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Additional Information

# Heterogeneous Packing and Hydraulic Stability of Cube and Cubipod Armor Units

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## Abstract

This paper describes the Heterogeneous Packing (HeP) failure mode of breakwater armors. HeP reduces the packing density of the armor layer near and above the mean water level (MWL) and increases the packing density below the MWL; armor units can move in the armor layer, although they are not actually extracted from it. When HeP occurs, armor layer porosity is not constant, and measurements obtained with conventional methods underestimate actual armor damage. First, in this paper the Virtual Net (VN) method is proposed to calculate armor damage considering both armor unit extraction (AUE) and HeP. The Cubipod concrete armor unit (CAU) is then described as a solution to the effects of HeP on conventional cubic block armors. The hydraulic stability of cube and Cubipod CAUs was compared in 2D laboratory experiments. Cube and Cubipod armor layers were tested in two wave flumes under non-breaking and non-overtopping conditions. The hydraulic stability was higher for double-layer Cubipod armors than for single-layer Cubipod armors, which had a higher hydraulic stability than conventional double-layer cube armors.

**ASCE Subject Headings:** Breakwaters; Damage; Armor units; Stability; Laboratory tests; Concrete blocks.

**Author Keywords:** Mound Breakwaters; Hydraulic Stability; Armor units; Armor damage; Heterogeneous Packing; Cubipod.

## **1. Introduction**

For centuries, rubble mound breakwaters built with natural quarriestones have been constructed to protect harbors areas. Over time, larger ships meant that breakwaters had to be constructed in deeper waters and in harsher wave climates; thus, larger stones were needed for armor layers. Later, precast concrete cubes and parallelepiped blocks were introduced as artificial armor units in the 19<sup>th</sup> century, when local quarries were not able to provide stones of the appropriate size. Since then, numerous concrete armor units (CAUs) have been designed to optimize mound breakwaters and increase safety while reducing construction and maintenance costs, as well as carbon and energy footprints.

The armor layer is a critical factor in mound breakwater cost and safety, and armor erosion from wave attack is considered the primary failure mode and the first problem to be addressed in the design process. According to Bruun (1979), failure mechanisms for mound breakwaters can be grouped as (1) the hydrodynamic stability of armor units, (2) the structural integrity of the units, (3) the geotechnical stability of the granular system as a whole, and (4) construction mistakes. In this research, only the hydrodynamic stability of the armor layer caused by wave action on the slope is analyzed. Bruun (1979), Burcharth (1993) and CEM (2006) described four breakwater armor failure modes related to hydrodynamic stability: (1) armor unit rocking (AUR) in their positions, (2) armor unit extraction (AUE) during down-rush, (3) AUE during up-rush, and (4) armor layer sliding as a whole (ALS). AUR is related to armor unit breakage from fatigue, while AUE and ALS are due to the loss of units and the consequent erosion of

the armor layer and under-layers. CIRIA/CUR/CETMEF (2007) also linked the armor failure mode to the loss of armor units and erosion of the front face. Additionally, there are a few references to settlement caused by compaction of the armor (see CEM, 2006) or CAU settling related to packing density of the armor (see Muttray et al., 2005); however, no clear description is available for armor failure involving slight armor settlements parallel to the slope, which is denoted in this paper as the Heterogeneous Packing (HeP) (see Fig. 1). When cubes or parallelepiped blocks are used to build the armor, the HeP failure mode should be taken into consideration because these units tend to move slightly and to position themselves in face-to-face arrangements, which may significantly alter the porosity in different areas of the armor. The changes in porosity often lead to a higher packing density below the mean water level (MWL) and a lower packing density above and near the MWL, which are the two critical areas for armor stability.

If CAU structural integrity is guaranteed, armor erosion is caused by: (1) AUE, (2) ALS and (3) HeP. According to Vidal et al. (2006), armor damage can be measured using conventional methods: (1) armor profiling, (2) visual counting (VC) of units extracted and relocated above the upper layer, and (3) visual estimation of displaced units. Armor profiling and VC assume constant porosity of the armor and do not take into account changes in porosity due to HeP. In this paper, the Virtual Net (VN) method is proposed to measure armor damage, considering AUE, ALS and HeP failure modes simultaneously.

Cubes and parallelepiped blocks have long been used for mound breakwaters around the world, and they are the CAUs most frequently used along the Spanish coast. Conventional cubes are massive CAUs, which have several advantages over bulky and slender CAUs: high structural strength, cheap molds, high production rate, easy handling with pressure clamps and efficient stacking in the block yard. However, Bruun (1979) attributed ALS to insufficient friction between the cube armor and the rock under-layer. Other disadvantages of cubic

blocks, namely low hydraulic stability, tendency to face-to-face fittings, high overtopping rates and high HeP during the placement and breakwater lifetime, have been described previously by Gómez-Martín and Medina (2007 and 2008). These researchers have designed the Cubipod, a massive CAU to maintain the advantages of the conventional cube while correcting its shortcomings by increasing hydraulic stability and friction with the filter layer, avoiding face-to-face fitting, and reducing HeP and overtopping rates.

The aim of this research is to analyze the hydraulic stability and HeP of massive cube and Cubipod CAUs in the trunk section of mound breakwaters. In this paper, the concepts of armor damage and HeP are defined, and the VN method is proposed to measure armor damage with significant HeP. Secondly, the experimental setup is described, for the cube and Cubipod armored model tests, carried out in the wave flumes at the *Universitat Politècnica de València* (UPV) and the *Instituto de Hidrodinámica Aplicada* (INHA). Thirdly, armor damage measurements with VC and VN methods are compared. Finally, the measured stability numbers ( $N_s$ ) for Initiation of Damage (IDa) and Initiation of Destruction (IDe) are analyzed for double-layer cube and Cubipod armors as well as for single-layer Cubipod armors.

## **2. Armor damage**

Mound breakwaters are designed to force waves to break on the slope. Wave forces acting on units in the armor layer are determined by a number of environmental and structural variables, including significant wave height and period, wave direction, storm duration and core permeability; if wave forces exceed a certain limit, armor units may move from their original positions and the armor may be damaged. The CEM (2006) distinguished between armor hydraulic stability and structural integrity of CAUs; as indicated in the introduction, only the hydrodynamic stability failure modes, AUR, AUE, ALS, and HeP are considered in this paper

(see Fig. 1).

*[Insert Fig. 1 here]*

### **2.1. Armor Unit Extraction (AUE) and Armor Layer Sliding (ALS) failure modes**

The purpose of the armor layer in a mound breakwater is to prevent the wave action from extracting stones from the under-layers and the breakwater core. If CAU integrity is guaranteed, AUR is irrelevant and failure is caused primarily by units being removed from the armor layer, which exposes the under-layer. Armor damage is usually calculated in terms of unit loss from the armor layer. AUE is the main failure mode used to describe armor erosion, and popular methods for measuring armor damage, such as armor profiling and visual unit counting (see Vidal et al., 2003), calculate AUE assuming constant armor porosity. ALS is usually related with steep slopes and/or insufficient friction with the under-layer. ALS also affects high-porosity cube armors, as described by Bruun (1979), if filter rocks are too small to generate sufficient friction with the under-layer.

HeP is caused by the CAUs' natural tendency to reduce armor layer porosity under the MWL and increase porosity above and near the MWL. AUE is the most common failure mode of armor layers under wave attack; however, AUE is always accompanied by HeP. So while HeP may be negligible in quarrystone armors, it should be taken into account when designing artificial CAU armors as neither armor layer porosity nor packing density is constant during the construction process and breakwater service time.

### **2.2. Heterogeneous Packing (HeP) failure mode**

It is well known that for both small-scale models and prototypes, cubic blocks are difficult to place randomly in conventional double-layer armors (see Medina et al., 2010a). Gómez-Martín and Medina (2006) found that cube CAUs in conventional double-layer armors have a tendency to face-to-face positioning, even though no cube is extracted from the armor during wave attack. Although the breakwater armor was constructed with a homogeneous porosity,

the gravitational tendency of cube units reduces the porosity in the lower area of the armor, resulting in a significantly higher porosity in the upper area of the armor, accompanied by a decrease in placing and packing density above and near the MWL, with the subsequent exposure of the armor sub-layer. This armor damaging process without AUE was denominated the HeP failure mode by Gómez-Martín and Medina (2006 and 2007).

The HeP process is relevant in the case of cubes and other CAUs, which tend to undesired face-to-face arrangements. The effect of HeP is similar to the erosion caused by AUE and ALS, because the reduction in the local packing density around the MWL may facilitate the extraction of armor units from the under-layer. The relative impact of the HeP failure mode depends on four main factors: (1) armor unit geometry, (2) difference between the initial and the minimum armor porosity, (3) armor layer slope, and (4) friction between armor layer and the under-layer. While HeP is easy to detect in cube armored breakwaters, HeP occurs to a greater or lesser degree with any CAU; in fact, most armor settlements reported in the literature are caused by HeP.

As mentioned in the introduction, the conventional cube is known for its logistical advantages, but also for its significant shortcomings, which increase HeP and the risk of ALS. According to Medina et al. (2010a), while it is quite difficult to obtain an initial random placement of cube blocks in the armor, it is nearly impossible to maintain the initial randomness in the long-term because of the cube's tendency to face-to-face arrangements.

Gómez-Martín and Medina (2007) designed the Cubipod, a massive CAU, which is a cubic block with pyramidal frustum protuberances on the faces, designed to prevent face-to-face coupling, separate the adjacent units and increase friction with the under-layer. Previous studies indicated that the Cubipod CAU significantly increases hydraulic stability, reduces runup and overtopping, and increases friction with the under-layer (see Medina et al., 2010b). Cubipods can be used in single- and double-layer armors. Finally, the Cubipod tends to self-

position randomly on the slope with uniform porosity maintained over time and, as will be explained later, this can reduce the relative impact of HeP.

### 2.3. Armor Damage Measurement

Although it is relatively easy to define qualitatively, it is not so easy to formulate a precise quantitative definition for armor damage. Armor damage can be calculated either by counting the displaced units or by armor profiling. Displacement can then be defined, for example, as units being removed from the armor layer, or units moving more than a minimum distance ( $D_n$ ) on the slope. Three quantitative armor damage definitions are given in the literature: (1)  $D\%$  = percentage of displaced units, (2)  $N_{od}$  = relative damage number, and (3)  $S$  = dimensionless armor damage.

The SPM (1984) and CEM (2006) defined the percent of damage,  $D\%$ , as the ratio of armor units displaced from the breakwater active armor removal zone. To measure damage in CAU armors, Van der Meer (1988a) proposed the relative damage number,  $N_{od}$ , which is defined as the number of units displaced out of the armor layer ( $N_e$ ) within a vertical strip of width  $D_n$  stretching from the bottom to the top of the armor. Finally, the dimensionless armor damage parameter  $S=A_e/D_n^2$ , proposed by Broderick (1983) and popularized by Van der Meer (1988b), is widely used to measure armor damage, whereby  $A_e$  is the average eroded cross-sectional area, and  $D_n=(M/\rho_r)^{1/3}$  is the equivalent cube size or nominal diameter;  $M$  is the armor unit mass, and  $\rho_r$  is the armor unit mass density.  $A_e$  can not only be measured using mechanical or laser profilers, but it can also be estimated using the VC method, as reported by Vidal et al. (2006), assuming constant armor porosity during the erosion process.

With the conventional VC method, the visually eroded area in the breakwater sections ( $A_{ev}$ ) is defined using Eq. 1 and the visual dimensionless damage parameter ( $S_v$ ) using Eq. 2.

$$A_{ev} = \frac{N_e D_n^3}{((1 - p\%) b)} \quad (1)$$



$$S_v = \frac{A_{ev}}{D_n^2} \quad (2)$$

where  $N_e$ = number of extracted units relocated above the upper layer;  $p\%$ = armor porosity, and  $b$ = observed width of the tested section. It is worth noting that  $S$ ,  $N_{od}$  and  $D\%$ , frequently used in the literature to measure armor damage, can only be related to each other with caution. To analyze armor damage in trunks and roundheads, Vidal et al. (2003 and 2006), Gómez-Martín and Medina (2006) and Lomónaco et al. (2009) used qualitative approaches along with two quantitative damage measurement methods based on: (1) percentage of visually counted displaced units and (2) laser or mechanical armor profiles. The accuracy and sensitivity of  $S_v$  and profile-based damage,  $S_p$ , depend on the damage level. If only a few stones or CAUs are displaced,  $S_v$  is more accurate than  $S_p$ ; however, as the damage level increases, profile-based armor damage,  $S_p$ , is more reliable (see Vidal et al., 2003).

Gómez-Martín and Medina (2004) described quantitative methods like VC, photo measurements and profile measurements, and showed VC to be a precise and reliable method for calculating low and moderate armor damage levels in rubble mound breakwaters. Later, Gómez-Martín and Medina (2006) proved that conventional methods based on VC were inadequate when CAUs showed significant HeP, as in the case of cube armors.

Regardless of the quantitative armor damage definition used, two qualitative armor damage limits are frequently considered in the literature: IDa and IDE. The most popular armor damage limit found in the literature, “No-damage”, “start of damage” or IDa is used to refer to the limit below which CAUs do not move significantly. “Failure” or IDE, frequently refer to a damage level in which the filter layer is visible and indicate the limit above which progressive failure can occur.

Until now, there have been two main approaches for assessing armor damage, one based on quantitative criteria and the other based on qualitative criteria regarding changes in the protection of the under-layer. While a quantitative analysis may lead to reasonably objective

numerical values for armor damage, it can not always provide sufficient information as to the severity of damage, as this depends on the geometry of the sections and on the spatial distribution of damage on the slope. The advantage of qualitative criteria is that they provide intuitive information regarding the actual severity of damage. A combination of quantitative and qualitative criteria is, therefore, used in this paper to assess armor damage.

Following the criteria given by Losada et al. (1986) and Vidal et al. (1991), four qualitative armor damage levels may be considered for conventional double-layer armors: (1) IDa, when the upper armor layer has lost some units, (2) Initiation of Iribarren's Damage (IIDa), described by Iribarren (1965), when damage in the upper armor layer has spread over an area large enough to permit the extraction of units from the bottom armor layer, (3) IDe, when one or more units from the bottom armor layer have been removed and the filter is clearly visible, and (4) Destruction (De), when several stones from the filter layer have been removed. These qualitative armor damage levels are based on photographic visual analysis after each test run.

In this paper, a detailed quantitative analysis was conducted using both the conventional VC method described by Vidal et al. (2006) as well as the VN method proposed by Gómez-Martín and Medina (2006). When HeP is significant, the porosity of the armor layer changes in time and space and Eq. 1 is no longer valid. The VN method projects a virtual net over the photographed armor dividing it into strips of a constant width. The armor units whose center of gravity is within each strip ( $N_i$ ) are counted, and the porosity of each strip before and after the wave attack can be estimated using Eq. 3, where  $a=m*D_n$  and  $b=k*D_n$  are the strip width and length. Accordingly, the dimensionless armor damage in each strip ( $S_i$ ) is calculated using Eq. 4, where  $m$  is the number of rows in each strip;  $p_i$  is the porosity of the strip  $i$  after the wave attack, and  $p_{0i}$  is the initial porosity in strip  $i$ . Integrating these dimensionless armor damages over the slope, the equivalent dimensionless armor damage parameter ( $S_e$ ) can be obtained using Eq. 5, where  $I$  is the number of strips. This method takes into account AUE,

ALS and HeP failure modes. If any one of the three failure modes is significant,  $S_e$  provides a reasonable measurement of the integrated effects.

$$p_i = 1 - \frac{N_i D_n^2}{(a b)} = 1 - \frac{N_i}{m k} \quad (3)$$

$$S_i = m \left( 1 - \frac{1 - p_i}{1 - p_{0i}} \right) = m \left( \frac{p_i - p_{0i}}{1 - p_{0i}} \right) \quad (4)$$

$$S_e = \sum_{i=1}^I S_i \quad \forall S_i \geq 0 \quad (5)$$

Even though both methods (VC and VN) provide values for dimensionless damage without taking into account the number of layers in the armor (single- or double-layer), the values reflect the total damage of the upper armor layer. Therefore, dimensionless armor damage values for double-layer armors are not directly comparable with those for single-layer armors. In single-layer armors, S-values for IDa are similar to S-values for IDe, but these values are quite different in double-layer armors.

### 3. Experimental Design

In order to analyze the hydraulic stability of conventional cube and Cubipod CAUs, similar 2D tests with H/V=2/3 slope breakwater models were carried out in the wave flumes of the Laboratory of Ports and Coasts at the *Universitat Politècnica de València* (UPV) and the *Instituto de Hidrodinámica Aplicada* (INHA) in Cerdanyola del Vallés (Barcelona). Single-layer and double-layer armors were tested under non-breaking and non-overtopping conditions. The characteristics of the core, filter, and armor layers are specified in Table 1. 2D hydraulic stability tests using random waves were conducted in the UPV and INHA laboratories with runs of 1000 waves. Tests were grouped in series of constant wave steepness having target Iribarren numbers  $2.9 < I_{rp} = (2/3) T_p / (2\pi H_{m0}/g)^{0.5} < 5.6$ , where  $T_p$  is the peak period and  $H_{m0}$  is the incident significant wave height, which was increased progressively from zero

damage to destruction. The LASA-V method (see Figueres and Medina, 2004) was used to estimate incident and reflected waves since it analyzes both non-stationary and non-linear waves. The armor was photographed before and after each run of waves, allowing armor damage to be measured with the VC and VN methods described previously. The VN method was applied to the photographs taken perpendicular to the armor so as to calculate the corresponding equivalent dimensionless damage parameter,  $S_e$ , given by Eq. 5. The VC method requires counting  $N_e$  to calculate  $S_v$  given by Eq. 2. The breakwater model was rebuilt after each series of tests, with constant  $I_{rp}$ .

*[Insert Table 1 here]*

### **3.1. UPV hydraulic stability tests**

Double-layer cube and Cubipod armor models were tested. The UPV wave flume is 30.0m long, 1.2m wide and 1.2m deep. The wavemaker was a piston-type paddle that generates regular and irregular waves. Water surface elevation was measured using capacity wave gauges at eight points along the wave flume. One group of wave gauges was placed near the model and the other group near the wavemaker. The water depth was  $h[\text{cm}]=50$  by the model and  $h[\text{cm}]=75$  by the wavemaker with a 4% slope transition. The breakwater section had a core with  $D_{n50}[\text{cm}]=0.70$ , a filter layer with  $D_{n50}[\text{cm}]=1.80$  and a conventional double-layer armor with randomly placed units. Using the same core and filter layer, two breakwater models were tested with two different CAUs: cubes with  $D_n[\text{cm}]=4.00$ , and Cubipods with  $D_n[\text{cm}]=3.82$ . The crest freeboards of the double-layer cube and Cubipod models were  $R_c[\text{cm}]=+40.0$  and  $+39.6$ , respectively (see Fig. 2). The initial armor porosities were  $p\%\approx 37\%$  for cube armors and  $p\%\approx 41\%$  for Cubipod armors. The bottom armor layer was painted white (cube model) and black (Cubipod model) to enhance color contrast while the upper armor layer was constructed with strips of different colored units to facilitate the visual counting.

*[Insert Fig. 2]*

15 irregular wave tests were conducted with runs of 1000 waves following JONSWAP spectra ( $\gamma=1.0$ ) of constant wave steepness with target  $2.9 < I_{rp} < 5.6$ . The target wave characteristics are indicated in Table 2.

*[Insert Table 2 here]*

### **3.2. INHA hydraulic stability tests**

Single- and double-layer Cubipod armors were tested. The INHA wave flume is 52.0m long, 1.8m wide and 2m deep. The wavemaker was a piston-type paddle that generates regular and irregular waves. Four capacity wave gauges were placed in front of the structure to measure water surface elevation. The water depth was  $h[\text{cm}]=60$  by the model and  $h[\text{cm}]=95$  by the wavemaker with a 1.55% slope transition. The breakwater section had a core with  $D_{n50}[\text{cm}]=0.25$ , a filter layer with  $D_{n50}[\text{cm}]=1.25$ , and an armor layer built with randomly placed Cubipod units with  $D_n[\text{cm}]=3.82$ ,  $\rho_r[\text{g}/\text{cm}^3]=2.30$ , and  $M[\text{g}]=128$ . Using the same core and filter layer, two cross-sections were tested: single-layer and double-layer Cubipod armors. These cross-sections were similar to those tested at the UPV with minor differences, namely the core crest elevation +55.7 cm above SWL instead of +25.3 cm, and a slight difference in core permeability. The core crest width was 24.0 cm; the filter layer was 6.7 cm thick, and the Cubipod armor layer was placed on top of the filter layer. The crest freeboards of the single-layer and double-layer models were  $R_c[\text{cm}]=+66.2$  and  $+70.0$ , respectively. The initial porosities of the armor layers were  $p\% \approx 40\%$ . The bottom armor layer was painted black for contrast and the upper armor layer was painted in strips of different colors in order to detect armor unit movements.

Considering a 1/50 scale, the Cubipod units used in these tests were equivalent to the 16-tonne Cubipod CAUs previously subjected to prototype drop tests (see Medina et al., 2011). A total of 11 irregular wave tests with the target parameters indicated in Table 3 were conducted with runs of 1000 waves following JONSWAP spectra ( $\gamma=3.0$ ) of constant wave

steepness with target  $2.9 < I_r < 4.9$ . Additionally, one irregular test was conducted increasing significant wave height from zero damage to destruction and maintaining constant a peak period typical for the Mediterranean,  $T_p[s]=10$  (prototype scale).

*[Insert Table 3 here]*

## **4. Analysis of hydraulic stability test results**

### **4.1. UPV test results**

Double-layer cube and Cubipod test results were analyzed. Armor damage measurements were obtained using the VC and VN methods described previously.  $S_v$  obtained with the VC method for cube and Cubipod tests was lower than the  $S_e$  obtained with the VN method. The VC method did not take into account HeP or ALS; thus, VC underestimated the reduction in the placing density near the MWL. If HeP was significant but no armor unit was extracted, the VC method provided a “zero damage” observation. Table 4 indicates the average  $S_v$  using the VC method and the  $S_e$  obtained with the VN method for double-layer cube and Cubipod armors; the conventional VC method significantly underestimated armor damage. Moreover, from Table 4 it is clear that the relative difference,  $(S_e - S_v)/S_e$ , increased faster for cubes than for Cubipods as armor damage increased.

*[Insert Table 4 here]*

The VC and VN methods provided significantly different measurements for cube armors, while there were only slight differences for Cubipod armors. These differences were larger if the initial porosity of cube armors were higher than  $p\%=37\%$ , e.g. 41% or 45%, corresponding to common prototype porosities. The VN method provided better measurements for damage, taking into account the different porosities in each of the armor areas. However, neither the VC nor the VN method considered changes in the porosity of the bottom armor layer.

Porosity refers to the percentage of voids in a granular system. In this paper, armor porosity is defined as  $p\%=(1-\Phi/n)$ , in which  $\Phi$  is the packing density and  $n$  is the number of CAU layers in the armor;  $n=1$  and  $n=2$  for single- and double-layer armors, respectively. The placing density  $\phi$ [units/m<sup>2</sup>] is related to the packing density ( $\Phi$ ) by  $\phi=\Phi/(D_n)^2$ , where  $D_n$ [m] is the nominal diameter or equivalent cube size of the CAU.

Table 5 provides the average values of strip porosity ( $p$ [%]) in the upper layer around the MWL for UPV double-layer cube and Cubipod armors before and after the wave attack when damage was lower than IDa.

*[Insert Table 5 here]*

Considering only the upper layer of the armor, the initial porosity of each strip in the cube model was between  $35\%<p\%<37\%$ ; after a number of wave runs (lower than IDa), HeP was significant, and the porosity of each strip varied between  $33\%<p\%<40\%$ . Gravity tended to reduce the porosity in the lower part of the breakwater ( $33\%<p\%<34\%$ ) and increase the porosity in the upper part ( $38\%<p\%<40\%$ ), which led to maximum strip porosity increments  $\Delta p\%=\pm 4\%$ .

On the other hand, the initial porosity of each strip in the Cubipod model was  $40\%<p\%<42\%$  before the wave attack and in the range of  $39\%<p\%<43\%$  after the wave attack (lower than IDa), with maximum strip porosity increments  $\Delta p\%=\pm 1\%$ . HeP is lower in Cubipod armors than in cube armors because the protuberances on the faces of the Cubipod prevent face-to-face fittings.

The damage to the breakwater armor layer was calculated qualitatively after each test run by visually analyzing the model and the photographs. Three damage levels were considered in the experiments: IDa, IIDa and IDE. The average quantitative equivalent dimensionless damage values corresponding to these qualitative damage levels were:  $S_e$ [IDa] $\approx 1.0$ ,  $S_e$ [IIDa] $\approx 3.4$  and  $S_e$ [IDE] $\approx 8.3$  for double-layer cube armors and  $S_e$ [IDa] $\approx 1.0$ ,  $S_e$ [IIDa] $\approx 3.7$

and  $S_e[\text{IDe}] \approx 9.9$  for double-layer Cubipod armors.

According to Medina et al. (1994), rough quarrystone armor damage observations provided by SPM (1984) and Van der Meer (1988b) follow the one-fifth power relationship; therefore, the linearized equivalent dimensionless armor damage  $S_e^* = S_e^{1/5}$  is used in this paper for cube and Cubipod armors.

The generalized Hudson's formula can be written as

$$M = \frac{1}{K_D} \frac{H_{sd}^3}{\left(\frac{\rho_r}{\rho_w} - 1\right)^3} \cot \alpha \quad (6)$$

where  $M$  is the armor unit mass;  $K_D$  is the stability coefficient;  $\rho_r$  and  $\rho_w$  are the mass density of the armor units and water, respectively;  $H_{sd}$  is the design significant wave height at the structure site, and  $\alpha$  is the slope angle of the structure. Eq. 6 can be re-written as

$$N_{sd} = \frac{H_{sd}}{\Delta D_n} = (K_D \cot \alpha)^{1/3} \quad (7)$$

where  $N_{sd}$  is the design stability number;  $\Delta = (\rho_r/\rho_w - 1)$ , and  $D_n = (M/\rho_r)^{1/3}$ . For a given armor damage,  $N_{sd}$  is directly proportional to the cubic root of  $K_D$ .

The linearized equivalent dimensionless armor damage  $S_e^* = S_e^{1/5}$  obtained in the UPV experiments is represented in Fig. 3 as a function of the measured stability number,  $N_s = H_{m0}/(\Delta D_n)$ . For comparison purposes, the simplified model proposed Medina et al. (1994) can be used to compare different failure functions corresponding to different CAUs.

$$S_e^* = S_e^{1/5} = (1.6)^{1/5} \left(\frac{4}{K_D}\right)^{1/3} \frac{N_s}{(4 \cot \alpha)^{1/3}} \approx 0.96 \frac{N_s}{K_D^{1/3}} \quad (8)$$

**[Insert Fig. 3 here]**

Fig. 3 shows the failure functions given by Eq. 8 corresponding to cubes and Cubipods using the  $K_D$  proposed by Medina et al. (2010b);  $K_D=6$  and  $K_D=28$  for double-layer cube and Cubipod armors, respectively. The qualitative armor damage levels are indicated by the



horizontal lines representing IDa ( $S_e=1.0$  for cubes and Cubipods), IIDa ( $S_e=3.4$  for cubes and  $S_e=3.7$  for Cubipods) and IDE ( $S_e=8.3$  for cubes and  $S_e=9.9$  for Cubipods).

Fig. 4 shows the measured stability numbers (incident waves) corresponding to IDa (white), IIDa (grey) and IDE (black) for double-layer cube (squares) and Cubipod (triangles) armors. The hydraulic stability of double-layer Cubipod armors ( $p\%=41\%$ ) is much higher than that of conventional double-layer cube armors ( $p\%=37\%$ ).

*[Insert Fig. 4 here]*

The stability numbers represented in Fig. 4 refer to approximately constant wave steepness runs with measured Iribarren numbers in the range  $3.0 < I_{rp} = (2/3)T_p / (2\pi H_{m0}/g)^{0.5} < 7.0$ , calculated using the incident significant wave height,  $H_{m0}$ , and the peak period,  $T_p$ . The experimental observations of  $N_s$  cube armors are in reasonable agreement with the results of the four cube tests reported by Van der Meer (1988a) and CEM (2006), although wave steepness did not reflect any clear influence on  $N_s$ . The IDa and IDE in double-layer Cubipod armors showed  $N_s(\text{IDa}) > 3.0$  and  $N_s(\text{IDE}) \approx 4.8$  (only one UPV test with Cubipods reached the IDE limit without overtopping).

### 4.3. INHA test results

Single- and double-layer Cubipod armors were tested. The armor damage was evaluated qualitatively after each test run by visually analyzing the model and the photographs. Three qualitative damage levels were considered in the experiments: IDa, IDE and De.

Fig. 5 provides the observed stability numbers (incident waves) for single-layer (circles) and double-layer (triangles) Cubipod armors, from IDa (white) to IDE (black) or De (grey).

*[Insert Fig. 5 here]*

The stability numbers in Fig. 5 refer to approximately constant wave steepness runs with measured Iribarren numbers in the range  $2.5 < I_{rp} = (2/3)T_p / (2\pi H_{m0}/g)^{0.5} < 7.0$ . The IDa limit for double-layer Cubipod armors (white triangles) appears to be independent of wave steepness,

$N_s(\text{IDa}) \approx 3.4$ ; by contrast, the  $\text{IDe}$  limit for the double-layer Cubipod armors (black triangles) seems to be dependent on wave steepness, with the minimum value of  $N_s(\text{IDe}) \approx 4.0$  for the lowest  $\text{Ir}_p \approx 2.5$ .

The 2D hydraulic stability test results obtained at the INHA and the UPV wave flumes for the double-layer Cubipod armors agreed. In the case of single-layer Cubipod armors, the stability numbers for  $\text{IDa}$  and  $\text{IDe}$  showed minimum values  $N_s(\text{IDa}) = 2.8$  and  $N_s(\text{IDe}) = 3.4$ , lower than  $N_s$  for double-layer Cubipod armors but higher than  $N_s$  for double-layer cube armors.

## **6. Summary and conclusions**

The hydraulic stability of armor layers of mound breakwaters has been thoroughly studied over the years. Most authors consider armor unit extraction (AUE) and armor layer slides as a whole (ALS) as the main failure modes of the armor layer, as long as the structural integrity of armor units is guaranteed. This description is reasonable for quarystone armors; however, when concrete armor units (CAUs) are used, the natural tendency of CAUs to packing, produces changes in the porosity of the armor layer over space and time. The packing density of the armor layer is reduced near and above the Mean Water Level (MWL), as units move within the armor layer without being fully extracted. In this paper, this failure mode is called Heterogeneous Packing (HeP). Thus, armor damage may be attributed to three different failure modes: AUE, ALS and HeP; the three failures modes produce the same effect: a decrease in the placing density ( $\phi$ [units/m<sup>2</sup>]) near and above the MWL. The HeP failure mode affects the armor layer of mound breakwaters regardless of the CAU used, but the effects are highly significant when using armor units with flat faces, such as cubes or parallelepiped blocks.

Armor damage can be defined quantitative and qualitatively. Four qualitative damage levels are considered in this paper for double-layer armors: Initiation of Damage (IDa), Initiation of

Iribarren Damage (IIDa), Initiation of Destruction (IDe) and Destruction (De). Only three damage levels are relevant for single-layer armors: IDa, IDe and De. For this research, the quantitative damage analysis was conducted using both the conventional visual counting (VC) method described by Vidal et al. (2006) and the virtual net (VN) method used by Gómez-Martín and Medina (2006). Conventional VC methods for armor damage measurement are inadequate if HeP or ALS is significant because armor porosity is not constant. The VN method takes into account the effects of AUE, ALS and HeP failure modes. The results in table 4 show that the VC method significantly underestimates armor damage measurements and HeP is greater for cubes than for Cubipods. Although the VN method provides less biased armor damage measurements than the VC method, neither VC nor VN contemplates the damage caused by HeP to the bottom armor layer in double-layer armors.

Finally, this study analyzed the hydraulic stability of massive cube and Cubipod CAUs in the trunk section of mound breakwaters. Results from 2D hydraulic stability tests, carried out in similar conditions in two different laboratories, allowed for estimations of the stability number ( $N_s$ ) for single- and double-layer Cubipod armors and double-layer cube armors under non-breaking and non-overtopping conditions. Tests with an approximately constant wave steepness were carried out with Iribarren numbers in the range  $2.5 < I_{rp}(\cot\alpha=1.5) < 7.0$ ; and proved that both single- and double-layer Cubipod armors are much more stable than conventional double-layer cube armors.

The results from the UPV experiments, with the double-layer cube armors, showed stability numbers in agreement with results for the four cube tests reported by Van der Meer (1988a) and recommended by CEM (2006); however,  $N_s(\text{IDa}) \approx 2.0$  and  $N_s(\text{IDe}) \approx 3.0$  values observed in cube tests show no clear influence on wave steepness. Regarding the IDa and IDe for double-layer Cubipod armors, results obtained in UPV and INHA tests showed  $N_s(\text{IDa}) > 3.0$  and  $N_s(\text{IDe}) > 4.0$ . For single-layer Cubipod armors,  $N_s(\text{IDa}) > 2.8$  and  $N_s(\text{IDe}) > 3.4$ , which are

values lower than  $N_s$  for double-layer Cubipod armors but higher than the  $N_s$  obtained for double-layer cube armors.

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## Notation

The following symbols are used in this paper:

$a$  = strip width (m  $D_n$ )

$A_e$  = average eroded cross-sectional area

$A_{ev}$  = average visual eroded cross-sectional area

$b$  = strip length (k  $D_n$ ) of the tested section

$D\%$  = percentage of displaced units

$D_n = (M/\rho_r)^{1/3}$  = equivalent cube size or nominal diameter of the armor units

$D_{n50}$  = equivalent cube size of a stone whose mass does not exceed 50% percentile

$g = 9.81 \text{ m/s}^2$  = gravity acceleration

$h$  = water depth

$H$  = wave height

$H_d$  = design wave height

$H_{m0} = 4 (m_0)^{1/2}$  = significant wave height

$I_{rp} = \tan \alpha / (H_{m0}/L_p)^{1/2} = T_p \tan \alpha / (2\pi H_{m0}/g)^{1/2}$  = Iribarren's number associated to  $H_{m0}$  and  $T_p$

$K_D$  = stability coefficient in Hudson's formula

$M$  = armor unit mass

$n$  = number of layers in the armor

$N_e$  = number of extracted armor units relocated above the upper layer

$N_i$  = number of armor units whose center of gravity is within strip  $i$

$N_{od}$  = relative damage number

$N_s = H_{m0}/(\Delta D_n)$  = stability number

$N_s(IDa)$  = stability number corresponding to IDa

$N_s(IDE)$  = stability number corresponding to IDE

$N_{sd} = H_d/(\Delta D_n)$  = design stability number

$N_w$  = number of waves

$p\%$  = porosity of the armor layer

$p_{0i}$  = porosity of strip  $i$  before wave attack

$p_i$  = porosity of strip  $i$  after wave attack

$R_c$  = crest freeboard

$S$  = dimensionless armor damage

$S^* = S^{1/5}$  = linearized dimensionless armor damage

$S_e$  = equivalent dimensionless armor damage

$S_e^* = S_e^{1/5}$  = linearized equivalent dimensionless armor damage

$S_i$  = dimensionless damage in strip  $i$

$S_p$  = profile dimensionless damage

$S_v$  = visual dimensionless damage

$T_p$  = peak period of a sea state

$\Delta = (\rho_r/\rho_w - 1)$  relative submerged mass density

$\Delta p$  = porosity increment

$\phi$ [units/m<sup>2</sup>] = placing density

$\Phi$  = packing density

$\gamma$  = peak enhancement factor

$\rho_r$  = armor unit mass density

$\rho_w$  = water mass density

The following acronyms are used in this paper:

ALS = Armor Layer Slides

AUE = Armor Unit Extraction

AUR = Armor Unit Rocking

CAU = Concrete Armor Unit

De = Destruction

HeP = Heterogeneous Packing

IDa = Initiation of Damage

IIDa = Initiation of Iribarren Damage

IDe = Initiation of Destruction

MWL = Mean Water Level

SWL = Still Water Level

VC = Visual Counting

VN = Virtual Net

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Table 1. Characteristics of the tested models.

Laboratory	Armor thickness		Armor unit			Filter		Core	
	Number of layers	Type	M [g]	D <sub>n</sub> [cm]	ρ <sub>r</sub> [g/cm <sup>3</sup> ]	Type	D <sub>n50</sub> [cm]	Type	D <sub>n50</sub> [cm]
UPV	2	Cube	140	4.00	2.18	gravel	1.80	gravel	0.70
	2	Cubipod	108	3.82	1.94	gravel	1.80	gravel	0.70
INHA	2	Cubipod	128	3.82	2.30	gravel	1.25	gravel	0.25
	1	Cubipod	128	3.82	2.30	gravel	1.25	gravel	0.25

Table 2. Test matrix for UPV irregular wave tests.

Test	Armor unit	Number of layers	I <sub>r</sub> (H <sub>m0</sub> , T <sub>p</sub> ) [cotα=1.5]	H <sub>m0</sub> [cm]	T <sub>p</sub> [s]	Waves per series
1	Cube	2	3.6	5.0 to 15.7	0.95 to 1.93	1000
2	Cube	2	3.6	5.0 to 16.4	0.95 to 1.99	1000
3	Cube	2	3.6	5.0 to 15.7	0.95 to 1.93	1000
4	Cube	2	4.2	5.0 to 15.0	1.16 to 2.50	1000
5	Cube	2	4.2	5.0 to 15.0	1.16 to 2.50	1000
6	Cube	2	4.2	5.0 to 15.0	1.16 to 2.50	1000
7	Cube	2	4.9	5.0 to 14.3	1.39 to 3.14	1000
8	Cube	2	4.9	5.0 to 14.3	1.39 to 3.14	1000
9	Cube	2	4.9	5.0 to 14.3	1.39 to 3.14	1000
10	Cube	2	5.6	5.0 to 12.9	1.70 to 3.74	1000
11	Cubipod	2	2.9	8.6 to 20.0	1.03 to 1.70	1000
12	Cubipod	2	3.6	5.0 to 17.1	0.98 to 2.06	1000
13	Cubipod	2	4.2	5.0 to 15.7	1.16 to 2.60	1000
14	Cubipod	2	4.9	8.6 to 15.0	2.03 to 3.28	1000
15	Cubipod	2	5.6	4.3 to 12.9	1.53 to 3.74	1000

Table 3. Test matrix for INHA irregular wave tests.

Test	Armor unit	Number of layers	I <sub>r</sub> (H <sub>m0</sub> , T <sub>p</sub> ) [cotα=1.5]	H <sub>m0</sub> [cm]	T <sub>p</sub> [s]	Waves per series
1	Cubipod	1	2.9	7.1 to 21.4	0.88 to 1.62	1000
2	Cubipod	1	2.9	7.1 to 17.1	0.88 to 1.40	1000
3	Cubipod	1	3.6	10.0 to 22.9	1.33 to 2.38	1000
4	Cubipod	1	4.2	10.0 to 20.7	1.68 to 2.99	1000
5	Cubipod	1	4.9	10.0 to 17.9	2.10 to 3.45	1000
6	Cubipod	1	3.7-2.6	10.0 to 20.0	1.4	1000
7	Cubipod	2	2.9	10.0 to 23.6	1.04 to 1.74	1000
8	Cubipod	2	3.6	12.9 to 23.6	1.55 to 2.44	1000
9	Cubipod	2	4.2	10.0 to 22.9	1.68 to 3.26	1000
10	Cubipod	2	4.9	10.0 to 20.0	2.10 to 3.83	1000
11	Cubipod	2	4.0-2.4	8.6 to 23.6	1.4	1000

Table 4. Mean values of dimensionless armor damage measurements for UPV double-layer cube and Cubipod models using Visual Counting (VC) and Virtual Net (VN) methods.

Type of armor unit	Damage level	DAMAGE MEASUREMENTS	
		Visual Counting (Sv)	Virtual Net (Se)
Cube (p%=37%)	IDa	0.2	1.0
	IIDa	2.2	3.4
	IDe	6.7	8.3
Cubipod (p%=41%)	IDa	0.2	1.0
	IIDa	2.8	3.7
	IDe	9.6	9.9*

\* this damage level was only reached in one test

Table 5. Upper armor layer strip porosity for UPV double-layer cube and Cubipod armor models before and after wave attack.

Strip porosity (%) of upper armor layer						
Level	Cube model			Cubipod model		
	Before wave attack Ns = 0 Se = Sv = 0	After wave attack (<IDa) Ns = 1.7 Se=0.6; Sv=0.1	Porosity increment ( $\Delta p\%$ )	Before wave attack Ns = 0 Se = Sv = 0	After wave attack (<IDa) Ns = 3.4 Se=0.2; Sv=0.1	Porosity increment ( $\Delta p\%$ )
+9Dn	37%	40%	3%	41%	42%	1%
+6Dn	35%	39%	4%	42%	43%	1%
MWL +3Dn	36%	38%	2%	41%	40%	-1%
-3Dn	35%	34%	-1%	40%	39%	-1%
-6Dn	37%	33%	-4%	40%	39%	-1%

Fig. 1. Armor failure modes: Armor Unit Rocking (AUR), Armor Layer Sliding (ALS), Armor Unit Extraction (AUE) and Heterogeneous Packing (HeP).

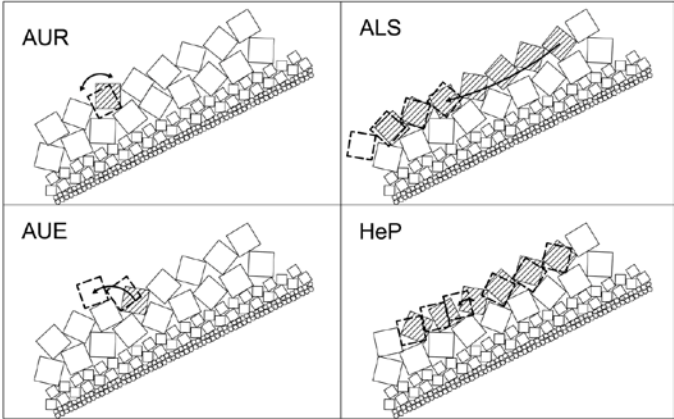


Fig. 2. Cross-section of UPV cube breakwater model (dimensions in cm).

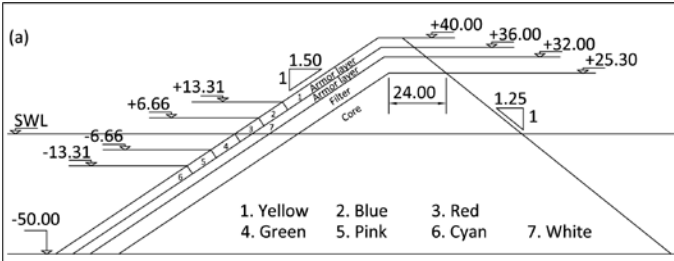


Fig. 3. Linearized equivalent dimensionless armor damage as a function of measured stability number (UPV double-layer cube and Cubipod armor models).

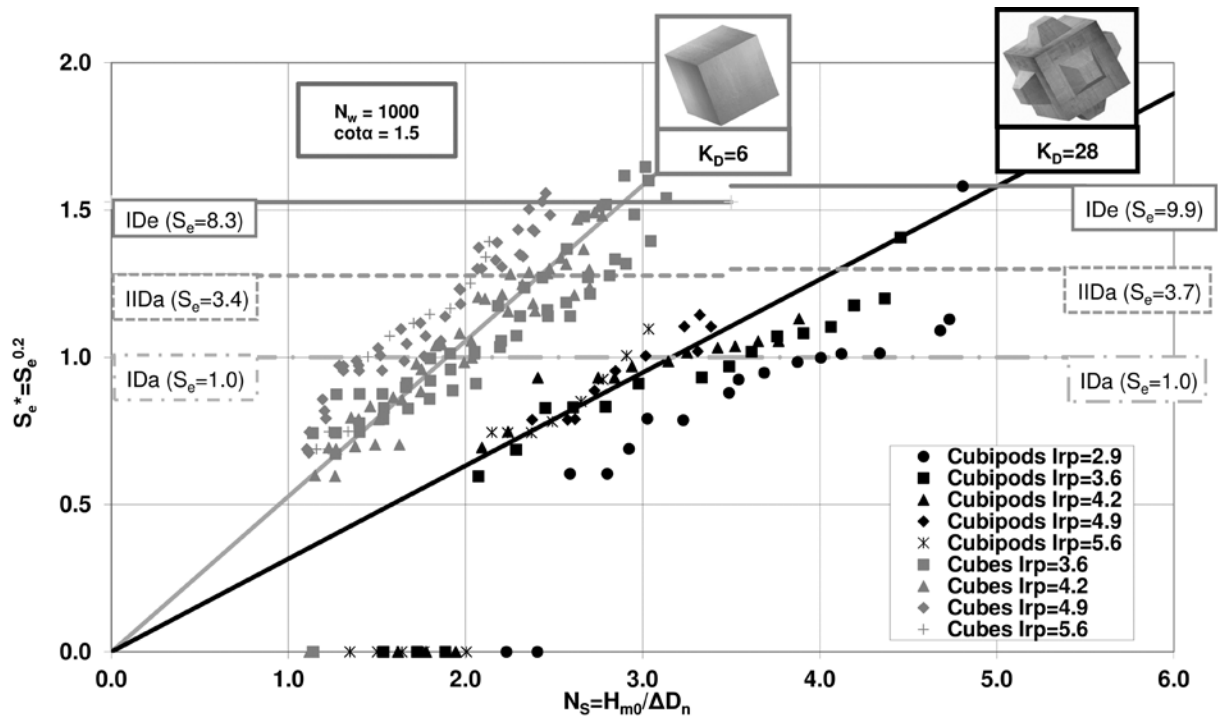


Fig. 4. Measured stability numbers of double-layer cube and Cubipod armors in UPV irregular tests.

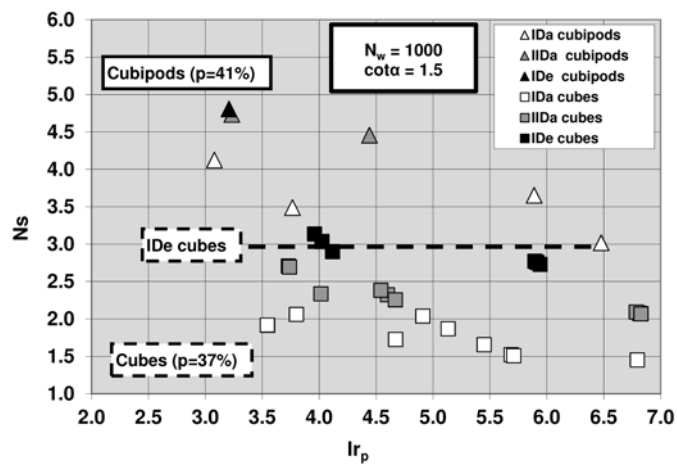


Fig. 5. Measured stability numbers of single- and double-layer Cubipod armors in INHA irregular tests.

