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Stability of breakwater roundhead protected with a Cubipod single-layer armor

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A B S T R A C T

This paper presents an analysis of the stability of breakwater roundheads protected with a Cubipod single-layer armor. This model was then subjected to a battery of 22 physical model tests, and the most significant variables were observed to be wave steepness (s_{pr}), the radius divided by the nominal diameter (R_n), and the relationship between the radius and wavelength at the breakwater toe (R/L_{rp}). It has been demonstrated that there are two behavioral patterns for stability according to the parameter R/L_{rp}, with large roundheads defined as $R/L_{rp} \geq 0.15$ and small roundheads as $R/L_{rp} < 0.15$. The stability reserve (SR [%]) was also calculated and it was demonstrated that this parameter decreased with an increase in steepness. A design criterion was also defined based on the stability reserve (SR [%]) of these kinds of structures. The stability coefficient (K_d) was calculated to account for initial damage, destruction, and the design stage, and it was verified that this parameter depends primarily on wave steepness, to which it is directly proportional. Finally, a comparison with double-layer armors was made confirming that under certain conditions, the single-layer ones have the same stability as the ones with double layer armors, but their behavior is more rigid.

1. Introduction

Roundheads are fundamental to the design of a breakwater. Its behavior is more fragile than that of the trunks. Moreover, the point at which the damage occurs depends on the direction of the incident wave. An overview of the main parameters affecting the stability can be found in [1]. According to recent research, one of the most significant parameters for the roundhead's stability is its radius at sea level (R); specifically the relative size of the roundhead with respect to waves, which is mainly defined using the parameters: ratio of roundhead radius to wavelength, R/L, [2–5], the ratio of roundhead radius to the nominal diameter of the armor layer $R_n = R/D_n$, [2,3], and the ratio of roundhead radius to the significant wave height, R/H_s [3].

In recent years, the design of the armor layer has been optimized due to newly developed pieces. Therefore, it is necessary to perform a thorough analysis of the hydraulic and structural stability, along with the damage and its evolution. There are three ways in which these elements dissipate wave energy: massive blocks (Antifer, Cubipod®, cubes, …) do so by their own weight, bulky elements (Xbloc®, Core-Loc®, …) use their interlocking capacity, and the third category uses a combination of both patterns (tetrapod, …). Furthermore, each of these elements has to be placed in a specific mode, either randomly or regularly using one or two layers.

The Cubipod was created in 2005. It is a massive piece that can be implemented in single and double-layer armor for both roundheads and trunks. Due to its geometrical characteristics, this element does not exhibit heterogeneous packing density [6]. Previous studies have been done on the stability trunks protected with double and single-layer armors, and roundheads with double-layer ones [7]. This book specifies the coefficient values for the stability coefficient (K_d) calculated using Eq. (1), where H_s is the significant wave height, N_s is the stability number, α is the slope angle, and ρ_r and ρ_w are the densities of concrete and water, respectively. In this book, $K_d = 7$ has been proposed for double-layer armors, whereas trunks have $K_d = 28$ and 12 for double-layer and single-layer armor, respectively.

$$K_d = N_s^3/\cot\alpha, \quad \text{where } N_s = H_s/\Delta D_n \text{ and } \Delta = \rho_r/\rho_w - 1 \tag{1}$$

So far, there has not been any exhaustive analysis of the roundhead stability of Cubipod single-layer armor. Only [8,9] have attempted to analyze the relevance of the roundhead's relative size and prove that, with all sea conditions being equal, roundheads of different sizes will have the same stability.

The most recent study on this kind of structure is mentioned in [10]. A brief summary of that paper is given here as it includes relevant information regarding the new analysis presented here. This study focuses on analyzing the damage and its evolution and makes a proposal for

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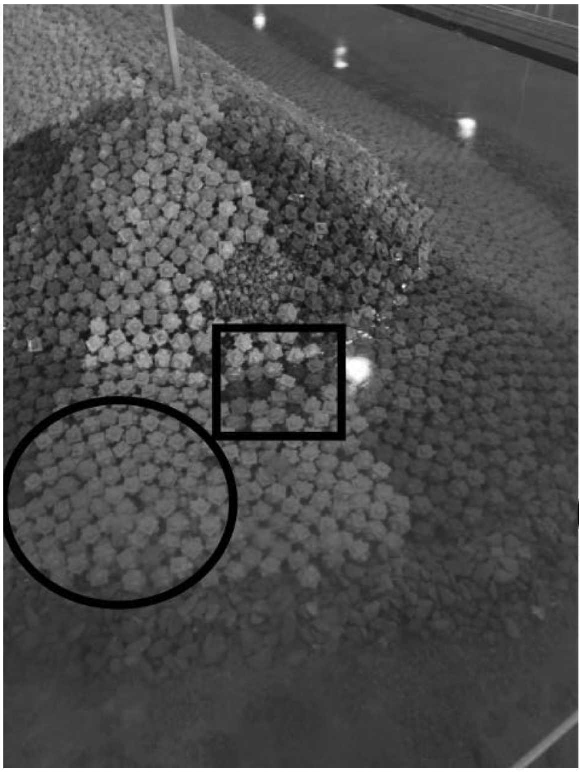

Fig. 1. Definition of a Cubipod that no longer provides stability to the roundhead, according to [10].

categorizing it into two levels. It has also defined a scenario when an element can no longer provide stability to the breakwater, though it has only been verified in two specific cases. In the first case, the Cubipod moves to the second layer (as shown by the circle in Fig. 1). These pieces cannot provide stability to the roundhead without the required lateral support. The second case occurs when the pieces move to the adjacent sector (as shown by the square in Fig. 1). In the roundhead area, sectors can be defined within a 45° range from the beginning to the end. The movements of these pieces have been proven to be random and thus cannot be defined by any parameters. Due to this, it is possible to underestimate the damage if these pieces were analyzed as providing stability to the sector that has moved.

In addition, this work has also proved that D [%] is the parameter that best describes the damage [10], defined in accordance with Eq. (2), where the size of the vertical active zone in such types of structure is 1.5 $H_{s.}$

$$D\,[\%] = Number\ of\ pieces\ fallen/Number\ of\ pieces\ in\ the\ active\ zone \tag{2}$$

[10] defined the two stages of damage: initial damage (ID) and destruction (DE). The first one is produced when the initial piece falls off the roundhead. The second occurs when the first filter piece is extracted. These two stages were quantified using a 5th percentile, with the values being $D_{ID\ 5^{th}}$ [%] = 0.4 for the ID and $D_{DE\ 5^{th}}$ [%] = 10.9 for DE.

One relevant aspect of single-layer armors is that classical levels of damage, as defined by [11], do not always have a possible direct application in this case. Some specific studies for this kind of armor layer were done by [12,13], defining the ID in terms of interlocking units as a percentage of pieces with rocking. On the other hand [14], defined the ID in massive pieces based on the settlements within single-layer armor of cubes. In addition, the conclusions obtained in [6,10] showed that the settlements of Cubipods did not exist in single-layer armor before the first piece fell down due to its geometric characteristics. Hence, these damage criteria cannot be applied directly to the single-Cubipod-layer armor. This fact reinforce the originality of the definition of ID and DE given by [10], and it could be used in other single-layer armor formed with massive pieces in which the settlements and rocking do not affect the initial stages of damage.

This paper presents a study of the stability of roundheads protected with a single-layer Cubipods armor by using a physical model test. The main objective is to analyze the use of this massive piece in roundheads with single-layer armor and derive their design formulas, which also involves studying the hydrodynamic and geometric parameters that influence stability. Additionally, different stability patterns have been presented as functions of the relative size parameters (R_n and R/L_{rp}) of the roundhead, thus confirming similar studies done in the past [3,4]. A design criterion was also defined based on the stability reserve (SR [%]). All the conclusions obtained from this work were included in the presented design formulas along with the stability coefficient (K_d) for the Hudson design formula [15]. Finally, a comparison was made between the stability of a single layer systems of Cubipod concrete armor unit and that of a double-layer Cubipod armor with this and other protection units, to compare the possible optimization in the future design of breakwaters.

2. Material and methods

The series of experiments in this study were carried out at the R&D Center for Technological Innovation in Construction and Civil Engineering (CITEEC) at the Universidade da Coruña, Spain. The center is equipped with a wave basin, whose dimensions are 32 × 28 × 1.2 m, which was utilized in this study with only half of its width (32 × 16 × 1.2 m). The wave front was created by using four paddles: three of them with length dimensions of 4.05 m and one with 2.05 m. These paddles were used to generate unidirectional waves with no absorption software being used and three beaches formed by rocks were located at the end of the wave basin for dissipation.

The bathymetry was parallel to the wave generation unit and had different slopes along the 24 m length of the wave basin. To be specific, it was formed by eight sections, with the first stretch having a 11% slope and the rest with a slope range between 0–2.18%. The objective of its design was to create different types of model placements depending on the existing bathymetry in each. Fig. 2 shows the layout of the

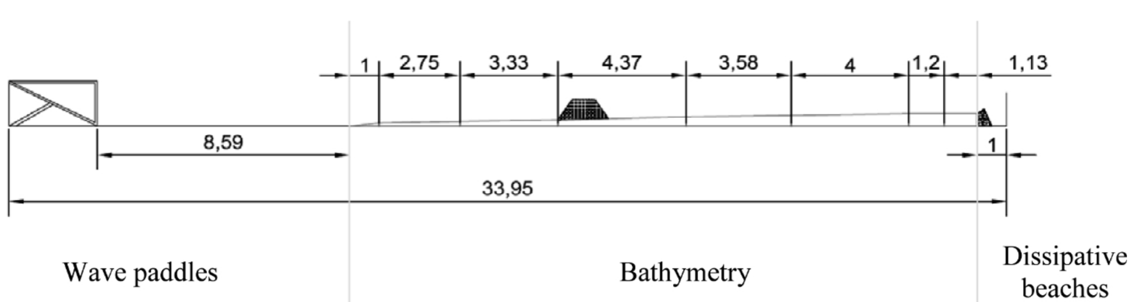

Fig. 2. Layout of a wave basin and bathymetric, and location of the model (units in m).