CHAPTER 102

CONSIDERATIONS ON FACTORS IN BREAKWATER MODEL TESTS

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ABSTRACT

In the light of tests on breakwater armor units conducted at Laval University on behalf of the Department of Public Works of Canada, a discussion on various factors involved in model tests on breakwater armor units is presented in comparison with previous studies made on the subject. Tests have been carried out on natural stones, tetrapods and mainly dolosse.

Various factors whether they pertain to waves or to the structure are analysed in view of the factors resulting from the interaction of both of them, that is stability of the armor units, damage to the structure or run up of the facing. These factors are the ones for which model tests are conducted. The interpretation of results for the given test conditions should not be evaluated without considering possible scale effects.

From the analysis of test results presented by different investigators, a need for the standardization of test results became apparent. Recommendations are made concerning the presentation of results for their future use in engineering design. A standard weight of 100 grs with a standard length of 100 cms for model values are proposed to present the results on a diagram showing significant wave height versus damage, where damage should be expressed in terms of the number of units displaced in the area between ± the wave height giving 1% damage.

INTRODUCTION.

Scale model tests of rubble-mound breakwaters is concerned with factors resulting from the interaction of waves and the structure itself. As shown in fig. 1, these are commonly referred to as stability, damage and wave run up. On one side the factors pertaining to the structure could be divided into the structure itself, that is its slope, its orientation with respect to wave attack and whether its trunk or its head is attacked by waves, the units, their weight, density and shape and the layers that is their thickness, porosity and the way the units are placed in them. On the other side the waves which are caracterized by their height, period and duration, can act under different conditions such as whether they are shallow or deep water, breaking or non breaking, linear or non linear, regular or irregular, overtopping or non overtopping.

Because of the great difficulty in obtaining prototype results, a great amount of scale model tests of breakwaters have been carried out in different laboratories over the world. The tests were first conducted on natural stones then later on artificial concrete blocks in order to get a stability formula, that is the required weight of given units for no damage under certain wave conditions. Afterwards the notion of damage to the structure was introduced above this level, which in turn made other factors such as storm duration, wave period, types of waves, run up and overtopping, intervene in this kind of study. All these tests were done in view of making possible a better design of the structure. With the knowledge of damage suffered by a breakwater under different wave conditions of which the frequency of occurence is known, it was then possible to think of achieving an optimum design by comparing the construction cost versus the cost of damage risks including the malfunction of the structure. This is the ultimate goal to be obtained in a study of that sort after all the factors involved have been taken into account.

EFFECT OF WAVE HEIGHT.

The wave height is the primary factor belonging to waves for the study of rubble-mound breakwaters. Whether constant or significative wave height is used, it is always referred to the incident wave characteristics. It is the factor most involved concerning the stability, damage or run up incurred on the breakwater. Imprecision in measuring the wave height will result in the scattering of the results.

EFFECT OF WAVE PERIOD.

The wave period is of secondary importance on stability as long as we are near the value of maximum interest. For given conditions, a small change in wave period near value does not affect much stability.

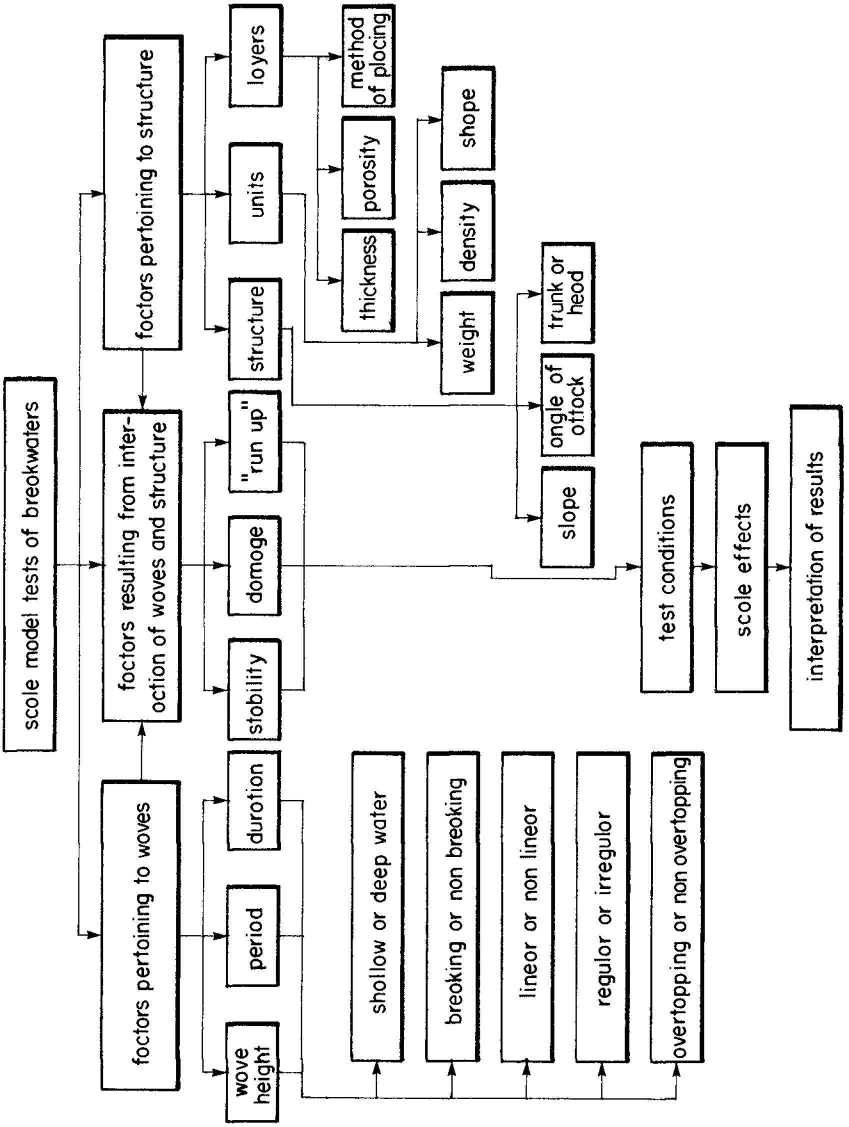

Fig. 1 —FACTORS CONCERNED WITH SCALE MODELS TESTS OF BREAKWATERS

The values of prototype wave periods reported in the literature should not be taken as such since they depend on the scale adopted by the author (see table 1) and accordingly on the size of the prototype units which results. In order to make possible a comparison, we have reported all values to a standard model weight of 100 grs by scaling down the true weight of the units used for model tests given in table 1 to this standard weight. By taking the cubic root of this scale we get the length scale which is given in table 2 with the other corresponding values scaled accordingly. It can be seen that the range of most damaging model wave periods is between 1.5 to 2.0 seconds. In fact a variation should take into account other factors such as the wave height which results in wave steepness and the water depth which results in relative depth for non breaking wave conditions. As reported by hydraulic Research Station, Wallingford, it appears that the effect of wave period is more important in the advanced stage of damage.

EFFECT OF STORM DURATION.

The storm duration is specified in terms of the number of waves attacking the structure. This factor, which is important in the scattering of test results is of considerable importance in the advanced stage of damage. Above a certain level of wave height, damage to the structure will increase if sufficient duration is allowed. Below this level the damage to the structure stops to a certain limit where a new equilibrium profile is obtained. The limit would then approximatively be when for the new equilibrium profile the protective layer is uncovered.

Which is of interest regarding storm duration is the time history of wave attack, that is whether the new built structure is first attacked by smaller or bigger waves. Most of the time for model tests wave heights are increased in steps until the maximum conditions are obtained. This sometimes permits to some units to get into a more stable position before the higher waves come. However some tests conducted directly with greater wave heights on a newly placed facing have shown a slight difference between these two test conditions.

EFFECT OF STRUCTURE.

Many tests have been conducted on breakwater with slope of facing in the range of 1 in 1.5 to 1 in 3, which is in the limit of most of the breakwaters built. Outside this range few tests are available because of their less practical interest. The variation of slope affects the wave form in the vicinity of the breakwater and in this way the conditions of attack of the protective layer. The most interesting point concerning the slope is its variation towards a new equilibrium composed of three different slopes when serious damage is suffered by the structure.

When waves arrive at an angle with the structure, the effect is less severe than perpendicular wave attack. However not much reduction is for angles smaller than 45^{o}.

TABLE 1- CHARACTERISTICS OF MODEL UNITS USED BY DIFFERENT INVESTIGATORS.

AUTHOR YEAR PLACE	NAME OF UNITS	VOLUME OF UNITS	WEIGHT OF UNITS	SPECIFIC GRAVITY	SPECIFIC WEIGHT	WATER DEPTH	WAVE HEIGHT (UP TO)	WAVE PERIOD	SCALE
---	---	cc	grs	---	lbs/ft^3	feet	feet	sec.	---
HUDSON 1959 Vicksburg, U.S.A.	Quarry stones Tetrapods (concrete) Tetrapods (leadite)	14-48 35-48 43-48	41-140 82-100 95-105	2.66-3.08 2.16-2.46 2.14-2.28	166-192 135-154 134-142	1.26-2.0 1.26-2.0 1.26-2.0	0.70 0.70 0.70	0.88 to 2.65	No scale
SINGH 1961 Wallingford, England	Stabits	55	129	2.32	145	1.0	0.68	1.45 1.75	1:47
PAAPE & WALTER 1962 Delft, Netherlands	Akmons Quarry stones Cubes Tetrapods Tripods Bipods	38 38 38 38 38 38	84 84 84 84 84 84	2.2 2.2 2.2 2.2 2.2 2.2	137 137 137 137 137 137	1.4 1.4 1.4 1.4 1.4 1.4	0.6 0.6 0.6 0.6 0.6 0.6	1.4 1.4 1.4 1.4 1.4 1.4	No scale
MERRIFIELD & ZWAMBORN 1965 C.S.I.R. South Africa	Dolosse Dolosse Dolosse Tetrapods Rectangulars Rectangulars Tetrahedrons	479 218 94 385 536 394 304	993 427 185 834 1262 929 594	2.07 1.96 1.96 2.16 2.36 2.36 1.95	130 123 123 135 148 148 122	2.5 2.5 2.5 2.5 2.5 2.5 2.5	1.2 1.2 1.2 1.2 1.2 1.2 1.2	1.2 2.4 and 3.0 for each units	1:25
CARSTENS & ALS. 1966 University of Norway	Quarry stones	104	280	2.70	168	3.3	1.0	0.5 to 3.0	No scale
FONT 1968 Central University Venezuela	Rocks Rocks Rocks	94 70 38	255 190 102	2.71 2.71 2.71	169 169 169	1.75 1.75 1.75	0.5 0.5 0.5	1.58 1.58 1.58	No scale
KREEKE 1969 University of Florida U.S.A.	Granite stones	0.65	1.86	2.86	178	1.0	1.0	0.75	No scale
OUELLET 1969 University Laval Canada	Quarry stones Tetrapods Tetrapods Dolosse Dolosse Dolosse Dolosse	457 325 155 69 66 66 20	1475 780 340 165 156 143 43	2.65 2.40 2.16 2.40 2.40 2.16 2.16	165 150 135 150 150 135 135	1.8 1.8 2.5 1.8 2.5 2.5 2.5	1.0 1.0 1.2 1.0 1.2 1.2 0.6	2.0 2.0 2.0 2.0 2.0 2.0 2.0	1:16
RAICHLEN 1969 Caltech, U.S.A.	Tribar	20.8	46.7	2.25	141	0.76	0.40	1.75	1:75
ROGAN 1969 Chatou, France	Quarry stones	24	63	2.6	162	1.15	0.4	1.0 to 2.0	No scale
FONT 1970 Central University Venezuela	Rocks Tetrapods	38 39	102 87	2.71 2.23	169 139	1.31 1.31	0.5 0.5	1.58 1.58	No scale
WHILLOCK 1970 Wallingford, England	Dolosse Dolosse	39.5 6.3	91.0 14.5	2.30 2.30	144 144	1.20 0.65	0.63 0.34	1.6 to 2.4 1.2 to 1.8	1:40 1:73.7
ERGIN & PORA 1971 Metu, Turkey	Stones	17.3	45	2.60	162	1.6	0.4	1.3	1:50
TZIMOPOULOS 1972 Chatou, France	Stones	23.6	61.3	2.60	162	0.33 to 0.80	0.42	1.0 to 2.0	1:40

TABLE 2- MODEL UNITS SCALED DOWN TO A STANDARD WEIGHT OF 100 GRS

AUTHOR YEAR PLACE	NAME OF UNITS	VOLUME OF UNITS	WEIGHT OF UNITS	SPECIFIC GRAVITY	SPECIFIC WEIGHT	WATER DEPTH	WAVE HEIGHT (UP TO)	WAVE PERIOD	SCALE
---	---	cc	grs	---	lbs/ft^3	feet	feet	sec.	---
HUDSON 1959 Vicksburg, U.S.A.	Quarry stones Tetrapods (concrete) Tetrapods (leadite)	32-38 40-46 44-47	100 100 100	2.66-3.08 2.16-2.46 2.14-2.28	166-192 135-154 134-142	1.1 to 2.6	0.6 to 0.9	0.84 to 3.0	1:0.74 to 1:1.12
SINGH 1961 Wallingford, England	Stabits	42.7	100	2.32	145	0.92	0.63	1.40 to 1.70	1:1.09
PAAPE & WALTER 1962 Delft, Netherlands	Akmons Quarry stones Cubes Tetrapods Tripods Bipods	45.2 45.2 45.2 45.2 45.2 45.2	100 100 100 100 100 100	2.20 2.20 2.20 2.20 2.20 2.20	137 137 137 137 137 137	150 150 150 150 150 150	0.64 0.64 0.64 0.64 0.64 0.64	1.5 1.5 1.5 1.5 1.5 1.5	1:0.94 1:0.94 1:0.94 1:0.94 1:0.94 1:0.94
MERRIFIELD & ZWAMBORN 1965 C.S.I.R. South Africa	Dolosse Dolosse Dolosse Tetrapods Rectangulars Rectangulars Tetrahedrons	48.2 51.0 51.0 46.2 42.4 42.4 51.3	100 100 100 100 100 100 100	2.07 1.96 1.96 2.16 2.36 2.36 1.95	130 123 123 135 148 148 122	1.16 1.54 2.03 1.23 1.07 1.19 1.38	0.56 0.74 0.98 0.60 0.52 0.57 0.66	0.6 to 2.6 2.6 2.6 2.6 2.6	1:2.15 1:1.62 1:1.23 1:2.03 1:2.33 1:2.10 1:1.81
CARSTENS & ALS. 1966 University of Norway	Quarry	37.1	100	2.70	168	2.34	0.71	0.42 to 2.53	1:1.41
FONT 1968 Central University, Venezuela	Rocks Rocks Rocks	36.8 36.8 36.8	100 100 100	2.71 2.71 2.71	169 169 169	1.28 1.41 1.74	0.43 0.45 0.50	1.35 1.42 1.58	1:1.37 1:1.24 1:1.01
KREEKE 1969 University of Florida U.S.A.	Granite stones	34.9	100	2.86	178	3.77	3.77	1.46	1:0.265
OUELLET 1969 Laval University Canada	Quarry stones Tetrapods Tetrapods Dolosse Dolosse Dolosse Dolosse	37.8 41.7 46.2 41.7 41.7 46.2 46.2	100 100 100 100 100 100 100	2.65 2.40 2.16 2.40 2.40 2.16 2.16	165 150 135 150 150 135 135	0.73 0.91 0.66 1.52 2.15 2.22 3.31	0.41 0.51 0.80 0.85 1.03 1.06 0.80	1.30 1.42 1.64 1.84 1.72 1.88 2.30	1:2.45 1:1.98 1:1.50 1:1.18 1:1.16 1:1.12 1:0.75
RAICHLEN 1969 Caltech, U.S.A.	Tribar	44.5	100	2.25	141	0.98	0.52	2.0	1:0.78
ROGAN 1969 Chatou, France	Quarry stones	38.4	100	2.60	162	1.34	0.47	1.10 to 2.26	1:0.85
FONT 1970 Central University Venezuela	Rocks Tetrapods	36.8 36.8	100 100	2.71 2.23	169 139	1.30 1.38	0.50 0.53	1.58 1.62	1:1.01 1:0.95
WHILLOCK 1970 Wallingford, England	Dolosse Dolosse	43.4 43.4	100 100	2.30 2.30	144 144	1.24 1.24	0.65 0.65	1.6 to 2.4 1.6 to 2.4	1:0.97 1:0.53
ERGIN & PORA 1971 Metu, Turkey	Stones	38.4	100	2.60	162	2.10	0.52	1.5	1:0.77
TZIMOPOULOS 1972 Chatou, France	Stones	38.5	100	2.60	162	0.4 to 0.9	0.5	1.1 to 2.2	1:0.85

It is well accepted that the head of a breakwater is more vulnerable than the trunk and accordingly should be more protected. Model tests on trunk section are one-dimensionnal while tests on the head are two-dimensionnal.

EFFECT OF UNITS.

The weight of the units is quite important in breakwater model tests. They should be small enough so that they are within the capabilities of test conditions but not too small otherwise scale effects result.

The density of the units tested are mainly those resulting from using rocks or concrete in salt or fresh water that is from 2.2 to 2.7. This factor is taken into account in Hydson's stability formula.

The shape, which could be more or less sophisticated, is responsible for the fact that units are more or less stable with respect to one another. This factor is taken care of in stability formulas by a coefficient which includes the degree of interlocking.

Tests with dolosse of approximataly the same weight 143 and 156 grs but with different densities 2.16 and 2.40 have been carried out under similar test conditions. A plot of damage coefficient K_D versus pencentage damage (fig. 2) shows a great scatter of test results. However these same results when plotted on a graph of wave height versus damage are grouped together (fig. 3). This would mean that for these units Hudson's formula would not apply.

Such a remark has also been made by Hydraulic Research Station, Wallingford with respect to a change of slope from 1:1.5 to 1:3 with the same kind of units. One can find the explanation of this phenomena by returning to the derivation of Hudson's formula in which the inertia term in the induced forces has been neglected with respect to the drag force and the friction and interlocking terms neglected with respect to buoyant wieght in the resistive forces. In case of dolosse, interlocking effect is more important than buoyant weight for the stability of the units.

EFFECT OF LAYERS.

The most important factors with respect to layers are related to the method of placing the units and the effect of the underlayers.

Most of the time units are randomly placed in two layers with some exceptions of units such as tribars where a one layer of uniform placing is used. This is an important factor in the scattering of results. It is more relevant in the early stage of damage where poorly placed units are displaced for lower wave heights.

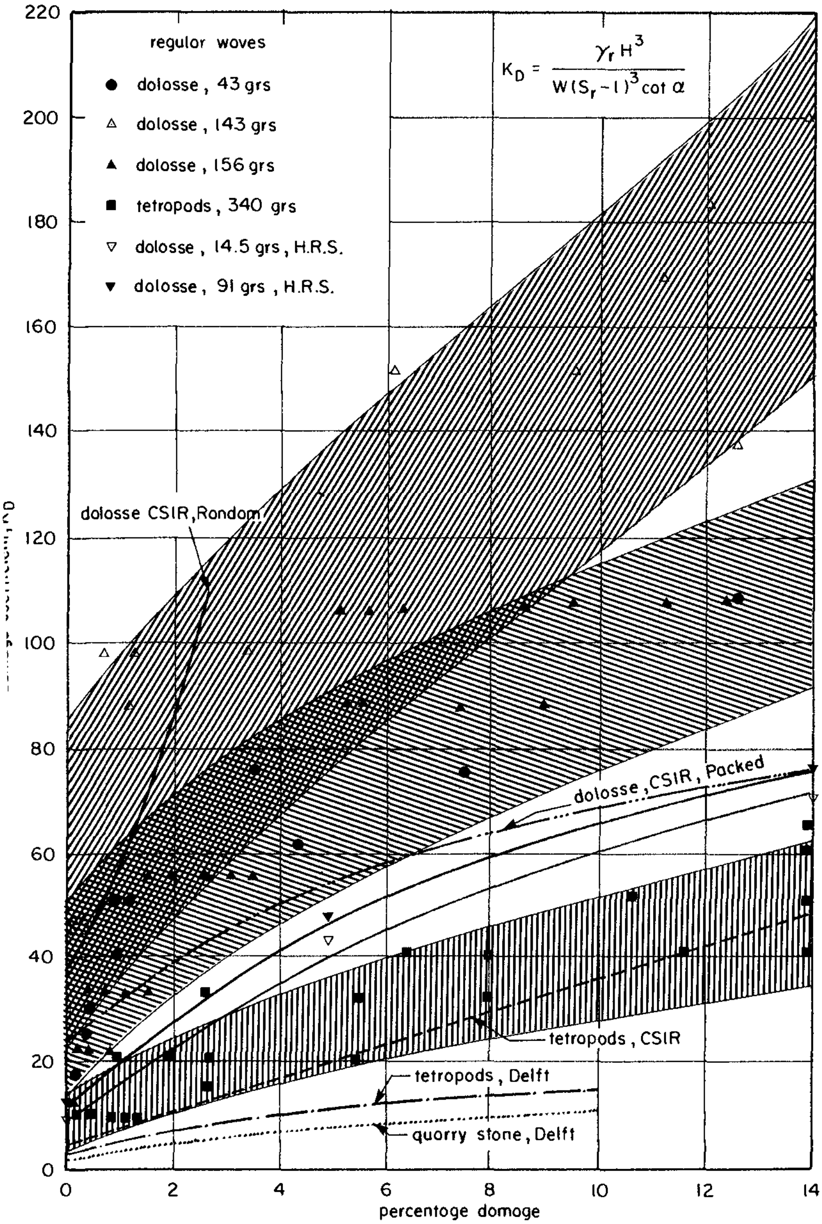

Fig. 2 — DAMAGE COEFFICIENT VERSUS PERCENTAGE DAMAGE.

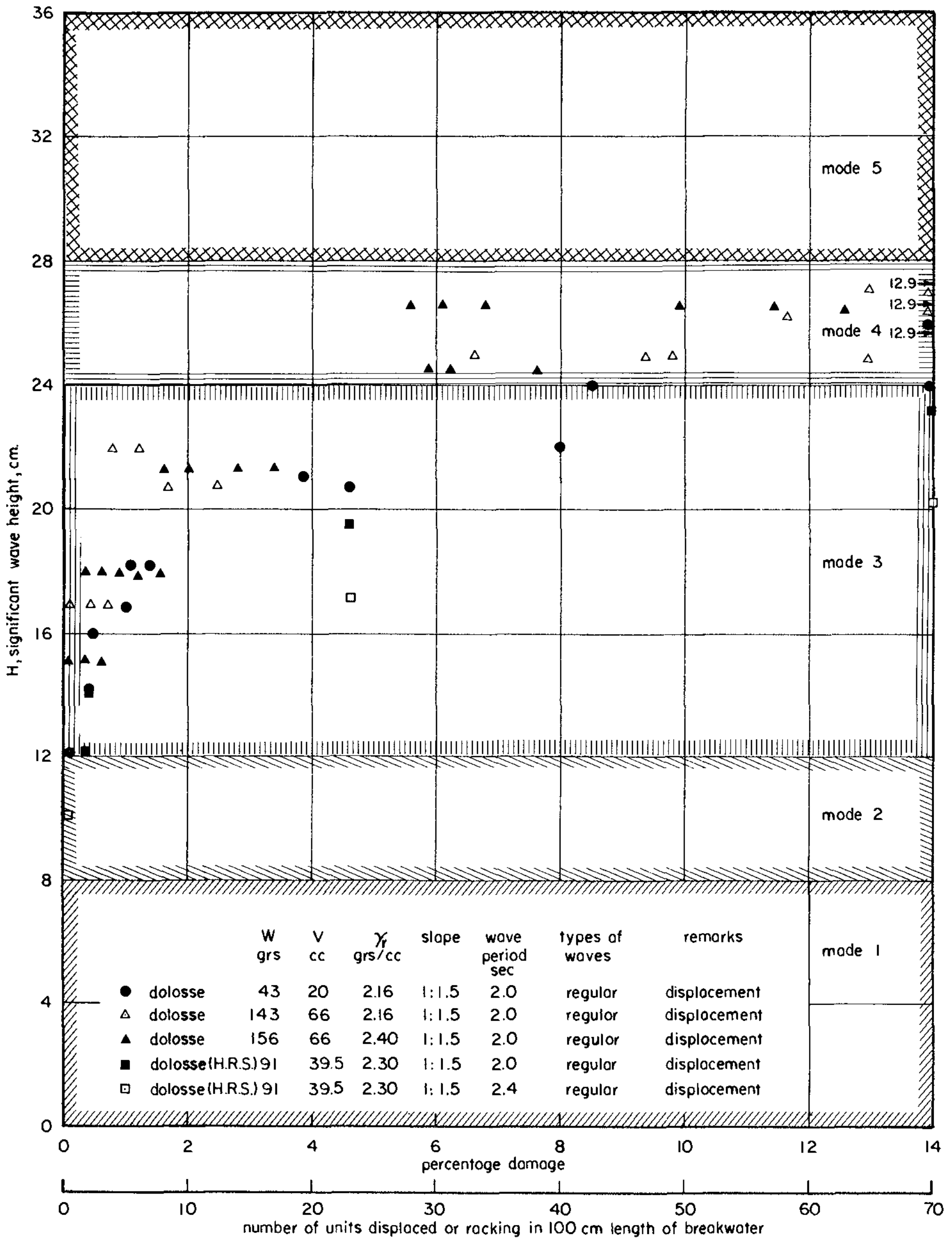

Fig. 3— SIGNIFICANT WAVE HEIGHT VERSUS DAMAGE FOR UNITS WITH AN EQUIVALENT WEIGHT OF 100 grs.

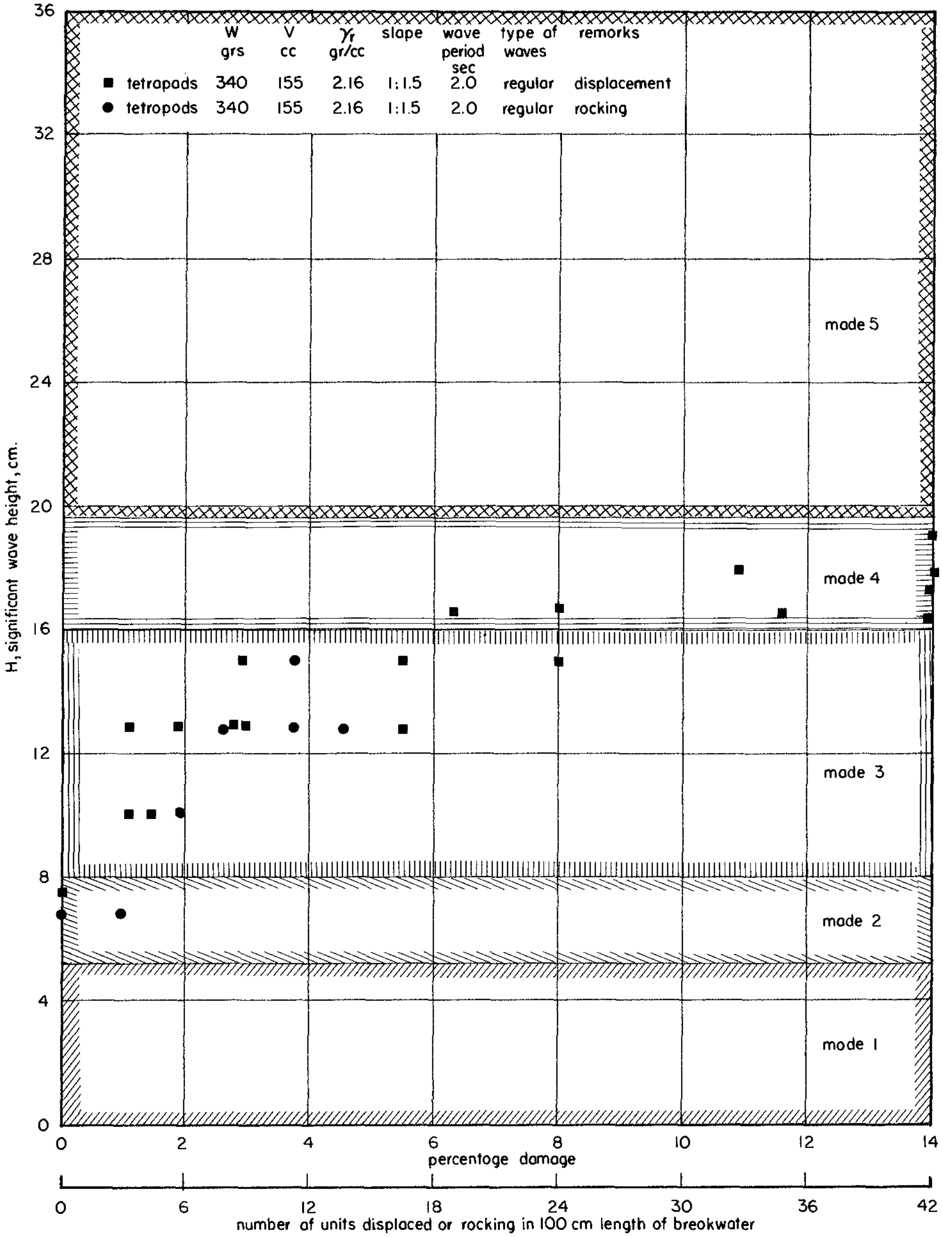

Fig. 4 — SIGNIFICANT WAVE HEIGHT VERSUS DAMAGE FOR UNITS WITH AN EQUIVALENT WEIGHT OF 100 grs.

The underlayers are built in order to present finer particles to escape through the cover layers and create enough friction between layers to prevent sliding of layers with respect to one another. Although literature reports the effect of underlayers is more or less of importance on stability, it is believed that its effect should not be overlooked when designing breakwaters, because these results come from model tests where scale effects could be important and limited amount of test results are available.

TEST CONDITIONS.

Scale model tests of breakwaters are conducted in order to evaluate the stability of the units, the damage to the structure for higher waves and the run up on its facing to determine its crest elevation. The interpretation of results should not be done without taking into account test conditions under which model testing have been conducted.

The depth of water and the bottom slope are responsible for the change of wave characteristics approaching the structure that is whether waves are shallow or deep water, breaking or non breaking, linear and non linear. In shallow water the wave height is limited by the water depth but in some cases the toe of the structure should be protected. These factors do not seem to have much influence on stability as long as the same wave height reach the structure.

The most important factors to take into account are those related to irregular waves and wave overtopping. From the few tests conducted with irregular waves, it is now accepted that the significant wave height of wave spectra having a Rayleigh type distribution is comparable to a corresponding regular wave height. Although wave run up, wave energy or the ratio of maximum wave height to the significant wave height are factors which have been proposed for consideration for describing irregular wave trains, it will necessitate more test results to specify the type of wave spectra.

When the crest elevation is not high enough, overtopping occurs and this happens when still water level is approximately equal to 60% of the breakwater height. In this case the leeside is in general more vulnerable than the seaside and maximum damage occurs when the still water level is slightly below the crest of the breakwater. The limited amount of tests have shown that the slope on leeside is less important than on the seaside, although overtopping height is difficult to estimate because of turbulence.

FACTORS RESULTING FROM INTERACTION OF WAVES AND STRUCTURE.

Scale model tests on breakwaters are usually conducted to determine the stability of the armor units, the damage to the structure or the run up on the facing. The most important factor is the damage incurred on the structure since it includes the stability of the units and that wave run up is an additionnal factors to be measured.

The wave run up which is of the order of the wave height delineates the breakwater height for non overtopping condition. It depends on many factors such as the slope of the facing, wave steepness, relative depth, permeability and roughness of the breakwater facing and angle of wave attack. Its measurement is made difficult because of the porosity of the layers.

Although the damage suffered by the structure is very important, it is one of the most confused term used by different investigators. Whether it refers to rocking, displacement or fracture of the units, its definition expressed in terms of percentage varies from one another. The unit displacement and unit rocking as proposed on reference 3 should be maintained in future tests. The difference comes from whether the distance of the movement of a unit is more or less than the overall length of the unit. Its description has mainly been used in terms of percentage with respect to a certain number of units placed in the test section.

But confusion introduced from the fact that the expression of percentage damage is referred to different numbers of units placed in the test section has led to define the damage by the number of units displaced in a given standard length. But since this number varies with the weight of the unit it is not as indicative as a percentage value to express the amount of damage produced. To remedy this, a new proposition is made further in this paper.

It is well known that the damage is located mainly in the area around still water level. This occurs mostly in sliding of isolated units which, although some of them are detached during the rush up, are deposited down the slope. A new equilibrium profile composed of three different slopes is attained if damage to the structure is not sufficiently high enough to produce failure of the structure which happens when the first underlayer becomes uncovered. The wider the test section, the more precise is the damage measured.

Comparison of damage is usely done in graphs showing damage coefficient versus percentage damage or wave height versus damage. A damage band rather than a damage curve is obtained and from these curves, a design wave exceedance versus damage (fig. 5) can be obtained for future use in a optimum design procedure. Comparing the curves shown in figure 5, it is expected that a single curve would apply for most of the units used as armor units on the recommended sections given in Technical Report no 4. This would be obtained by a small change in the value H_{S0} which is much influenced by the method of placing the units.

Consideration of these curves and observation of the armor layers under wave attack led to the conception of modes of failure, where the approximative limits are given in terms of the design wave height (no damage criteria):

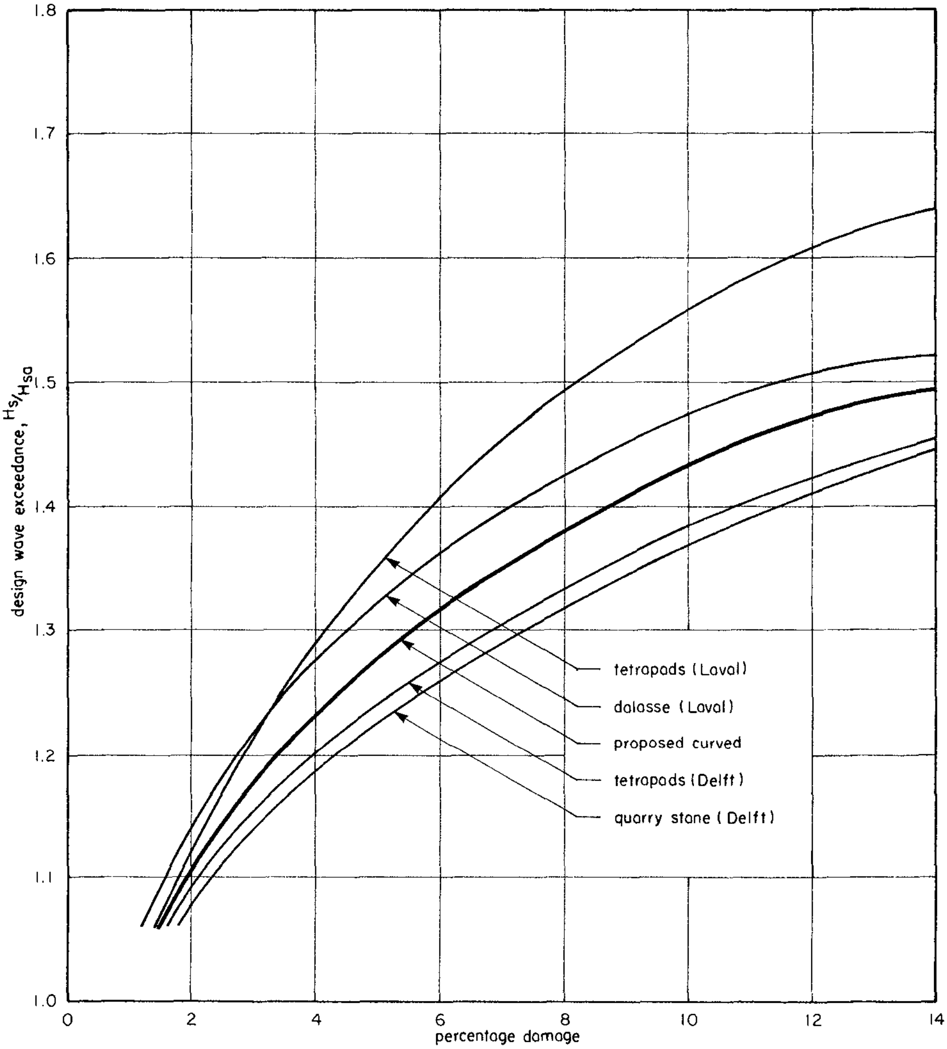

Fig. 5 —— DESIGN WAVE EXCEEDANCE VERSUS PERCENTAGE DAMAGE.

Mode 1:	0 H - 0.5 H	No movement of the units.
Mode 2:	0.5 H - 0.9 H	Rocking of the units but no displacement.
Mode 3:	0.9 H - 1.5 H	Some units are displaced but the armor layer remains stable.
Mode 4:	1.5 H - 1.8 H	Units are displaced and the armor layer would fail if time is allowed.
Mode 5:	above 1.8 H	Immediate failure of the armor layer.

These modes of failures can be show as in figures 3 and 4 on a wave height versus damage diagram and could be useful to design engineers.

SCALE EFFECTS.

The interpretation of results or their transposition from model to prototype depends on scale effects for the given test conditions. For a model based on Froude's similarity, the inertial forces should be large compared to viscous forces or otherwise the Reynolds number should be high enough that the flow is turbulent for both model and prototype. For breakwater scale model tests, this intervenes in the drag forces expressed in terms of a drag coefficient which is affected by the Reynolds number and by the flow through a porous structure according to Darcy's law. Such effect occurs when the weight of the units is relatively small. From our tests, a weight of 100 grs seems to appear as a lower limit in order not to have scale effects.

But many other factors can produce scale effects. For example is the flow in the underlayers to scale? What is the effect of using a board which permits to vary the slope? What are the effects of the types of waves whether regular or irregular if they are produced either by wind or paddle movement? Are the test conditions, that is the history and the duration of wave attack to scale? These are as many questions concerning scale effects which would be difficult to answer. Moreover one can add other factors such as reflexion of waves in the flume, side wall effects, stopping and starting the machine, etc...

RECOMMENDATIONS FOR BREAKWATER MODEL TESTS.

Since Hudson's formula seems not to apply when interlocking effects are more important, like it is the case for dolosse compare to natural stone, a plot of significant wave height versus damage with the different modes of damage on it (Fig. 3 and 4) appears more valuable than a plot showing damage coefficient versus damage. In this case the other parameters such as the density of the units, the slope, the wave period, etc... should be indicated. It can be seen that the scatter of test results are less spread on the former graph than on the latter one.

The damage used as such should mean the unit displacement that is the act of a unit moving a distance greater than its overall length. If unit rocking is referred to, it should be indicated.

The idea of expressing the damage as percentage of a certain number of units should be maintained since it is indicative of the amount of damage suffered by the structure. In order to make any comparison possible, it is suggested in the light of past experiments that these are referred to the number of units placed in the area between ± the wave height giving 1% damage.

If one likes to express the damage in terms of the number of units displaced in a given length of breakwater, the same weight of units has to be used in order to make possible any comparison. A standard weight of 100 grs with a standard length of 100 cms are proposed for presenting the test results (fig. 3 and 4).

For the determination of the wave height giving 1% damage, it is proposed to estimate it from the limit between mode 3 and mode 4 which is less influenced by the way of placing the units. In this case some help can be received from a graph showing the design wave exceedance versus damage.

The presentation of results could be standardized on a plot of significant wave height versus damage by adopting a standard weight of 100 grs and a standard length of 100 cms. By scaling other test conditions to these standard values, comparison between results is made possible. It would also be easy from such a figure to obtain prototype values corresponding to a given design wave height from Froudian scales.

CONCLUSION.

An analysis of various factors concerned with breakwater scale model tests reveal the need for a standardization of the presentation of test results. A simple method which does not included any formulas is proposed for the presentation of these results.

Although it is not the intention of the author to exclude any further need of research on the knowledge of what is damage related to, wave energy, wave power, wave steepness, wave height, wave run up, ... the presentation as suggested does not take that into account. To the author's point of view, it appears that better chances of success appear in locking in a correlation between damage and wave run up.

The ultimate goal to be obtained from such model testing is towards a better design of rubble-mound breakwater. For use in optimum design breakwater, it is proposed that only unit displacement be considered for damage. Since damage in mode 3 is not cumulative, it should be considered only once and for practical reasons this damage is not repaired after a storm has passed. Finally storm duration in mode 4 should be considered such that it is smaller than an usual duration of a storm and for that reason breakwater will fail if wave height is in that mode.

The proposed standardization is not intended to be final, but the author's goal would be attained if only this paper would sensitize those concerned with breakwater design on the various factors involved in breakwater model tests and that the presentation of test results asks for a plea of uniformity.

ACKNOWLEDGEMENT.

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