HYDRAULIC STABILITY OF RUBBLE MOUND BREAKWATERS’ ARMOUR LAYER - PHYSICAL MODEL STUDY

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ABSTRACT

The main objective of this research is to assess the impact of different placement methods on the hydraulic stability of tetrapod armour layers. The experimental research was carried out in the wave flume of the Hydraulics and Water Resources Laboratory of Instituto Superior Técnico. A bidimensional model of a breakwater was built and two tetrapod placement methods were tested, with the same packing density. The model was tested with irregular wave series, according to the JONSWAP energy spectrum. A total of eight experiments were performed, with one wave peak period and four significant wave heights.

Despite the limited number of tests performed, the results suggest that different placement methods with the same packing density can have different reactions to wave action. Placing a given number of blocks in a slope may not be enough to guarantee the stability of a breakwater’s armour layer. The geometry of the layer is also an important factor.

INTRODUCTION

A breakwater is a structure built to reduce wave action in designated areas, to assist cargo handling or to protect natural shore lines from wave action. This is done by means of wave reflection and turbulent dissipation of the wave energy. In the latter, the main mechanisms are wave breaking and turbulent flow through the structure’s core. A rubble mound breakwater is the most primitive but still widely used breakwater type. In its simple form, a breakwater is a mound of rocks. Quarrying’s technical and economical restraints led to the development of armour layers formed by concrete blocks. Nowadays, most breakwaters are armoured with concrete blocks.

Since 1950, a large variety of concrete breakwater armour units has been developed. Today, design engineers can choose between completely different breakwater armour concepts. One of the most used armour units worldwide is the tetrapod. Introduced in 1950 by the Laboratoire Dauphinois d’Hydraulique for a breakwater in Casablanca, Morocco, the tetrapod was the first concrete block without a cubical shape, to replicate the interlocking of natural rock (DANEL, 1953). The tetrapod can be described as an
element of non-reinforced concrete schematically formed by four tapering legs radiating from a central point (PITA, 1986). Its shape denotes a compromise between the interlocking (feature of slender blocks, like Dolos) and structural strength, associated with self-weight (feature of compact blocks, like the Antifer Cube) (VAN DER MEER and HEYDRA, 1991; GÜRER et al., 2005). The permeability of tetrapod armour layers increases the absorption of incident wave, reducing reflection and overtopping, while its roughness stimulates energy dissipation of the incident wave. However, this block has some limitations. Some authors mention the frequent stress related damage, with legs broken off and broken pieces causing further damage within the armour layer (USACE, 2006).

The design of a breakwater applies semi-empirical formulae based on hydraulic model tests. At present, using physical models in this field is absolutely essential, since the complicated flow of waves impacting armour layers makes it impossible to calculate the flow forces acting on the structure. In addition to this, the complex shape of units together with their placement makes calculation of the reaction forces impossible. The Hudson formula (CIRIA, CUR, CETMEF, 2007) was developed in 1959 and has been widely used to calculate the mass of an armour layer unit. This formula is based on a large number of model tests, with non-overtopped rock structures with permeable core under regular wave action.

\[
W_{50} = \frac{\rho_r \ g \ H^3}{K_D \Delta^3 \cot \alpha}
\]  

(1)

in which:

- \(W_{50}\) = Average rock weight;
- \(g\) = Gravity acceleration;
- \(\rho_r\) = Mass density of rocks;
- \(H\) = Characteristic wave height at the toe of the structure;
- \(K_D\) = Stability coefficient;
- \(\Delta\) = Relative buoyant density \(\left(\frac{\rho_r}{\rho_w} - 1\right)\);
- \(\alpha\) = Slope angle.

The Hudson formula is one of the most used, given its simplicity. However, it has some limitations:

- No account of the wave period and storm duration (number of waves);
- No account of wave breaking type;
- Limited description of the damage level;
- The use of non-overtopped and permeable structures only.

Nevertheless, some of these factors are implicitly included in the stability coefficient, \(K_D\). With concrete units, this value can include the type, shape, placement method of the block, as well as the roughness, interlocking and permeability of the layer. Regarding the damage level associated with this formula, for design purposes it is acceptable to consider that 0-5% of the armour layer is displaced. The recommended \(K_D\) values correspond to this “no damage” criteria.
Given the Hudson’s formula limitations, VAN DER MEER (1987) derived semi-empirical formulas based in factors like irregular wave action, permeability of the core, storm duration and also wave breaking type. Therefore, Van der Meer presented two formulas, for plunging (Eq. (2)) and surging (Eq. (3)) type breaking conditions for rock structures:

$$\frac{H_s}{\Delta D_{n50}} = 6.2 \, P^{0.18} \left( \frac{S}{\sqrt{N}} \right)^{0.2} \xi_m^{-0.5} \quad \text{(2)}$$

$$\frac{H_s}{\Delta D_{n50}} = 1.0 \, P^{-0.13} \left( \frac{S}{\sqrt{N}} \right)^{0.2} \sqrt{\cot \alpha} \, \xi_m^p \quad \text{(3)}$$

in which:

- \( H_s \) = Significant wave height at the toe of the structure;
- \( D_{n50} \) = Nominal diameter of stone;
- \( P \) = Permeability coefficient of the structure;
- \( S \) = Damage Level (ratio of eroded area in a certain cross-section);
- \( N \) = Number of waves;
- \( \xi_m \) = Breaker parameter or Iribarren Number.

In a subsequent study, VAN DER MEER (1988) has derived a similar formula for tetrapods placed in 1:1.5 slopes and deep water conditions:

$$\frac{H_s}{\Delta D_n} = \left[ 3.75 \, N_{od}^{0.5} \frac{N^{0.25}}{N^{0.25}} + 0.85 \right] s_{om}^{-0.2} \quad \text{(4)}$$

in which:

- \( D_n \) = Nominal diameter, in this case equivalent cube length, i.e. length of cube with the same volume of a tetrapod;
- \( N_{od} \) = Damage number, number of displaced out units of the armour layer within a strip width of one cube length \( D_n \);
- \( s_{om} \) = Average wave steepness.

Since Eq. (4) is only valid for surging waves, DE JONG (1996) developed a formula for tetrapods under plunging wave action:

$$\frac{H_s}{\Delta D_n} = \left[ 8.6 \, N_{od}^{0.5} \frac{N^{0.25}}{N^{0.25}} + 3.94 \right] s_{om}^{+0.2} \quad \text{(5)}$$

Nevertheless, Van der Meer and De Jong formulas have some restrictions:

- Limited to slopes of 1:1.5;
- Limited to surging and plunging wave breaking types, respectively.
SUH and KANG (2011) have developed a formula for tetrapods, based on model tests, which can be used for various slope angles and both wave breaking types:

\[
\frac{H_s}{A D_n} = \left[ 7.0 \frac{N_{od}}{N}^{0.3} + 1.66 \right] \xi_0^{0.1}
\] (6)

In the design of a breakwater, every stability formula should be regarded as no more than an indication for preliminary design of an armour layer. The results should be confirmed by other studies, namely physical model tests.

For tetrapod layer breakwaters, different placement methods with varied packing densities can be applied, which have been used and researched throughout the years. Although the impact of different placement methods on the stability of such breakwaters has been the purpose of many studies, there is still a need for research on this subject. The main objective of this research is to assess the impact of different placement methods on the hydraulic stability of tetrapod armour layers.

**EXPERIMENTS**

The experimental research was carried out in the wave flume of the Hydraulics and Water Resources Laboratory of Instituto Superior Técnico (IST). The wave flume (Figure 1) is 20 m long, 0.70 m wide and 1.00 m high. It is equipped with a piston-type wave-generator with a wave absorption unit that controls reflection. To measure the incident waves and enable the quantification of the reflected wave, four gauges were installed at constant water depth near the model toe.

![Wave flume](image)

Figure 1 – Wave flume (dimensions in meters).

During the design of a breakwater all failure mechanisms of the structure must be identified and analysed. This paper focuses only on the hydraulic stability of the armour layer. Therefore, the toe of the model consisted of a concrete test bar, which assured the toe stability. The same procedure was followed in the top of the model, to reduce the overtopping. The cross-section of the model is presented in Figure 2.
The used tetrapod blocks had an average mass \((M_a)\) of 192.5 g, an average height \((h)\) of 6.4 cm, a mass density \((\rho_c)\) of 2617 kg/m\(^3\) and an average volume of 73.5 m\(^3\). The nominal diameter \((D_n)\) can be defined by:

\[
D_n = \left(\frac{M_a}{\rho_c}\right)^{1/3}
\]

However, for tetrapods the nominal diameter is defined by another relation (VAN DER MEER, 1988):

\[
D_n = 0.65 \times h = 4.2 \text{ cm}
\]

The used tetrapod blocks were placed by hand on the trunk-section, which had a slope of 1:1.5. The core and the under layer material was chosen according to the general indications of USACE (2006) and CIRIA, CUR, CETMEF (2007). Two placement methods were tested, with the same packing density. The placed tetrapod layer was tested with irregular wave series, according to the JONSWAP spectrum. A total of eight experiments were performed, with a wave peak period of 1.40 s and four significant wave heights between 0.12 and 0.18 m. After every experiment, the armour layer was rebuilt. Each test was performed with a fixed cross-section, water depth, period and height. The cross-section was completely rebuilt before a new test was run. Each test was run in two stages: a first stage consisting of 1000 waves with the damage being recorded at the end, followed by a second stage consisting of 2000 waves and a cumulative damage recording.

Two placement methods were used. The first placement method (Figure 3) consists of a square mesh with the blocks rotated 180° in successive rows parallel to the slope, and inverted with identical modelling in the upper layer. The second placement method (Figure 4) consists of a triangular mesh with all the blocks placed in the same direction and the upper layer inverted, keeping the same modulation. Both placement methods have the same packing density.
The damage assessment was limited to the most active zone. In general, the majority of movements take place within the levels $SWL \pm H_s$ (FRENS, 2007), being $SWL$ the still water level and $H_s$ the significant wave height. In this case, considering the maximum significant wave height tested, a reference area within $SWL \pm 0.18 \ m$ was adopted. To visualize the movements within the armour layer, the overlay technique was used. Photos were made after each test from an exact location. Regarding damage, the blocks connecting to the glass of the wave flume were not included, not only for the different flow conditions in this area (HUGHES, 1993), but also for the possible wall-effect. These armour units are not connected to the other blocks at one side, which may influence their stability. According to the damage definition used in these studies (VAN DER MEER, 1988; FRENS, 2007), there is damage for movements greater than one nominal diameter. Two damage numbers were used (CIRIA, CUR, CETMEF, 2007): $N_d$ and $N_{od}$, respectively for the number of displaced armour units expressed as a percentage of the total
number of armour units in the active zone and the number of displaced armour units within a strip of breakwater slope of width $D_n$. Armour units may move under wave action but stay in their initial location. This type of movement, in which the block is disturbed but not displaced, is defined as rocking. This phenomenon can be relevant on concrete blocks, especially slender units like tetrapods, as rocking may cause breakage. Rocking is not typically recorded in many model tests due to the fact that armour blocks hardly break in small scale models. Regarding reflection, the incident energy wave spectrum was filtered by the data analysis software, in a slight adaptation of the method developed by MANSARD and FUNKE (1980).

RESULTS AND DISCUSSION

The relative damage with $N_d$ versus the stability parameter $N_s = H_s/\Delta D_n$ for both placement methods is plotted in Figure 5 and Figure 6, respectively for 1000 and 3000 waves.

![Figure 5 – Damage progress for N=1000.](image-url)
The damage concentration in the area of reference was almost total. While the blocks below the active zone did not show any damage, the upper blocks had some shifts, mostly caused by the damage of the active zone blocks that support them. In both placement methods tested, the armour layers suffered no significant damage. No block movement was greater than $2D_n$ and in no case the under layer was exposed. In all tests, it was impossible to observe the ruin of the breakwater. About the tested patterns, the test observation allows to conclude that in the first placement method the blocks show more points of contact with adjacent blocks than the second placement method.

CONCLUSIONS

The aim of this study was to research experimentally the impact of different placement methods on the hydraulic stability of a tetrapod breakwater’s armour layer. This was the first breakwater model tested in the wave flume of IST. There were some operational problems with the wave generator, which lead to the reduction of the number of tests originally planned. Still, the results are within the range of similar studies, suggesting that the model is valid for the focus of this project. Figure 7 and Figure 8 represent the Van der Meer formula (for tetrapods in a slope of 1:1.5) overlapping the obtained results, respectively for 1000 and 3000 waves. The plots suggest a reasonable match between the experimental results and the formula’s data. The first placement method approximates better the results of Van der Meer formula.
Despite the limited number of tests performed, it is possible to draw some conclusions. The experiments showed consistently that the first placement method displayed higher stability than the second placement method. Thus, placement methods with the same geometric parameters may have substantially different reactions to wave action. Placing a certain number of blocks per area of slope may not be enough. The geometry of the tetrapod layer may significantly influence the hydraulic stability of the armour layer and, as such, the durability of the structure. In addition to the packing density, the geometry of the layer may also be a factor to consider.
Considering the conclusions, it is possible to present some recommendations for future developments. Regarding the limited number of tests, it would be interesting to continue the study, testing other wave periods, in order to determine this parameter’s influence in the hydraulic stability of different placement methods. Constraints of the wave flume configuration and the probes dimensions discourage significant wave heights exceeding 0.18 m. With this wave parameters and the tetrapods used, it is impossible to have the ruin of the breakwater. It would be possible to use blocks with smaller dimensions, although the impact of the scale effects associated is unknown. There are significant differences between the placement of the blocks in the model (in dry conditions and by handpick), and in real breakwaters (with movement limitations of the equipment, wave conditions and reduced visibility). It would be interesting to undertake a similar study, placing the blocks under wave action with a miniature crane. This would not only approach the placement of the blocks of the used procedures but also test the applicability of the studied placement methods.

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LITERATURE CITED


