EROSION OF CUBE AND CUBIPOD ARMOR LAYERS UNDER WAVE ATTACK

M. Esther Gómez-Martín[1] and Josep R. Medina[2]

In this paper the performance of cube and Cubipod armor units is compared through a variety of laboratory and prototype experiments. The hydraulic stability of armor layers of cubes and Cubipods is contrasted by analyzing 2D and 3D small scale experiments in three different laboratories using similar non-breaking and non-overtopping cross sections. To measure armor damage, both armor unit extraction and Heterogeneous Packing (HeP) failure modes are considered using the virtual net method. Overtopping performance of one-unit and two-unit thick Cubipod armor layers is examined, as well as the conventional two-unit thick cube armor layer. Roughness factors are also estimated for a typical non-breaking and moderate overtopping cross section with crown wall. Finally, cube and Cubipod production areas, casting systems and results of prototype drop tests are compared.

Introduction

Rubble-mound breakwaters have been constructed for centuries to protect harbors and coasts. However, the construction of breakwaters for use in deeper waters and in severe wave climates requires heavier quarry stones which are difficult for most local quarries to produce. During the 19th century, simple cube and parallelepiped concrete armor units were used when local quarries were not able to provide the appropriate stone size. Since the invention of the Tetrapod in 1950, numerous concrete armor units have been designed to optimize mound breakwaters, increasing safety and reducing construction and maintenance costs.

Mound breakwaters have several failure modes, but armor erosion due to wave attack is usually the most critical for design. Armor erosion is widely considered the result of the armor unit extraction failure mode; however, Gómez-Martín and Medina (2006) have shown how armor Heterogeneous Packing, HeP, increases armor erosion. When wind waves attack a sloping structure, both armor unit extraction and HeP tend to reduce the armor unit packing density around the mean water level; if the local packing density is too low, stones from the filter layer may be extracted and the overall structure is prone to collapse.

The most common armor stability formula was published by Hudson based on the pioneering work of Iribarren (1938). Hudson's formula was originally

[1] Asst. Prof., Dep. Construction, *Universidad de Alicante*, Sant Vivent del Raspeig s/n, 03690 Alicante, Spain. esther.gomez@ua.es.
[2] Professor, Lab. Ports and Coasts, *Universidad Politécnica de Valencia*, Camino de Vera s/n, 46020 Valencia, Spain. jrmedina@upv.es.

proposed for regular waves, but SPM (1984) popularized the formula as well for irregular waves using the equivalence $H=H_{1/10}$ to represent the wave height for irregular wave attack. The structural and wave storm variables used in these formulas are wave height, water and armor density, armor slope and armor unit stability coefficient (K_D). Since 1950, a number of concrete armor units has been developed around the world to increase K_D and reduce the corresponding armor unit weight and volume of concrete required.

The existing types of concrete armor units can be classified according to structural robustness (massive, bulky and slender), the placement method (random or specific placement) and the armor thickness (one-unit and two-unit layers). The Cubipods and conventional cubes compared in this paper are both massive armor units with random placement; conventional design normally relies on two-unit thick armor layers but Cubipods can also be used for one-unit thick armor layer because of its self-repairing performance. Fig. 1 shows a 3D view of the cube and Cubipod armor units described by Gómez-Martín and Medina (2006, 2007).

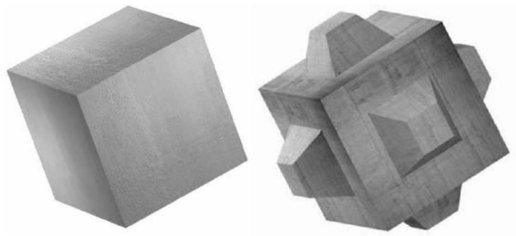

Figure 1. Cube and Cubipod concrete armor units.

As a general rule, K_D increases from massive units based on friction and gravity forces to slender units based on interlocking forces. However, structural strength decreases from the massive to slender category, and slender armor units are more likely to break during the armor layer construction and also during the breakwater lifetime. As demonstrated in the 1978 total failure of the unreinforced concrete Dolos armor layer of the Port of Sines, if slender armor units break in parts, the armor hydraulic stability decreases, causing a simultaneous loss of weight and interlocking; therefore, a progressive failure may occur. The relative structural strength of the armor unit decreases when the size of the armor unit increases, because loads are proportional to the third power of size while resistant sections are proportional only to the second power of size. Thus, the largest armor units for mound breakwaters in severe wave climates are massive unreinforced concrete armor units (i.e. 150-ton cubes in the new Port of A Coruña, Spain). Since the total failure due to unit breakage in Sines (Portugal) three decades ago, the use of slender units in the Iberian Peninsula has been avoided and numerous large mound breakwaters have been constructed with conventional cube and parallelepiped type armor units weighing more than 100 tons. On the Pacific coast of Japan, Hanzawa et al.

(2006) reported the use of Tetrapods up to 80 tons and fully reinforced Dolosse up to 80 tons.

The different categories of concrete armor units are not equally sensitive to breakage. Slender units tend to be the most vulnerable to cracking and breaking because interlocking may generate bendings and torsions as well as high tensile stresses. Reinforcing armor units may improve structural strength, but it also increases the construction costs and the uncertainty regarding the durability of the armor units. The failures of Tetrapod and Dolos armor layers all over the world have not only limited the use of slender armor units, but have also promoted the use of massive cube type blocks (cubic block, Antifer cube, etc.) and favored the development of new armor units such as Accropode®(1980), Haro®(1984), Core Loc®(1995) and Xbloc®(2004). In addition to a higher stability coefficient K_D, most of these new bulky armor units are designed to be uniformly placed in a one-unit thick layer instead of the conventional two-unit thick layer with random placement. The concrete volume savings of one-unit thick armor layers with specific unit placement are relevant but equally relevant is the increase in construction costs associated to the casting and placement systems; furthermore, if interlocking fails because the breakwater is not constructed as designed, a progressive failure may occur. Cube and parallelepiped armor units have been used extensively on the Spanish coast due to several clear advantages: high structural strength, easy casting, easy handling and storage, etc. However, cube armor units do have certain drawbacks such as face-to-face packing and high HeP, low friction with the filter layer, high overtopping rates and a low stability coefficient. The new armor unit, Cubipod, is designed to improve upon the effects of the cube's drawbacks by increasing K_D and the friction with the filter layer and reducing HeP and overtopping rates, while maintaining the cube's high structural strength.

Casting system, handling, storage and drop tests

To evaluate the production efficiency, handling and storage of the new Cubipod armor unit compared to conventional cubic blocks, the Spanish construction company SATO designed a casting system and specially adapted tongs for the efficient movement and manufacture of 7.1 m^3 (16-ton) Cubipods. Ten 16-ton Cubipods and eight conventional 15-ton cubic blocks were produced to assess the structural strength of cubes and Cubipods in the corresponding drop tests. Fig. 2b shows the casting system designed by SATO with a base and an upper part similar to the casting systems shown in Fig. 2a used for conventional cubic blocks. The base sustains the weight of the armor unit and the upper part can be removed vertically six hours after concrete filling and vibration. The molds were filled with a standard concrete mix, namely the Spanish designation HA-30/B/25/IIIa-Qb. It was used with 350 kg/m^3 of cement CEM I 42.5 R type and water/cement ratio of 0.5; compressive strength of each prototype was estimated from standard tests of two concrete samples broken at 7 and 28 days. The mean values (coefficients of variation) of the compressive strength of cubes and Cubipods were 63.5 (5.2) MPa and 60.1(7.8) MPa, respectively. Corredor et al. (2008) analyzed the optimum storage block yard for cubes and Cubipods with two different arrangements: (1) “open” with a porosity of about 50% and (2) “closed” with a porosity of about 30%. Figure 2c shows stored Cubipods (“open” arrangement) and cubic block prototypes ready for use in drop tests.

In order to compare the structural strength of cube and Cubipod armor units, overturning, free fall and extreme free fall tests were carried out using 16-ton Cubipods and 15-ton cubes. The results from these tests may be compared to overturning and free fall tests using other armor units (see Muttray et al., 2005). Figs. 3a and 3b show frontal overturning tests of cubes and Cubipods while Figs. 3c and 3d show 2-meter free fall tests of cubes and Cubipods. The Cubipod armor units were able to withstand higher drops than did the conventional cubic blocks.

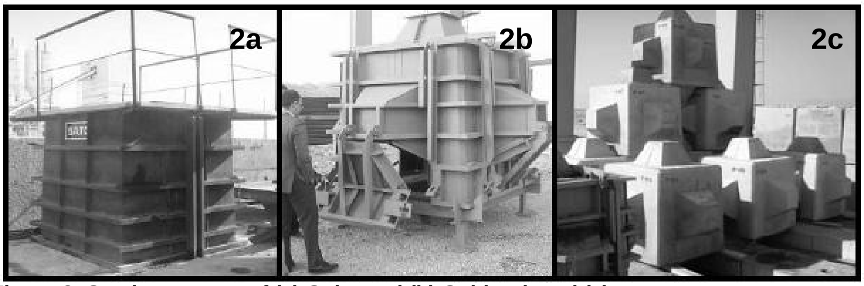

Figure 2. Casting system of (a) Cube and (b) Cubipod, and (c) storage area.

Figure 3. Overturning tests of (a) Cubipod and (b) Cube, and free fall tests of (c) Cube and (d) Cubipod.

Complete overturning (45º) and partial overturning (15º) of cubes were tested on the reinforced concrete overturning platform (10.0x5.0x0.9 meters). After 24 overturning drops, cubes lost 2% and 0.4% of their mass, respectively; Cubipods showed a maximum of 0.3% loss of weight after more than 60 overturning strikes. No serious damage was detected in the visual inspection.

Three different free fall tests were carried out both for cubes and Cubipods: (1) the “anvil drop” test in which one face of the prototype cube or Cubipod is parallel to the free fall platform during the fall, and the impact type is face-to-face, (2) the “edge drop” test in which the prototype is rotated 45º with one of its edges parallel to the platform during the fall, and the impact type is edge-to-face, and (3) the "random drop" test in which a prototype is put in an unstable position on top of a cubic block which is placed on the ground, and the impact type is unpredictable. Each prototype was dropped to the free fall platform up to six times (n=6) from a given "drop height", measuring loss in mass which each drop. The "drop height" (h) was defined as the distance from the lowest point of the prototype, just before dropping it, to the free fall platform. Cube and Cubipod prototypes were tested from the drop height h(m)=2.0 with anvil, edge and random drops. Cube prototypes were also tested from drop heights h(m)=0.5, 1.0 and 1.5 with anvil drops. Additionally, two extreme free fall tests were carried out dropping two Cubipod prototypes from drop heights h(m)=8.5 and 9.5 for anvil and edge drops, respectively. Four Cubipod prototypes were placed on the overturning platform to receive the impact of the falling prototype in the extreme free fall tests, and the loss of mass was measured for the five prototypes used in the experiments.

The observed loss of mass was dependent on four factors: the drop height (h), the number of repetitions (n), the drop type (anvil, edge or random), and the armor unit (cube and Cubipod). Anvil drops caused more damage than edge drops, and edge drops were more damaging than random drops. Cubipods resisted drops higher than conventional cubic blocks. Regarding the anvil drop test results, an equivalent anvil drop height (h_e) was defined considering both the drop height (h) and the number of repetitions (n)

$$h_e = h\sqrt[4]{n} \quad (1)$$

Fig. 4 shows the loss of mass in the free fall tests for both cubes (squares) and Cubipods (circles). Cube complete overturning tests were included (h=0.40).

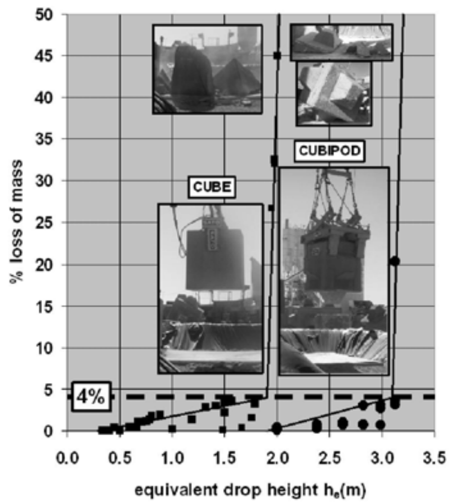

Figure 4. Loss of mass (%) versus equivalent drop height (h_e) of free fall tests.

The loss of mass for the prototypes showed a linear relation to h_e up to the critical 4% limit, when a global fracture affects the armor unit core. The critical equivalent anvil drop heights (h_{ec}) corresponding to the 4% loss in mass were h_{ec}(m)= 1.9 and 3.1 for cube and Cubipod, respectively. The loss of mass was irrelevant if h_e(m)<0.5 (cube) and h_e(m)<2.0 (Cubipod). Edge drop heights and random drop heights were equivalent to approximately 85% and 75% of the anvil drop heights to cause similar damage.

Hydraulic stability of cubes and Cubipods in 2D and 3D tests

Gómez-Martín and Medina (2006, 2007) described the experimental setup of the hydraulic stability 2D tests of standard armor layers of cube and Cubipod armor units carried out at the wave flume of the *Universidad Politécnica de Valencia* (UPV). The breakwater crest elevation and water depth were adequate for non-breaking and non-overtopping conditions. Two-unit thick armor layers of cubes and Cubipods with a 3/2 slope were tested on the same core material (D_{n50}(cm)=0.70) and filter (D_{n50}(cm)=1.80). The cube units used for testing were homogeneous: W(gr)=140, D_{n50}(cm)=4.00 and γ_r(gr/cm^3)=2.18. According to IH Cantabria (2008), the specific weight of Cubipod units showed some variability with an average dry specific weight γ_r(gr/cm^3)=1.94, nominal diameter D_{n50}(cm)=3.85 and mass W(gr)=108. Regular and irregular tests were carried out; irregular wave tests were conducted with runs of 1000 waves increasing significant wave height with constant Iribarren's numbers in the range of $3.0<Irp=(2/3)Tp/(2\pi H_{m0}/g)^{0.5}<7.0$. The virtual net methodology was used to estimate the armor damage of cube and Cubipod armors considering both armor unit extraction and HeP. Both regular and irregular tests showed a K_D for Cubipods six times higher than that of cubes. Visual records also revealed lower runup for Cubipod armors compared to conventional cube armors.

In this paper, additional 2D hydraulic stability and overtopping tests as well as 3D roundhead tests are discussed. Firstly, the 2D tests are described as carried out at the *Instituto de Hidrodinámica Aplicada* (INHA) to analyze the hydraulic stability of the one-unit thick and two-unit thick Cubipod armors in non-breaking and non-overtopping conditions. Secondly, the 3D roundhead hydraulic stability tests are related for cube and Cubipod armor layers as carried out at the *Instituto de Hidráulica Ambiental* (IH Cantabria). Thirdly, the 2D cube and Cubipod overtopping tests are discussed as conducted at the UPV wave flume.

2D hydraulic stability tests

INHA (2008) described the experimental setup and provided a detailed analysis of the results of experiments carried out in the wave flume of INHA (52.0x1.8x2.0 m.) at Cerdanyola del Vallés (Barcelona). The cross section was defined for non-breaking and non-overtopping conditions with a core (D_{n50}=0.25 cm), a filter layer (D_{n50}=1.25 cm), and an armor layer of Cubipod units (D_{n50}=3.82 cm, γ_r=2.30 gr/cm^3, W= 128 gr). The frontal slope was 3/2, the rear slope 5/4; water depth was 60 cm at the model area and 95 cm at the wavemaker with a 3% slope transition. The core crest elevation was +55.7 cm above SWL, and the core crest width was 24 cm; the thickness of the filter layer was 6.7 cm, and the Cubipod armor layer was placed above the filter layer. The crest elevation of one-unit and two-unit thick armor layer was +66.2 cm and +70.0 cm, respectively.

Irregular wave runs of 1000 waves following JONSWAP spectra (γ=3.0) were conducted with increasing significant wave height from no damage to initiation of destruction. Four capacitance wave gauges were placed in front of the structure at the model area to analyze incident and reflected waves using the LASA method (see Figueres and Medina, 2004). Fig. 5 shows the measured stability numbers of Cubipod one-unit thick (circles) and two-unit thick (triangles) armor layers from initiation of damage (IDa) in white to initiation of destruction (IDe) in black and destruction (D) in grey.

$$Ns = \frac{H_{m0}}{\Delta Dn} \tag{2}$$

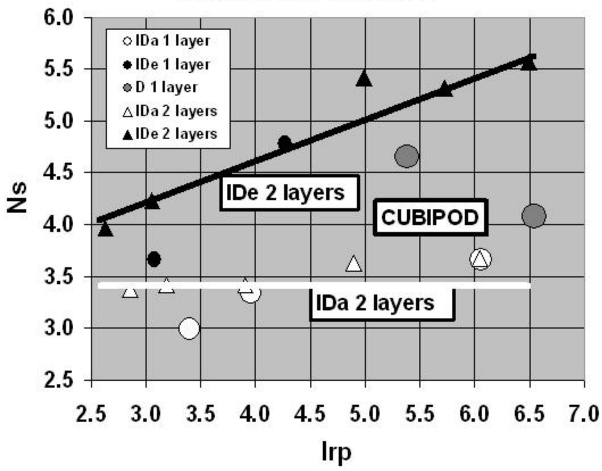

Figure 5. Stability numbers corresponding to 1-layer and 2-layer Cubipod armors.

The stability numbers represented in Fig. 5 refer to Iribarren's numbers, 2.5<Irp=(2/3)Tp/(2πH_{m0}/g)$^{0.5}$<6.5, calculated using the incident significant wave height, H_{m0}, and the peak period, Tp. The initiation of damage limit (white line) corresponding to the two-unit thick Cubipod armors (white triangles) appears to be independent of Irp, Ns(IDa)≈ 3.4, while the initiation of destruction limit (black line) seems to be dependent on Irp, Ns(IDe)≈ 3.0+0.4Irp. The initiation of damage and initiation of destruction of one-unit thick Cubipod armors showed minimum values Ns(IDa))≈ 3.0 and Ns(IDe)≈ 3.7.

The two-unit thick Cubipod armor hydraulic stability results observed at the INHA wave flume, using heavy Cubipod units (D_{n50}=3.82 cm, γ_r=2.30 gr/cm^3, W= 128 gr), were similar to the corresponding results obtained at the UPV wave flume using lighter Cubipod units (D_{n50}=3.85 cm, γ_r=1.94 gr/cm^3, W= 108 gr). Fig. 6 shows the stability numbers of two-unit thick cube and Cubipod armors tested at the UPV wave flume (see Gómez-Martín and Medina, 2007) as compared to the initiation of damage and destruction limits Ns(IDa)= 3.4 and Ns(IDe)= 3.0+0.4Irp shown in Fig. 5.

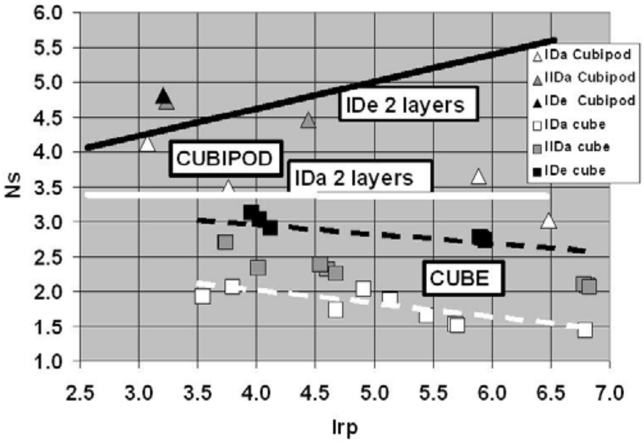

Figure 6. Stability numbers corresponding to 2-layer cube and Cubipod armors.

Fig. 6 shows measured stability numbers (incident waves) corresponding to two-unit thick Cubipod armors (triangles) and conventional two-unit thick cube armors (squares). The initiation of damage (IDa) is represented by white symbols; the initiation of Iribarren's damage (IIDa) is represented by grey symbols and the initiation of destruction (IDe) by black symbols. Initiation of damage and destruction limits for cubes are represented by white and black dotted lines, respectively; the hydraulic stability of Cubipod armors is much higher than that of conventional two-unit thick cube armors. When conventional cube armor reached the initiation of destruction limit (IDe), the Cubipod armor did not show any damage. Furthermore, the one-unit thick Cubipod armor layer is much more resilient than expected because of an observed self-repairing process; if a Cubipod unit is extracted from the Cubipod armor layer, the neighboring units roll slightly to cover the visible filter layer at the position where the unit was extracted. This self-repairing process is related with the self-arranging characteristic of Cubipod armor units which facilitates the random placement of the armor unit on the slope with homogeneous porosity.

3D hydraulic stability tests

IH Cantabria (2008) described the experimental setup and offered a detailed analysis of experiments carried out in the wave tank of IH Cantabria (24.8x8.5x1.5 m.) in Santander (Spain). The model was a trunk and a roundhead parallel to the wavemaker, and irregular long crested waves were generated to study the stability of the armor in a roundhead. The cross section was defined for non-breaking and non-overtopping conditions with a core (D_{n50}=0.88 cm), a filter layer (D_{n50}=1.81 cm), and two-unit thick armor layers of either Cubipod units (D_{n50}=3.82 cm, γ_r=2.30 gr/cm^3, W= 128 gr) or cube units (D_{n50}=3.98 cm, γ_r=2.30 gr/cm^3, W= 145 gr). The frontal slope was 3/2, the rear slope 3/2; water depth was 40 cm at the model area and 64 cm at the wavemaker with a 5% slope transition. Core crest elevation was +25.5 cm above SWL, and core crest width was 24 cm; the filter layer was 6.7 cm thick, and the Cubipod armor layer was placed above the filter layer. Crest elevation was +40 cm.

Irregular wave runs of 1000 waves following JONSWAP spectra (γ=3.0) were conducted with increasing significant wave height from no damage to initiation of destruction. Iribarren's number was kept approximately constant increasing significant wave height from no damage to initiation of destruction. Three cameras and laser profiles measured armor damage after each wave run. Nine resistance wave gauges were placed in three groups to measure total waves. Fig. 7 shows the measured stability numbers (total waves) of Cubipod (triangles) and cube (squares) roundhead armor layers from initiation of damage (white) to initiation of Iribarren's damage (IIDa) and initiation of destruction (black). The white and black lines are the fitting lines for Cubipod initiation of damage (white) and initiation of destruction (black).

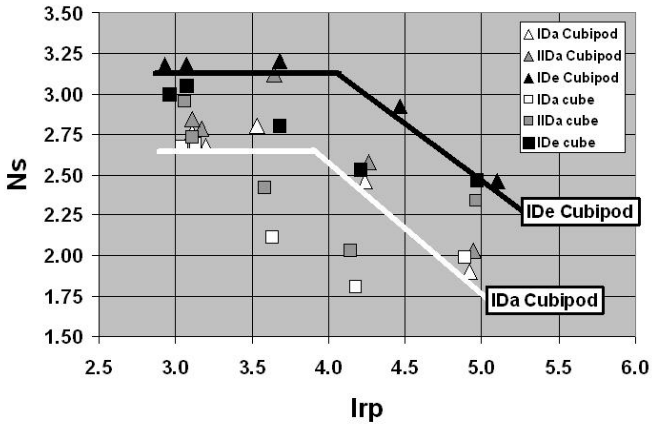

Figure 7. Stability numbers corresponding to cube and Cubipod roundhead armors.

Stability numbers corresponding to cubes are significantly lower than those for Cubipods, in the range of 3.5<Irp<4.5, but the hydraulic stability of Cubipods is much higher on the trunk as specified in Figs. 5 and 6. Considering

2D and 3D experiments on a 3/2 slope, the stability numbers for initiation of damage (IDa) and initiation of destruction (IDe) in the range of $3<Irp<4$ were: (1) Cube 2-layer trunk Ns= 2.0 (IDa) and 3.0 (IDe), (2) Cubipod 1-layer trunk Ns= 3.0 (IDa) and 3.7 (IDe), (3) Cubipod 2-layer trunk Ns= 3.4 (IDa) and 4.2 (IDe), (4) Cube roundhead Ns= 1.9 (IDa) and 2.7 (IDe), and (5) Cubipod roundhead Ns= 2.6 (IDa) and 3.2 (IDe).

2D overtopping tests

Runup and overtopping tests were conducted at the UPV wave flume (30.0x1.2x1.2 m.). A 3/2 slope cross section was defined for non-breaking and different overtopping conditions, a crown wall with two different crown wall elevations ($\Delta h + Rc$=25 and 31 cm) and two different water levels (Δh= 0 and 5 cm). One-unit and two-unit thick Cubipod armors (D_{n50}=3.82 cm, γ_r=2.30 gr/cm^3, W= 128 gr) and a conventional two-unit thick cube armor (D_{n50}=6.0 cm, γ_r=2.20 gr/cm^3, W= 475 gr) were tested on the same core material (D_{n50}=0.70 cm), filter layer (D_{n50}=1.80 cm) and crown wall. Fig. 8 shows the cross section of the model used for overtopping tests; three geometric parameters were considered: slope ($\cot\alpha$=3/2), crest freeboard (Rc) and armor elevation (Ac). 237 overtopping tests were completed in a series of irregular wave runs of 1000 waves following JONSWAP spectra (γ=3.0). The Iribarren's number of each series was kept approximately constant ($2.7<Irp<7.0$); the incident significant wave height was increased from no overtopping to the limit of the overtopping measurement system or initiation of damage (IDa). The conventional two-unit thick 6-cm cube armor was found to be less stable than the one-unit thick 3.82 cm Cubipod armor, in agreement with the stability numbers indicated in Fig. 6.

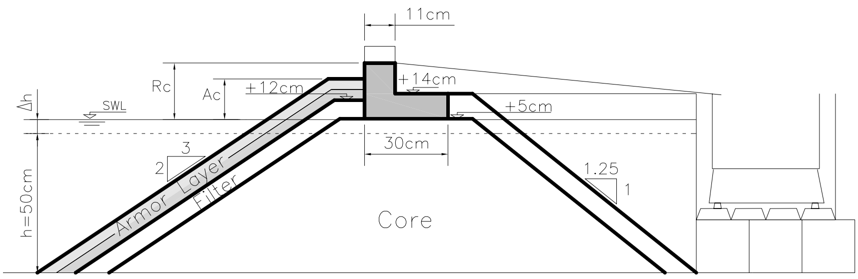

Figure 8. Cross section of the overtopping test model.

Four capacitance wave gauges were placed in front of the structure at the model area to analyze incident and reflected waves using the LASA method (see Figueres and Medina, 2004). Significant wave height, H_{m0}, and peak period, Tp, of incident waves were used to calculate dimensionless crest freeboard Rc/H_{m0}, and Iribarren's number $Irp= (2/3)Tp/(2\pi H_{m0}/g)^{0.5}$. In addition to Rc/H_{m0} and Irp, relative armor elevation, Ac/Rc, was considered to estimate the dimensionless mean overtopping discharge, $Q=q/(gH_{m0}^3)^{0.5}$. Since the core, filter and crown wall were the same for all the different armor layers, but armor layer thicknesses were different, Cube armor was tested in the range of 0.70<Ac/Rc<1.00, two-unit thick Cubipod armor was tested in the range of 0.58<Ac/Rc<0.80, and one-unit thick Cubipod armor was tested in the range of 0.40<Ac/Rc<0.65.

Corredor et al. (2008) found a negligible dimensionless overtopping rate limit, $Q=q/(gH_{m0}^3)^{0.5}<10^{-7}$ at $Rc/H_{m0}>2.6$, and proposed linear exponential models for significant overtopping rates similar to that proposed by Medina et al. (2002); dimensionless mean overtopping discharges of cube and Cubipod armors are estimated by $Q=a_k \exp(b_k Rc/H_{m0}+c_k Ac/Rc+d_k Irp)$. Smolka (2008) unified these overtopping models in a single formula considering the roughness factor associated with each armor unit, $Q=a \exp(bRc/\gamma_f H_{m0}+cAc/Rc+dIrp)$, in which γ_f is the roughness factor that depends on the armor unit and armor thickness. The parameters $\{a,b,c,d,\gamma_f\}$ were estimated minimizing the mean squared error between observations and calculations, and the resulting formula was

$$Q=\frac{q}{\sqrt{gH_{m0}^3}}=0.20\exp\left[-2.16\left(\frac{Rc}{\gamma_f H_{m0}}\right)-3.27\left(\frac{Ac}{Rc}\right)+0.53\left(Irp\right)\right] \quad (3)$$

The roughness factor estimated for one-unit and two-unit thick Cubipod armor layers were γ_f(Cubipod1)=0.46 and γ_f(Cubipod2)=0.44 respectively. Therefore, Cubipod armor units reduce overtopping better than conventional cubic blocks. Fig. 9 shows the observed dimensionless overtopping rates of one-unit (circles) and two-unit (triangles) thick Cubipod armors compared to estimations given by Eq. 3 using the roughness factor γ_f=0.46 for one-unit thick and γ_f=0.44 for two-unit thick Cubipod armor.

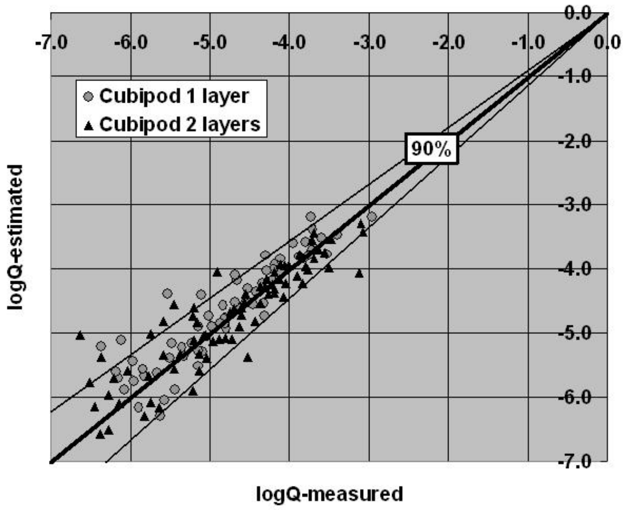

Figure 9. Measured versus estimated Cubipod armor overtopping rates using Eq. 3.

Summary and Conclusions

This paper describes the experiments carried out for Cubipod armor unit development. Results from prototype drop tests, 2D and 3D hydraulic stability tests and overtopping tests are analyzed. Casting systems of conventional cube and Cubipod units are described and eight 15-ton cube prototypes and ten 16-ton Cubipod prototypes were manufactured with standard concrete mix; the upper part of the molds can be removed vertically six hours after vibration. Production rates of cubes and Cubipods are similar as is the tong handling system; it is easier to place Cubipods on the breakwater slope because of the tendency for conventional cubes to fit face-to-face.

Prototype drop tests were carried out at the SATO's block yard in the Port of Alicante. Two reinforced concrete platforms were used for overturning and free fall tests. Both cubes and Cubipods were slightly damaged in overturning tests. Some free fall tests caused the breakage of the prototypes depending on: drop height (h), number of drop repetitions (n), drop type (anvil, edge or random) and armor unit (Cube and Cubipod). If the drop height and number of drop repetitions increased, the loss of mass increased as well; if the loss of mass was higher than 4%, breakage occurred with massive loss of mass affecting the prototype core. Anvil drops caused more damage than did edge drops and random drops. Cubipods withstood drops higher than cubes did, with critical equivalent drop heights of h_{ec}(m)=3.1 and 1.9, respectively. Prototype size and concrete strength also affected mass loss, but neither was considered in these experiments because of the similarity of both cube and Cubipod prototypes. Additionally, two Cubipod prototypes were tested in extreme free fall tests.

Non-breaking non-overtopping 2D hydraulic stability tests carried out in two different laboratories confirmed the fact that both one-unit thick and two-unit thick Cubipod armors are much more stable than conventional two-unit thick cube armors. Results from 3D hydraulic stability tests for two-unit thick cube and Cubipod armored roundheads indicate Cubipod armor is also more stable than conventional cube armor but the difference is not as pronounced as in the trunk. Finally, overtopping tests confirmed both two-unit and one-unit thick Cubipod armors reduce the overtopping rates of conventional two-unit thick cube armors with roughness factors γ_f=0.44, 0.46 and 0.50, respectively.

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