CUBIPOD CONCRETE ARMOUR UNIT AND HETEROGENEOUS PACKING

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A new armour unit named Cubipod is described. The Cubipod is similar to a cube except that it features protrusions on each face to prevent excessive packing as well as to increase the friction with the filter layer. The purpose of this armour unit design is not only to maintain most of the cube's advantages, such as high structural strength, easy casting and placement and low progressive failure risk, but also to avoid certain disadvantages of the cube itself, such as low hydraulic stability and Heterogeneous Packing (HeP). Additionally, the HeP failure mode which affects the armour layer of mound breakwaters is described. This failure mode tends to reduce the packing density of the armour layer near the mean water level (MWL) without extracting armour units but only moving them slightly within the armour layer. To measure dimensionless armour damage in terms of both HeP and armour unit extraction, the Virtual Net method proposed by Gómez-Martín and Medina (2006) is used and the results compared with the traditional method of visually counting the armour units on the third layer.

INTRODUCTION

During the last six decades, distinct concrete armour units have been developed around the world to reduce construction costs for mound breakwaters. Numerous armour units have shown high hydraulic stability, such as Tetrapod, Dolo, Accropode, Core-loc, X-block, etc., which permits a reduction in the concrete armour unit weight; however, cubes and parallelepiped blocks are the most commonly used armour units along the Spanish coast given their higher structural strength and easier casting and placement. Although traditional cube armour layers require larger volumes of concrete, the structural robustness and easy casting and placement of cubes are clear advantages compared to any other armour unit. Nevertheless, the cube armour units do have certain drawbacks that must be taken into consideration.

D'Angremond et al. (1999) discussed the impact of placement density on armour stability and Vandenbosch et al. (2002) analysed the influence of placement density on the stability of a mound breakwater with a two-unit thickness armour layer of concrete cube units. Cubes are structurally robust, cheap and easy to manufacture, store and put into place; furthermore, as opposed to many other armour units with much higher hydraulic stability, the damage function of cubes is gradual in terms of fragility and the units do not break. Nonetheless, cubes and parallelepiped blocks have performance limitations associated with face-to-face fitting, leading to increased packing density below the mean water level (MWL) and the corresponding reduction in packing density above and near the

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MWL. This change of porosity in different parts of the breakwater was identified by Gómez-Martín and Medina (2006) as the Heterogeneous Packing (HeP) failure mode.

When HeP occurs, porosity is not constant; therefore, armour damage cannot be measured using traditional methods based on counting armour units on the third layer or using armour profiles. HeP is a failure mechanism of mound breakwaters which tends to reduce the packing density of the armour layer near the MWL without extracting armour units, but only by moving armour units within the armour layer. Conventional analysis of mound breakwater takes into account only the armour unit extraction failure mode; therefore, traditional methods to measure damage consider only the extraction of armour units assuming constant porosity. In this paper, the Virtual Net method proposed by Gómez-Martin and Medina (2006) is used to measure dimensionless armour damage taking into account both armour unit extraction and the HeP failure mode, and then armour damage results are compared with measurements using conventional visual unit counting method.

In order to prevent HeP, researchers at the *Universidad Politécnica de Valencia* (UPV) designed a new concrete armour unit named Cubipod. The goal of this new armour unit design is to maintain most of the advantages of the cube armour unit while eliminating certain problems such as HeP, low hydraulic stability, placement randomness and friction with the filter layer. In addition to armour damage, visual run up for similar non-overtopping cube and Cubipod armour layers was measured for a preliminary comparison of the corresponding run up characteristics using series of regular wave tests carried out in the UPV wave flume (30x1.2x1.2 meters).

HETEROGENEOUS PACKING

The HeP failure mode causes changes in the porosity of the armour layer without extracting armour units, creating areas with high porosity near the MWL, leaving fewer armour units per unit surface. This failure mode is highly significant in the case of regular-shaped armour units, such as cubes or parallelepiped blocks, which tend to form undesired face-to-face arrangements under the MWL, leaving upper zones with higher porosity. Therefore, armour damage or armour erosion near MWL is not only produced by armour unit extractions that form an additional layer on the lower zone of the armour layer, but damage is also caused by HeP of the armour layer.

The HeP has an effect similar to the erosion caused by extracting armour units, because the reduction of the packing density near the MWL can facilitate the extraction of units from the inner layers. Thus, armour is damaged by two different failure mechanisms: armour unit extraction and HeP. In both cases, the result is similar: a decrease in the number of armour units near the MWL. The relative importance of the HeP failure mode depends on four main factors: (1) type of armour unit, (2) difference between the initial porosity and the minimum porosity, (3) slope of the armour layer, and (4) friction coefficient between the armour layer and the filter layer.

When HeP takes place, the porosity of the armour layer changes over time, and the equivalent dimensionless armour damage should be measured taking into account the changes in porosity for each area of the armour layer. Gómez-Martín and Medina (2006) described the Virtual Net method to measure the equivalent dimensionless armour damage. This method involves projecting a virtual net over the armour layer photograph (Figure 1) dividing it into strips (number of strips = j), each of which is n times the width of the equivalent cube ($a=n*D_{n50}$). The dimensionless damage in each strip (D_i) can be calculated using Equation 1, in which N_i is the number of armour units in strip i (upper layer), p_i and Φ_i are the porosity and packing density coefficient after the wave attack (calculated with Equation 2), b and a are the strip length and width, and p_0 and Φ_{0i} are the initial porosity and packing density coefficient, respectively. Integrating these armour damages over the slope, the equivalent dimensionless damage (D_e) can be obtained using Equation 3.

$$D_i = n\left(1-\frac{\Phi_i}{\Phi_{0i}}\right) = n\left(1-\frac{1-p_i}{1-p_0}\right) \tag{1}$$

$$p_i = 1-\frac{N_i D_{n50}^2}{(a*b)} = 1-\Phi_i \tag{2}$$

$$D_e = \sum_{i=1}^{j} D_i \tag{3}$$

Figure 1. Virtual net to measure the equivalent dimensionless damage (De).

CUBIPOD CONCRETE ARMOUR UNIT

The Cubipod was designed to prevent the HeP failure mode observed in concrete cubes while benefiting from cube robustness, easy castability and placement and, at the same time, avoiding cube weaknesses such as HeP and low hydraulic stability. The Cubipod design used in this experiment was a cubic element with equal protrusions on each face (Figure 2) to separate the adjacent units and to increase the friction with the secondary layer.

A common problem in the design of armour units is the need to choose between higher hydraulic stability and higher structural strength. Armour units can increase their hydraulic stability by interlocking, but this usually means a significant reduction in structural strength. The Cubipod is designed not only to avoid the HeP failure mode, but also to increase the hydraulic stability and the friction with the filter layer without reducing the structural strength.

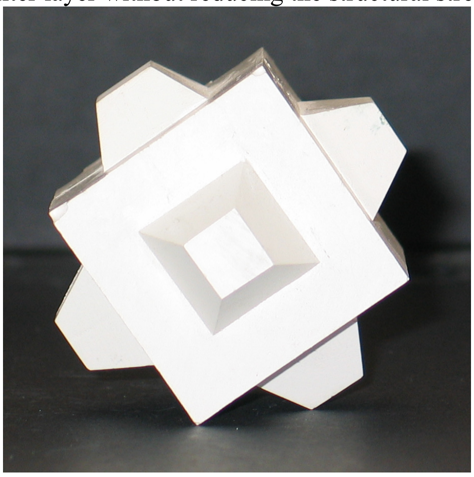

Figure 2. 3D view of Cubipod concrete armour unit

EXPERIMENTAL DESIGN

The breakwater models were built in deep water conditions with a crest elevation high enough to prevent overtopping. Figure 3 illustrates the longitudinal cross section of the UPV wave flume. Two groups of four wave gauges (S2 to S9) were placed to record the incident and reflected waves; one group was placed near the model and the other near the wavemaker. The LASA-V method (Figueres et al., 2003) was used to analyse incident and reflected waves.

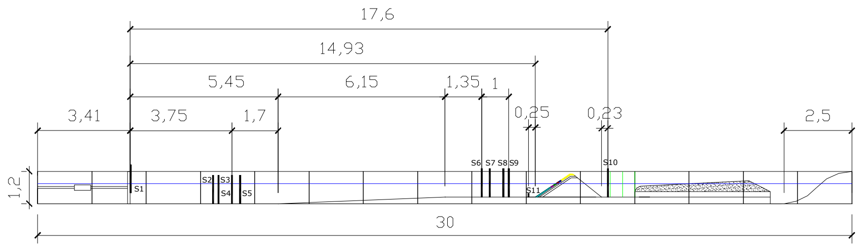

Figure 3. Longitudinal cross section of the UPV wave flume (dimensions in meters).

Using the same core and filter layer, two mound breakwater cross sections were tested with different armour units: cubes and Cubipods. Two-unit thickness armour layers of cubes and Cubipods were tested with initial packing density coefficients of Φ=1-p=63% for cube models and Φ=1-p=60% for Cubipod models. Cubipods were lighter (W_{50}=108g), and they also have a lower mass density (ρ_s=1.86 T/m^3) than cubes (W_{50}=140g and ρ_s=2.18 T/m^3).

Table 1. Parameters of materials used in the experiments

	CUBE MODEL			CUBIPOD MODEL		
	D_{n50} (cm.)	Density (T/m^3)	Weight (gr.)	D_{n50} (cm.)	Density (T/m^3)	Weight (gr.)
Armour layer	4.00	2.18	140	3.85	1.86	108
Filter (G1)	1.80	2.70	16	1.80	2.70	16
Core (G2)	0.70	2.70	0.90	0.70	2.70	0.90

Cubes (D_{n50}=4cm) and Cubipods (D_{n50}=3.85cm) were painted in different colours for a better visual identification of armour unit movements; the bottom armour layer was painted white (cube model) and black (Cubipod model) for contrast and the upper armour layer in bands of different colours so as to visually measure the damage. Armour damage was measured before and after each run of waves, using the visual unit counting method and the Virtual Net method described by Gómez-Martín and Medina (2006). Gómez-Martín and Medina (2004) considered visual unit counting as the most precise and reliable method for low and moderate damage levels if porosity of the armour layer was constant, but they did not take into account the HeP failure mode. The visual unit counting method defines the eroded area by Equation 4 and the dimensionless damage by Equation 5.

$$A = \frac{N_e D_{n50}^3}{b(1-p)} = \frac{N_e D_{n50}^3}{b\Phi} \tag{4}$$

$$S = \frac{A}{D_{n50}^2} \tag{5}$$

in which N_e is the number of eroded armour units on the third layer, D_{n50} is the equivalent cube size or nominal diameter, p and Φ=1-p are the constant porosity and packing density coefficient of the armour layer, b is the observed cross section width, A is the armour erosion and S is the dimensionless armour damage.

The stability experiments were carried out maintaining Iribarren's number (Ir) constant within each test series, increasing the wave height and period and recording from zero damage to destruction. Regular and irregular waves were used during the tests. In the case of regular waves, 500 waves were generated in runs of 25 waves (cubes) and 50 waves (Cubipods) for each wave height level with periods corresponding to $Ir= (1/1.5)/(H_{reg}/L_0)^{0.5}$ = 2.5, 3.0, 3.5 and 4.0. Irregular wave tests were conducted with runs of 1000 waves for each significant wave height level having mean periods corresponding to $Ir=(1/1.5)/(H_{reg}/L_{01i})^{0.5}$ = 2.5, 3.0, 3.5 and 4.0, taking into account the relationship $H_{reg}=1.4*H_{m0i}$.

Regular and irregular cube tests were repeated three times from zero damage to destruction except in the case of Ir=4.0. Cubipod tests with Ir=2.0 were repeated twice.

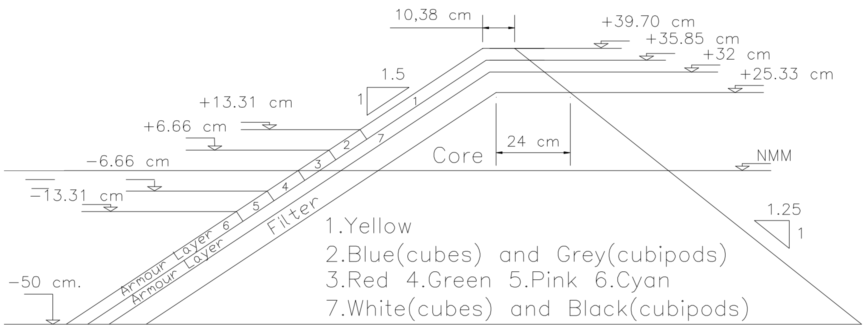

Figure 4. Cross section of cube and Cubipod breakwater models with armour units in different colours (dimensions in centimetres).

Visual run up was also measured during regular wave tests using cameras placed perpendicular to the armour layer and the cross section of the model. The performances of Cubipods and cubes were observed.

RESULTS OF THE EXPERIMENTS

Hydraulic stability

Armour damage measurements for cube and Cubipod models were obtained using the visual unit counting method and the Virtual Net method. The visual unit counting method gives lower equivalent dimensionless damage values than does the Virtual Net method. The visual unit counting method does not take into account the HeP produced within the armour layer; thus, it underestimates the actual erosion of the armour layer near the MWL. If the HeP failure mode has begun to damage the armour layer but no armour units are extracted, the visual unit counting method provides a "zero damage" observation. The visual unit counting method and the Virtual Net method provide significantly different measurements for cube armour units.

The Virtual Net method provides an alternative armour damage measurement of the "dimensionless damage" named "equivalent dimensionless damage" in this paper. Table 2 shows the dimensionless armour damage using the traditional visual unit counting method and the Virtual Net method for cube and Cubipod breakwater models.

Using the Virtual Net method in the experiments did not reveal any armour unit movements on the bottom armour layer but only the movements of the upper armour layer. Neither of these methods takes into consideration the changes in porosity of the bottom armour layer. The armour damage values shown in Table 2 may then be lower than actual armour damage.

Table 2. Dimensionless armour damage measurements using traditional visual unit counting and Virtual Net methods for cube and Cubipod models.

		DAMAGE MEASUREMENT METHOD	
		Classical (S)	Virtual Net (D_e)
Dimensionless Damage	CUBES	0.1	1.3
		0.8	2.5
		7.2	10.6
	CUBIPODS	0.2	1.4
		1.5	2.4
		9.5	10.3

The damage level of the breakwater armour layer was analysed qualitatively through a visual analysis of the photographs after each test run. Three significant damage levels were defined: (1) start of damage (IA), (2) Iribarren's damage (IAI) and (3) start of destruction (ID). The average quantitative equivalent dimensionless damage values corresponding to these qualitative damage levels were: $D_e \approx 1.0$ for IA, $D_e \approx 3.2$ for IAI and $D_e \approx 8.6$ for ID. Cubipods showed much higher hydraulic stability than cubes because wave heights causing IA, IAI and ID were higher for Cubipods than cubes although their armour unit weight and specific weight were much lower.

Equivalent dimensionless damage (D_e) was measured for cube and Cubipod armoured breakwater models, testing with both regular and irregular waves. For clarify's sake, the equivalent dimensionless armour damage measurements were transformed according to the 1/5 power function given by Medina et al. (1994) for the quarrystone armour damage function. The transformed dimensionless armour damage $D^*=D_e^{0.2}$ is represented in Figures 5 and 6 as a function of the dimensionless wave height. The dimensionless wave heights shown in Figures 5 and 6 were obtained dividing the measured characteristic incident wave height by the calculated wave height that leads to the start of damage ($H_{D=0}$) using Hudson's formula (SPM, 1984) for an equivalent armour unit having a stability coefficient K_D=4, corresponding to rough quarrystone.

The experimental results for regular waves are specified in Figure 5. Points corresponding to cubes (circles) and Cubipods (triangles) are used to compare the armour damage function. The horizontal lines corresponding to the start of damage (D_e=1.0), Iribarren's damage (D_e=3.2) and start of destruction (D_e=8.6) indicate the qualitative armour damage levels IA, IAI and ID, respectively. Figure 5 illustrates the rough quarrystone (K_D=4) armour damage function given by Medina et al. (1994) and damage functions corresponding to stability coefficients of K_D=6 and K_D=35.

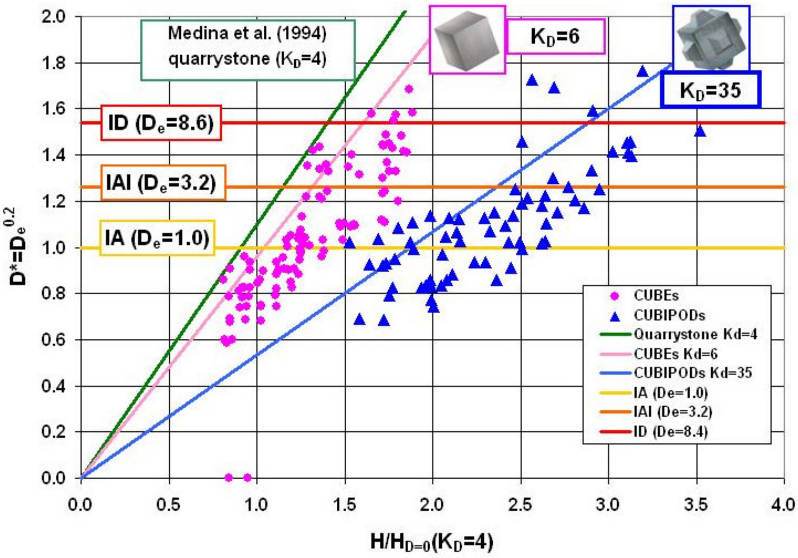

Figure 5. Hydraulic stability of cube and Cubipod. Linearised dimensionless armour damage as a function of dimensionless incident wave height (regular tests).

According to the data represented in Figure 5, the hydraulic stability of Cubipods is quite high compared to cubes under regular wave attack. Wave heights causing the start of destruction (ID) for cubes do not cause the start of damage (IA) for Cubipods.

Analogously, Figure 6 reveals large differences between the hydraulic stability of cubes and Cubipods under irregular wave attack. The stability coefficient of Cubipods seems to be approximately six times higher than that of cubes; this preliminary result should be taken with caution since Cubipods had a lower mass density than cubes (1.86 T/m^3 > 2.18 T/m^3) during the experiments, and some model effect may occur.

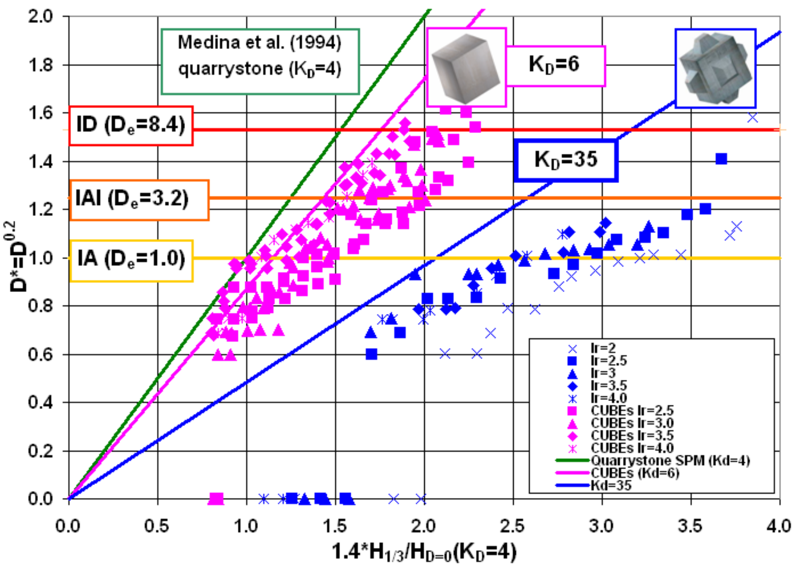

Figure 6. Hydraulic stability of cube and Cubipod. Linearised dimensionless armour damage as a function of dimensionless incident wave height (irregular tests).

Figures 5 and 6 show the high hydraulic stability of Cubipods compared to cubes for regular and irregular tests. Wave heights that cause destruction of the cube armour layers do not even cause the start of damage for the Cubipod armour layer. The stability coefficient K_D of Hudson's formula (SPM, 1984) for the trunk section of the breakwater takes on values six times higher for Cubipods than for cubes. Model effects may reduce the differences between the stability coefficient observed in the experiments given the use of materials with different mass densities for cubes and Cubipods; however, the new Cubipod armour unit provides an extremely high stability coefficient

Run up observations

The visual run up (R_u) was measured for the regular tests with Iribarren's numbers Ir = 2.5, 3.0 and 4.0 both for cubes and Cubipods. Figure 7 shows the dimensionless run up (R_u/H_i) observed as related to the dimensionless incident wave height (H_i/D_n) for cubes (squares) and Cubipods (circles), where H_i is the incident wave height and D_n is the equivalent cube size. Visual run up observations for Cubipod models are approximately 85% of those for the cube models. Therefore, the use of Cubipods instead of cubes may allow for a reduction in the breakwater crest elevation for given environment conditions and overtopping rates.

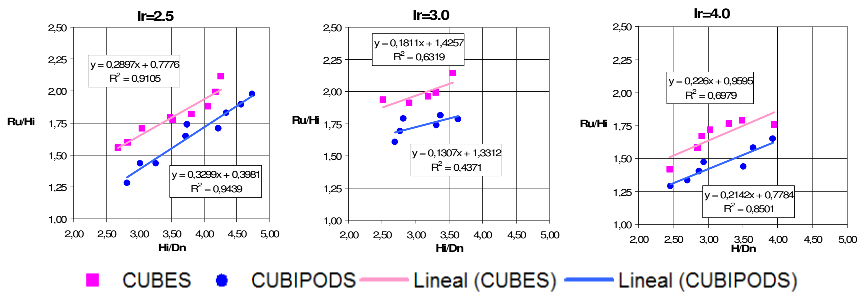

Figure 7. Dimensionless run up versus dimensionless incident wave height for cubes and Cubipods (regular tests).

CONCLUSIONS

In this study, the hydraulic stability of the new Cubipod armour unit is analysed and compared to conventional cubes. Cubipod armour units are similar to cubes but have protrusions on each face to prevent the face-to-face fitting processes observed in cube armoured breakwaters. The goal of this armour unit design is to maintain the advantages of the cubes (high structural strength, easy casting and placement and low risk of progressive failure) and avoid problems such as low hydraulic stability, Heterogeneous Packing (HeP) and low friction with the filter layer. Additionally, the HeP which affects the armour layer of mound breakwaters is described as it tends to reduce the packing density of the armour layer near the MWL by only moving units within the armour layer. Conventional visual counting methods for armour damage measurement are inadequate if the HeP is significant; therefore, the Virtual Net method is used to measure armour damage. Finally, visual observations of run up on cube and Cubipod armoured breakwater models are presented.

2D tests with regular and irregular waves were conducted at the UPV wave flume (30.0x1.2x1.2 meters) using constant Iribarren's numbers Ir=2.0, 2.5, 3.0, 3.5 and 4.0 for cube and Cubipod armoured breakwater models in nonbreaking and non overtopping conditions. Cubipods armour units showed a stability coefficient (K_D>35) six times higher than that of cubes both for regular and irregular tests. However, these preliminary results should be regarded cautiously because the mass density of the Cubipods used in the experiments (ρ_s=1.86 T/m^3) was much lower than that of cubes (ρ_s=2.18 T/m^3) and certain model effects may alter the results. Nevertheless, the performance of the Cubipods during the experiments was consistent with an armour unit with a very high hydraulic stability.

The Virtual Net method was used to measure armour damage, taking into consideration both armour unit extraction and HeP. Conventional visual unit counting to measure armour damage was found to be inadequate because it requires a constant armour porosity which is not the case when using cubes for the armour layer. The HeP failure mode, which changes the initial porosity of the different areas of the armour layer, was analysed as dependent on the armour unit type. The breakwaters with armour units having a significant difference between the original packing density and the maximum packing density are the most sensitive to HeP failure mode. The version of the Virtual Net method used in this study must be improved to take into account not only the HeP of the upper layer within the two-unit thickness armour layer, but also the HeP of the bottom layer which is not visible during the experiments.

The visual run up measured on the Cubipod and cube armoured breakwater models for regular tests showed consistently higher run up for cubes. The dimensionless run up measured on the Cubipod models was approximately the 85% of that of the cube models.

During the construction of the breakwater models, it was observed that Cubipods were much easier to place at random than cubes, because the protrusions and characteristics of symmetry favour the self organizing random placement of Cubipods on the slope. On the contrary, the random placement of cubes is not so easy due to the face-to-face fitting problem. The higher friction of the armour layer with the filter layer was also clear when using Cubipods to construct the laboratory breakwater models. Finally, face-to-face fitting and HeP were clearly observed when armour damage progressed on the cube armoured breakwater models. Therefore, the results from the experiments and the subsequent comparative analysis seem to support the validity of the Cubipod armour unit design. Its simple and robust design, its easy-to-place shape and high hydraulic stability make the Cubipod an excellent alternative to regular cubes in situations where the extreme conditions or the available equipment influence the construction of mound breakwaters with large concrete cubes.

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REFERENCES

D'Angremond, K., Berendsen, E., Bhageloe, G.S., Van Gent, M.R.A. and Van der Meer, J.W., 1999. Breakwaters with a single armour layer. *Proceedings of 5th International Conference on Coastal and Port Engineering in Developing Countries*, 1441-1449.

Figueres, M., Garrido, J.M. and Medina, J.R., 2003. Cristalización simulada para el análisis de oleaje incidente y reflejado con un modelo de onda Stokes-V. *VII Jornadas españolas de Costas y Puertos*, Almeria, Spain. (CD in Spanish).

Gómez-Martín, M.E. and Medina, J.R., 2004. Wave-to-wave exponential estimation of armor damage progression. *Proceedings of 29th International Conference on Coastal Engineering,* ASCE, 3592-3604.

Gómez-Martín, M.E. and Medina, J.R., 2006. Damage progression on cube armored breakwaters. *Proceedings of 30th International Conference on Coastal Engineering*, ASCE, (Vol. 5): 5229-5240.

Medina, J.R., Hudspeth, R.T., and Fassardi, C., 1994. Breakwater armor damage due to wave groups. *Journal of Waterway, Port, Coastal, and Ocean Engrg.,* ASCE, 120(2), 179-198.

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

Vandenbosch, A., Angremond, K.D., Verhagen, H.J. and Olthof, J., 2002. Influence of the density of placement on the stability of armor layers on breakwaters. *Proceedings of 28th International Conference on Coastal Engineering,* ASCE, 1537-1549.

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