Laser Scanner Technique to Quantify Randomness in Cube and Cubipod Armor Layers

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Abstract

Most concrete armor units (CAUs) are designed to be placed randomly; however, CAUs can also be placed uniformly, patterned or oriented (Dupray and Roberts, 2009). When CAUs are not randomly placed, special attention is given to the placement technique, construction monitoring and the differences between small-scale models and prototypes. When CAUs are placed randomly, less attention is usually paid to the placement technique, which might give the impression that random placement is easy to achieve, but it is not. In the case of randomly placed CAUs, armor randomness is not considered when testing small-scale models and it is not monitored at prototype scale; thus, model effects may be significant.

What does "random placement" mean? Quantitative measurement of armor unit randomness is not available for small-scale models or prototypes. Conventional cube CAUs are supposed to be placed randomly, but it is obvious that cubes tend to position one face parallel to the underlayer slope and to the faces of neighboring units. In this paper, the methodology proposed by Medina et al. (2011) is used to measure the armor randomness, valid for CAUs with three orthogonal symmetry planes such as cube and Cubipod CAUs. The armor randomness is characterized by three Armor Randomness Indexes (ARIs) associated with the different orientations between CAUs and the underlayer slope plane.

1. Introduction

Over the last two centuries, mound and vertical breakwater dimensions have increased. In the 19th century, when the quarries could not provide heavy enough quarry stones for the armor layer of mound breakwaters, the first concrete armor units (CAUs) were produced. Cube and parallelepiped blocks were used until the invention of the Tetrapod in 1950 and other types of CAU, designed to reduce construction and maintenance costs. CAUs can be grouped as "massive", "bulky" and "slender", depending on relative structural strength.

Most breakwaters in Spain are constructed using conventional cubic CAUs, which have logistic advantages such as efficient production and stacking, and easy handling with pressure clamps. Compared to bulky and slender CAUs, the main advantages of massive cubic blocks are their high structural strength and low risk of progressive failure. Nevertheless, cubic CAUs have several drawbacks (see Gómez-Martín and Medina, 2008): low hydraulic stability (K_D=6), high overtopping rates, low friction with filter layer, and high heterogeneous packing (HeP). Gómez-Martín and Medina (2008) designed the Cubipod, a massive CAU, to maintain the logistic and structural advantages of cubes, but correcting the drawbacks. The protrusion-faced design significantly reduces HeP within the armor by increasing friction with the underlayer. Moreover, compared to conventional double-layer cube armors, the lower roughness factors of single- and double-layer Cubipod armors reduce run-up, overtopping and forces on crown walls.

Figure 1. Cubipod CAUs stacked in the block yard (Port of Málaga, Spain).

Armor porosity and armor randomness are two parameters which should be considered in the design of a mound breakwater. Some engineering manuals provide recommended values for armor porosity and placing density for different CAUs. To minimize model effects, placing density should be the same in prototypes and the corresponding small-scale models. Armor units in laboratories are usually placed by hand in optimum conditions. In contrast, armor construction at prototype scale is highly dependent on wind and waves, underwater visibility and the available equipment (crawler cranes with pressure clamps or slings). As CAU hydraulic stability is directly related to placing density and placement pattern (see Frens, 2007 and Medina et al., 2010), model effects corresponding to armor porosity and placement may significantly increase the risk of failure. Armor porosity and placement patterns affect not only hydraulic stability but also wave reflection, run-up and overtopping. Additionally, armor porosity directly affects the amount of materials required to build the armor.

Unlike uniformed and patterned armor placements, which are carefully designed and executed, there is no clear definition of what "random placement" means (see Medina et al., 2011). Random placement is usually taken for granted if the crane operator does not try to place each CAU with a specific orientation.

In this study the armor randomness was analyzed for cubes and Cubipods, two massive randomly-placed CAUs with three orthogonal symmetry planes. Realistic 3D small-scale placement tests were carried out with cube and Cubipod units, using a small-scale crawler crane and pressure clamps, similar to those used at prototype scale, under moderate wave attack. In this study, the armor randomness was measured with the three Armor Randomness Indexes (ARIs), introduced by Medina et al. (2011) and employed by Pardo et al. (2012).

2. Armor Porosity and Armor Unit Randomness

2.1 Armor Porosity and Placing Density

Porosity is a general concept referring to the percentage of voids in a granular system. To calculate armor porosity, first armor thickness should be defined, which can be fixed for uniformly or patterned placed CAUs, but it is difficult to determine for randomly placed CAUs. The armor thickness usually refers, for single- and double-layer armors, to one or two times the equivalent cube size or nominal diameter, $D_n=(W/\gamma_r)^{1/3}$. However, most engineering manuals recommend fixed nominal armor porosities (P%) for different CAUs associated to a layer coefficient or layer thickness factor (k_Δ), which is arbitrarily fixed. Only the placing density (φ[units/m^2]) can be controlled by the placement grid, and this density is related to both nominal armor porosity (P%) and layer coefficient (k_Δ). According to the formula given by SPM(1984), the placing density is

$$\varphi = \frac{N_r}{A} = n(k_\Delta)(1-P\%)\left(\frac{\gamma_r}{W}\right)^{2/3} = \frac{n(k_\Delta)(1-P\%)}{D_n^2} \quad (1)$$

where N_r= number of armor units placed on a surface A; n= number of layers of CAUs; k_Δ=layer coefficient; P%= nominal armor porosity, and W/γ_r= volume of CAU. However, from Eq. 1 it is clear that different pairs of layer coefficients, k_Δ, and nominal porosities, P%, lead to the same placing density, φ. For example, a nominal porosity of P%=47% with a layer coefficient of k_Δ=1.10 (corresponding to modified cubes in SPM, 1984), is equivalent to a porosity of p%=42% with a layer coefficient of k_Δ=1.00. Frens (2007) analyzed problems caused by researchers using different criteria by different authors regarding the layer coefficient and the porosity concept. In order to prevent misunderstandings, in this paper, armor porosity $p\%=(1-\Phi/n)$ refers to a layer coefficient of k_Δ=1.00. Eq. 1 relates dimensionless packing density, $\Phi=n(1-p\%)$, with the corresponding placing density, $\varphi= \Phi/D_n^2$.

Van der Meer (1999), Yagci and Kapdasli (2003), Bakker et al. (2005) and others, have analyzed a variety of CAUs and reported a significant influence of p% on hydraulic stability. Moreover, p% is directly related to the number of CAUs in the armor, concrete consumption and hence the construction cost. Thus, significant differences between design and prototype p% can affect the provision of materials, the construction cost and also the probability of failure.

2.2 Armor Unit Randomness

CAUs can be placed uniformly, patterned, oriented or randomly (see Dupray and Roberts, 2009). Although random placement is frequently used with cubic and parallelepiped blocks, Tetrapods, Cubipods, etc., no measurement of randomness is given for prototypes or small-scaled models. Random placement of a specific CAU refers to its orientation with the armor slope plane and neighboring units. Armor randomness is higher when the placed units cannot face parallel to the slope plane and when the units cannot arrange themselves face to face. Nevertheless, some armors appear to be more randomly-placed than others and thus, armor randomness has become a crucial but elusive characteristic of breakwater armors.

Breakwater performance is be affected by armor randomness. For instance, poor randomly-placed cube armors can change the hydraulic stability and significantly increase overtopping rates. Randomly-placed armors are easy to achieve in the laboratory with hand-constructed small-scale physical models. On the contrary, armor randomness is difficult to achieve when placing prototypes with cranes and poor underwater viewing conditions.

Armor randomness is measured using the three Armor Randomness Indexes (ARIs), developed by Medina et al. (2011) and tested by Pardo et al. (2012). The spatial orientation of each CAU is defined by the normal vectors of its faces. The present paper is focused on the case of cubic blocks and Cubipods, which feature three orthogonal planes of symmetry. True armor randomness is nearly impossible to achieve because CAU symmetric geometry favors self-organization on the slope, which tends to reduce armor unit randomness. For example, cubes placed randomly on a breakwater slope tend to put a face parallel to the slope and face-to-face arrangements with neighboring cubes.

ARI_0 measures the spatial orientation of each armor unit in relation to the armor slope plane. ARI_1 and ARI_2 measure the relative orientation of one CAU in relation to the two closest CAUs within the armor. ARI_1 measures the relative orientation of a CAU with the closest CAU within the armor, and ARI_2 is analogous to ARI_1 but using the second closest CAU within the armor. ARI_1 and ARI_2 can be used to assess the face-to-face CAU arrangements.

The ARIs are calculated using α and β angles in the 3D space; α is the angle between the CAU and the underlayer plane, while β is the angle between two CAUs. For each CAU placed in the armor layer, α is defined as the minimum of the three angles between the breakwater underlayer slope plane and the three orthogonal faces of the CAU. β is defined as the average of the βi (i=1, 2 and 3) angles of the three orthogonal pairs of faces of the two CAUs (see Fig. 2a). Below, angles α and β are defined in detail.

For each CAU placed in the armor layer, α is defined as the minimum of the three angles between the breakwater underlayer slope plane and the three orthogonal faces of the CAU. For randomly-placed CAUs, α is in the range of $0^o \leq \alpha \leq 54.73^o$. If α=0, the CAU has one face completely parallel to the slope plane.

Using numerical simulations, one million cubes were randomly oriented in the 3D space; thus, cumulative distribution functions of α and β were calculated for true randomly-oriented units. ARI values were defined to obtain ARI0=ARI1=ARI2=1.00 for numerically simulated randomly-placed CAUs and ARI0=ARI1=ARI2=0.00 for uniformly-placed cubes parallel to the armor slope plane. Real armors have ARI values between 0 and 1, when comparing the experimental results with numerically-simulated 3D unit orientations. F(α) and F(β) are the sample cumulative distribution functions for physical experiments, corresponding to the angles α and β, respectively. $F_0(\alpha)$ and $F_0(\beta)$ are the cumulative distribution functions, from numerically simulations corresponding to the angles α and β, respectively.

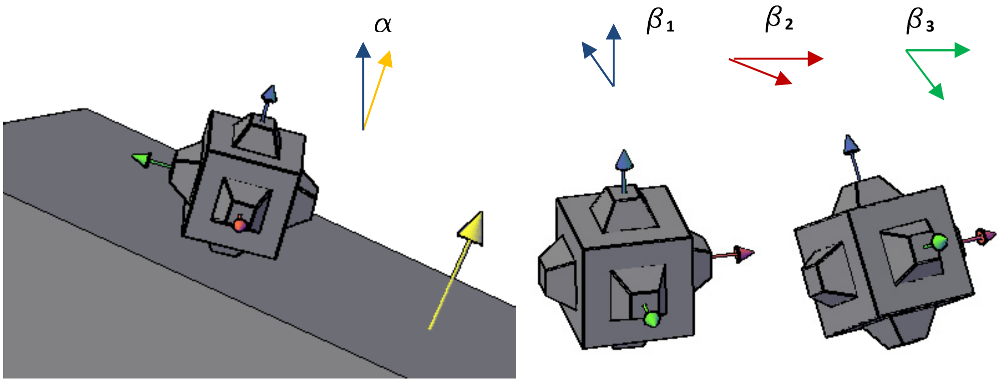

Figure 2. Orientation of angles of cubic blocks: (a) α, and (b) βi (i=1, 2 and 3).

For CAUs placed on breakwater armor layers, ARI_0 is defined as the average of the ratios, not higher than 1.0, between percentiles α_{10}, α_{50} and α_{90} of the sample distribution function F(α) and the corresponding percentiles of $F_0(\alpha)$ as given by Eq. 2. Fig. 3 shows a CAU placement which differs from true random orientation.

$$ARI_0 = \frac{\left(\left[\min\left(1.0, \frac{\alpha_{10}}{[\alpha_{10}]_0}\right)\right] + \left[\min\left(1.0, \frac{\alpha_{50}}{[\alpha_{50}]_0}\right)\right] + \left[\min\left(1.0, \frac{\alpha_{90}}{[\alpha_{90}]_0}\right)\right]\right)}{3} \qquad (2)$$

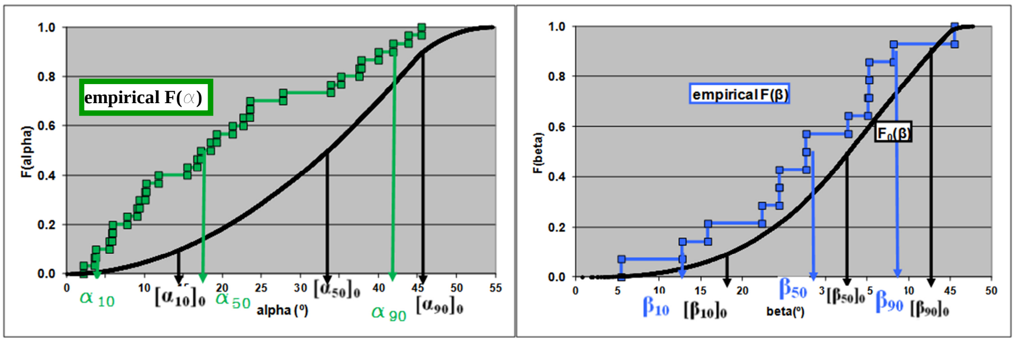

Figure 3. Comparison of empirical distribution function F() and distribution function $F_0()$ for true random placement. Cubes case.

An $ARI_0 \approx 1.0$ indicates CAUs are randomly-oriented in relation to the armor slope. An $ARI_0 \approx 0.0$ indicates all CAUs have two faces parallel to the armor slope. The lower the ARI_0, the poorer the armor randomness.

To calculate ARI_1 and ARI_2, it is necessary first to measure the β_i angles. The β_i (i=1, 2 and 3) angles are defined as the minimum of the three angles between a fixed face "i" of one unit and the three orthogonal faces of the neighboring unit. The β angle between two units placed on the armor layer is defined as the average of the β_i angles, $\beta=(\beta_1+\beta_2+\beta_3)/3$. Based on numerical simulations, the maximum β_i for randomly-placed cubes is 54.7º while the maximum β is 47.9º; therefore, $0^o \leq \beta i \leq 54.7^o$ and $0^o \leq \beta \leq 47.9^o$. Fig. 2b provides an example of β_i calculation between two neighboring cubes in the armor slope.

ARI_1 and ARI_2 are calculated analogously to ARI_0. For a given group of CAUs placed on the breakwater armor layer, each unit in the group was compared to the two closest units; the closest unit was used to calculate the ARI_1, and the second closest unit to calculate ARI_2. The β angle was calculated for each pair of CAUs. ARI_1 and ARI_2, defined by Eq. 3, are the average of ratios, not higher than one, between the 10%, 50% and 90% percentiles (β_{10}, β_{50}, β_{90}) of the sample distribution function $F(\beta)$ and the corresponding percentiles of $F_0(\beta)$.

$$ARI_j = \frac{\left(\left[\min\left(1.0, \frac{\beta_{10}}{[\beta_{10}]_0}\right)\right] + \left[\min\left(1.0, \frac{\beta_{50}}{[\beta_{50}]_0}\right)\right] + \left[\min\left(1.0, \frac{\beta_{90}}{[\beta_{90}]_0}\right)\right]\right)}{3} \quad (3)$$

The index j indicates the order of the neighboring unit to be related, being j=1 for the closest armor unit and j=2 for the second closest armor unit. An $ARI_j \approx 1.0$ indicates CAUs are randomly orientated in relation to the j-closest neighboring unit. An $ARIj \approx 0.0$ indicates the three orthogonal faces of each CAU face the others in a perfectly ordered pattern. The lower the ARI_j (j=0, 1 and 2), the poorer the armor randomness.

3. Experimental methodology

3.1. Realistic 3D placement tests

Small-scale models are usually built in ideal conditions: perfect viewing, no water and construction by hand. Therefore, it is relatively easy to construct low porosity randomly-placed cube armors in laboratories. However, at prototype scale, armor construction is highly restricted by wind and wave conditions, blind placement in the underwater zone, machinery and the handling method. Thus, model effects may be relevant because p% and ARIs for prototypes and small-scale models can be significantly different.

In this study, the methodology described by Medina et al. (2010) and experimentaly-checked by Pardo et al. (2010 and 2012) is used to estimate the range of feasible armor porosities built at prototype scale. Different placement grids for cube and Cubipod CAUs are compared in realistic 3D placement tests designed to emulate prototype armor construction. Fig. 4 shows a general view of the tests carried out at the *Universitat Politècnica de València* (UPV) wave basin, using a small-scale crawler crane and pressure clamps, similar to those used at prototype scale. A 1/100 scale trunk model corresponding to the Punta Langosteira breakwater was constructed. The main characteristics of the breakwater are: {Hs[m]=15 and Tp[s]=18} design storm, armor slope H/V=2/1, conventional double-layer 150-tonne cube armor, and double-layer 15-tonne cube underlayer. The typical wave attack during construction (spring and summer) was {1.5<Hs[m]<2.5 and 10<Tp[s]<12)}.

Two types of placement grids were tested: conventional fixed and progressive diamond-shaped grids. Progressive placement grids have decreasing distances between successive rows to account for the row packing during construction.

After the placement test was completed, p% was calculated counting the units whose gravity centers were located within a reference area, A, in a rigid virtual planar boundary parallel to the slope. Although this measurement method is very reliable, due to border effects are significant sampling errors. To reduce the sampling error, the rigid area boundary was displaced to different nearby locations to estimate porosity as the mean value of the different measurements of the same model. The armor porosity was calculated as: $p\% = 1 - [(Nr^*Dn^2)/A]$, where Nr is the average value of the number of units in the reference area; Dn is the nominal diameter of the equivalent cube size, and A is the reference area.

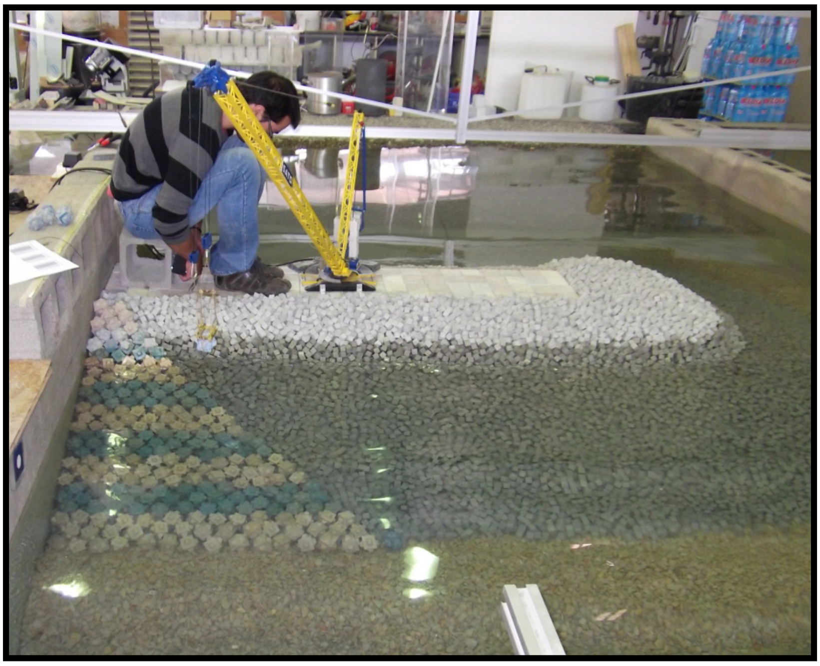

Figure 4. View of realistic 3D placement test using a small-scale crawler crane and pressure clamps.

3.1. Laser scanner technique

To measure armor unit randomness after each realistic 3D placement test, a short-range high-precision (0.1mm) laser scanner was used to scan cube (D_n[mm]= 40) and Cubipod (D_n[mm]= 38) armors. Fig. 5 shows images from the laser scanning process.

The gross data were processed to determine the position and orientation of each armor unit placed on the breakwater slope. The goal was to calculate the ARIs and to measure the armor randomness of each model. Fig. 6a shows the point cloud obtained from laboratory tests using laser scanning, which is similar to those obtained from terrestrial LIDAR at prototype scale. Fig. 6b shows a view of the raw data which may be obtained from a real multi-beam echosounder for submerged armor survey.

Data obtained from both systems are quite similar, a point cloud identified by 3D coordinates in the space. This similitude between small-scale and prototype methods makes it easy to estimate the prototype p% and armor randomness using methods and concepts similar to those applied for small-scale models.

Figure 5. Laser scanning process for a Cubipod armor.

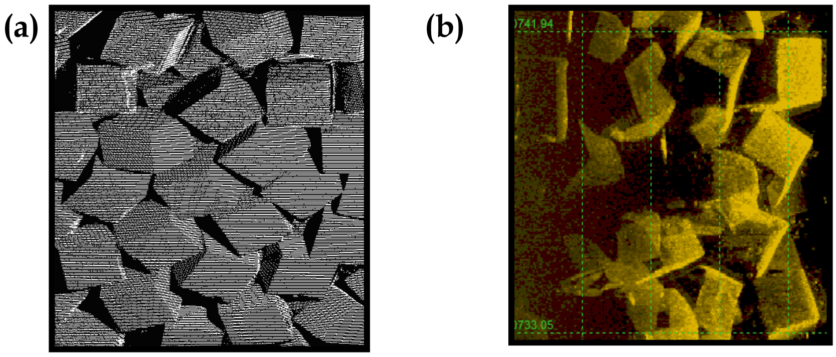

Figure 6. Cube raw data from (a) laboratory laser scanner and (b) prototype multibeam echosounder.

To quantify the armor randomness, the following procedure was followed:

1. The point cloud corresponding to the CAUs surface was obtained by laser scanning, similar to terrestrial LIDAR for the aerial part or multibeam echosounder for the submerged part of the armor.
2. The raw data was processed to obtain the center of gravity and the three orthogonal vectors for each armor unit.
3. The three ARIs were calculated to characterize the armor randomness.

The average ARI values for Cubipod armors were ARI_0= 93%, ARI_1= 74% and ARI_2= 82%; for cube armors, the average ARI values were ARI_0= 67%, ARI_1= 60% and ARI_2= 70%. Fig. 7 shows the ARI_0 measurements of the 11 models compared to average values. In the realistic 3D small-scale placement tests conducted at the UPV, using crawler cranes and pressure clamps under moderate wave attack, showed armor randomness to be higher for Cubipod than for cube armors.

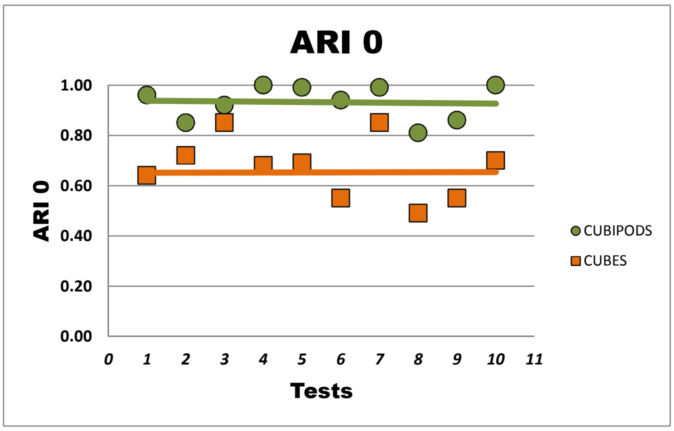

Figure 7. Measured ARI_0 for cube and Cubipod armors corresponding to realistic 3D small-scale placement tests.

4. Summary and conclusions

Armor porosity (p%), CAU placement and armor randomness are rarely considered when testing randomly-placed CAUs so, this study focused on measuring armor randomness for massive, randomly-placed cube and Cubipod CAUs handled with pressure clamps.

Small-scale models, constructed by hand in optimum conditions, are relatively easy to build in laboratory with a prescribed p% and a good armor randomness. However, p% and armor randomness are much more difficult to control at prototype scale. Differences between design and prototype p% and armor randomness may lead to significant model effects. In this study, p% and armor randomness of cube and Cubipod armors were analyzed. Feasible CAU placement grids were obtained for p% commonly used in small-scale tests.

When studying randomly-placed CAUs, p% is difficult to quantify. Engineering manuals usually determine the p% prescribing a specific nominal armor porosity (P%) associated to a layer coefficient (k_Δ) for each CAU type. However, misunderstandings have arisen in engineering descriptions because different criteria are used to define k_Δ; therefore, to avoid misunderstandings in this paper, p%=(1-Φ/n) corresponding to a layer coefficient of k_Δ= 1.00 is used for randomly-placed CAUs. The armor thickness is one or two times the equivalent cube size or nominal diameter, for single or double-layer armors, respectively.

In order to estimate the feasible range of p% which can actually be achieved at prototype scale, realistic 3D small-scale placement tests were carried out to emulate prototype armor placement of cube and Cubipod CAUs. The placement tests were conducted at the UPV wave basin, using a small-scale crawler crane and pressure clamps, similar to those used at prototype scale. A 1/100 scale cross-section of the Punta Langosteira breakwater (conventional double-layer 150-tonne cube armor on double-layer 15-tonne cube underlayer with a slope H/V=2/1) was used under typical moderate wave conditions similar to those in summer (Hs[m]= 1.5 and 2.5; Tp[s]= 10 and 12).

A high-precission (0.1 mm) laser scanner was used to measure the 3D positioning of armor units in the space. Three armor randomness indexes (ARIs) were employed to characterize armor randomness: ARI_0 for the spatial orientation of each CAU in relation to the armor slope plane, and ARI_1 and ARI_2 for the relative orientation of the CAU to the first and second closest

CAUs within the armor. The methodology described in this paper to measure armor randomness is applicable to both small-scale models and prototypes.

The ARIs were calculated from the angles between cube and Cubipod faces, the slope plane and the neighboring CAU faces. The average ARI values for Cubipod armors were ARI_0= 93%; ARI_1= 74% and ARI_2= 82%; the average ARIs for cube armors were ARI_0= 67%; ARI_1= 60% and ARI_2= 70%. Measured armor randomness was higher for Cubipod than cube armors when placed randomly using crawler cranes and pressure clamps.

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