1  **PLACEMENT TEST, POROSITY AND RANDOMNESS OF CUBE AND**

2  **CUBIPOD ARMOR LAYERS**

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4

5  **Abstract:** Although little attention is usually given to the armor porosity and armor randomness

6  of randomly-placed concrete armor units in mound breakwaters, significant model effects may

7  occur if armor porosity and randomness are different for prototype and small-scale models.

8  Armor randomness and porosity are easier to control in small-scale models because they are

9  generally constructed by hand in dry and perfect viewing conditions; equipment and

10  environmental constraints make control at prototype scale more difficult. Results from 3D

11  small-scale placement tests are analyzed when cube and Cubipod units are placed with a small-

12  scale crawler crane and pressure clamps. Armor porosity was not workable below 37% for cubes

13  and 35% for Cubipods; placement grids were obtained for feasible armor porosities, considering

14  row settlements during construction as well. A methodology to measure armor randomness

15  using high-precision laser scanning, similar to terrestrial LIDAR, was tested with small-scale

16  cube and Cubipod armor. Three armor randomness indexes (ARIs) measured the randomness

17  of cube and Cubipod armor; the values for ARIs were higher for Cubipod armor than for cube

18  armor.

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## Introduction

For centuries, mound breakwaters have been constructed to protect ports from wave attack. Over the last 60 years, small-scale laboratory tests using Froude similarity have been able to assess breakwater armor performance under storm conditions and to optimize breakwater design. Small-scale tests are useful to reduce construction and maintenance costs, as well as to enhance long-term breakwater safety and reliability. In most cases, an initial design is significantly improved after conducting the corresponding model tests. However, not all the prototype characteristics are properly reproduced in the scale models. In addition to scale effects, which may be negligible when using the appropriate scale, model effects may be significant when prototype and scaled models have relevant differences.

Armor porosity and the orientation of the armor units are two parameters which can cause significant model effects. This research focuses on cube and Cubipod concrete armor unit placement grids to obtain the armor porosity tested in the laboratory and on the quantification of armor unit randomness. These two armor characteristics may significantly reduce the model effects of scale models.

Researchers, including Van der Meer (1999), VandenBosch et al. (2002) and Frens (2007), have carried out small-scale physical experiments to analyze the hydraulic stability of different CAUs; all report a significant influence of armor porosity on the hydraulic stability of the armor layer, higher armor porosity leads to less stable structures. However, very few armor stability formulae explicitly include armor porosity as a parameter. Armor porosity is usually considered a constant design parameter; USACE (1984) fixed a nominal armor porosity $P=47\%$ and a layer coefficient $k_\Delta=1.10$ for modified cubes, packing density $\phi = 2k_\Delta(1-P) = 1.17$.

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1

The armor unit placement technique is widely recognized as a variable relevant to the stability of the armor layer (Hudson et al., 1979). Specific placement patterns are the simplest way to obtain a given target porosity in the laboratory; nevertheless, it is not easy to reproduce the patterns at prototype scale. Breakwater armor layers are easier to construct with higher porosity, regardless of the equipment used. Real breakwater armors tend to increase porosity above the recommended values, and the armor unit placement technique is a critical consideration. In the design phase, armor porosity must be defined to estimate the volume of materials required to build the armor layer; an uncontrolled increase in armor porosity during the construction phase may result in an uncontrolled change in the construction logistics and hydraulic stability.

It is widely accepted that armor layers built with uniform, patterned or oriented armor units have specific structural responses which are highly dependent on armor unit placement; therefore, armor units must be accurately placed, both in prototype and in laboratory tests. However, the engineering community views randomly placed armor units differently because there is no clear definition for "random placement". Armor units, such as conventional cubes, parallelepiped blocks, Antifer cubes and Cubipods, are usually placed randomly, but no measurement of armor randomness is given for small-scale models or prototypes.

In this study, the placement method, armor porosity and armor randomness of cube and Cubipod units are analyzed. Realistic 3D small-scale placement tests were carried out using a small-scale crawler crane and pressure clamps under moderate wave attack. The Punta Langosteira and San Andrés breakwater models were studied to obtain feasible armor porosities at prototype scale. These models were also used to determine the placement grids required to obtain the armor porosity tested in laboratory ($p=37\%$ and $p=42\%$ for cube and Cubipod armors, respectively). The placement tests were carried out in straight trunks, curved trunks and roundheads. The prototype placement grid used in the Punta Langosteira main breakwater, armored with 150 tonne cubes, was also tested. To quantify the randomness of cube and Cubipod armor layers, the methodology developed by Medina et al. (2011) was followed. Three armor randomness indexes (ARIs) described herein were used to measure armor randomness.

1    **Placement Grids, Armor Porosity and Model Effects**

2    **Prototype versus Small-Scale: Model Effects**

3    The construction of armor layers at prototype scale is restricted by underwater viewing conditions, the

4    availability of equipment and the given environmental conditions. On the contrary, small-scale model

5    construction is generally done by hand, with perfect views and optimal environmental conditions. As a

6    result, armor porosity and armor unit randomness are two parameters that can differ significantly between

7    prototype and scale models.

8

9    On the one hand, armor hydraulic stability depends on porosity; therefore, it should always be measured

10   in laboratory tests. A significant deviation between armor porosity measured in the small-scale model

11   and the prototype may lead to a significant model effect with an uncontrolled outcome in terms of

12   breakwater armor performance. The higher the discrepancy, the higher the structural uncertainty is. On

13   the other hand, it is well known for coastal engineers that overtopping rates depend on the orientation of

14   the concrete armor units; runup and overtopping rates significantly increase in poor randomly-placed

15   cube armor with common face-to-face fitting arrangements.

16

17   **The Importance of Specifying Armor Porosity in Scale Tests**

18   Porosity or void porosity is an intuitive concept that refers to the percentage of voids in a granular system.

19   Normally, armor porosity is used to characterize the armors of mound breakwaters; however, it is not

20   easy to define or quantify. Armor thickness must first be defined, which is not a simple task for randomly-

21   placed armor units. Generally, the armor thickness is assumed to be one or two times the equivalent cube

22   size or nominal diameter, $D_n=(W/\gamma_r)^{1/3}$, for single- and double-layer armors. Most engineering manuals,

23   like USACE (1984) or CIRIA (2007), recommend pairs of nominal armor porosity and layer coefficient

24   ($P$ and $k_\Delta$ or $n_v$ and $k_t$) for different armor units. According to USACE (1984), the placing density ($\varphi$

25   [units/m$^2$]) is related to both nominal armor porosity ($P$) and layer coefficient ($k_\Delta$) by:

26
$$\varphi = \frac{N_a}{A} = nk_\Delta(1-P)(\frac{\gamma_r}{W})^{2/3} \qquad (1)$$

27   where $N_a$= number of armor units placed on the surface, $A$, $n$= number of layers, $k_\Delta$= layer coefficient,

28   $P$= nominal armor porosity, $W$= armor unit weight, and $\gamma_r$= armor unit material specific weight. Different

29   pairs of nominal armor porosity and layer coefficient ($P$, $k_\Delta$) have the same value for placing density, $\varphi$.

1  A nominal porosity of $P$=47% with a layer coefficient of $k_\Delta$=1.10 (modified cube in USACE, 1984) is

2  equivalent to a porosity of $p$=42% with a layer coefficient of $k_\Delta$=1.00. Unfortunately, the different criteria

3  used by different authors to define $k_\Delta$ has caused some misunderstandings (see Frens, 2007); for instance,

4  both USACE (1984) and CIRIA (2007) recommend a nominal armor porosity of 50% for double-layer

5  Tetrapod armor, but different layer coefficients, $k_\Delta$=1.04 and $k_t$=1.02, respectively.

6

7  To prevent misunderstandings, this study applies the criterion given by Medina et al. (2010), valid for

8  randomly-placed armor units; the armor porosity, $p=(1- \phi /n)$, is defined as the porosity associated to a

9  layer coefficient of $k_\Delta$=1.00. The assumed armor layer thickness is $D_n$ for single-layer armor and $2D_n$ for

10 double-layer armor. The packing density ($\phi$) is a parameter to measure the relative consumption of

11 concrete in the armor layer, associated to armor porosity and the number of layers. The packing density

12 can be considered the dimensionless placing density using $D_n$ as the length unit:

$$\phi = n(k_\Delta)(1 - P) = n(1 - p) = \varphi D_n^2 \tag{2}$$

14 where $n$= number of layers, $k_\Delta$= layer coefficient, $P$= nominal armor porosity, $p$= armor porosity, $\varphi$=

15 placing density, and $D_n=(W/\gamma_r)^{1/3}$= equivalent cube size or nominal diameter.

16

17 Although it is well known that armor porosity may significantly affect hydraulic stability (see Van der

18 Meer, 1999, and VandenBosch et al., 2002) and breakwater armor performance during lifetime, most

19 armor stability formulae and tests reported in the literature do not explicitly consider this a significant

20 parameter. When no measurements for placing or packing densities are given in the corresponding papers

21 or reports, armor porosity may not be fully considered despite its importance; in some cases, laboratory

22 tests and prototypes are implicitly assumed to be built with the same packing density.

23

24 During the construction phase, armor porosity is a critical issue because it affects material procurements

25 and payments. However, armor porosity is hard to measure in practice and difficult to measure below the

26 mean water level (MWL) due to poor visibility. Additionally, porosity changes during the lifetime and

27 heterogeneous packing is more likely to occur if armor porosity is higher than designed.

28

29 **Appropriate Placement Grids for Trunks and Roundheads**

1   Armor units may be placed uniformly, patterned, oriented or randomly (Dupray and Roberts, 2009).

2   Whatever the armor unit orientation required, all units are placed using a specific placement grid whose

3   characteristics depend on the type of armor units and design considerations. The placement grid provides

4   the exact planar X-Y coordinates, indicating how each unit must be placed by the crawler crane, which

5   is often equipped with precise GPS positioning.

6

7   There are a variety of techniques to place each type of armor unit. The specific placement technique is

8   directly related to armor porosity and interlocking. Hudson et al. (1979) placed long-axis stones with the

9   long axis perpendicular to the slope plane to increase the stability in the rock armor layer under wave

10  attack. Yagci and Kapdasli (2003) analyzed different laboratory placement arrangements for Antifer

11  cubes; the optimum placement technique was selected considering armor stability, prototype placement,

12  clarity of the placement technique definition, armor cost and wave runup. Özkan-Çevik et al. (2005)

13  compared the effects of two alternative placement arrangements for Core-Loc$^{TM}$ on armor stability; they

14  concluded that random placement was preferable because it was more stable.

15

16  In addition to placement arrangement, the armor unit handling method may have a significantly impact

17  on the completed armor. Depending on armor unit geometry, a variety of slings methods may be used

18  for handling and placement. Furthermore, conventional cubes, Cubipods and other armor units may be

19  handled and placed using several types of pressure clamps. Muttray et al. (2005) tested two different

20  sling methods for placing Xbloc®; attaching the sling to one leg of the X-shaped base achieved the

21  recommended armor porosity which led to significantly higher armor stability and facilitated unit

22  placement.  Medina et al. (2010) pointed out the advantages of using pressure clamps to handle armor

23  units; however, the clamps tended to produce undesired arrangements of conventional cubes with the

24  faces being parallel to the armor slope.

25

26  Special attention must be given to the toe berm and the placement of the first row of armor units in the

27  armor. Gravitational force is always relevant for armor stability; an armor unit placed in the armor layer

28  is supported by the neighboring units in the lower rows. If the first row of armor units is not correctly

29  placed on the toe berm, the errors may affect the interlocking, porosity and stability of the complete

30  armor, especially in the case of single-layer armor. Turk and Melby (1997) recommended placing the toe

6

1 berm and the first two rows of Core-Loc™ armor units with special care to obtain a more stable

2 arrangement. Yagci et al. (2004) focused on the first row to assure that the semi-cylindrical grooves of

3 Antifer cubes made contact with the base surface. Oever et al. (2006) attached a different sling for the

4 first row of the Xbloc® armor to achieve accurate placement.

5

6 As a general rule, random placement requires placing armor units with a fixed placement diamond grid,

7 which means the units of one row are placed in the openings of units in the lower row. Fig. 1 shows a

8 typical placement grid, where $a$ is the fixed horizontal distance between two contiguous armor unit

9 centers of gravity, and $b$ is the fixed distance between two contiguous armor unit rows measured in a

10 horizontal plane.

11 **[Insert Fig. 1 here]**

12 In this study, a new type of placement grid was developed to take into consideration row settlements

13 during armor construction; instead of a fixed row distance ($b$ in Fig. 1), the grid progressively reduces

14 the distance between rows from the toe berm to the armor crest. Fig. 2 shows the progressive placement

15 grid, where $a$ is the fixed horizontal distance between two contiguous armor unit centers of gravity, and

16 $b$ is the distance between two contiguous armor unit rows measured in a horizontal plane. The distance

17 between armor unit rows $i$ and $i$-1 ($i=2,3,...I$) is given by:

18
$$b_i = b_2 \left[ 1 - \Delta b (i - 2) \right]$$
(3)

19 where $i$= row index ($i=1$ is the first row placed on the toe berm), $\Delta b$= reduction in b to compensate for

20 armor settlement on the slope, and $I$=the number of armor unit rows in the armor layer.

21 **[Insert Fig. 2 here]**

22 Roundheads and curved trunks also require special attention. The curvature of roundheads and curved

23 trunks reduces the lengths of the armor unit rows from the bottom to the crest; therefore, the placement

24 grids must be modified to ensure a workable placement. In these cases, the average horizontal distance

25 between armor units decreases progressively from the bottom row to the top ($a_i > a_{i+1}$). When the

26 horizontal distance between armor units in a row is too small, the homogeneous grid geometry described

27 in Fig. 1 is no longer adequate. If the curvature of the armor is large (roundheads), it is not possible to

28 place all the armor units in the openings between the two units in the previous row; thus, a heterogeneous

29 placement scheme is required. To correctly place units in roundheads or curved trunks, it is necessary to

30 adapt the placement grid to the slope and curvature to minimize the number of irregular points in the

7

1     grid. Oever et al. (2006) recommended a placement grid for Xbloc® in roundheads and curved trunks in

2     which each armor unit may be shifted up to $0.4D_n$ from its original placement center to create more space

3     for the next unit; when the unit to be placed requires armor units to be moved more than $0.4D_n$, the new

4     unit is not placed.

5

6     In this study, specific heterogeneous placement grids were developed for curved trunks and roundheads.

7     Fig. 3 shows the basic placement grid scheme proposed for low-curvature curved trunks, where $a_j$

8     ($j=1,2,3,…J$) is the distance between two contiguous armor unit centers of gravity in the row j, $b$ is the

9     fixed distance between two contiguous armor unit rows, and $R_j$ ($j=1,2,3,...J$) is the radius of the

10     circumference corresponding to row $j$; all of these are measured in the horizontal plane projection.

11                                   **[Insert Fig. 3 here]**

12     In roundheads and high-curvature curved trunks, the distance between elements in the row (i)

13     significantly decreases in regard to the next row (i+1); the reduction rate is given by $a_{i+1}/a_i=R_{i+1}/R_i$.

14     Therefore, the criteria for placing units of row (i+1) in the openings of the previous row (i) cannot be

15     maintained if the radius reduction is too high. Fig. 4 shows a placement grid scheme appropriate for

16     roundheads and high-curvature curved trunks; the unit rows are grouped in an annulus of a specific

17     placement grid which is decoupled from the placement grid of the contiguous annulus. The grid number

18     index $m$ ($m=1,2,3,...M$) identifies the annulus sector, $a_{m.j}$ is the distance between two contiguous armor

19     unit centers of gravity in the row $j$ ($j=1,2,3,...J$), $b$ is the fixed distance between two contiguous armor

20     unit rows, and $R_{m.j}$ is the row radius. The distance between elements in the first row, $a_{m.1}$, is the same for

21     all annulus placement grids, and the distance between elements in the upper row in the annulus must

22     fulfill $a_{m.J} \geq a_{min}$ and $a_{m.J+1}< a_{min}$.

23                                   **[Insert Fig. 4 here]**

24     Dimensionless placement grids are usually defined according to a specific geometric armor unit

25     characteristic, such as the equivalent cube size or nominal diameter, $D_n$, which allows for a comparison

26     of different placement grids ($a/D_n$ and $b/D_n$) at different scales.

27

28     In laboratory tests, placement is most often done by hand (Gürer et al., 2005, Özkan-Çevik et al., 2005).

29     Sometimes armor units are dropped from a given height (Verhagen et al., 2002, Yagci and Kapdasli,

30     2003) or more realistic placement devices are used such as slings manipulated by hand (Muttray et al.,

2005, Oever et al., 2006). In this study, the realistic 3D placement technique, proposed by Medina et al. (2010), using a small-scale crawler crane and pressure clamps, was applied to place cube and Cubipod units in the small-scale armor layers.

**Methodology to Measure Armor Unit Randomness**

Armor layers are frequently constructed using crawler cranes equipped with either pressure clamps (conventional cubes, parallelepiped blocks, Cubipods, etc.) or slings (Tetrapod, Accropode™, Core-Loc™, Xbloc®, etc.) which place the armor units according to the horizontal coordinates on a specific placement grid. Even for armor units that are meant to be randomly-oriented, a pure random arrangement is unlikely to occur because some armor unit geometries favor self-arrangement on the slope, which tends to reduce armor randomness. Cubic blocks, which should be placed randomly on a breakwater slope, tend to put one face parallel to the slope and create face-to-face arrangements with neighboring blocks. Usually "random placement" is taken for granted when the crane operator does not follow specific placement arrangements. During cubic block placement, the crane operator will try to favor randomness (above MWL) by preventing the blocks from having one face parallel to the slope plane and thus avoid face-to-face arrangements among neighboring units. However, poor underwater viewing makes it difficult for crane operators to avoid self-arrangements and poor randomness. Therefore, some breakwater armors are actually more randomly-placed than others.

In this study, the methodology proposed to measure armor randomness considers each 3D armor unit orientation in relation to two specific references: (a) the breakwater slope plane, and (b) the faces of the two closest armor units. This research focuses on cube and Cubipod armor units, which both have three orthogonal planes of symmetry. Cube and Cubipod orientations in the space can be described by these three orthogonal planes which are parallel to the cube and Cubipod faces.

To quantify the randomness of cube and Cubipod armor units placed on the armor, the three armor randomness indexes (ARIs) proposed by Medina et al. (2011) are considered:

- $ARI_0$, to measure the spatial orientation of an armor unit in relation to the armor slope plane,
- $ARI_1$, to measure the relative orientation of an armor unit with the closest unit in the armor layer,

1    - ARI$_2$, to measure the relative orientation of an armor unit with the second closest unit in the armor

2      layer.

3

4    Thus, ARI$_0$ assesses the parallelism between the armor unit faces and the underlayer slope plane on which

5    the armor units are placed, while ARI$_1$ and ARI$_2$ evaluate the face-to-face arrangements.

6

7    ARIs were calculated from angles $\alpha$ and $\beta$, defined between cube and Cubipod faces and the armor slope

8    plane or the neighboring armor unit faces, respectively. For each armor unit placed on the armor layer, $\alpha$

9    is defined as the minimum of the three angles of the breakwater slope plane and the three orthogonal

10   faces of the armor unit. Fig. 5 illustrates $\alpha=10º$ between a cube armor unit and the armor slope plane. For

11   randomly-placed cube-like armor units, the maximum $\alpha$ is $\alpha_{max}=\arctan(2)^{1/2}\approx54.7º$; thus, $0º\leq\alpha\leq54.7º$. If

12   a specific armor unit has $\alpha=0º$, one of its faces is parallel to the underlayer slope plane.

13                          **[Insert Fig. 5 here]**

14   Using Monte Carlo numerical simulations, one million cubes were randomly oriented in the space to

15   estimate the cumulative distribution function of $\alpha$, $F_0(\alpha)$ for pure randomly-oriented armor units. The

16   10%, 50% and 90% percentiles of $\alpha$ ($[\alpha_{10}]_0$, $[\alpha_{50}]_0$ and $[\alpha_{90}]_0$) were used to characterize $F_0(\alpha)$. Given a

17   group of randomly-placed armor units in the breakwater armor, the same three percentiles of $\alpha$ ($[\alpha_{10}]$,

18   $[\alpha_{50}]$ and $[\alpha_{90}]$) were used to characterize the sample distribution function, $F(\alpha)$. Fig. 6 shows a scheme

19   of the percentiles of the distribution function $F_0(\alpha)$ and the sample distribution function $F(\alpha)$ used to

20   calculate the first armor randomness index (ARI$_0$) for one specific case of cube armor. If the armor units

21   were randomly placed, $F(\alpha)$ would be similar to $F_0(\alpha)$ and the ratios between corresponding percentiles

22   would be $[\alpha_m]/[\alpha_m]_0\approx1.0$, for $m=10$, 50 and 90. The observations of the case represented in Fig. 6 suggest

23   that the actual cube armor placement may differ significantly from pure random placement.

24                          **[Insert Fig. 6 here]**

25   For cube and Cubipod armor units placed on the breakwater armor layer, the ARI$_0$ is defined by Eq. 4 as

26   the average of ratios, not higher than one, between percentiles $\{\alpha_{10}, \alpha_{50}, \alpha_{90}\}$ of the sample distribution

27   function, $F(\alpha)$, and the corresponding percentiles of the pure random distribution function, $F_0(\alpha)$. If

28   ARI$_0\approx100\%$, the armor units are randomly placed in relation to the armor slope plane. If ARI$_0\approx0\%$, all

29   the armor units are placed with one face parallel to the armor slope plane. The lower the ARI$_0$, the worse

30   the armor randomness. The cube geometry and the use of pressure clamps favor units being positioned

                                       10

1   with one face parallel to the underlayer slope plane; therefore, in the case of cubes, $ARI_0$ is expected to

2   be significantly lower than $ARI_0 = 100\%$, depending on variables such as armor slope, armor porosity or

3   placement technique.

4
$$ARI_0 = \frac{\left(\left[\min\left(1.0, \frac{\alpha_{10}}{[\alpha_{10}]_0}\right)\right] + \left[\min\left(1.0, \frac{\alpha_{50}}{[\alpha_{50}]_0}\right)\right] + \left[\min\left(1.0, \frac{\alpha_{90}}{[\alpha_{90}]_0}\right)\right]\right)}{3}$$
(4)

5   To measure the armor unit randomness in relation to the first and second closest neighboring armor units,

6   for each orthogonal face of the unit, the $\beta_i$ ($i$=1, 2 and 3) is defined as the minimum of the three angles

7   between face $i$ of one unit and the three orthogonal faces of the neighboring unit. The $\beta$ between two

8   armor units placed on the breakwater armor layer is defined as the average of $\beta_i$ of the three orthogonal

9   faces of the unit, $\beta = (\beta_1 + \beta_2 + \beta_3)/3$. For a randomly-placed armor unit, the maximum $\beta_i$ is

10  $\arctan(2)^{1/2} \approx 54.7°$ and the maximum $\beta$ is 47.9°; therefore, $0° \leq \beta_i \leq 54.7°$ and $0° \leq \beta \leq 47.9°$. Fig. 7 shows an

11  example $\beta$ calculation between two neighboring cubes.

12                              **[Insert Fig. 7 here]**

13  Using Monte Carlo numerical simulations, one million pairs of cubes were randomly oriented in the

14  space to estimate the cumulative distribution function of $\beta$, $F_0(\beta)$ for randomly placed armor units. The

15  10%, 50% and 90% percentiles of $\beta$ ($[\beta_{10}]$, $[\beta_{50}]$ and $[\beta_{90}]$) were used to characterize the distribution

16  function of pure randomly placed armor units. Fig. 8 shows a scheme of the three percentiles of the

17  distribution function $F_0(\beta)$ and the sample distribution function $F(\beta)$ used to calculate the $ARI_1$ for one

18  specific case of cube armor.

19                              **[Insert Fig. 8 here]**

20  After selecting a group of armor units placed on the breakwater armor layer, each unit was compared

21  with the two closest units in the group; the closest one was used to calculate the $ARI_1$, and the second

22  closest unit was used to calculate the $ARI_2$. The $\beta$ was calculated for each pair of armor units in the group.

23  $ARI_1$ and $ARI_2$ are defined by Eq. 5 as the average of ratios, not higher than one, between $\{\beta_{10}, \beta_{50}$ and

24  $\beta_{90}\}$ percentiles of the sample distribution function $F(\beta)$ and the corresponding percentiles of $F_0(\beta)$). If

25  $ARI_1 \approx ARI_2 \approx 100\%$, the armor units are pure randomly placed. If $ARI_1 \approx ARI_2 \approx 0\%$, all armor units have

26  their three orthogonal faces parallel to each other in a perfectly ordered pattern. The lower the $ARI_1$ and

27  $ARI_2$, the worse the armor randomness. The cube geometry tends to favor face-to-face arrangements;

11

1    therefore, $ARI_1$ and $ARI_2$ are expected to be significantly lower than 100%, depending on variables such

2    as armor slope, armor porosity or placement technique.

3
$$ARI_j = \frac{\left(\left[\min\left(1.0, \frac{\beta_{10}}{[\beta_{10}]_0}\right)\right] + \left[\min\left(1.0, \frac{\beta_{50}}{[\beta_{50}]_0}\right)\right] + \left[\min\left(1.0, \frac{\beta_{90}}{[\beta_{90}]_0}\right)\right]\right)}{3}; \quad j=1,2 \qquad (5)$$

4

## 5    Placement Grids from Realistic 3D Small-Scale Placement Tests

6    In small-scale models, the usual placement of armor units by hand is faster and much more flexible than

7    placement with small-scale crawler cranes. At prototype scale, using a crawler crane with GPS

8    positioning, the armor unit placement grid is the most critical tool to control armor porosity. The main

9    objective of these realistic 3D placement tests was to define workable placement grids that provide the

10    prescribed armor porosity used in small-scale hydraulic stability tests to minimize the corresponding

11    model effects.

12

13    A series of realistic 3D small-scale placement tests was carried out at the UPV wave basin (15.0m x 7.0m

14    x 0.45m), equipped with a piston-type wavemaker, emulating prototype armor construction of cube and

15    Cubipod armors. Both cubes and Cubipods are massive armor units usually handled with pressure clamps

16    and placed with crawler cranes. These small-scale placement tests employed the methodology described

17    by Medina et al. (2010) and Pardo et al. (2012). The placement tests were based on two different models

18    corresponding to real prototypes:

19

20        1)    Straight trunk. 1/100 scale model of the straight trunk in the Punta Langosteira breakwater (Port

21            of A Coruña, Spain), armored with conventional 150 tonne (64 m³) cubic blocks (Burcharth et

22            al., 2002). The breakwater armor is placed on a conventional double-layer 15-tonne cube filter,

23            slope $H/V$=2.0. The placement of cube and Cubipod units was executed under moderated wave

24            attack (prototype values $H_s$=1.5 m and 2.5 m; $T_p$=10 s and 12 s). Fig. 9 shows the 1/100 small-

25            scale crawler crane (LIEBHERR LR 11350) used in these tests.

26        2)    Curved trunk and roundhead. 1/36 scale model of the San Andrés breakwater (Port of Málaga,

27            Spain), armored with 6 tonne (2.55 m³) Cubipod units. The breakwater armor is placed on a

double-layer 1-tonne rock filter, slope $H/V$=2.0. The placement of the Cubipod units was executed without waves.

The characteristics of the units used in the placement tests were the following: {$D_n$=4.00 cm, $W$=145 g, and $\rho_r$=2.26 g/cm$^3$} for cubes and {$D_n$=3.82 cm, $W$=128 g, and $\rho_r$=2.29 g/cm$^3$} for Cubipods.

**[Insert Fig. 9 here]**

Depending on the unit size, a conventional prototype crawler crane takes 4 to 15 minutes to place a cube or Cubipod unit on the armor using pressure clamps. In the realistic 3D placement tests, a small-scale crawler crane takes one to two minutes to place each unit on the armor; therefore, these tests are intensive and time-consuming compared to conventional placement by hand as done in most laboratory tests, which just take a few seconds per unit. To reduce the time required to build the models in the realistic 3D small-scale placement tests, the cartesian blind placement system (CBPS), described in detail by Pardo et al. (2010), was used to estimate the minimum and maximum armor porosity which can be achieved in real construction. The CBPS is more realistic than the usual armor unit placement by hand in small-scale experiments, but the CBPS is not as realistic as armor unit placement with small-scale crawler cranes and pressure clamps similar to those used at prototype scale. The advantage of the CBPS is the reduction in the placement cycle time; it takes approximately 10 seconds per unit. Hence, as a rule-of-thumb, placement by hand requires one second per unit; the CBPS requires 10 seconds per unit, and a small-scale crawler crane requires 100 seconds per unit.

The minimum porosities when constructing by hand in the laboratory are $p$=0% and $p$=29% for cubes and Cubipods, respectively. By contrast, using pressure clamps and slings requires placement grids with a much higher porosity. If the target armor porosity is too small, it is not possible to place all the armor units in the desired position on the armor layer; if it is too large, armor units are subjected to excessive settlement after placement. The CBPS was employed for a preliminary estimation of the feasible porosity ranges for cube and Cubipod armor units. The placement quality of the CBPS was visually assessed after each test; acceptable and unacceptable armor layer placements were subjectively determined to calculate the acceptable porosity range for each armor unit. The workable armor porosities obtained with the CBPS were 37%<$p$<51% for cubes and 35%<$p$<45% for Cubipods. USACE (1984) recommends $p$=42% for

cubes; therefore, attention should be paid both to the armor porosity in small-scale models and the feasible porosity at prototype scale.

Once the feasible armor porosity was known for cubes and Cubipods, realistic 3D placement tests were carried out. As stated earlier, the conventional and the progressive placement grids were tested using the Punta Langosteira trunk breakwater model. The placement grid for curved trunks and roundheads was tested using the San Andrés breakwater model. After each placement test, the armor porosity was estimated by counting the units in a given area, $A$. The sampling porosity was calculated by counting the units whose centers of gravity were placed within the sampling area, $p=1-[(N_a D_n^2)/A]$, where $N_a$ is the number of units within the sampling area, $D_n$ is the nominal diameter, and $A$ is the sampling area. To reduce the boundary error, the sampling area was displaced ten $D_n/5$ intervals horizontally and along the slope; armor porosity was then estimated as the average value of the 21 sampling values.

For the double-layer Cubipod armor in a straight trunk, the progressive grid $\{a/D_n=1.61$, $b/D_n=1.05$ and $\Delta b/b=1.0\%\}$ obtained an average porosity $p=41.3\%$, close to the target porosity $p=42\%$. For the double-layer cube armor in a straight trunk, the conventional placement grid $\{a/D_n=1.44$ and $b/D_n=1.06\}$ gave an average porosity $p=36.9\%$, close to the target porosity $p=37\%$.

For the double-layer Cubipod armor in the curved trunk ($R_1/D_n =109$), the placement grid $\{a_1/D_n=1.61$ and $b/D_n=1.05\}$ obtained an average armor porosity $p=42.0\%$. For the roundhead ($R_{1.1}/D_n =19$), the placement grid $\{a_{m.1}/D_n=1.61$ , $b/D_n=1.05$, and $M=4$ with $a_{min}/D_n=1.34\}$ gave an average porosity $p=45.4\%$.

**Armor Randomness Measurement**

To measure armor randomness, cube and Cubipod armor units were characterized by the position of their centers of gravity and their three orthogonal vectors, associated with the three orthogonal planes of symmetry. After each placement test, a short-range high-precision (0.1mm error) laser scanner, similar to terrestrial LIDAR survey, was used to scan small-scale cube and Cubipod armors. Fig. 10 shows images from the laser scanning process and a screen view of the raw data.

1                                            **[Insert Fig. 10 here]**

2    The raw data were processed to determine the position and the orientation of each armor unit; ARIs were

3    calculated to measure the armor randomness. The average ARIs and the coefficient of variation (CV)

4    values for the straight trunk were: (1) $ARI_0$=67% (CV=17.9%), $ARI_1$=60% (CV=15.7%) and $ARI_2$=70%

5    (CV=11.5%) for cube armors, and (2) $ARI_0$=93% (CV=7.5%), $ARI_1$=74% (CV=14.5%) and $ARI_2$=82%

6    (CV=12.9%) for Cubipod armors. Comparing cubes and Cubipods randomly placed using a crawler crane

7    and pressure clamps, Cubipods show significant-ly higher randomness. The CV values for $ARI_0$ indicate

8    that Cubipod armor randomness is more homogeneous than cube armor in regard to the underlayer plane.

9    On average, $ARI_1 < ARI_2$, which further indicates that proximity affects armor unit randomness; the 3D

10   orientation of a specific armor unit has a greater effect on the 3D orientation of the closest armor units in

11   the armor layer.

12

## Discussion

14   Model effects caused by differences between prototype and small-scale models can lead to significant

15   differences in terms of structural response. For cube armor, uncontrolled armor unit randomness, as well

16   as differences between design and prototype armor porosity, may alter the hydraulic stability, run-up,

17   overtopping rates and forces on the crown wall. In general, insufficient attention is given to armor

18   porosity and armor unit randomness in prototype and in small-scale model tests for armors with

19   randomly-placed units.

20   Armor unit randomness and armor porosity are relatively easy to control in laboratory small-scale

21   models, constructed by hand, with complete views in ideal conditions. However, they are difficult to

22   control at prototype scale, with crane placement, waves and poor underwater viewing conditions.

23   Different engineering manuals recommend a specific nominal armor porosity for each armor unit

24   associated to a given layer coefficient, $k_\Delta$; different criteria used to define the layer coefficient has lead

25   to misunderstandings. To avoid confusion, packing density $\phi$ and armor porosity $p=(1-\phi/n)$

26   corresponding to a layer coefficient of $k_\Delta$=1.00 are recommended for randomly placed armor units; layer

27   thickness is one or two times the equivalent cube size for single-layer or double-layer armors,

28   respectively.

29

The realistic 3D small-scale placement tests allow us to determine the placement grids and feasible porosities with which the armor units can be placed on the slope. Placement grids for straight and curved trunks as well as roundheads should be carefully designed to avoid weak points in the armor that jeopardize the integrity of the structure. The toe berm and the placement of the first row of armor units in the armor require special care, particularly in the case of single-layer armors. The minimum feasible armor porosity in the trunk is $p=37\%$ for cubes and $p=35\%$ for Cubipods. Placement diamond grids adapted for curved trunks and roundheads increase the minimum feasible armor porosities. Armor porosity depends to the placement grid and size of the bottom layer; in double-layer armor, armor porosity is higher in the upper layer.

Short-range high-precision laser scanning proved to be valuable to estimate armor unit positioning and to assess armor randomness. Similar to terrestrial LIDAR, which may be used at prototype scale, laser scanning of small-scale armor models may be routinely used to measure the armor for placement or hydraulic stability tests. The results obtained in this study proved cubes are more likely to reduce armor randomness than Cubipods.

## Conclusions

The construction by hand of small-scale armor models in laboratory is very efficient; however, small-scale models should emulate prototype placement to reduce model effects. Both armor porosity and armor randomness must be controlled and characterized for small-scale physical models and prototypes. In this study, placement grids for cubes and Cubipods, randomly placed using a small-scale crawler crane and pressure clamps, were tested in the laboratory. Cube and Cubipod placement grids were obtained for double-layer armor, H/V=2.0 slope, in straight and curved trunks and in roundheads. Double-layer cube armors were only tested in the straight trunk, while double-layer Cubipod armors were tested in the straight trunk, curved trunk (maximum radius $R_l/D_n=109$) and roundhead (maximum radius $R_{l.l}/D_n=19$). Armor porosity in the trunk was found to be not feasible below 37% for cubes and 35% for Cubipods; placement grids were obtained for feasible armor porosities, considering row settlement during construction as well. These minimum feasible armor porosities were higher for curved trunks and roundheads.

Armor units can be placed in straight trunks using a homogeneous placement grid; by contrast, curved trunks and roundheads require different placement annulus with non-homogeneous placement grids. Using similar placement grid parameters, the armor porosity of roundheads is higher than that of straight trunks, and the armor porosity of the bottom armor layer is lower than that of the upper layer. There are several parameters affecting the placement (slope, radius, armor unit, $b/Dn$, $a/Dn$, $\Delta b/Dn$, etc.), but only a limited number of combinations were tested. Therefore, more research is needed to properly optimize the design of the placement grids for general cases.

A short-range high-precision laser scanner, similar to terrestrial LIDAR survey, was used in this study to assess the randomness of cube and Cubipod armors. The comparison of armor randomness indexes revealed that cube armor was significantly less random than Cubipod armor.

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