INFLUENCE OF ARMOR UNIT PLACEMENT ON ARMOR POROSITY AND HYDRAULIC STABILITY

Josep R. Medina[1], M. Esther Gómez-Martín[2] and Antonio Corredor[3]

The handling procedure and placement grid of concrete armor units (CAUs) are the key construction factors of armor layers. This paper analyzes conventional cube and Cubipod CAUs which are handled by pressure clamps and placed randomly. Two methodologies for small-scale blind construction of armor layers in laboratories are compared using a Cartesian system and crawler cranes. Model construction by hand in laboratories is usually done in excellent conditions contrary to actual construction at prototype scale which is blind underwater and is influenced by wind, waves and equipment constraints. For randomly placed CAUs, the layer coefficient is an unnecessary and subjective concept which should be disregarded to prevent misunderstandings when considering armor porosity. For a given CAU, the placement grid affects armor porosity which is directly related to armor hydraulic stability. Crawler cranes can only place CAUs in a narrow armor porosity band; therefore, porosity of small scale armor models constructed by hand must be selected within that viable porosity band to avoid uncontrolled model effects. Armor layers of conventional cubes placed randomly by hand are not realistic if porosity is p%<35% and have more hydraulic stability than the higher porosity armors which can actually be constructed with crawler cranes.

Keywords: rubble-mound breakwater; armor porosity; armor unit placement; Cubipod armor unit; cube armor unit; placement test; placement grid; crawler crane

INTRODUCTION

Mound breakwaters have been erected throughout the centuries. Constructing breakwaters for harbors in deeper waters and severe wave climates required heavier quarry stones then were often available at local quarries. Cube and parallelepiped concrete armor units (CAUs) were used in the 1800s when local quarries could not provide the appropriate stone size. In more recent times, numerous CAUs have been designed to optimize breakwaters, enhancing safety and reducing construction and maintenance costs. Since 1950, many different CAUs have been developed around the world to improve the stability of the armor layer in mound breakwaters. The existing types of CAUs for random placement can be divided into three categories of structural strength: (1) massive, (2) bulky and (3) slender. In this paper, the placement method and hydraulic stability of cubes and Cubipods, both massive CAUs, are analyzed.

After the catastrophic failure of the Dolos breakwater in the Port of Sines in 1978, modern CAU design methods have aimed to balance hydraulic stability and structural strength (see Dupray and Roberts, 2009). Conventional cubic blocks have many advantages, namely high structural strength, short production cycle and easy handling and stacking. However, conventional cubic blocks also have drawbacks such as low hydraulic stability, face-to-face fitting and low friction with filter layer. On the Iberian Peninsula, the largest mound breakwaters are constructed with cube-type CAUs, weighing more than 100 tonnes, as in the case of the 150-tonne unreinforced cubic blocks used at A Coruña (Spain) (Burcharth et al., 2002).

Gómez-Martín and Medina (2008) described the Cubipod, a new massive armor unit designed to maintain the advantages of the conventional cubic blocks while correcting the drawbacks. The hydraulic stability of both single-layer and double-layer Cubipod armors are much higher and overtopping rates are lower than conventional double-layer cube armors. Medina et al. (2009) reported the results of prototype drop tests of cube and Cubipod CAUs which showed that Cubipods resisted higher drops than cubic blocks of similar size. Furthermore, the cost analysis of breakwater construction in different conditions showed that Cubipods can reduce significantly the construction and maintenance costs when compared to conventional cubic blocks.

Conventional cubes and Cubipods are massive CAUs which can be safely handled using pressure clamps, as shown in Fig. 1. Both can be efficiently manufactured using vertical molds (2 units/day) and can be stacked in low porosity block yards. Cube and Cubipod CAUs are similar in the logistic aspects of breakwater construction; nevertheless, the Cubipod is a self-arranging CAU which favors random placement in a homogeneous armor porosity while the conventional cube tends to face-to-face fitting and heterogeneous packing both during construction and under wave attack. Homogeneous porosity

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Cubipod armors have higher hydraulic stability and lower overtopping rate than heterogeneous porosity conventional cube armors.

In this paper, the concept of armor porosity and its influence on armor stability is analyzed first. Secondly, a Cartesian blind placement system (CBPS) is used to approximately define the placement grids for maximum and minimum porosity cube and Cubipod armors. Thirdly, realistic small-scale crawler cranes are used in the wave tank to study the adequate placement grids for cubes and Cubipods depending on the target porosity and wave intensity during construction. Finally, some conclusions are given related to armor porosity in both small-scale modeling and prototype scale breakwater construction.

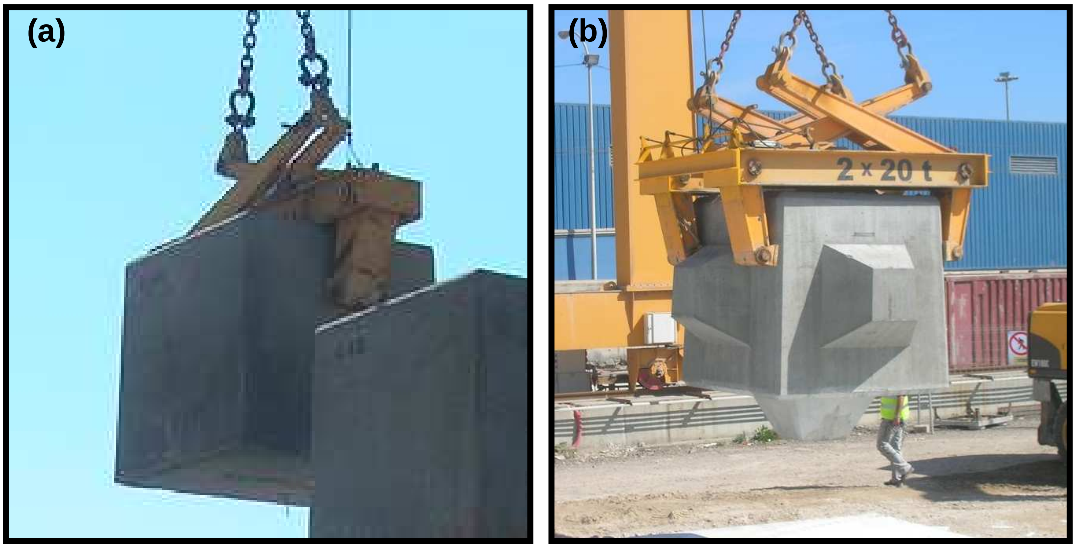

Figure 1. Massive CAUs handled with pressure clamps: (a) conventional cubic block and (b) Cubipod.

ARMOR POROSITY AND HYDRAULIC STABILITY

Armor Porosity, Placing Density and Packing Density

Porosity is a well known and intuitive general concept referring to the percentage of voids in a granular system. However, armor porosity is not a clear concept; it first requires defining armor thickness which is not straightforward for randomly placed CAUs. Usually, the armor thickness is referred to as one or two times the equivalent cube size or nominal diameter, $D_n=(W/\gamma_r)^{1/3}$, which is the cubic root of the CAU volume for single-layer and double-layer armors. However, most engineering manuals recommend specific nominal armor porosities (P%) for different CAUs associated with a given layer coefficient or layer thickness factor (k_Δ). Placing density (φ[units/m^2]) is the actual variable which is controlled by the placement grid and is related to both nominal armor porosity (P%) and layer coefficient (k_Δ) according to the formula (see SPM, 1984)

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

where N_a= 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. Different layer coefficients, k_Δ, and different nominal porosities, P%, may lead to the same placing density, φ. Frens (2007) analyzes some misinterpretations caused by the use of different criteria by different authors regarding the layer coefficient and the porosity concept. For instance, a nominal porosity of P%=47% with a layer coefficient of k_Δ=1.10 is equivalent to a porosity of p%=42% with a layer coefficient of k_Δ=1.00.

A convenient parameter to measure the relative consumption of concrete in the armor layer, associated with the armor porosity and number of layers, is the packing density, Φ, which is the dimensionless placing density using the equivalent cube size, D_n, as length unit

$$\Phi = \varphi(D_n)^2 = n(k_\Delta)(1-P\%) = n(1-p\%) \qquad (2)$$

in which φ= placing density, n= number of layers of CAUs, k_Δ=layer coefficient, P%= nominal armor porosity and p%= armor porosity. In order to prevent misunderstandings in engineering communication, it is better to refer to armor porosities p%=(1-Φ/n) corresponding to a layer coefficient of $k_\Delta=1$, then to refer to nominal porosities P% associated to a variety of specific layer coefficients $0.95<k_\Delta<1.10$. In this paper, dimensionless packing densities, Φ, and related armor porosities, p%, and number of CAU layers in the armor, n, are the preferred parameters used to characterize armor porosity and placing density of small-scale and prototype breakwater armor layers.

Armor Porosity and Hydraulic Stability

Hydraulic stability of armor layers depends on a number of structural and design storm variables such as D_n, Δ, α, H_{m0}, Ir, etc. Armor porosity affects energy dissipation, wave reflection, hydraulic stability, run-up, overtopping and heterogeneous-packing. However, most formulae and armor stability tests reported in the literature do not take into consideration the porosity of the armor layer. Usually, the engineering manuals (see SPM, 1984) recommend a nominal armor porosity and a packing density for each specific CAU and it is assumed that both laboratory tests and prototypes would construct armor layers with the corresponding placing densities. Unfortunately, the construction of armor layers at prototype scale is restricted and affected by available equipment, visibility, wind and waves, while small-scale laboratory construction is unrestricted with an optimal environment.

Armor porosity directly affects material procurement and payments during construction; however, a given armor porosity and packing density for a specific CAU is not only difficult to obtain in practice but it is also difficult to measure below mean water level (MWL) at prototype scale. Additionally, armor porosity changes during breakwater service lifetime. Heterogeneous packing is more likely if actual armor porosity is higher than designed, and runup and overtopping rates may increase when armor porosity decreases. Furthermore, armor hydraulic stability seems to significantly increase when armor porosity decreases, for massive, bulky and slender CAUs.

Frens (2007) tested three double-layer randomly placed Antifer cube armors with porosities 39%<p%<43%; observed stability number, Hs/(ΔDn), increased approximately 20% when armor porosity decreased by 10%. Yagci and Kapdasli (2003) tested the hydraulic stability of two Antifer cube armors with porosities p%=44% and p%=53%; measured armor damage was much higher for the high porosity armor.

Bakker et al. (2005) tested the hydraulic stability of single-layer Xbloc armors of porosities ranging 41%<p%<46% with different placement techniques. Random placement was recommended for Xbloc. High porosity armor showed undesired settlement and hydraulic stability significantly increased for Xbloc armors from p%=43% to p%=41%; observed stability numbers, Hs/(ΔDn), increased approximately 15% when armor porosity decreased by 5% .

Van der Meer (1999) tested the hydraulic stability of double-layer Tetrapod armors with porosities in the range 49%<p%<56% with random placement. Hydraulic stability significantly increased for Tetrapod armors from p%=56% to p%=49%; observed stability number, Hs/(ΔDn), increased approximately 10% when armor porosity decreased by 12% .

2D Small Scale Tests

In order to assess the influence of armor porosity on hydraulic stability, two conventional double-layer cube armors, H/V=2/1 slope, randomly placed by hand, were tested in similar conditions. A series of 1000 random waves corresponding to JONSWAP (γ=3.3) spectrum were generated with increasing significant wave height, H_{m0}, and constant Iribarren`s Number, Irp= $(Tp/2)/(2\pi H_{m0}/g)^{1/2} \approx 4.25$. The physical tests were carried out in the wind and wave test facility at the *Universidad Politécnica de Valencia* (UPV). Fig. 2 shows a longitudinal cross section of the wave flume (30.0x1.2x1.2 meters). The wave flume had a constant water depth h[cm]=60, and no wind and random waves were generated by the piston wavemaker with AWACS active wave absorption. The filter layer, core and toe berm corresponded to a typical breakwater in the Atlantic coast of Spain without the main armor layer and crown wall; the armor layer in these tests was the secondary armor layer of the prototype, which plays an important role during the construction phase.

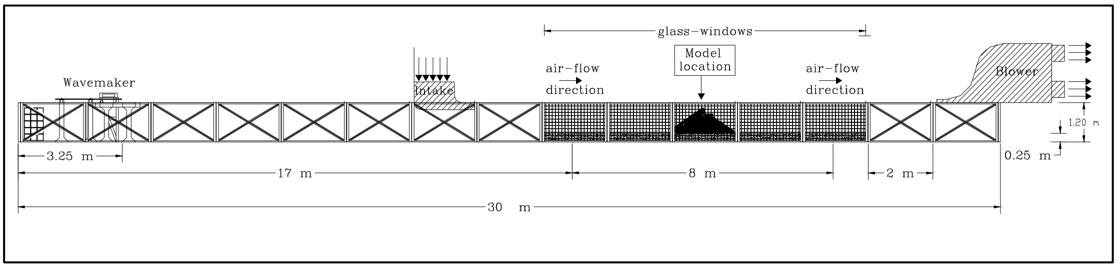

Figure 2. Longitudinal cross section of the UPV wind and wave test facility.

Fig. 3 shows the cross section of the tested double-layer cube armored model at 1/50 scale. The armor units were colored in bands to measure the damage using the Virtual Net method (VN), described by Gómez-Martín and Medina (2006). Photographs taken perpendicularly to the slope were used to calculate the number of units displaced from each band and the corresponding equivalent dimensionless damage, D_e, defined as the dimensionless accumulated erosion. VN takes into consideration both extracted and displaced units to estimate the equivalent dimensionless damage, D_e.

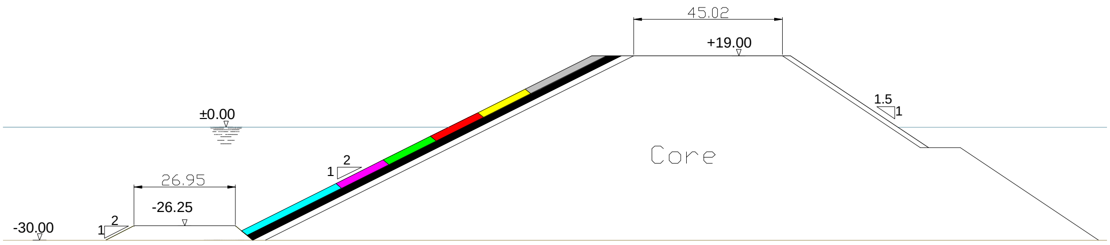

Figure 3. Cross section of the double-layer cube armored model (prototype dimensions in m.).

To define the failure functions of low porosity (p%=36%) and high porosity (p%=42%) cube armors, four capacitance wave gauges were placed in front of the structure in the model area, to analyze incident and reflected waves using the LASA method (see Figueres and Medina, 2004). Fig. 4 shows the equivalent damage, D_e, as a function of the stability number, $Ns=H_{m0}/\Delta Dn$, in which H_{m0} is the incident significant wave height, $\Delta=(\gamma_r/\gamma_w-1)$ is the relative submerged specific weight, and $D_n=(W/\gamma_r)^{1/3}$ is the nominal diameter of the armor units.

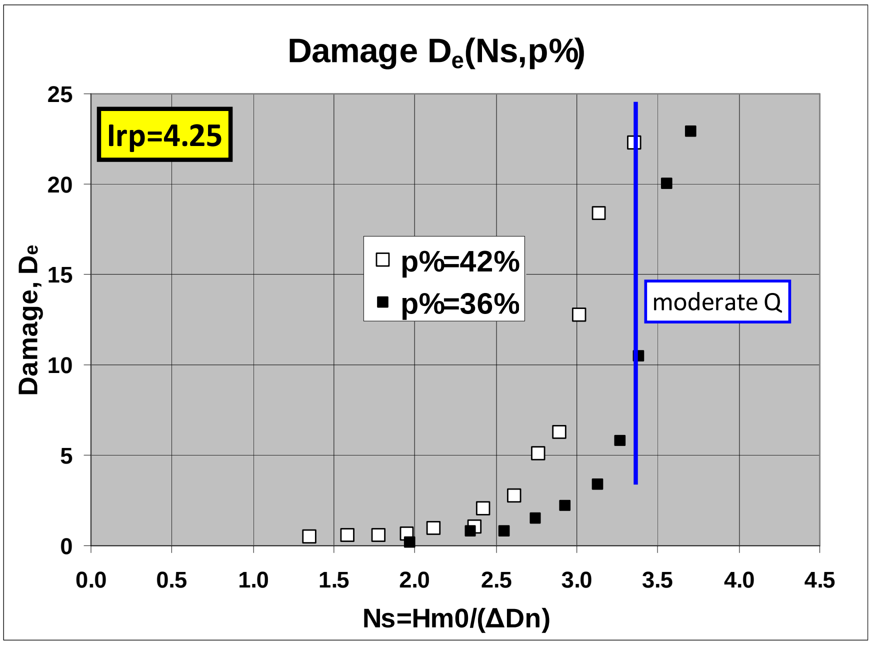

Figure 4. Failure functions of low porosity and high porosity cube armors (slope H/V=2/1).

Low porosity (p%=36%) cube armor showed much higher hydraulic stability than high porosity (p%=42%) cube armor. These experimental results of cube armors in a H/V=2/1 slope are in agreement with the observations by different authors in literature described in the previous section, and confirmed the influence of armor porosity on hydraulic stability. In this case, a 15% reduction in armor porosity roughly increased the stability numbers of the start of damage and initiation of destruction by 10%, Ns(IDa) and Ns(IDe).

Comparison of Prototype and Small Scale Model: Model Effects

Small-scale models are usually constructed in ideal conditions (no water, perfect view and hand placement). It is relatively easy to construct low porosity randomly placed cube armors, which are much more stable than high porosity armors. If armor porosity is neglected at the experimental design phase, it may be difficult to compare hydraulic stability results because actual breakwaters are not constructed in laboratory conditions. Specifically, cube armors with random placement are difficult to build up at low porosity.

Fig. 5 shows a small-scale model and a prototype breakwater during construction; the placement by hand, in a clean and safe environment without water, is much better than the placement using crawler cranes, affected by wind and waves, and GPS positioning grids. The result is more uncertain at prototype scale than it is in the laboratory.

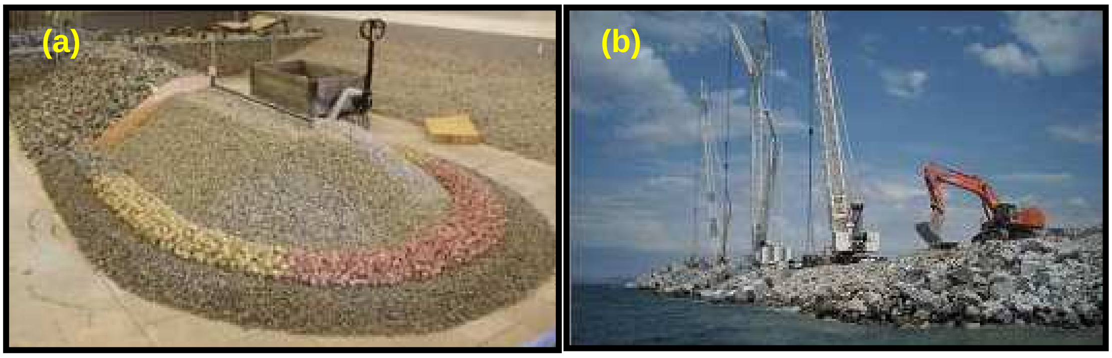

Figure 5. Breakwater under construction: (a) small-scale and (b) prototype.

Full-scale armor construction is restricted by available equipment and environmental conditions (waves, wind, crawler crane and underwater blind placement); therefore, high porosity cube armors are likely to be constructed regardless of the design armor porosity. An achievable armor porosity may significantly depart from the design armor porosity and the armor porosity of the models tested in the laboratory. CAU placement method and construction environmental conditions during construction influence armor porosity at prototype scale. Therefore, a significant model effect due to uncontrolled armor porosity may be affecting numerous armor stability tests reported in literature.

Hydraulic stability depends on packing density (porosity and number of layers in the armor). Therefore, armor porosity should always be measured in laboratory tests, just as placement method and armor porosity are controlled and measured in real constructions, at prototype scale. A significant deviation between armor porosity measured in the small-scale model and prototype will lead to a significant model effect with an uncontrolled outcome on breakwater performance. The higher the discrepancy between prototype and small-scale armor porosity, the higher the structural uncertainty is; an uncertainty which is clearly biased towards insecurity.

If prototype armor porosity is higher than it is in the tested small-scale models, as is usually the case, the actual breakwater is less stable than anticipated by physical tests. For a given CAU, feasible armor porosity at the construction site should be estimated first, as the design armor porosity, and then physical model tests should consider it in the experimental design phase. If a prototype workable armor porosity is not established before physical experimentation, a significant model effect due to armor porosity must be taken into consideration.

3D PLACEMENT TESTS

CAU Placement with Crawler Cranes and Pressure Clamps

In order to estimate workable armor porosities at prototype scale, a series of placement methods at small-scale, emulating prototype construction, were carried out at the UPV wave tank (15.0m x 7.0m x 0.45m). In this paper, only conventional cube and Cubipod CAUs are analyzed. Both are massive CAUs handled with pressure clamps and typically placed with crawler cranes. Therefore, small scale crawler cranes and pressure clamps are used in the placement tests. Fig. 6a and 6b shows prototype and small-scale pressure clamps used during the Cubipod placement tests. Fig. 6c show a general view of one of the small-scale crawler cranes used for cube and Cubipod placement tests. Both small-scale crawler cranes and pressure clamps are mechanically similar to the equipment used for handling and construction at prototype scale.

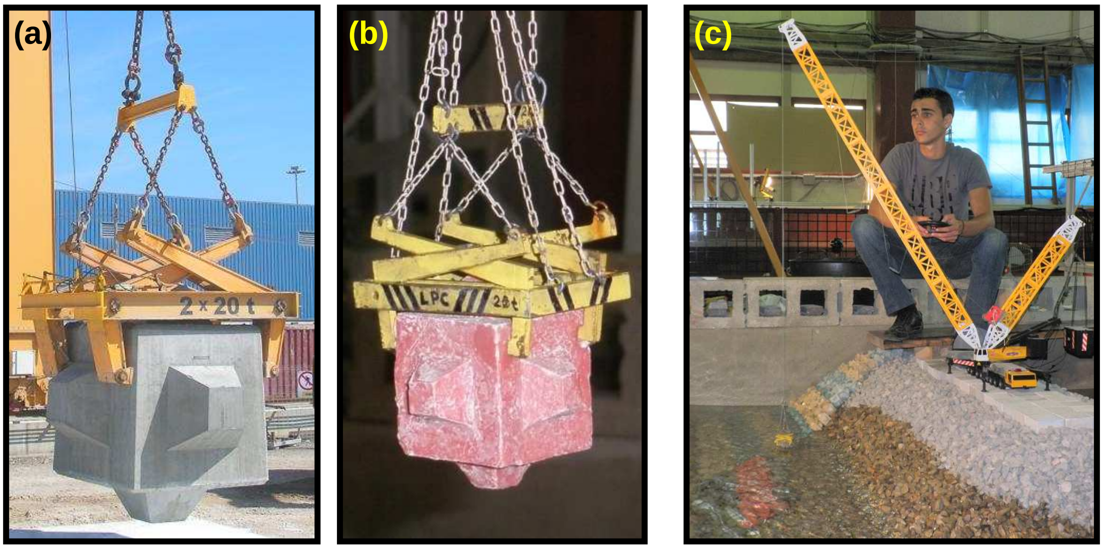

Figure 6. Cubipod handling and placement: (a) prototype pressure clamps, (b) small-scale pressure clamps, and (c) small-scale crawler crane.

Crawler cranes are equipped with a GPS positioning system to place the CAU at given X-Y coordinates. Actual construction at prototype scale first requires the definition of a placement grid similar to that described in Fig. 7. The key parameters of the placement grid are a/D_n and b/D_n, in which D_n is the nominal diameter of the CAU; if centers of gravity of CAUs are placed on the armor according to the placement grid, the porosity is $p\%=1-(D_n/a)(D_n/b)$. However, the Cartesian grid shown in Fig. 7 is valid for centers of gravity but not for CAU orientation; crawler cranes imposed a radial orientation towards the crane basement. Furthermore, there is always error positioning which is small when above MWL but depends on the waves and wind when below MWL.

Radial orientation of CAUs and error positioning put limits on the minimum armor porosity which can be achieved at prototype scale, induce changes on the theoretical armor porosity of the placement grid and produce uncertainty on the final armor porosity depending on the wind and wave action during placement. These limits, changes and uncertainty on armor porosity depend on the type of CAU. In this paper, conventional cube and Cubipod CAU placement is analyzed using small-scale models to assess the feasible armor porosities of cube and Cubipod armors at prototype scale.

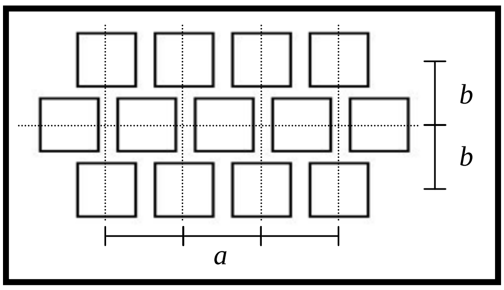

Figure 7. Scheme of a CAU placement grid (view perpendicular to the armor slope).

Preliminary 3D Placement Tests: Dry Cartesian X-Y Blind Placement

Typical crawler crane placement takes approximately 15 minutes to put a conventional cube on the armor layer using pressure clamps. Pardo (2009) described in detail the 3D small-scale placement systems used in this paper. In laboratory tests, a small-scale crawler crane takes approximately 2 minutes to place a unit on the armor. The realistic 3D placement tests with small-scale crawler cranes are time-consuming.

In order to reduce the time consumption of the realistic 3D placement tests, a Cartesian system was used; the underwater placement was blind but waves were not affecting the system. Therefore, this placement method was more realistic than the usual placement by hand of the small-scale experiments, but not as realistic as the placement using small-scale crawler cranes. The advantage of this intermediate blind placement method is the consumption of time which is one order of magnitude lower, approximately 10 seconds per unit. Fig. 8 shows pictures of the dry Cartesian blind placement system (CBPS) and a general view of the small-scale armor model. The clamp is positioned following a given X-Y coordinate on a placement grid similar to that represented in Fig. 7, and the clamp operator released the unit when touching the slope without watching the slope.

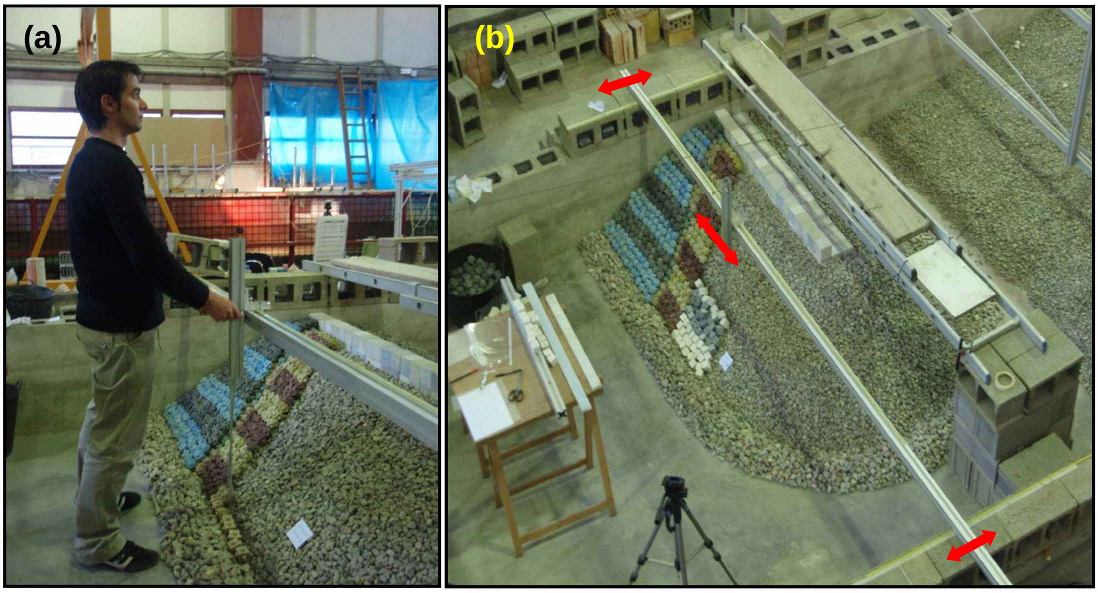

Figure 8. Cartesian blind placement system (CBPS): (a) operator releasing the unit and (b) general view.

The main objective of these preliminary tests with CBPS was to roughly estimate the maximum and minimum armor porosity which could be achieved in real constructions. The minimum porosity of armor layers constructed by hand in a laboratory are p%=0% and p%=29% for cube and Cubipod CAUs, respectively. However, using CBPS, the minimum armor porosity was p%=35%>0% for cubes and p%=37%>29% for Cubipods at H/V=3/2 slope. A variety of positioning grids were tested to find the optimum result. The visual appearance of the armor layer after placement was used as a qualitative criterion to discriminate between acceptable and unacceptable armor layers. Based on visual appearance, the maximum armor porosity using CBPS was p%=45%>35%>0% for cubes and p%=51%>37%>29% for Cubipods. Fig. 9 shows cube armors constructed with CBPS with minimum and maximum porosity.

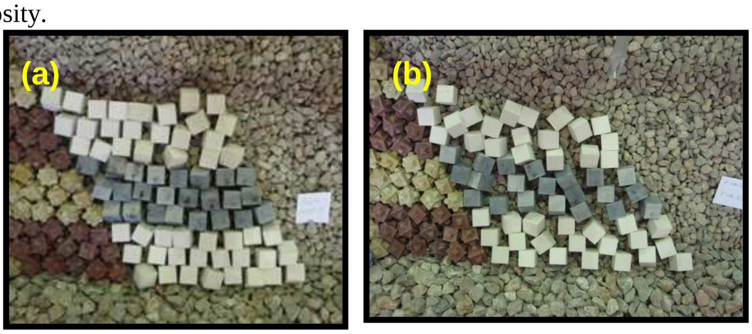

Figure 9. Cube armors with CBPS: (a) minimum porosity p%=35%, and (b) maximum porosity p%=45%.

Fig. 10 shows Cubipod armor layers constructed with CBPS with minimum and maximum armor porosity. Both Fig. 9 and Fig. 10 are referred to armor layers with a H/V=3/2 slope.

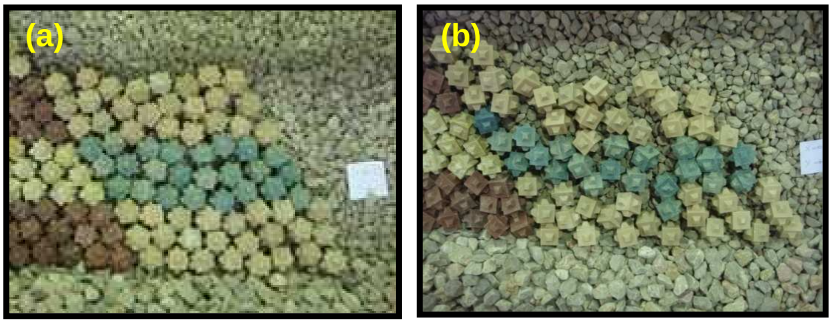

Figure 10. Cubipod armors with CBPS: (a) minimum porosity p%=37%, and (b) maximum porosity p%=51%.

3D Placement Tests with Small-Scale Crawler Cranes

Once the placement grids and feasible armor porosity ranges were approximately known, small-scale crawler cranes were used to find workable armor porosities and to assess the uncertainty due to wave action during CAU placement. In these time-consuming tests, mean porosity and local armor porosities were measured as indicated in Fig. 11. The constructed area was divided into eight sectors to assess the variability of the armor porosity.

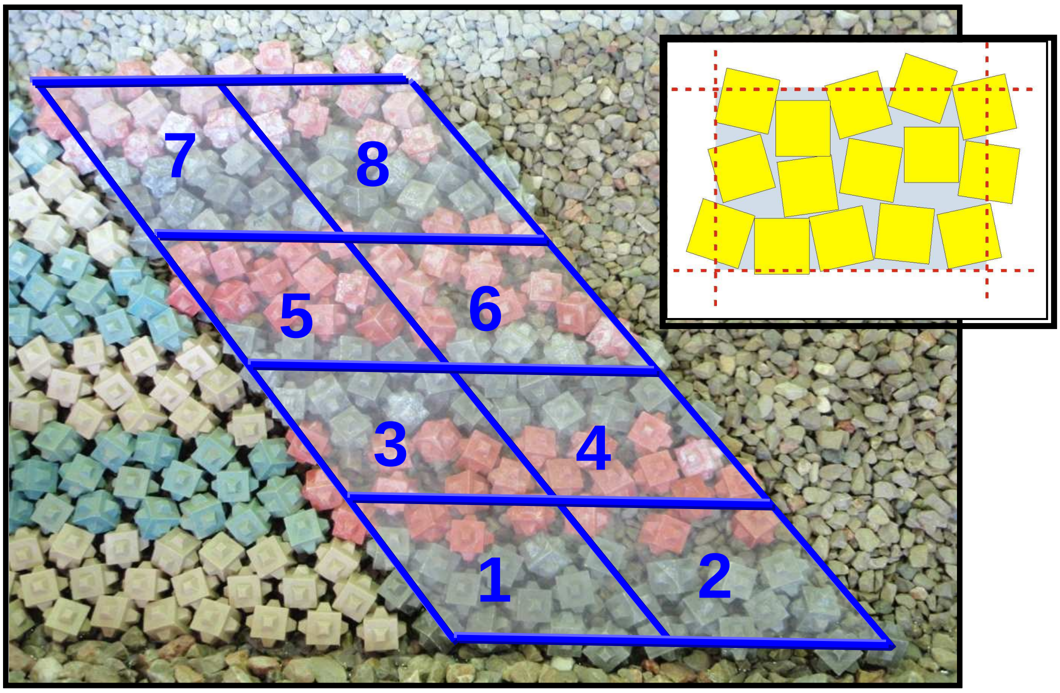

Figure 11. Measurement of armor porosity in different sectors.

Using a small-scale crawler crane similar to that shown in Fig. 6c, the cube and Cubipod positioning grids corresponding to a target porosity p%=41% were taken from the preliminary CBPS tests. The small-scale crawler crane was driven in a similar way to that of prototype crawler cranes in full-scale real constructions. The first two realistic placement tests were done without waves to check if CBPS was acceptable to find appropriate positioning grids of CAUs.

The armor layers are shown in Fig. 12; both cube and Cubipod armors achieved the target armor porosity with the CBPS positioning grids. In order to obtain a cube and Cubipod armor porosity of p%=41%, the CBPS positioning grids were {a/Dn=1.58, b/Dn=1.25} for cubes and {a/Dn=1.57, b/Dn=1.22} for Cubipods. Note that the theoretical porosity of the positioning grids (p%=49% and p%=48%) were higher than the target porosity (p%=41%).The final measured porosities for cube and Cubipod armors were p%=41.3% and p%=40.4%, respectively, very close to the target porosity.

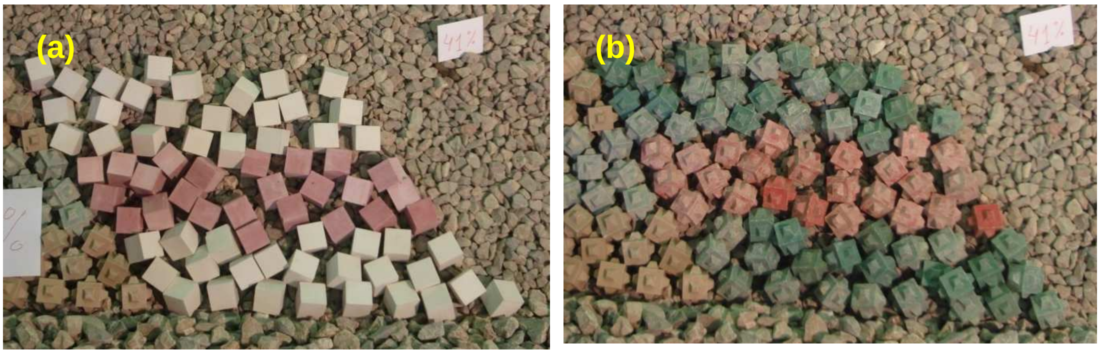

Figure 12. Realistic 3D CAU placement, on H/V=3/2 slope, using a small-scale crawler crane with CBPS positioning grids: (a) cubes, and (b) Cubipods.

Fig. 13 shows a general view of the placement method using small-scale crawler cranes under wave action. This model corresponds to a typical large mound breakwater in the Spanish Mediterranean coast at a 1/50 scale. Cube and Cubipod armors were constructed under JONSWAP (γ=3.3) spectrum with prototype significant wave height, H_{m0}[m]=1.0 and 2.0, and peak period, T_p[s]=6 and 8. These four sea states affected the underwater blind placement increasing CAU positioning error and CAU movements on the slope after being released from the pressure clamps.

Fig. 14 shows the measured maximum, minimum, and mean armor porosities for each sea state. Armor porosity data was ordered by wave power ($H_{m0}^2 * T_p$). Cubipod armor was less sensitive to wave action, showing a very low variability for the more energetic wave conditions.

Cubipod units tend to re-arrange on the slope toward a homogeneous porosity close to the usual armor porosity obtained in a laboratory when simply dropping the units onto the slope by hand. On the contrary, a wide range of armor porosities may be obtained dropping cubic blocks by hand on the slope. Therefore, hydraulic model tests of cube armors must take into consideration a reasonable target armor porosity, which could be achieved at prototype scale using crawler cranes under the wind and wave conditions at the construction site.

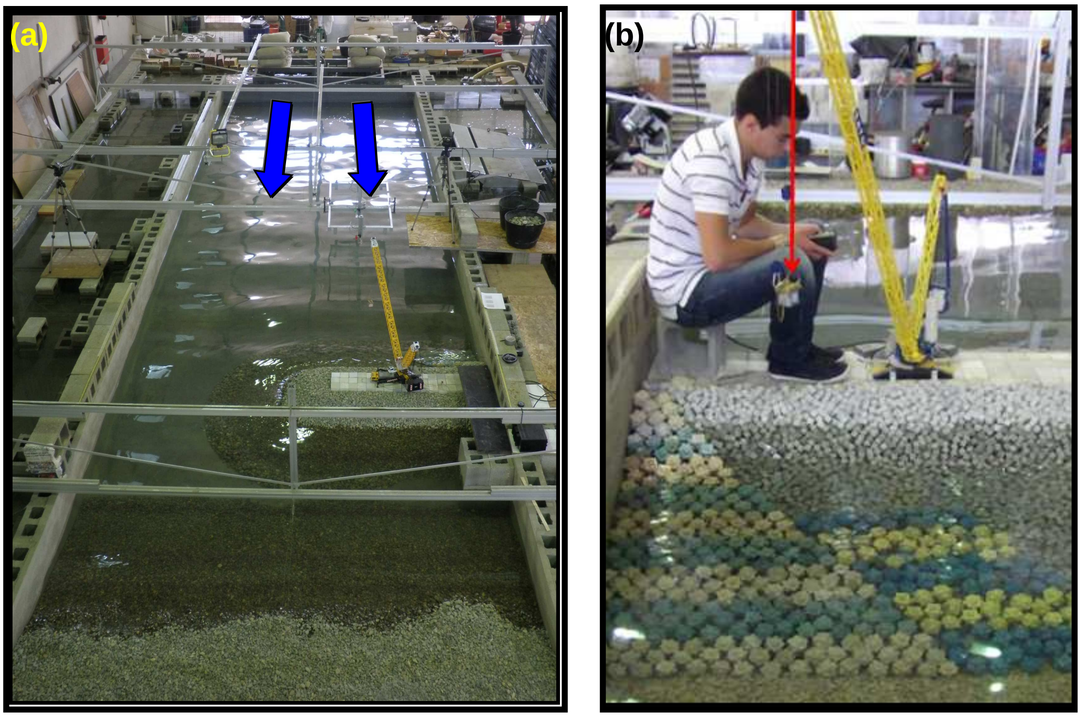

Figure 13. Small-scale crawler crane under wave action: (a) general view, and (b) Cubipod placement.

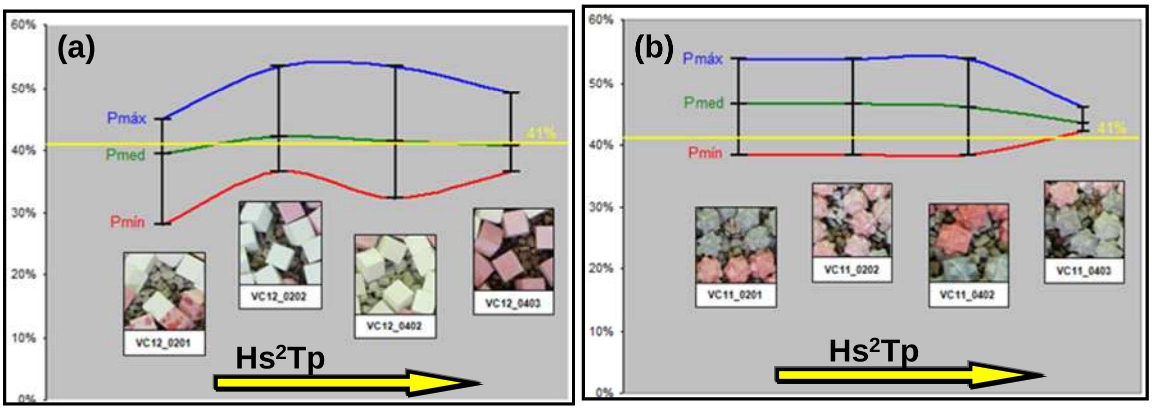

Figure 14. Armor porosity ranges versus wave power: (a) cubes, and (b) Cubipods.

The results given above are valid only for H/V=3/2 slopes. Figure 15 shows a general view of the ongoing 3D placement tests and 2D stability and overtopping tests for H/V=2.0 slope. The optimum placement grids and feasible armor porosities are different for H/V=2.0 slope, although the qualitative performance of cube and Cubipod CAUs are similar. Cubipod CAUs tend to re-arrange on the slope towards a uniform porosity in the range 41% to 43%, very close to the usual armor porosity obtained in the 2D hydraulic stability tests, when the units were dropped by hand on the slope.

Figure 15. General view of ongoing 3D placement and 2D hydraulic stability tests of H/V=2.0 slope models.

SUMMARY AND CONCLUSIONS

Armor porosity and placement methods of two massive CAUs were analyzed: conventional cubes and Cubipods. Both cubic blocks and Cubipods are manufactured and stacked in similar conditions and handled with pressure clamps.

Armor porosity affects hydraulic stability, overtopping, wave reflection, etc. However, most formulae and armor stability tests reported in the literature do not take into consideration the armor porosity. Engineering manuals recommend a nominal armor porosity, a layer coefficient and a packing density for each specific CAU, supposedly based on experience. It is assumed that both laboratory tests and prototypes would be constructed with the corresponding placing densities. Unfortunately, the construction of armor layers at prototype scale is strongly restricted by equipment, underwater visibility, wind and waves, while small scale laboratory models are usually constructed by hand in ideal conditions.

Armor porosity (p%), nominal armor porosities (P%), layer thickness factor (k_Δ), number of layer of CAUs in the armor (n), placing density (φ[units/m^2]) and packing density (Φ) are cross-related concepts used in literature which may cause some misunderstandings. For randomly placed CAUs, the layer coefficient (k_Δ) is an unnecessary and subjective concept which should be avoided to prevent misunderstandings of the armor porosity (p%) concept.

To estimate the influence of armor porosity on hydraulic stability, two conventional double-layer cube armors, H/V=2/1 slope, randomly placed by hand, were tested in similar conditions. Low porosity (p%=36%) cube armor showed much higher hydraulic stability than high porosity (p%=42%) cube armor. These experimental results of cube armors in a H/V=2/1 slope were in agreement with the observations by different authors given in literature and confirmed the influence of armor porosity on hydraulic stability. In this case, a 15% reduction on armor porosity increased the stability numbers of the start of damage and initiation of destruction, Ns(IDa) and Ns(IDe) by approximately 10%.

Small-scale models are usually constructed in ideal conditions (no water, perfect view and hand placement). It is relatively easy to construct low porosity randomly placed cube armors, which are much more stable than high porosity armors. However, full-scale armor construction is strongly conditioned by equipment and environmental conditions (waves, wind, crawler crane and underwater blind placement); therefore, high porosity cube armors are likely to be constructed differently than the design armor porosity. Equipment for CAU placement and environmental conditions during construction determine the range of achievable armor porosity at prototype scale. Therefore, significant model effect due to uncontrolled armor porosities may be affecting numerous armor stability tests reported in literature. If breakwater armor porosity is higher in prototype than it is in small-scale model, as is usually the case, the actual breakwater is less stable than estimated by hydraulic stability tests.

To estimate achievable armor porosities at prototype scale, CBPS and small-scale crawler cranes were used in a wave tank to emulate realistic CAU placement at prototype scale. As a rule of thumb, armor placement by hand, in hydraulic stability tests, takes 1 second per unit; CBPS takes 10 seconds; a small-scale crawler crane takes 100 seconds; and a full-scale crawler crane 1000 seconds. Based on visual appearance, CBPS was used to estimate the maximum and minimum single-layer armor porosity on H/V=3/2 slope, 35%<p%<45% for cube armors and 37%<p%<51% for Cubipod armors. Armor layers of conventional cubes placed randomly by hand are not realistic if porosity is p%<35% and have more hydraulic stability than the higher porosity armors which can be constructed with crawler cranes at prototype scale.

CBPS positioning grids for both cube and Cubipod armors were validated for a target armor porosity of p%=41% using realistic small-scale crawler cranes without waves. 1/50 scale tests of 3D armor placement a crawler crane under four different wave conditions were carried out. Cubipod armor was less sensitive to wave action, showing a very low variability for the stronger wave conditions. Optimum placement grids are different for H/V=3/2 and 2.0 slopes; however, qualitative performance of cube and Cubipod CAUs are similar. Cubipod CAUs tend to re-arrange on the slope towards a uniform porosity in the range 41% to 43%, very close to the usual armor porosity obtained by dropping the units onto the slope by hand.

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REFERENCES

Bakker, P., M. Klabbers, M. Muttray, and A. van den Berge. 2005. Hydraulic performance of Xbloc® armour units. *Proceedings of 1st International Conference on Coastal Zone Management and Engineering in the Middle East*. Dubai, November 2005.

Burcharth, H.F., E. Maciñeira, and P. Canalejo. 2002. Model testing and reliability evaluation of the new deepwater breakwater at A Coruña, Spain. *Proceedings of 27th International Conference on Coastal Engineering*, ASCE, 1581-1593.

Dupray, S., and J. Roberts. 2009. Review of the use of concrete in the manufacture of concrete armour units. *Proceedings of Coasts, Marine Structures and Breakwaters 2009,* ICE (in press).

Figueres, M., and J.R. Medina. 2004. Estimation of incident and reflected waves using a fully non-linear wave model. *Proceedings of the 29th International Conference on Coastal Engineering,* ASCE, 594-603.

Frens, A.B. 2007. *The impact of placement method on Antifer-block stability*. M.Sc. thesis, Delft University of Technology, May 2007.

Gómez-Martin, M. E., and Medina, J. R. 2006. Damage progression on cube armoured breakwaters. *Proceedings. of the 30th International Conference on Coastal Engineering*, ASCE, 5229-5240.

Gómez-Martín, M.E., and J.R. Medina. 2008. Erosion of cubes and Cubipods armour layers under wave attack. *Proceedings of 30th International Conference. on Coastal Engineering,* ASCE, 3461-3473.

Medina, J.R., M.E. Gómez-Martín, A. Corredor, R. Torres, J.V. Miñana, E. Fernández, C.F. Menéndez, and M. Santos. 2009. Cube and Cubipod armour unit drop tests and cost analysis. *Proceedings of Coasts, Marine Structures and Breakwaters 2009,* ICE, (in press).

Pardo, V. 2009. *Análisis de la colocación de bloques cúbicos y cubípodos en el manto principal de diques en talud. Aplicación a la ampliación del Puerto de Valencia*. Proyecto Fin de Carrera de la ETSI Caminos, Canales y Puertos, Julio 2009 (in Spanish).

SPM. 1984. *Shore Protection Manual,* U.S. Army Corps of Engineers, Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Yagci, O., and S. Kapdasli. 2003. Alternative placement technique for antifer blocks used on breakwaters. Ocean Engineering, 30(2003), 1433-1451.

Van der Meer, J. 1999. Design of concrete armour layers. *Proceedings of the Coastal Structures ´99.* A.A. Balkema, 213-221.