CHAPTER 128

A UNIVERSAL ANALYSIS FOR THE STABILITY OF BOTH LOW-CRESTED AND SUBMERGED BREAKWATERS

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Abstract.

Three-dimensional physical models of detached rubble-mound breakwaters have been built with separate Total Section, Front Slope, Crest and Back Slope sections. The stability responses of the armor units of this sections have been tested using irregular waves and differents freeboards.

The stability curves relating the level of damage, the stability number, N_s, and the freeboard, have been obtained for each one of the different sections defined on the breakwaters. A distinct behaviour of the different sections have been found. The curves that plot the stability number against the freeboard for a given level of damage shows a minimun for a intermediate freeboard for the Crest and Back Slope sections. The total section stability response is a combination of the response of each one of its components. As a consequence, relative minimums of stability may appear for intermediate freeboards, due mainly to the contribution of the Crest failure to the total stability.

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Introduction.

Low-crested and submerged breakwaters are designed to allow the transmission of a significant amount of wave energy due to overtopping. Conventional breakwaters have the traditional multi-layer cross-section. Reef breakwaters are low-crested or submerged breakwaters composed by a homogeneous rubble.

Because of the overtopping, the flow over the front slope section of the breakwater attenuates as the freeboard decreases and the weight of the armour stones on the front slope can be significantly reduced, as proposed by Van der Meer (1988). However, the crest and back slope armour units may need increased weight to withstand the wave forces caused by overtopping. The combination of increasing stability on the front slope and the decreasing stability on the crest and back slope can lead to stability minimums in intermediate positive freeboards, as suggested by Ahrens et al. (1990). Losada et al. (1992) used experimental velocity data and analytical values, obtained from Kobayashi et al. (1987, 1990), to show that the minimum stability of crest units occurs when the crest is at the mean water level. Experimental studies of the U.S. Army (1965), Raichlen (1972), Magoon et al. (1975) and Walker et al. (1976), suggested that the Back Slope section of low-crest breakwaters is more susceptible to damage than the seaward slope.

The aim of this paper is to establish that the different sections of the breakwater trunk have very diverse stability response to a sea state condition and that the behavior of the Total Slope section, (generally the only probed in two-dimensional model tests), reflects the stability response of each section component of the breakwater trunk. A complete description of this study is described in Vidal et al. (1992).

Damage criteria.

The average erosion area, A_e and the number of displaced units, N are usually used to describe the damage in the breakwater tests. The values of these variables do not give complete information of the state of damage of the breakwater, because they depend upon the geometry of the study sections. To relate the state of damage of a section of the structure with the values of these variables, it is necessary to define some general damage criteria.

Losada et al. (1986) defined three different degrees of armour damage that can be recognized by visual assessment. These are: Initiation of Damage, (ID), Iribarren's Damage, (IR) and Destruction, (D). Recently, Vidal et al. (1991) proposed and aditional damage level called Start of Destruction, (SD). These global damage definition will be used in the following. Relations between the S parameter and the damage level will also be given (see Table 3) in this paper for the different sections tested.

Experimental set-up and data analysis.

Experimental set-up.

The physical tests were carried out at the Hydraulics Laboratory of the National Research Council, Ottawa, Canada.

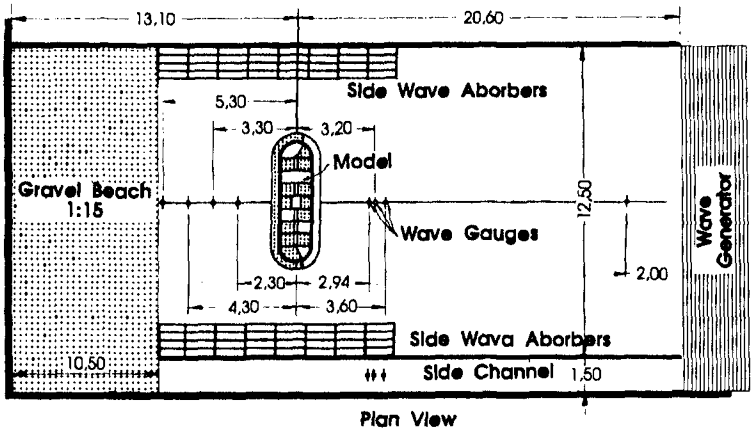

Figure 1.

The net area used in the facilities was 34x14 m^2. Figure 1 shows a plan view of the experimental set-up. A 1.5 meter-wide channel was constructed on one of the sides of the basins. In the side walls near the model heads, five modules of upright wave absorbers were placed in order to dissipate the diffracted energy from the model. On the side opposite the wave board, a 1/15 sloped gravel beach was built in order to ensure an efficient dissipation of wave energy. Excluding the gravel beach, the bottom in all the testing area was kept horizontal. The models were placed with their longitudinal axis paralel to the wave board. A distance of approximately 5 m between the rear toe of the breakwater and the front toe of the rear gravel beach was available to monitor the transmitted and diffracted wave energy.

Figure 2. shows a plan view of the models. A steel frame covering the upper 0.35 m of the breakwater was built. Using this frame, the structure was subdivided into six components, four trunk- and two head-sections. The trunk sections, 0.5 m long each, were: **F**ront **S**lope, (FS), **B**ack **S**lope, (BS), **C**rest, (C) and **T**otal **S**lope, (TS). The remaining parts of the breakwater sections, which were not included in these sectors were covered with a steel mesh having square openings of 1x1 cm in size. This prevented any motions or damage to these parts without changing the flow characteristics through and over the structure.

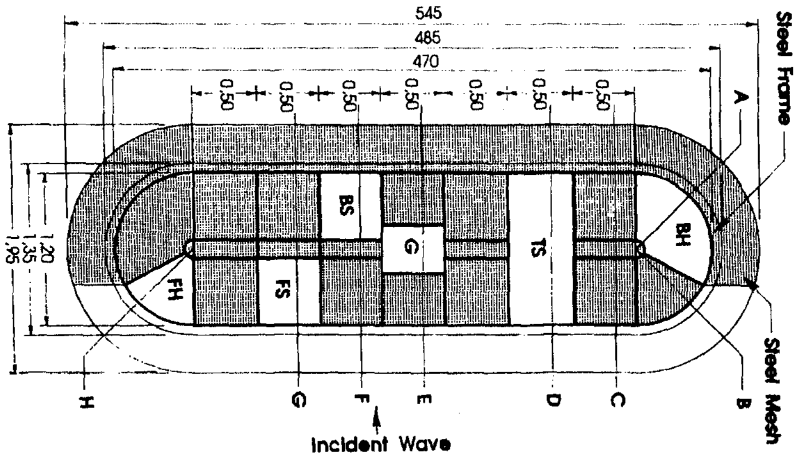

Figure 2.

The breakwater cross-section was composed of a permeable core armoured with two layers of rocks which were carefully selected in term of weight. Some main characteristics of the armour and core stones are provided in Table 1. In order to assure easy tracking of the armour units displacement, a colour coding was deployed. All the slopes of the trunk and heads were 1:1.5 and the crest width was equivalent to $6 \bullet D_{n50}$ and therefore, approximately 0.15 m. The water surface elevations of sea states were measured at eleven different locations as shown in Figure 1.

Before and after every test profiling, VCR pictures and color photographs were taken in order to assess the damage. During the wave generation period of each test, VCR pictures were taken to survey the evolution of the damage. The profiling of the breakwater cross-sections was performed using a electro-mechanic profiler. Nine profiles, 0.05 m apart, were taken for each trunk sector.

PARAMETER	ARMOUR	CORE
D_{n15} cm	2.37	1.64
D_{n50} cm	2.49	1.90
D_{n85} cm	2.64	2.24
ρ_r g/cm^3	2.65	2.65
P_s	0.45	0.44

TABLE 1: Model rubble characteristics

The one hour time series were synthesized using the Random Phase Spectra Method. The synthesized time series had JONSWAP spectra with two different peak periods (T_p= 1.4 and 1.8 s) having a peak enhancement factor of c = 3.3 and variable cero-moment wave height H_{mo}.

TEST NUMBER	d_s cm	h_c cm	T_p sec	H_{mo} cm
1,4,5,2,3	40	40	1.4	5,8,8,10,13
13	60	60	1.4	15
9,6,7,8	45	40	1.4	8,10,13,15
14,15	65	60	1.4	15,18
12,10,11	38	40	1.4	8,10,12
16,17	58	60	1.4	5,18
18,19,20,21,22,23	56	60	1.4	5,8,10,13,16,19
24,25,26,27,28,29	54	60	1.4	6,8,10,12,14,16
30,31,32,33	58	60	1.8	6,9,12,15
34,35	54	60	1.8	8,11

TABLE 2: Target parameters for the stability tests.

A total of 35 tests were carried out. The relevant target parameters of these tests are summarized in Table 2. The damaged breakwater sections were rebuilt after each test.

Data analysis.

The wave data from the probes was subjected to spectral, SIWEH, zero crossing and probability distribution analysis. The data collected from the three probes in front of the sea side of the test structure was subjected to reflection analysis.

The global damage figure for each part of the breakwater was obtained from the visual inspection of the model after the test. The final figures for the relation between the global damage levels and the S parameter was obtained after the tests and is given in Table 3. To assess the number of units displaced during each test, still colour photographs and video pictures were taken before and after the test.

SECTION DAMAGE	TS	C	BS	FS
ID	1.5	1.0	0.5	1.0
IR	2.5	2.5	2.0	2.5
SD	6.5	5.0	3.5	4.0
D	12.0	10.0	---	9.0

TABLE 3: Approximate 'S' minimun threshold values for the different definitions of damage and breakwater trunk sectors.

If N_{ex} is the number of units displaced in a trunk sector of length X and porosity P_s, the following expression, was used to translate this number into an equivalent visual damage parameter, S_v:

$$S_v=N_{ex}.D_{n50}/((1-P_a).X) \qquad \textbf{(1)}$$

Using the data from the mechanical profiler the average profile for each section of the breakwater before and after each test was calculated and the eroded average area, A_e, was derived. The adimensional damage parameter 'S_p' was evaluated from this eroded area, A_e, using the expression:

$$S_p=A_e/(D_{n50})^2 \qquad \textbf{(2)}$$

Using the indicated procedure, four values of S_p and S_v, corresponding to the four trunk sectors were obtained for each test.

Discussion of stability results.

To represent an overall dimensionless sea state parameter, the stability number, N_s, was used:

$$N_S = H_S / (\Delta \, . \, D_{n50}) \tag{3}$$

Where $\Delta = (\rho_r - \rho)/\rho$. It was decided to classify the results according to the values of the adimensional freeboard, $F_d = F/D_{n50}$, where F is the breakwater freeboard, $F = h_c - d_s$. For a given breakwater, water depth, time domain characteristics of incident waves and sea state duration, the damage should be a function of the stability number and the adimensional freeboard:

$$S = f(N_S, F_d) \tag{4}$$

For fixed damage levels, $S = S_o$, this function can be represented in a bidimensional plot relating the stability number for this damage level, N_{so}, with the freeboard:

$$S = f_o(F_d) \tag{5}$$

If this function has a minimum for a given freeboard, this freeboard will give the minimum stability for the corresponding section of the breakwater.

Comparison between damage levels.

In the following plots of the stability results F_d-N_s for each one of the trunk sections will be presented. Each set of data will be related to a global damage level.

- Front slope section 'FS':

Figure 3 plots the stability results for the 'FS' section. The lines drawn at the right correspond to the limiting N_s values for each line, taken from Van der Meer's (1988) data of non-overtopped breakwaters.

The curves fitted to each set of data in Figure 3 are straight lines suggesting a linear relation between the freeboard and the stability number for each damage level. The minimum value for a given damage level always corresponds to the non-overtopped breakwater. The values of N_s for initiation of damage and destruction are closer for the positive than for the negative freeboard or that the section is more brittle for the positive freeboards. The freeboard of minimum stability increases as the level of damage increases. This is because the minimum stability corresponds to the non-overtopping condition and if the wave height increases to attain bigger damages, the freeboard for non-overtopping must also increase.

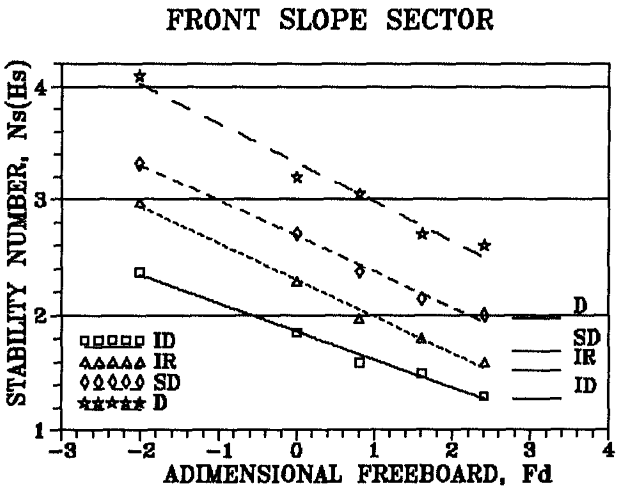

Figure 3.

Any damage in the breakwater that decreases the freeboard will cause better stability conditions in the 'FS' section. As the deformation of the 'FS' section due to damage also improves its stability, the result is that the 'FS' section in low-crested breakwaters is always in a stable condition (any damage increases the stability of the section).

- Crest section, 'C'.

Figure 4 despicts the results for the 'C' section. The curves that fit the data are 2^{nd} order parabolas.

For a given damage level, the freeboard of minimum stability is found slightly below the zero freeboard. The minimum of stability moves somewhat to the negative freeboards as the damage level increases, indicating the effect of the increasing wave height. The slope of the curves for positive freeboard is higher than for negative freeboard. That implies that the 'C' section increases its stability faster with the increase of positive freeboard than with the decrease of the negative freeboard. When the freeboard is positive, the armour units removed from the

Crest section by the waves are mainly carried with the forward movement of the waves to the 'BS' section. When the freeboard is negative, a higher proportion of armour units are carried to the front slope with the backward movement of the waves, due to the increase of the symmetry of the flow over the crest as the freeboard decreases. The proportion of units that moves to the FS or to the BS depends also on the wave height.

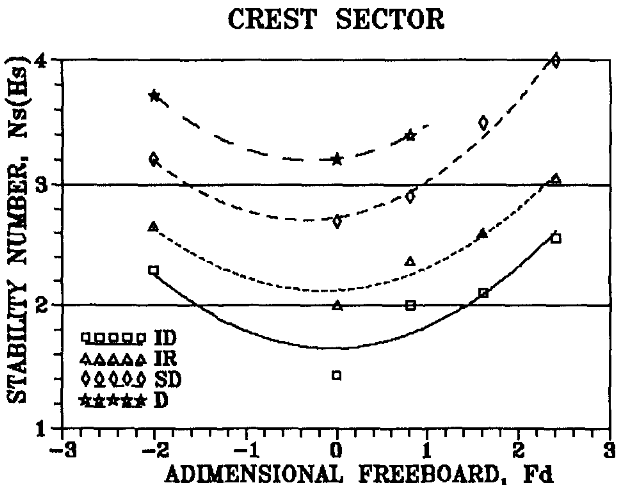

Figure 4.

Taking into account only the freeboard, the Crest section is in an unstable situation for positive freeboards: when the damage reduces the freeboard, the stability decreases. Figure 4 shows that the crest section is not more brittle for positive than for negative freeboards. The factors that compensate the decrease in stability due to de reduction of the crest height should be the increase of the width of the crest and the change in the crest slope that results from this reduction of crest height.

- Back slope section, 'BS'.

Figure 5 plots the results for the 'BS' section. Due to the high stability of this section, only the Initiation of Damage has enough information to show the complete trend. The fitted curve is a 2nd order parabola that has its minimum in a F_d value between 1 and 2. The other curves for higher levels of damage must have their minimums for higher freeboards and stability numbers. Extrapolating the trend of the curves for Iribarren's Damage and Starting of Destruction, and assuming that they are parabolas it can be concluded that the a high brittleness could be expected.

The behavior of the 'BS' section can be explained by the characteristics of the flow over the armour. For negative freeboards, the waves go over the crest and break (backward and forward) on the water that protect the back slope armour units. When the crest emerges, the water jet starts to impinge over the back slope armour units and the stability continues to decrease because the flow works with gravity to move the armour units. With the crest emerged, a minimum N_s is necessary for the initiation of overtopping and the origin (S=0) of the line N_s-S moves to higher N_s.

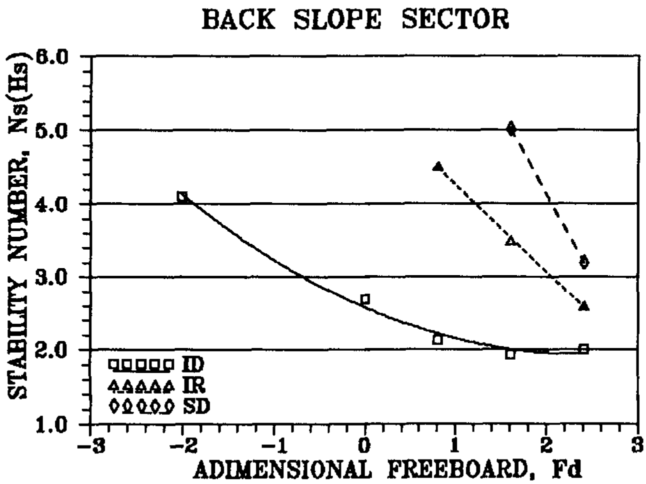

Figure 5.

The distribution of damage in the 'BS' section is more irregular than in the other sections. The shape and concentration of the water jet that impinges over the 'BS' creates areas where the damage is concentrated. Because of that, the values of S for a given damage level are smaller in this section than in the others (see Table 3).

- Total slope section, 'TS'.

Figure 6 shows the results for the 'TS' section. The horizontal lines at the right of the figure indicates the values of N_s for the different damage levels corresponding to the non-overtopping case, obtained from Van der Meer (1988). Instead of the straight lines of the 'FS' section

(Figure 3), the best fits are 2nd order parabolas with a minimum corresponding to the freeboard of non-overtopping. The interaction between the damage on the sections, particularly between the Crest and the Front Slope, produces relative minimums in the curve F_d-N_s. This complex behavior is the cause of controversy about which is the F_d of minimum stability.

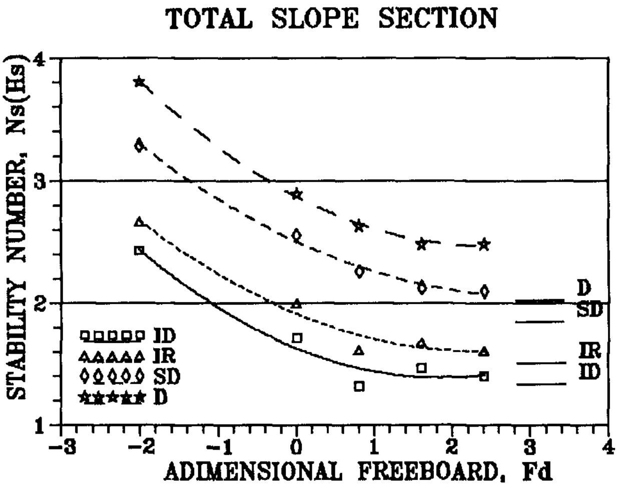

Figure 6.

The separation between the curves for the different damage levels is slightly minor in the positive freeboard range. This is due to the increase of brittleness for the positive freeboards in the Front Slope section. This brittleness is maximum for the non-overtopping case.

Comparison between sections.

The comparison between sections can be performed for fixed damage levels. As a representative example, the comparison for Iribarren's damage is discussed here.

Figure 7 plots the stability results F_d-N_s for Iribarren's Damage. Each set of data represents a different breakwater trunk section. The fitted curves are the same as used in Figures 3 to 6.

The 'FS' section is the least stable for $F_d \geq 0.5$. For $F_d \leq 0.5$, the 'C' section is the least stable of the trunk sectors. The Back Slope section is the most stable section of the breakwater for $F_d \leq 2.0$. For $F_d \geq 2.0$, the Crest section is the most stable. For this reason, if the freeboard is high and the armour of the Crest is the same as the Back Slope, the damage can start in the Back Slope and desegregate the Crest.

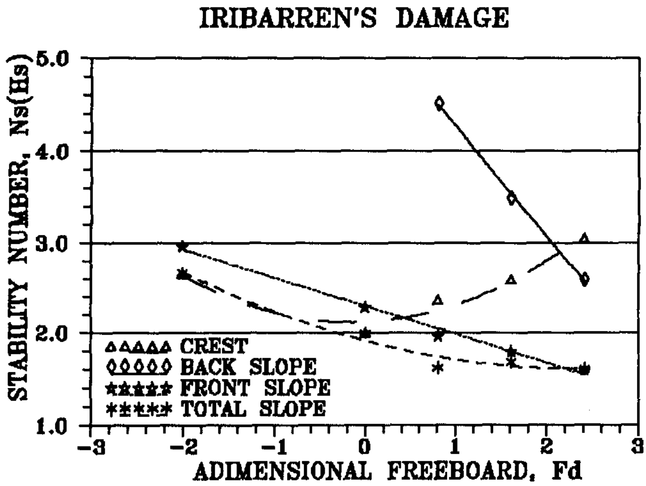

Figure 7.

The curve corresponding to the 'TS' section reflects the influence of the damage in all its components: for high positive freeboards, it behaves like the 'FS' section and for negative freeboards, it approaches the 'C' curve. Because the Crest section is more stable than the Front Slope for $F_d \geq 0.5$, the damage produced on the crest region of the 'TS' section is mainly caused by the spreading of the damage from the seaward slope to the crest. Several tests with positive freeboards have reported Destruction of the crest region of the 'TS' section while the Crest section had only Initiation of Damage. This damage on the crest region of the 'TS' was also attained for high positive freeboards due to the spread of the damage in the landward slope, because in these cases, the crest region is more stable than the back slope region.

Conclusions and recomendations.

The damage in a low-crest or submerged breakwater is the response to the different flow and stability conditions that support the armour units in the differents sections of the breakwater. The different sections of the breakwater have distinct stability responses to a sea state condition. The behavior of the Total Slope section, (generally tested in conventional model tests), reflects the stability behaviour of each section component of the breakwater trunk. If the objective of the model tests is to optimize the armor weight to obtain a similar security condition in each part of the breakwater, the stability curves for each section should be determined.

The stability of low-crested rubble-mound breakwaters is very dependent on the freeboard. This implies that, any comparative evaluation of breakwater stability should be based on low levels of damage such as Iribarren's Damage or lower. Higher level of damage could affect the crest level of the structure, thereby, affecting the stability and performance characteristics.

More experimental and theoretical work is necessary to establish the influence of other variables held constant in these tests: slope angles, crest width, type of armour units, etc. The high stability of the Back Slope section has impeded the completion of the stability curves for high levels of damage.

Aknowledgements.

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