EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF ARMOR UNIT PLACEMENT METHOD ON ARMOR POROSITY

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Most engineering manuals recommend given armor porosities for specific concrete armor units (CAUs), which ignores the fact that the armor unit placement method affects armor porosity. Usually, it is assumed that both laboratory tests and prototypes have armor layers with the given armor porosity; however, experience tells us that laboratory models are constructed in ideal conditions, whereas prototype construction is influenced by wind, waves, visibility and equipment. This paper describes the placement method of cubes and Cubipods, both handled with pressure clamps. Cartesian blind placement system was used to define grid parameters in order to obtain maximum and minimum armor layer porosity. Small-scale crawler crane tests were designed to study CAU placement under moderate wave conditions. Cubipods showed relatively homogeneous porosity for a range of wave conditions; nevertheless, cubes showed greater variability. Cube placement is affected by wave characteristics while Cubipod placement is much less sensitive to wave characteristics. Cubipods tend to self-arrange on the slope to achieve homogeneous porosity.

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

1. Intoduction

Mound breakwaters are frequently used around the world to shelter port areas from wave action. Increasing transportation and ship dimensions means that breakwaters must be larger. Quarry stone has always been used for these structures, but it has limited weights; thus, cubic blocks and parallelepiped concrete armor units (CAUs) were generally used when local quarries could not provide the appropriate quarry stone size. Since the mid-20th century, many types of CAUs have been proposed to optimize breakwaters, giving more stability and reducing construction and maintenance costs. These CAUs can be divided into three groups depending on relative structural strength: massive, bulky and slender.

The massive conventional cube is the most commonly used CAU in Spain because of its simple production, easier stacking and handling, high structural strength and low risk of progressive failure. However, the cubic block presents some disadvantages like low hydraulic stability (K_D=6) and high heterogeneous packing (face-to-face fitting, high overtopping and low friction with filter layer). Gómez-Martín and Medina (2008) designed the Cubipod, which is a new massive CAU that maintains the advantages of the cubic block while improving its disadvantages. The Cubipod features higher hydraulic stability (K_D=12 for single-layer and K_D=28 for double-layer) and low heterogeneous packing (no face-to-face fitting, decreased overtopping and increased friction with filter layer).

The hydraulic stability of armor layers depends on a number of structural and wave climate variables such as D_{n50}, Δ, α, H_{m0} and Ir. Usually, nominal armor porosity and packing density are given for each specific CAU and those values are assumed for both laboratory tests and prototypes. Unfortunately, the construction of armor layers at prototype scale is highly conditioned by equipment, visibility, wind and waves, whereas small-scale laboratory constructions are not. The armor layer porosity of mound breakwaters is a crucial factor; differences between design and construction values involve significant risk. Armor porosity influences the hydraulic performance of the structure affecting wave reflection, stability, run up and overtopping, and also the volume of materials necessary for the construction.

In this paper, the design of armor layers and the differences between prototype and scaled models are first analyzed. Second, armor layer construction is briefly discussed. Third, the experiments conducted are explained. The Cartesian Blind Placement System (CBPS) was used (1) to reduce the time of the 3D realistic placement tests, (2) to define the relationship between grid and real porosity and (3) to obtain the minimum and maximum cube and Cubipod armor porosities. In 3D realistic placement tests, a small-scale crawler crane was used in the wave basin to study the wave effect on CAU placement under random wave conditions. Finally, conclusions about armor layer design and construction are given.

2. Armor layers

When breakwaters were constructed with quarry stone, both design and construction were simple. With the new CAUs, new parameters like shape and structural strength began to affect the design.

Related to neighboring orientations, there are two types of placements: regular and random. Regardless of neighboring orientations, CAUs are placed according to a placement grid, such as the diamond shaped grid (see Figure 1), where *a* is the distance between two CAU gravity centers in the trunk breakwater direction, and *b* is the distance between two CAU gravity centers in the toe-crown direction.

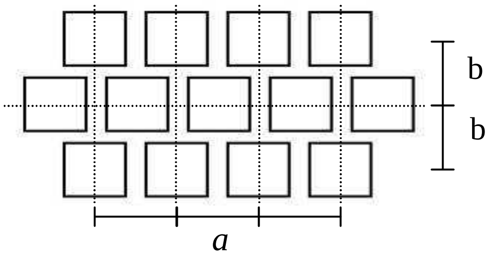

Figure 1. Placement grid with diamond shape.

Usually engineering manuals like SPM (1984) recommend specific nominal armor porosities for the different CAUs associated with a given layer coefficient. The layer coefficient is an armor thickness corrector, because the thickness of armor layer with a specific CAU is not an exact natural number of layers multiplied by the nominal diameter. On the other hand, porosity is an intuitive and clear concept (percentage of voids in a granular system), whereas armor porosity is not. It requires first defining an armor thickness which is not simple for randomly placed CAUs as illustrated in Figure 2. SPM (1984) gives a formula to obtain the armor thickness related to the layer coefficient (Eq.[1]).

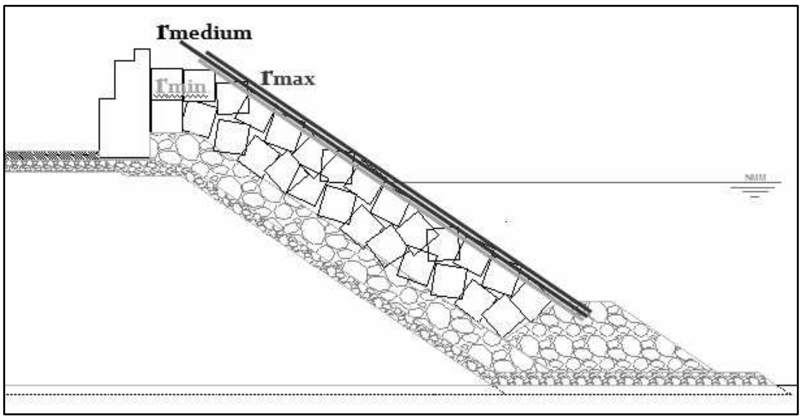

Figure 2. Armor thickness selection.

$$\text{Armor thickness: } r = nk_{\Delta}(W/\gamma_r)^{1/3} \qquad [1]$$

where, r = armor thickness, n = number of layers of CAUs, k_{Δ} = layer coefficient and W/γ_r = volume of CAU.

Other design parameters are the placing density and the packing density. The placing density (Nr/A) is the variable which is actually controlled by the placement grid and is related to both nominal armor porosity and layer coefficient according to Eq.[2].

$$N_r/A = nk_{\Delta}(1-P)(\gamma_r/W)^{2/3} \qquad [2]$$

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. As observed in [2], different layer coefficients and nominal armor porosity values may generate the same placing density. The packing density (Φ) is a parameter to measure the relative consumption of concrete in the armor layer (Eq.[3]).

$$\Phi = nk_{\Delta}(1-P) \qquad [3]$$

where, Φ = packing density, n = number of layers of CAUs, k_{Δ} = layer coefficient and P = nominal armor porosity.

Thus, in order to prevent misunderstandings in engineering communication, it is better to refer to armor porosity corresponding to a layer coefficient 1.00 for randomly placed CAUs rather than to refer to nominal porosities associated to a variety of specific layer coefficients.

The construction of armor layers at prototype scale is restricted by environmental conditions (wind, waves, underwater blind placement, etc.) and available equipment (machinery and handling). Small-scale models are usually constructed in ideal conditions (perfect view, no water, construction by hand, etc.). Therefore, scale effects should be carefully considered.

The porosity of the armor layer of mound breakwaters is a relevant factor: differences between design and prototype armor porosities involve significant risk. Armor porosity affects the hydraulic behavior of the structure changing wave reflection, stability, run up and overtopping, and also the volume of materials required for the construction. At the design phase, it is necessary to know the porosity values in order to estimate the volume of material needed to construct the main layer and to correctly design the cross sections.

3. Background

Tests related to armor porosity and armor unit placement methods are not common; thus, it is important to conduct research and draw conclusions.

VandenBosch et al. (2002) described the influence of placement density on the stability of cubes in a double armor layer and Tetrapods and rocks in a single armor layer. In the case of cubes, higher density of placement leads to more stable construction until a certain value, with higher values lowering the stability. The structure starts behaving as a placed block revetment. In the case of high placement densities, uplifting and sliding failure appear. In the case of Tetrapod and rock armored mound breakwaters, the higher the placement density, the higher the stability.

Yagci and Kapdasli (2003) proposed a new placement technique for Antifer blocks called “alternative placement technique”. This placement technique consists in placing the first layer of blocks on the filter layer so that the Antifer block base makes contact with the filter layer and with a distance between neighboring blocks equal to (base width/2). And for the second layer, the neighboring blocks were adjacent to each other and the base of units was in contact with the first layer. This new placement technique was compared with others such as the regular, irregular and the sloped wall placement techniques. Considering armor layer stability, prototype placement, clarity of the placement technique definition, armor layer cost, and wave runup, the “alternative placement technique” was found to be superior to other existing placement techniques.

Gürer et al. (2005) compared two methods of Tetrapod placement related to breakwater stability. The first armor layer for both methods consisted of Tetrapods placed with one leg normal to the breakwater slope and pointed outwards from the slope. The first method placed the units with one leg directed inwards on the slope and at a right angle to the breakwater slope (P=54% and Nr/A=1.03). The second method placement is identical to that of the first layer (P=61% anp Nr/A=0.90). The tests showed that the second method provided higher stability for initial damage than first one. However, the initial low level of damage was followed by rapid failure. Finally, with the first method, failure was reached gradually increasing wave height.

Cevik et al. (2005) used two placement methods to study the stability of Core-Loc elements on a 1:1.5 slope attacked by regular and random waves in non-breaking and breaking conditions. The two placement methods were: regular (P=61%) and random (P=63%). They concluded that random placement with a one-layer system is preferable because it is more stable and the run up is lower.

Muttray et al. (2005) studied two different Xbloc placement methods. First, the sling was attached to a leg of the X-shaped base, and second, the sling was attached to a cubical leg. With the first method, it was easier to obtain higher values of packing density. Tests revealed that stability increases when packing density increases and for higher values of packing density, the settlements decrease. For this reason, prototype Xbloc construction with the first method was recommended.

Oever et al. (2006) continued with Xbloc studies, by examining the Xbloc placement, specially the effect of upslope, horizontal distance between elements and asymmetric placement patterns. Tests were carried out using a standard diamond grid with and without guidance and off-centre placement. The units on the slope were placed with one leg of the X pointing downwards. Generally, the quality of placement without guidance was lower than placement with guidance. Accumulative placement errors appeared without guidance. The off-centre placement was possible, but to achieve this, the off-centre distance must be larger than $2D_n$.

4. Experiments

In order to analyze the influence of cubic CAU placement methods on the armor porosity, 3D series placement tests were carried out in the wave basin (15x7.5x0.5m) of the Laboratory of Ports and Coasts at the *Universidad*

Politécnica de Valencia. A typical breakwater model was constructed in the wave basin at a reference scale of 1/50 (slope 3/2).

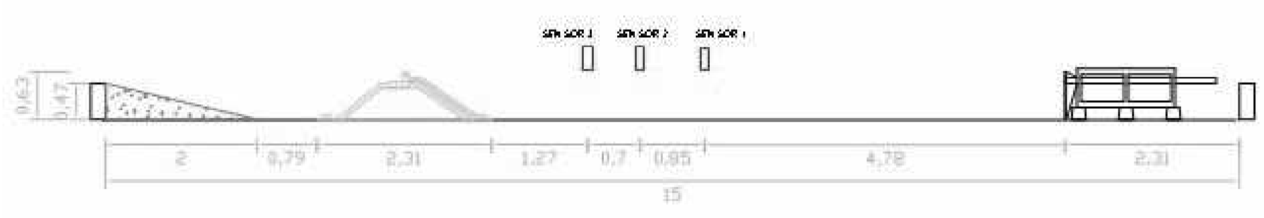

Figure 3. Wave basin section.

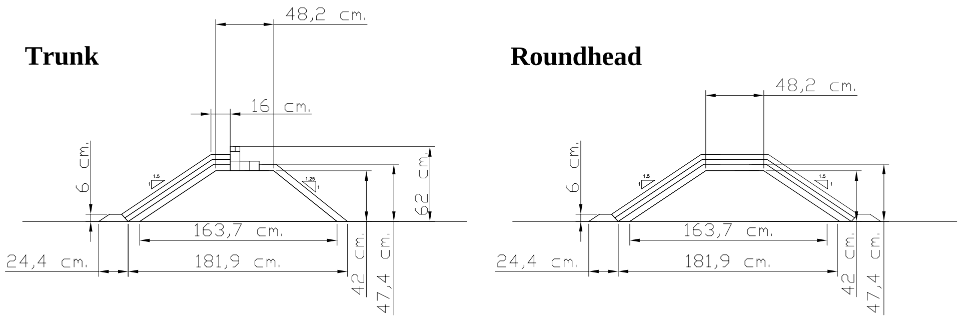

Figure 4. Physical model.

Conventional cube and Cubipod CAUs were used for the armor layer, the CAUs being placed using different constructions grids and wave conditions. The CAU characteristics were:

Table 1. CAU characteristics.

	Weight (gr)	Density (gr/cm3)	Dn (cm)	Volume (cm3)
Cube	138.87	2.26	4	61.41
Cubipod	131.47	2.29	3.82	57.29

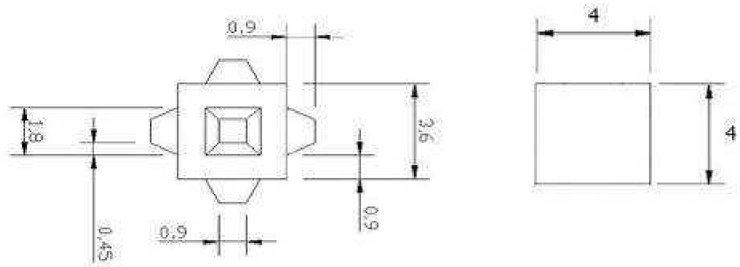

Figure 5. CAU dimensions.

Because of CAU reorganization movements, grid porosity differs from real porosity. If the gravity centers of the elements are placed exactly on the armor layer according to the placement grid, grid and real porosity would be the same. Grid porosity depends on *a* and *b* grid parameters (P_{grid} = 1-(D_n/a)(D_n/b)), while real porosity depends on the number of units placed in a given area (P_{real} = 1-[(Number units*D_n)/Area]).

CAU placement tests were conducted in three phases: (1) using a CBPS to simulate construction without waves, (2) using a small-scale crawler crane without waves and (3) using the same crawler crane with different random wave conditions during placement. The CAUs were placed blindly to simulate the underwater placement of real construction conditions, in which the crane operator cannot see what is happening under the water surface. Pardo (2009) described in detail the placement tests used for this study.

Cartesian Blind Placement System (CBPS)

In order to decrease the time required for the 3D realistic placement tests, a CBPS was used. The underwater placement was blind but waves did not affect the system. Therefore, this placement method was more realistic than the normal manual placement of small-scale experiments, but it is not as realistic as placement using a small-scale crawler crane, which imposes a CAU radial orientation towards the crane base. The main advantage of this method was time savings, which was one order of magnitude lower than that required for the small-scale crawler crane, which is 100 seconds per unit. Figure 6 shows the dry CBPS and a general view of the small-scale armor model.

Figure 6. Cartesian Blind Placement System: crane operator (left) and general view (right).

The clamp is positioned following a given X-Y coordinate on a placement grid, and the clamp operator released the unit when it touched the slope but without being able to see it.

The main objective of this preliminary test was to estimate the minimum and maximum armor porosity which could be obtained in real construction. The minimum porosities of armor layers constructed in a laboratory by hand were 29% for Cubipod and 0% for cube.

With the CBPS, various positioning grids were studied to determine the minimum armor porosity, obtaining 37% for Cubipod and 35% for cube. In order to obtain the maximum porosity, positioning grids were tested too. Finally maximum porosities of 51% for Cubipod and 45% for cube were achieved.

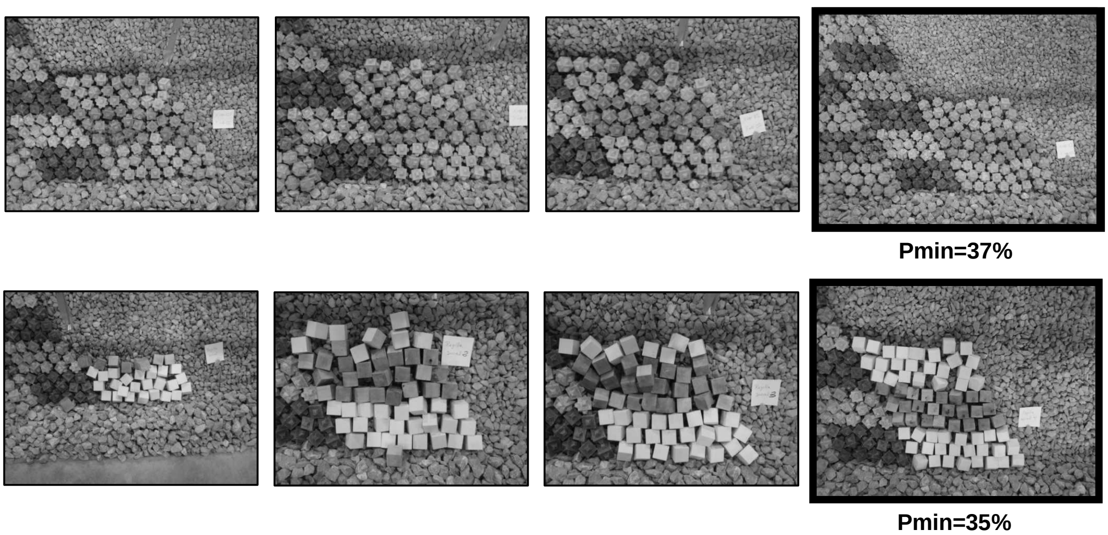

Figure 7. CBPS minimum porosity tests. Cubipod (top) and cube (bottom).

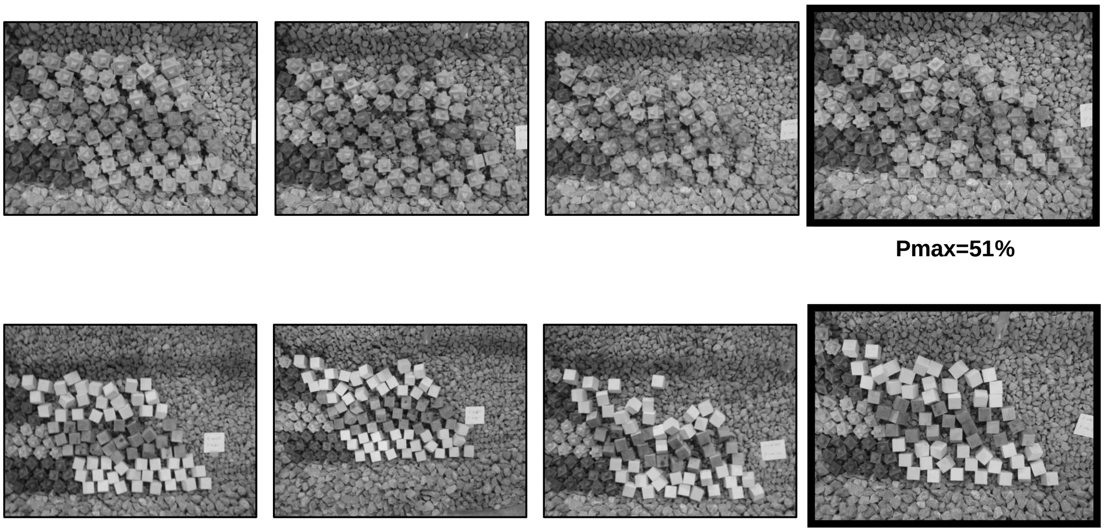

Figure 8. CBPS maximum porosity tests. Cubipod (top) and cube (bottom).

The visual appearance of the armor layer after the placement test was used as a qualitative criterion to discriminate between acceptable and unacceptable armor layer constructions. The tables below provide the real and grid porosity for each placement test. Unacceptable armor layers are crossed out.

Table 1. Real and grid porosity for Cubipod CBPS tests.

CUBIPOD	Grid a=1.46Dn b=1.22Dn	Grid a=1.61Dn b=1.22Dn	Grid a=1.76Dn b=1.22Dn	Grid a=1.90Dn b=1.22Dn	Grid a=2.05Dn b=1.22Dn	Grid a=2.20Dn b=1.22Dn	~~Grid a=2.34Dn b=1.22Dn~~
Real Porosity	0.368	0.456	0.428	0.447	0.508	0.477	~~0.538~~
Grid Porosity	0.441	0.492	0.534	0.570	0.601	0.628	~~0.651~~

Table 2. Real and grid porosity for cube CBPS tests.

CUBE	Grid a=1.3Dn b=1.25Dn	Grid a=1.43Dn b=1.25Dn	Grid a=1.56Dn b=1.25Dn	Grid a=1.69Dn b=1.25Dn	Grid a=1.82Dn b=1.25Dn	~~Grid a=1.95Dn b=1.25Dn~~
Real Porosity	0.347	0.360	0.413	0.427	0.453	~~0.493~~
Grid Porosity	0.382	0.438	0.485	0.525	0.559	~~0.588~~

Figure 9 illustrates the relationship between grid and real porosities. Two formulae (one for Cubipods and one for cubes) were fitted using statistical analysis. This is useful to identify grid dimensions to obtain a specific real porosity for the CBPS.

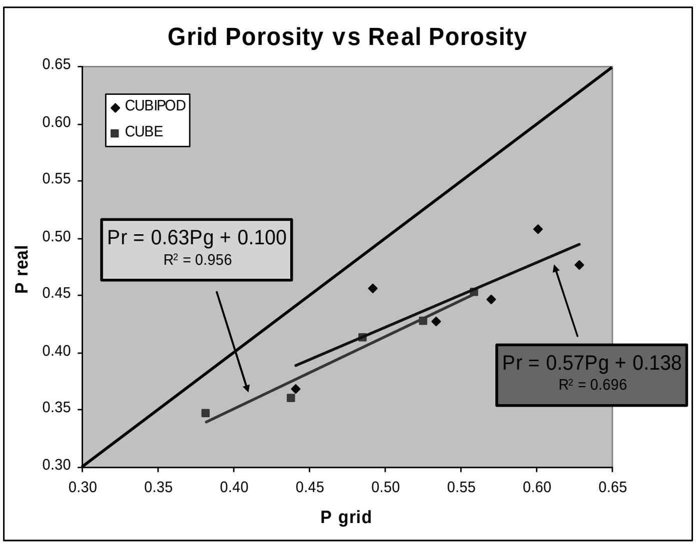

Figure 9. Grid porosity vs real porosity.

Crawler Crane Test

In this phase, a small crawler crane was used to construct armor layers. The small-scale crawler crane had a two degree half circle to identify the grid coordinates. The crane operator placed the CAU in this spherical coordinate and after that, the unit was placed on the slope. When the crane operator saw that the crane did not support any weight, he released the unit. All crawler crane tests were conducted using scaled pressure clamps similar to those used in real construction.

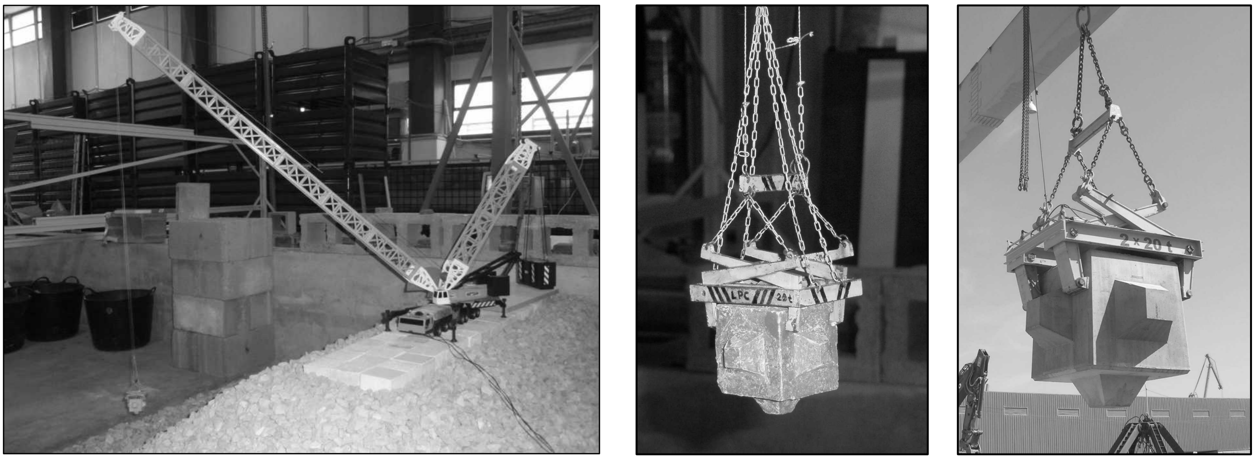

Figure 10. Small-scale crawler crane (left). Pressure clamp: scaled (center) and real (right).

Using a small-scale crawler crane, the first two realistic placement tests were conducted without waves to determine if the CBPS was acceptable to find appropriate placement grids for the CAUs. These two tests were designed to obtain a cube and Cubipod armor porosity of 41%. Grid parameters, *a* and *b*, were estimated using the CBPS formulae (a/Dn=1.57 and b/Dn=1.22 for Cubipods with a grid porosity of 48%; a/Dn=1.58 and b/Dn=1.25 for cubes with a grid porosity of 49%). After that, the two armor layers were constructed, the real porosity was calculated and later compared with the target porosity (41%). Figure 6 shows the results of the crawler crane dry test.

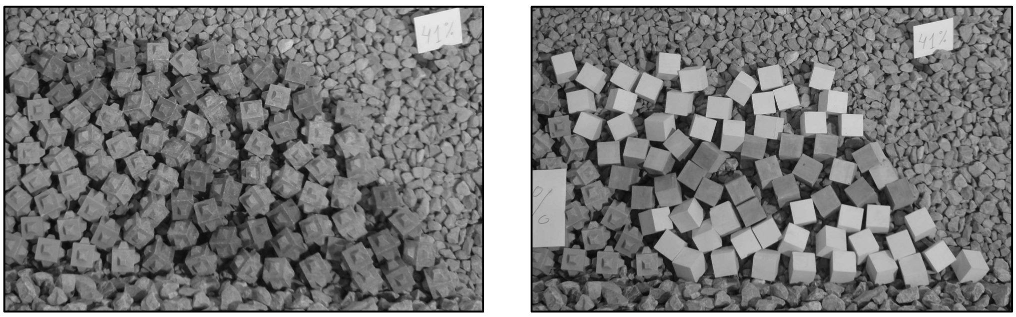

Figure 11. Crawler crane dry test results.

Measured porosities for each test were 40.4% for Cubipods and 41.3% for cubes, both very close to the target porosity of 41%. Thus, the CBPS was acceptable to find appropriate positioning grids of CAUs.

The crawler crane with waves was the last test phase of this study. Cubipod and cube armors were constructed with a small-scale crawler crane under random wave conditions to examine the wave effects on CAU placement. The same construction grid defined for the crawler crane dry test with a target real porosity of 41% was used. Wave conditions were JONSWAP (γ=3.3) spectrum with a prototype significant wave height of H_{m0}[m]=1.0 and 2.0, and peak periods T_p[s]= 6, 8 and 11. These different sea states affected underwater blind placement increasing CAU position error and CAU movements after being released from the pressure clamps.

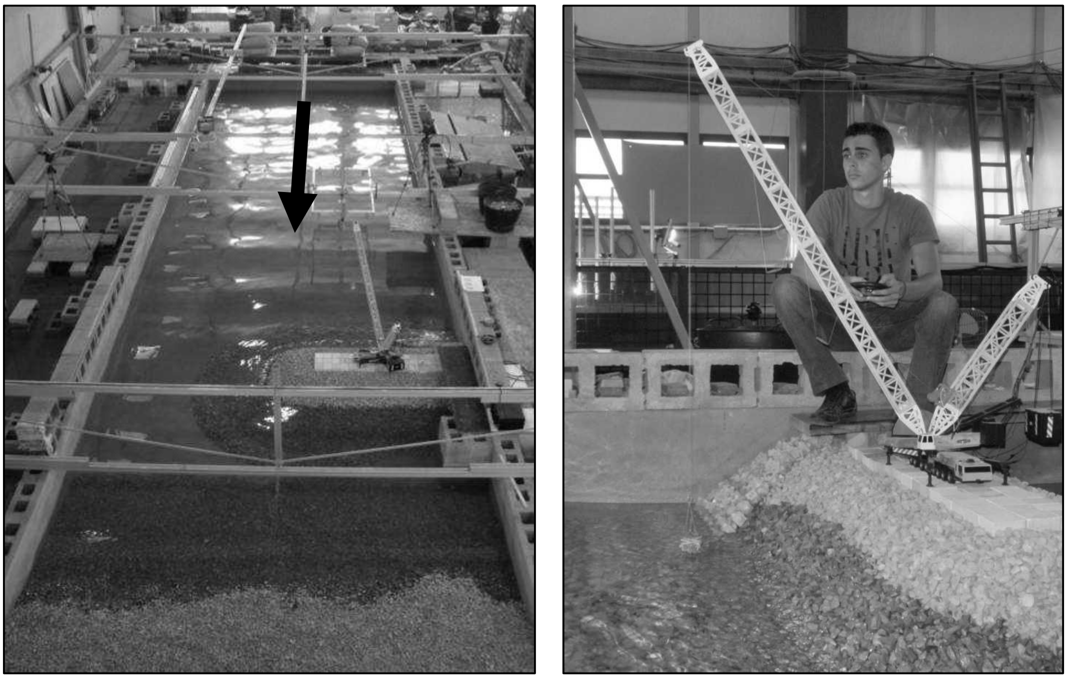

Figure 12. Crawler crane with waves: general basin view (left) and Cubipod placement (right).

The constructed area was divided into eight sectors to study the variability of the armor porosity. The analysis focused on the area below sea level, because this is the crane operator's blind spot. For each sector, real porosity was calculated. With maximum, minimum and medium porosity values, the parameter (Pmax-Pmin)/Pmed was also calculated. This parameter indicates if the porosity distribution was homogeneous or not. Cubipods showed higher homogeneous armor porosity distributions than cubes, as specified in tables 3 and 4.

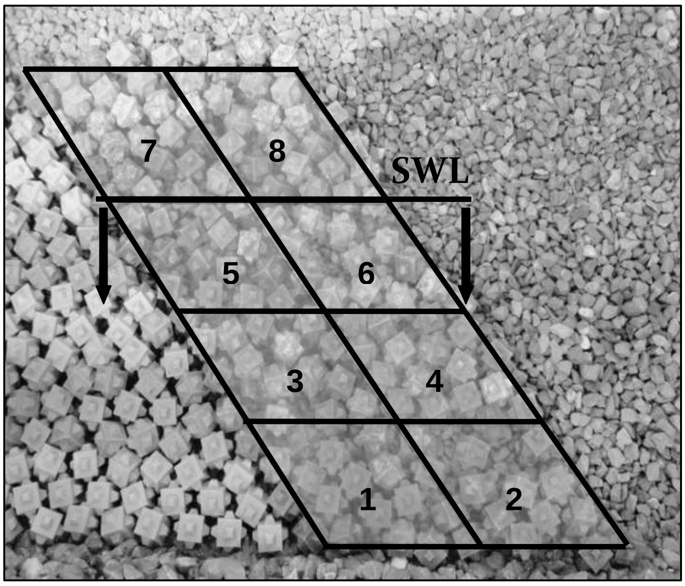

Figure 13. Reference area used to measure the real armor porosity.

Table 3. Results from Cubipod crawler crane with waves.

CUBIPOD Test	H (m)	T (s)	Pmax	Pmin	Pint	$\frac{Pmax-Pmin}{Pint}$
VC11_0201	1	6	0.537	0.383	0.466	0.33
VC11_0202	1	8	0.537	0.383	0.466	0.33
VC11_0402	2	8	0.537	0.383	0.460	0.34
VC11_0403	2	11	0.460	0.421	0.434	0.09

Table 4. Results from cube crawler crane with waves.

CUBE Test	H (cm)	T (s)	Pmáx	Pmín	Pint	(Pmax-Pmin) / Pint
VC12_0201	1	6	0.450	0.281	0.394	0.43
VC12_0202	1	8	0.535	0.365	0.422	0.40
VC12_0402	2	8	0.535	0.323	0.415	0.51
VC12_0403	2	11	0.492	0.365	0.408	0.31

Figure 14 provides the maximum, minimum and intermediate data for armor porosities for each sea state (ordered by the amount of wave energy ($H_s^2xT_p$)).The Cubipod armor seems to be less affected by wave conditions with an extremely low variability under the highest energy wave conditions.

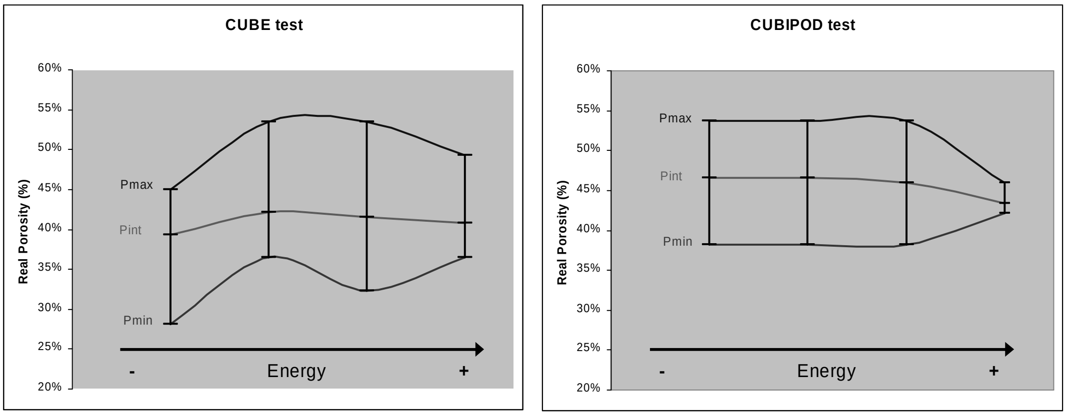

Figure 14. Armor porosity vs wave energy. Cube (left) and Cubipod (right).

5. Summary and conclusions

In this paper the armor porosity and placement methods for two concrete armor units (cube and Cubipod) are analyzed. Both are massive CAUs which can be safely handled using pressure clamps.

The parameters involved in CAU placement are nominal armor porosity (P%), armor porosity (p%), armor thickness (r), layer coefficient (k_Δ), number of layers (n), placing density (Nr/A) and packing density (Φ). Most engineering manuals recommend specific nominal armor porosities for different CAUs associated to a given layer coefficient. For randomly placed CAUs, the layer coefficient is an unnecessary parameter, which should be avoided to prevent misunderstanding when armor porosity is considered.

The hydraulic stability of armor layers depends on a number of structural and wave climate variables such as Dn50, Δ, α, Hm0 and Ir. Armor porosity affects energy dissipation, wave reflection, hydraulic stability, run-up, overtopping and self-packing. Frequently, nominal armor porosity and packing density are given for each specific CAU and it is assumed that both laboratory tests and prototypes have armor layers with the given armor porosity. However, construction of real armor layers is highly conditioned by equipment, visibility, wind and waves, while small-scale laboratory constructions are not. The porosity of mound breakwater armor layers is a relevant factor; differences between design values and real constructed armor porosity values lead to significant risk. Armor porosity affects the hydraulic behavior of the structure changing wave reflection, stability, run up and overtopping, and also the volume of materials needed for construction.

The minimum and maximum armor porosities which may be achieved in real construction are estimated from CBPS results, obtaining the porosity range 37%<p<51% for Cubipods and 35%<p<45% for cubes. The CBPS relationship between grid and real porosity is useful to establish grid dimensions to obtain a given real porosity.

Using a small-scale crawler crane, Cubipod and cube armor layers were constructed under random waves to study the wave effect on CAU placement. Cubipods showed relatively homogeneous porosity under sea level for a range of wave conditions; however, cubes showed much more variability. Cube placement is affected by wave characteristics while Cubipod placement is much less sensitive to wave actions. Cubipods tend to rearrange on the slope to achieve homogeneous porosity.

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