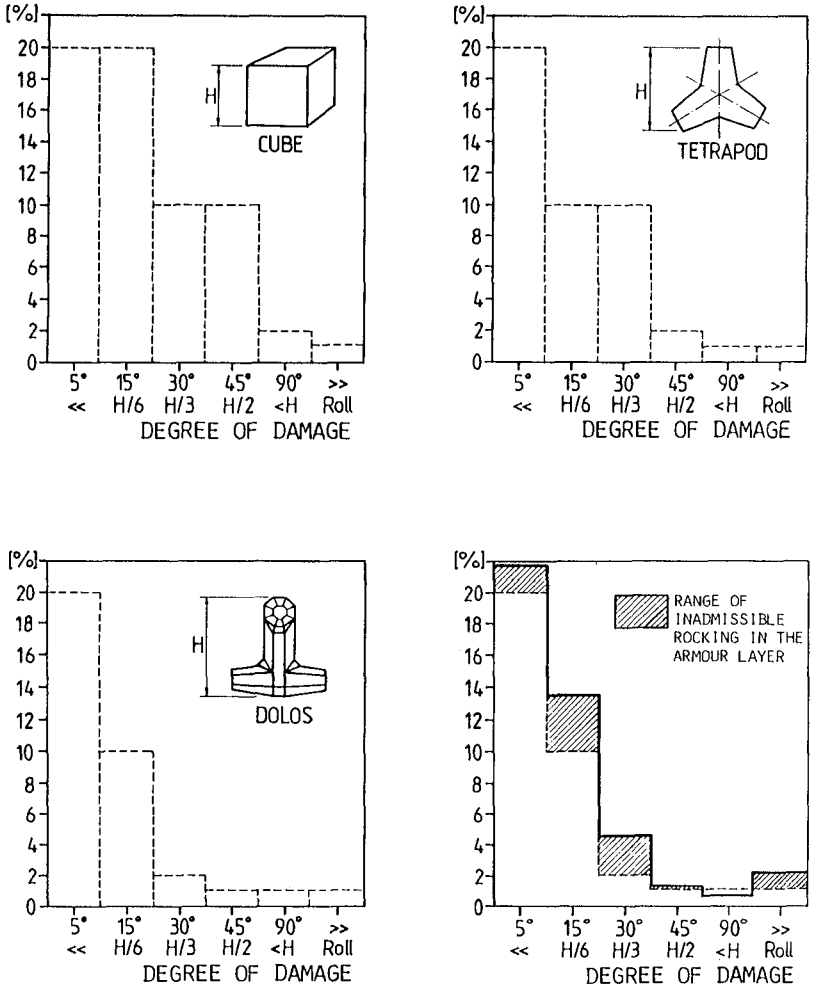

FIGURE III

Allowable Rocking for Individual Damage Classes for Cubes, Tetrapods and Dolos Elements

4 RESULTS

As part of a program of basic research sponsored by the German government's Special Research Department (SFB), extensive model tests of rubblemound breakwaters were conducted using dolos, cube and tetrapod surface layer elements.

Each test was begun using a moderate wave height in order to allow initial consolidation to take place. Following this settlement phase, wave heights were gradually increased until the breakwater failed or a state of progressive damage signaled eminent failure.

Each test at a particular wave height was interrupted twice (ie. subdivided into three parts) so that photographs could be taken. Positive-negative overlays were made from these photos, which were then evaluated using the system previously described. Video recordings of every test were used to confirm the accuracy of the overlays.

The K_D-values determined from these evaluations showed considerable variation in some cases. The influences of the wave period and the offshore slope can be offered as two of the probable reasons for these wide fluctuations.

4.1 INFLUENCE OF THE WAVE PERIOD

Assertions by various authors that wave periods become increasingly critical for breakwaters as they either increase or decrease, depending on the author, were not substantiated. Greater damage was most often associated with a wave period of intermediate length, with the extent of damage decreasing for wave periods both shorter and longer than this critical, intermediate length.

The height of a short (period) wave is limited by its maximum steepness, or breaking limit. Longer waves, on the other hand, roll more slowly over the breakwater. The resulting forces from the up- and downrush of water therefore remain small and the breakwater is not so heavily stressed.

This tendency for more intermediate length wave periods to be more critical was clearly borne out by every series of tests, with all conditions remaining constant except the length of wave period. The actual numerical values of these critical periods varied depending on the type of armour layer element and the form of the foreshore.

4.2 INFLUENCE OF THE SLOPE OF THE FORESHORE

It is obvious that the slope of the foreshore greatly influences the extent of damage. The slope largely controls the form of the wave as well as the interplay between the water rushing up and down the face of the breakwater. The breaking point of a wave, for example, is affected by the extent of the water cushion in front of the breakwater.

At the same time, the dolos elements proved to be extremely sensitive to changes in the foreshore slope and form. The results of different model tests could be characterized as varying from stable to total destruction for a prototype storm duration of 3 hours or less. The wave heights generated and the type of spectra used were identical for these tests, with the only variable being the form of the

foreshore. Statements regarding the reasons for this phenomenon and the various interrelated factors involved, however, would be premature at this point in our continuing study.

The influences of the wave period and foreshore slope were considerably smaller in the case of tetrapods and were hardly noticeable for cube elements, on the basis of these tests.

4.3 INFLUENCE OF THE UNIT WEIGHTS

Test conparisons between two dolos types of different unit weights with the same total block weight, aluminium with 2.7 g/cm^3 (169 lbs/ft^3) and concrete with 2.24 g/cm^3 (140 lbs/ft^3), came out clearly in favor of the less dense (larger) concrete elements. The denser (smaller) elements were similar in terms of stability only in those model tests in which the wave heights were limited by shallow water depths directly in front of the breakwater. The reasons for this can be attributed to the larger stresses exerted on the surface layer when water rushes back down and, at the same time, out of the breakwater; the wave having already broken and lost most of its energy. In such a case a denser element becomes more effective.

On the basis of the model tests, however, the absolute size of the individual elements appears to be the more important factor in those cases where the approaching and breaking waves (plunging and collapsing breakers) exert the principle stresses on the breakwater.

Exactly where the optimum unit weight lies is not yet known. The K_D-values for aluminium dolos determined from these tests were considerably lower than those of the cement elements.

4.4 K_D - VALUES

K_D-values were determined according to the HUDSON formula for the different element types used, as summarized in Table I. These values are valid for the breakerwater trunk and were determined for slopes of between cot = 1.5 - 1.8 (also cot = 1.33 for tetrapods).

Elements Tested	K_D-Values Measured Range	Medium	K_D-Value Recommended
Dolos (aluminum)	5.8 - 10.0	7.9	10.0
Dolos (concrete)	7.6 - 23.1	11.8	
Tetrapod (concrete)	5.9 - 10.6	7.5	7.2
Cube (concrete)	9.5 - 22.0	12.5	7.0

TABLE I

K_D-Values Determined from Tests at the Franzius Institute

In all tests the simple cube showed itself to be surprisingly stable. To be safe, however, the authors hesitate to recommend a drastic increase in the K_D-value for cubes. On the other hand, the K_D-values determined for dolos were so low that hydraulic model tests are strongly recommended as a design check for all larger-scale construction projects involving dolos elements. At the same time, it is very important to incorporate the underwater topography in front of the breakwater to a sufficient extent into the model.

FIGURE IV

Cube Protection at Bari / Italy

5 CONCLUSIONS AND RECOMMENDATIONS

For 25 years now the HUDSON equation has been the principle tool used in the design of rubblemound breakwaters. This despite the fact that the equation is widely known to be less than fully reliable. In his paper "State of the Art" I.W. STICKLAND (1983) determined that considerable damage has occured to 40 rubblemound breakwaters out of a worldwide survey of 148 breakwaters conducted by the P.I.A.N.C. .

This fact is underlined by the recently published book by PER BRUNN, "Design and Construction of Mounds for Breakwaters and Coastal Protection" (1985), in which a great many cases of failure are presented. Despite these serious problems and the obvious shortcomings of the HUDSON equation, research on rubblemound breakwaters has often not gone beyond recommending simple changes in the K_D-values used in the equation.

Completely new breakwater design criteria are not likely to be developed in the foreseeable future. On the contrary, it is more likely that it will become increasingly difficult to make general recommendations as more of the numerous complex factors related to the stability of such structures become better known.

Research conducted on behalf of the Special Research Program of the F.R.G. provided the opportunity to take up and more closly investigate some of these complex factors in hydraulic model tests. Federal support made it possible to conduct this study completely free of constraints on the scope and direction of the research, which are often elements of privately funded work. While these test results are not sufficient to develop a completely new method of designing rubblemound breakwaters, they nevertheless shed new light on several of the more important factors involved.

From the tests conducted thusfar it is clear that the individual components of the design sea state cannot be considered as isolated elements. Rather, the wave height, wave period, and the underwater beach profile, as well as the water depth in front of the structure and the type of surface element used are all closely interrelated factors which determine the effectiveness of the breakwater design. The entire structure can become surprisingly stable or instable as a result of a change in any one of these parameters. As an example, dolos elements are particularly unstable for steep underwater beach profiles with shallow water depths directly in front of the breakwater, while the same conditions have no great negative effect on tetrapods.

A standardized system for evaluating and interpreting test results is urgently needed so that all future work in this field can be better coordinated and compared. The evaluation method presented in the paper, employing positive-negative overlays, is meant to serve as a step in this direction. This method is sufficiently accurate and considerably less costly than installing accellerometers on each and every surface layer element or the use of armour elements of scale-reduced strenght. Furthermore, it is important that additional boundary conditions be made known, such as the actual wave heights used during the test, the water depth at the toe of the breakwater, as well as the inclination and length of the foreslope.

It is the authors' hope that in the near future the present uncertainties surrounding the design of rubblemound breakwaters can be sufficiently clarified so that the need for expensive model tests can be eliminated. For the time being, however, it is highly recommended that design plans be verified by hydraulic model tests. Although such tests can be rather costly, they can protect considerably larger investments in breakwater structures against extremely unpleasant surprises.

6 REFERENCES

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