

CASTING SYSTEM AND DROP TESTS OF THE CUBIPOD ARMOR UNIT

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The casting system and drop tests of the new Cubipod armor units are described and compared to these of conventional cubes. 2D and 3D hydraulic stability and overtopping tests are also discussed. The Cubipod is similar to a cube armor unit, but it is designed with protrusions on its faces to avoid heterogeneous packing and to increase friction with the underlayer; it is randomly placed in single or double layers. This new massive armor unit combines high structural strength with high hydraulic stability in both the breakwater trunk and the roundhead. Drop tests using 15-ton cube and 16-ton Cubipod prototypes proved Cubipods withstand drops more than 50% higher than conventional cubes of similar size. The manufacturing time was similar for both armor units.

INTRODUCTION

The construction of rubble-mound breakwaters in deep waters under severe wave attack requires the use of dense and heavy quarry stones. Where local quarries do not produce sufficient armor stones, concrete armor units are used. Conventional cube and parallelepiped concrete armor units have been used worldwide since the 19th century.

The publication of the Hudson's formula and the invention of the Tetrapod in 1950 started a technological race to design new concrete armor units with higher hydraulic stability to reduce construction and maintenance costs. Hudson's formula, based on the pioneering work of Iribarren (1938), was originally proposed for regular waves, and SPM (1984) popularized the formula for irregular waves using the equivalence $H=H_{1/10}$. In Hudson's formula, the weight of the armor unit for initiation of damage was proportional to the inverse of the stability coefficient (K_D), so higher K_D allowed for a reduction of armor weight and the volume of concrete required for construction. The Dolo was the first armor unit characterized with a very high K_D measured in different laboratories and breakwaters constructed in many countries; however, the catastrophic failure of the 40-ton Dolo breakwater in the Port of Sines (Portugal) in 1978 focused attention on the armor unit structural strength and not only its hydraulic stability. Larger armor units are more fragile because loads are roughly proportional to the third power of size while resistance is only proportional to the second power of size. Dolosse and other slender armor units generate interlocking; they resist impact and wave force in small scale

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experiments and small prototypes, yet they break very easily when prototypes are large.

After the Sines breakwater failure, numerous bulky armor units have been designed in the attempt to balance structural strength and hydraulic stability. Armor units can be classified according to structural robustness (slender, bulky and massive), the placement method (random or special) and the armor unit thickness (single or double layer). The slender armor units randomly placed and single-layer armors with special placement usually generate strong interlocking forces and favor high hydraulic stability; however, armor unit integrity and placement tolerances must be guaranteed at prototype scale. Therefore, the world's larger rubble-mound breakwaters are armored with randomly placed massive unreinforced concrete armor units or slender reinforced concrete armor units. Details about these structures can be found in Burcharth et al. (2002) who described the new 150-ton cube breakwater at La Coruña (Spain) and Hanzawa et al. (2006) who reported on the use of fully reinforced Dolosse up to 80 tons in Japan.

If armor unit integrity is guaranteed, armor erosion due to wave attack is the most critical rubble-mound breakwater failure mode for design. Nevertheless, Gómez-Martín and Medina (2006, 2007) found that both armor unit extraction and Heterogeneous Packing (HeP) tend to diminish the armor unit packing density around the mean water level. Both the Cubipods and conventional cubic blocks compared in this paper are massive armor units with random placement. Conventional design usually involves double-layer armor, but Cubipods can also be used to construct single-layer armors with random placement because the extraction of one Cubipod unit from the armor often causes the self-arrangement of the surrounding armor units which increases the armor stability. Fig. 1 shows 3D views of the Cubipod and cube armor units.

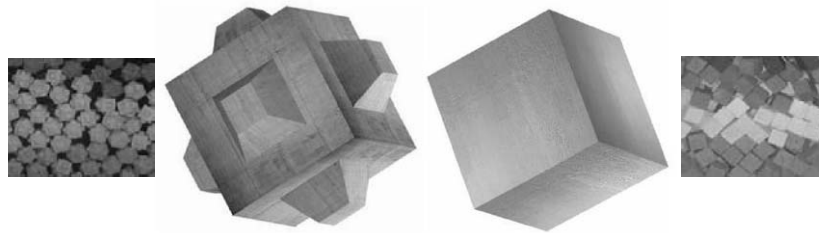


Figure 1. Cubipod and cube armor units.

HYDRAULIC STABILITY AND OVERTOPPING TESTS

In order to analyze the hydraulic stability and overtopping performance of the Cubipod, a series of experiments were conducted in different laboratories to compare Cubipod armor units with conventional cubic blocks.

2D and 3D hydraulic stability tests

Gómez-Martín and Medina (2008) described 2D and 3D hydraulic stability tests with cubes and Cubipods carried out in three different laboratories. Rubble-mound breakwater models with 3/2 slope were tested with crest elevations and water depths adequate for non-breaking and non-overtopping conditions both in 2D and 3D experiments. Similar core, filter layer and armor unit sizes were used in the different laboratories. Several regular and mostly irregular tests were carried out with runs of 1000 waves increasing significant wave height with constant Iribarren's number in the range of $2.5 < I_{rp} = (2/3)T_p / (2\pi H_{m0}/g)^{0.5} < 7.0$ from the initiation of damage (IDa) to the initiation of destruction (IDe). Table 1 specifies the characteristics of the 2D and 3D cube and Cubipod hydraulic stability tests.

Table 1. Characteristics of 2D and 3D cube and Cubipod hydraulic stability tests								
laboratory	breakwater model			armor units		Dn50(cm)		
	test	armor unit	armor thickness	W(gr)	$\gamma_s(\text{gr/cm}^3)$	armor	filter	core
UPV	2D-trunk	cube	double layer	140	2.18	4.00	1.80	0.70
	2D-trunk	Cubipod	double layer	108	1.94	3.85	1.80	0.70
INHA	2D-trunk	Cubipod	double layer	128	2.30	3.82	1.25	0.25
	2D-trunk	Cubipod	single layer	128	2.30	3.82	1.25	0.25
IH Cantabria	3D-head	cube	double layer	145	2.30	3.98	1.81	0.88
	3D-head	Cubipod	double layer	128	2.30	3.82	1.81	0.88

2D trunk stability tests of double-layer cube and Cubipod armors were carried out at the wave flume (30.0x1.2x1.2 m.) of the *Universidad Politécnica de Valencia* (UPV). 2D trunk stability tests of single-layer and double-layer Cubipod armors were carried out at the wave flume (52.0x1.8x2.0 m.) of the *Instituto de Hidrodinámica Aplicada* (INHA). 3D roundhead stability tests of double-layer cube and Cubipod armors were conducted at the wave tank (24.8x8.5x1.5 m.) of the *Instituto de Hidráulica Ambiental* (IH Cantabria). There was good agreement between the 2D stability results obtained by UPV and INHA for the double-layer Cubipod armor while consistent results were obtained by INHA (2008) for single-layer Cubipod armor and by UPV for double-layer cube armors. Table 2 and Fig. 2 show results for the stability numbers corresponding to the initiation of damage (IDa) and the initiation of destruction (IDe) for double-layer cube and Cubipod armors as reported by Gómez-Martín and Medina (2008).

For single-layer Cubipod armors, the initiation of damage and initiation of destruction showed minimum values of stability numbers $N_s(\text{IDa}) \approx 3.0$ and $N_s(\text{IDe}) \approx 3.7$, significantly lower than double-layer Cubipod armors yet much higher than conventional double-layer cube armors. Finally, results from the 3D

roundhead hydraulic stability tests of cube and Cubipod armor layers obtained by IH Cantabria (2008) showed minimum values for stability numbers $Ns(IDa) \approx 2.1$ and $Ns(IDe) \approx 2.8$ for cubes and $Ns(IDa) \approx 2.6$ and $Ns(IDe) \approx 3.2$ for Cubipods in the range $3.0 < Irp < 4.0$.

Table 2. Stability number for initiation of damage and initiation of destruction		
damage limit	armor unit	$0 < Irp = Irp - 3 < 3$ $Irp = (2/3)Tp / (2\pi H_{m0}/g)^{0.5}$
IDa	cube	2.2-0.2 IR
	Cubipod	3.4
IDe	cube	3.1-0.15 IR
	Cubipod	4.2+0.4 IR

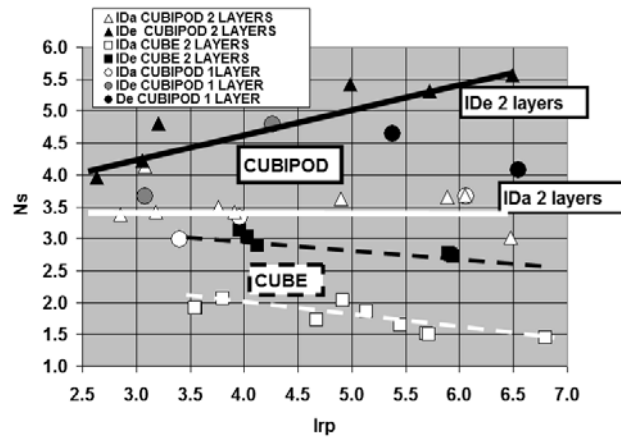


Figure 2. Stability numbers corresponding to Cubipod and cube armors.

Overtopping tests

Smolka (2008) analyzed the results of the overtopping tests described by Gómez-Martín and Medina (2008) providing Eq. 1 to predict mean overtopping discharges, q , as a function of crest freeboard R_c , and armor elevation A_c , shown in Fig. 3, as well as the incident significant wave height H_{m0} , the Iribarren's number Irp , and the roughness factor γ_f which depends on the armor unit and armor thickness. The best-fitting values for roughness factors were: $\gamma_f = 0.50$ for double-layer cube armor, $\gamma_f = 0.46$ for single-layer Cubipod armor, and $\gamma_f = 0.44$ for double-layer Cubipod armor. Therefore, both single-layer and double-layer Cubipod armors significantly reduce overtopping rates when compared to the conventional double-layer cube armor. The measured dimensionless overtopping discharge was negligible, $Q < 10^{-7}$, when $R_c/H_{m0} > 2.6$.

$$Q = \frac{q}{\sqrt{gH_{m0}^3}} = 0.20 \exp \left[-2.16 \left(\frac{Rc}{\gamma_f H_{m0}} \right) - 3.27 \left(\frac{Ac}{Rc} \right) + 0.53 (Irp) \right] \quad (1)$$

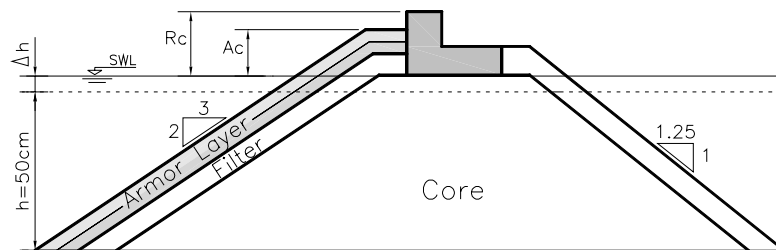


Figure 3. Breakwater cross section for overtopping tests.

CUBIPOD CASTING, HANDLING AND STORAGE

To evaluate the manufacturing, handling and storage of the new Cubipod armor unit, a special casting system and adapted tongs were designed by SATO technicians for the efficient production and handling of 7.1 m³ (16-ton) Cubipods. Fig. 4b shows the Cubipod casting system with a base and an upper part similar to the one shown in Fig. 4a used for conventional cubic blocks. The upper part can be lifted six hours after concrete filling and vibration. Fig. 4c shows 16-ton Cubipods and 15-ton cubes placed in the storage area ready for use in prototype drop tests.

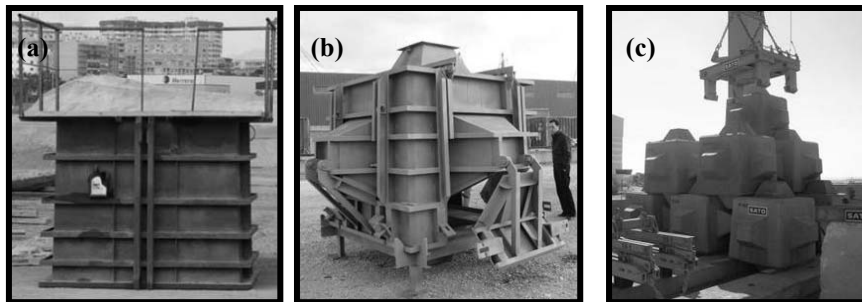


Figure 4. (a) Cube and (b) Cubipod casting systems, and (c) stacked Cubipods.

Standard HA-30/B/25/IIIa-Qb concrete mix was used to fill both the Cubipod and cube molds. Concrete was made with 350 kg/m³ of CEM-I-42.5-R cement and a water/cement ratio of 0.5. The mean values (coefficients of variation) of

the compressive strength, estimated from standard concrete samples broken at 28 days, of cubes and Cubipods were 63.5(5.2) MPa and 60.1(7.8) MPa, respectively. In order to facilitate the lifting maneuver of the upper part of the casting system, both conventional cubes and Cubipods have horizontal faces and not exactly vertical faces but rather quasi-vertical faces with an inclination of about 3%. Fig. 5 illustrates the geometric characteristics of 15-ton cubes and 16-ton Cubipods used for the drop tests.

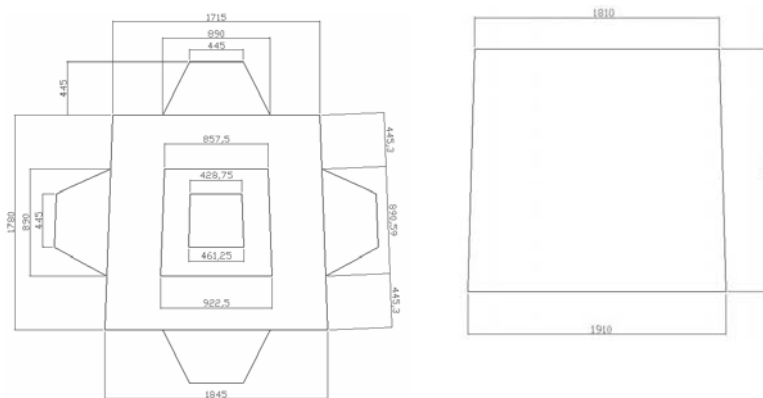


Figure 5. Dimensions (mm) of the 16-ton Cubipod and the 15-ton cube.

The conventional tongs used for cubic blocks were adapted by SATO technicians to handle Cubipods efficiently; Fig. 6 shows the double tongs used to handle Cubipod prototypes at the block yard of the Port of Alicante. The functioning and performance of single tongs for cubes and double tongs for Cubipods are quite similar and were used during the prototype drop tests to handle and to drop 15-ton cubes and 16-ton Cubipods.



Figure 6. Double tongs adapted to handle prototype Cubipods.

Once the armor unit casting system and the handling are efficiently resolved, it is necessary to create an optimum design of the armor unit storage area. The

optimum storage block yard for cubes and Cubipods described by Corredor et al. (2008) are based on two different arrangements: (1) “open” with 50% porosity and (2) “closed” with 30% porosity compared to the typical cubic block yard with 20% porosity. Fig. 7 shows Cubipods stored in open and closed arrangements; in Fig. 4c Cubipod prototypes are stacked in an open arrangement ready for use in drop tests.

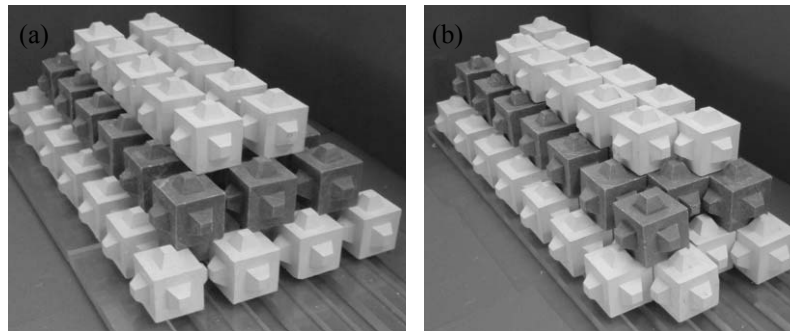


Figure 7. Cubipod storage: (a) open arrangement and (b) closed arrangement.

DROP TESTS OF PROTOTYPE CUBES AND CUBIPODS

To assess the structural strength of the Cubipod, a systematic drop test program was carried out using unreinforced concrete cubes and Cubipods in similar conditions. During the experimental design phase, the conventional cubic block was considered the most resistant massive armor unit as well as the most appropriate reference armor unit to evaluate the structural strength of Cubipod. Similar unit sizes, concrete strength and drop conditions were planned for the drop tests. A 90-cm thick reinforced concrete platform (10x7.5x0.9 m.) was constructed for the overturning tests, and a 115-cm thick reinforced concrete platform (5.0x5.0x1.15 m.) protected with a 20-mm thick steel plate was used for the free fall tests. Although both are massive armor units, the methodology of these drop tests was developed from that used for bulky armor units (see Muttray et al., 2005).

The drop tests of prototype 15-ton cubes and 16-ton Cubipods were completed during the first week of March 2008 in the SATO block yard at the Port of Alicante. Fig. 8 shows the 63/25-ton gantry crane used to handle and drop armor units, as well as the 2x20-ton double tongs with load cell used to weigh the prototypes. A single 20-ton tong was used to handle and drop prototype cubes while a double 2x20-ton tong was used to handle and drop prototype Cubipods with the gantry crane. The gantry crane operator easily handled cubes and Cubipods with the single and double tongs, respectively. A wheel excavator was used to tip prototype cubes and to push Cubipods during the overturning tests. With the 10-kg precision load cell, as indicated in Fig. 8b, prototypes were weighed before and after each free fall test or series of overturning strikes to

measure the relative loss of mass, as an indicator of structural integrity; the lower the loss of mass, the higher the structural integrity and structural strength.

Overturning tests

The possible overturning maneuvers on a given armor unit depend on its geometric characteristics, symmetry planes and positioning on the ground. Cubes can only be overturned one way while two overturning maneuvers are possible with Cubipods. Overturning maneuvers were made on the reinforced concrete platform (10x7.5x0.9 m.).



Figure 8. Port of Alicante: (a) gantry crane and (b) double tong with load cell.

Since the cube has only one position on the ground it can only be overturned maintaining two of the four vertical faces in the vertical position. In Fig. 9a, a wheel excavator tips the cube for overturning; complete overturning is achieved when the horizontal faces are inclined more than 45°; for partial overturning the cube is released when the horizontal faces are inclined 15°. One 15-ton cube was used for complete overturning and another for partial overturning. The prototypes were weighed every 8 impacts; after 24 overturning impacts, cubes lost 2% and 0.4% of their mass, respectively.

The Cubipod has only two stable positions on the ground with the same vertical symmetry plane, and frontal overturning maintaining this symmetry plane is one of the overturning maneuvers; the other overturning maneuver is achieved by pushing the Cubipod laterally for diagonal overturning. Two 16-ton Cubipods were used for frontal overturning and another two for diagonal overturning. In Fig. 9b a wheel excavator pushes the upper part of the Cubipod in a frontal overturning strike. The prototypes were weighed every 20 strikes; after 60 overturning strikes, the maximum measured loss of mass was 0.3%.

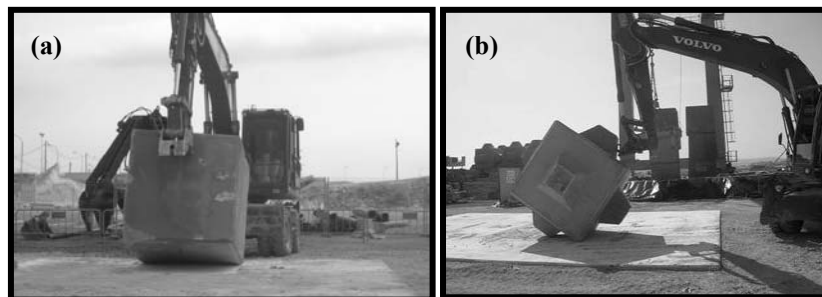


Figure 9. (a) Overturning of cube and (b) frontal overturning of Cubipod.

No serious damage was detected in the visual inspection of either cubes or Cubipods; both armor units resisted very well the numerous overturning impacts. The damage to prototype Cubipods was negligible, which allowed for them to be used as receptors during the extreme free fall tests, in which two prototype Cubipods were dropped from the top of the gantry crane on the four overturning test Cubipods assembled on the overturning platform.

Free fall and extreme free fall tests

The loss of mass in free fall tests basically depends on the stiffness of the free fall platform, drop height, prototype size, concrete strength, type of impact, and accumulation of internal damage. The 15-ton cubes and 16-ton Cubipods used in the free fall tests were similar in size; they were also manufactured using similar procedure and concrete mix. They were dropped alternatively on the same reinforced concrete platform (5.0x5.0x1.15 m.) protected with a 20-mm thick steel plate, constructed on a compacted surface of the block yard.

Three different free fall tests were conducted for both cubes and Cubipods: (1) the “anvil drop” test, in which the prototype is dropped with one face parallel to the platform, (2) the “edge drop” test, in which the prototype is rotated 45° with one of its edges parallel to the platform, and (3) the “random drop” test is achieved when a prototype is put in an unstable position on top of a cubic block, placed on the ground, and then falls.

Each prototype was dropped to the free fall platform from a specified drop height (h), a maximum of six times ($1 \leq n \leq 6$). The loss of mass was measured after each drop. The drop height (h) was defined as the distance from the lowest point of the prototype to the platform just before the prototype was released. Cube and Cubipod prototypes were dropped from $h(m)=2.0$ in anvil, edge and random positions. Cubic blocks were also tested in the anvil position from drop heights $h(m)=0.5, 1.0$ and 1.5 .

Four factors determined the loss of mass measured in the tests: the drop height (h), the number of repetitions (n), the drop type (anvil, edge or random), and the armor unit (cube or Cubipod). Anvil drops produced more damage than edge drops, and edge drops damaged the prototypes more than random ones. In terms of drop heights, the Cubipods withstood higher drops than did the cubes.

In addition to overturning and free fall tests, two extreme free fall tests were carried out dropping two Cubipod prototypes from heights $h(m)=8.5$ (anvil drop) and 9.5 (edge drop). The four Cubipod prototypes used for overturning tests were placed on the overturning platform to receive the impact during the two extreme free fall tests; the loss of mass was measured for the prototypes used in each of the two extreme free fall tests.

Regarding anvil drops, an equivalent drop height (h_e) was defined taking into account both the drop height (h) and the number of repetitions (n)

$$h_e = h\sqrt[4]{n} \quad (2)$$

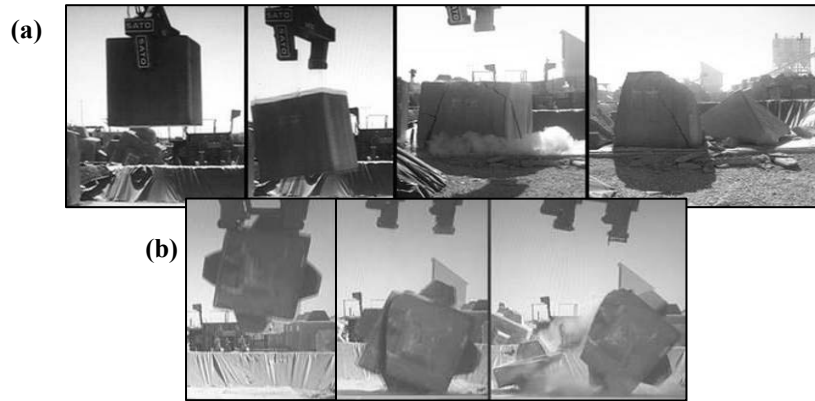


Figure 10. Anvil drop from $h(m)=2.0$: (a) cubic block ($n=1$) and (b) Cubipod ($n=6$).

Figs. 10a and 10b show images of the first cube drop (anvil, $n=1$) and the sixth Cubipod drop (anvil, $n=6$) from $h(m)=2.0$. Results from both free fall tests and overturning tests are specified in Fig. 11 which depicts the measured loss of mass after the free fall tests for cubes (squares) and Cubipods (circles). For overturning tests, the drop height $h(m)=0.40$ was calculated as the vertical distance between the cube's center of gravity before release and after impact on the overturning platform.

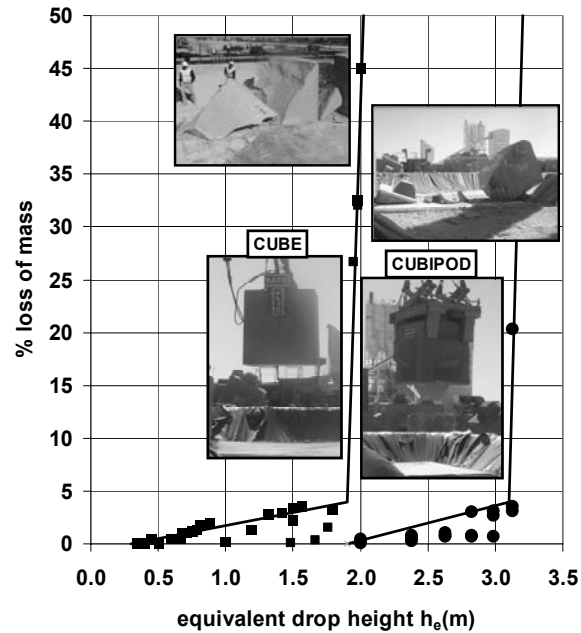


Figure 11. Loss of mass (%) versus equivalent anvil drop height (h_e).

Loss of mass showed a linear relation to h_e up to the critical 4% limit, when the core is fractured. The critical equivalent anvil drop heights (h_{ec}) were $h_{ec}(m) = 1.9$ for cubes and 3.1 for Cubipods, corresponding to the 4% loss in mass. The loss of mass was not significant if $h_e(m) < 0.5$ (cube) and $h_e(m) < 2.0$ (Cubipod). Edge drop heights and random drop heights caused less damage than anvil drops; edge drops caused damages corresponding to 85% anvil drop heights, and random drops caused damages equivalent to 75% anvil drop heights.

ECONOMIC ANALYSIS

Another objective of this study was to analyze the economic viability of using Cubipods instead of conventional cubic blocks in real breakwater constructions. In a recent report, Corredor et al. (2008) described a parametric study of costs of typical mound breakwaters on Spanish coasts. The economic comparison in their study included multiple logistic conditionings of real constructions: concrete supply, handling equipment (molds and tongs), manpower and equipment for production, casting and block yard design, transport and placement equipment, storage, etc.

The costs depended basically on the weight of the armor unit and the length of the breakwater. Breakwater lengths of $L(m) = 400, 1000$ and 2500 were considered in this parametric study as representative of short, medium and long breakwaters. 10-ton to 150-ton armor units were considered with typical breakwater cross sections for conventional double-layer cube armor (B2) as well as single-layer and double-layer Cubipod armors (C1 and C2). Given the breakwater geometry and armor unit weight, the number of armor units to manufacture is calculated considering 40% and 43% porosity for cube and Cubipod armors, respectively. A typical block yard with gantry crane and direct filling of molds from above was assumed; this is not the optimum solution for the smallest breakwaters but it is valid for comparing cube and Cubipod armor units.

The production cost was higher for Cubipods than for conventional cubes due to the need for additional personnel and equipment for the more complex casting system. The handling costs included energy costs, equipment and labor. The placement costs were estimated as a function of the armor unit weight and distances; the tongs for Cubipod handling were considered 50% heavier than those for handling cubes. The appropriate crane for placement was selected from a list of conventional cranes, considering the working cycle as function of the lifting force, turning speed, lifting velocity, etc. The working efficiency of each crane was calculated for each breakwater cross section.

Once the production and placement were optimized, the block yard and storage system was designed. The schedule was adjusted to minimize the construction time. The open and closed arrangements shown in Fig. 7 were considered for

Cubipods with porosities of 50% and 30%, respectively; a conventional cubic block yard has a porosity of approximately 20%, with a handling corridor width $0.5 < c(m) < 1.0$. The closed arrangement for Cubipods saves space with regard to open arrangement, but can only be used for 18-ton or larger prototypes to be handled with tongs. Three casting bases were considered for each mold for a two units/day production scheme for each mold of both Cubipods and conventional cubes.

Fig. 12 specifies the price (€/m³) for the different cases depending on the armor unit weight and the breakwater length. Conventional double-layer cube armor (B2) is represented by squares; double-layer Cubipod armor (C2) is represented by circles, and single-layer Cubipod armor (C1) is represented by triangles. The cost decreases as armor unit weight and breakwater length increases. A fixed and constant cost of concrete supply (60 €/m³) was considered for all cases.

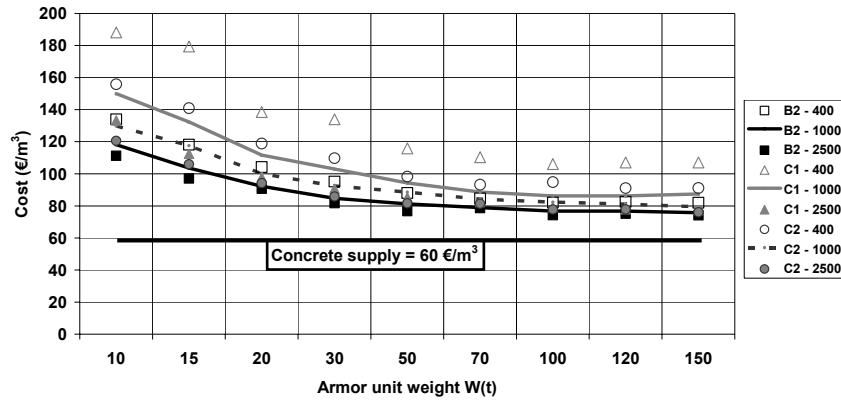


Figure 12. Cost (€/m³) as dependent on armor unit weight and breakwater length.

It must be pointed out that conventional double-layer cube armor requires about 5% more armor units than double-layer Cubipod armor with the same armor unit weight, and a single-layer Cubipod armor requires half the number of armor units as the double-layer one. Taking into consideration the hydraulic stability of the different armors, single-layer and double-layer Cubipod armors significantly increase safety and reduce costs as compared to conventional double-layer cube armors; reduction in armor construction costs between 15% and 40% for medium size breakwaters are reported by Corredor et al. (2008); the cost saving is higher for larger breakwaters and lower for smaller breakwaters.

SUMMARY AND CONCLUSIONS

This study aims first to describe the casting system and drop tests with the Cubipod armor unit and the conventional cubic block. In addition, results from

2D and 3D hydraulic stability and overtopping tests for each unit type are compared. Finally, a parametric cost analysis is presented.

The casting systems of conventional 15-ton cube and 16-ton Cubipod armor units are described. Eight cubes and ten Cubipods were manufactured for the prototype drop tests using the described casting system; the upper part of the molds was lifted six hours after vibration. Production rates of cubes and Cubipods were similar as were the tong handling systems.

A reinforced concrete overturning platform (10.0x7.5x0.9 m) was used for the overturning tests and extreme free fall tests while a reinforced concrete overturning platform (5.0x5.0x1.15 m) protected with a 20-mm thick steel plate was used for the free fall tests. Cubes and Cubipods were only slightly damaged in overturning tests with loss of mass lower than 0.3% and 2%, respectively. The armor unit size, concrete and platform stiffness were similar for both armor units; the loss of mass was dependent on factors related to drop height (h), number of drop repetitions (n), drop type (anvil, edge or random) and armor unit (cube or Cubipod). A critical loss of mass limit was observed for both cubes and Cubipods; below the critical 4% level, the loss of mass increased almost linearly with the drop height, but core breakage and a drastic increase in loss of mass occurred when that critical level was exceeded. The anvil drop type was more damaging than the edge drop type which, in turn, was worse than the random drop type.

Cubipods withstood higher drops, being the critical equivalent drop heights of $h_{ec}(m)=3.1$ for Cubipods and $h_{ec}(m)=1.9$ for cubes. Armor unit size, platform stiffness and concrete characteristics also affected mass loss, but these factors were not considered in these experiments. In the extreme free fall tests, two 16-ton Cubipod prototypes were dropped from the maximum elevation of the gantry crane, $h(m)=8.5$ (anvil) and $h(m)=9.5$ (edge); neither was broken because the impact energy was apparently distributed between the falling prototype and the four Cubipods which received the impact.

As described herein, the 2D hydraulic stability tests indicated both single-layer and double-layer Cubipod armors are much more stable than conventional double-layer cube armors. Results from the 3D hydraulic stability tests for double-layer cube and Cubipod armored roundheads indicated Cubipod armor is also more stable than conventional cube armor. Overtopping tests confirmed that both double-layer and single-layer Cubipod armors reduce the overtopping rates of conventional, double-layer cube armors with roughness factors of $\gamma_r=0.44$, 0.46 and 0.50, respectively.

Finally, the parametric cost analysis of typical breakwater cross sections of different sizes reveals that Cubipod armors can significantly reduce construction costs in addition to increasing safety.

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REFERENCES

- Burcharth, H.F., Maciñeira, E., P. Canalejo, 2002. Model testing and reliability evaluation of the new deepwater breakwater at la Coruña, Spain. *Proc. 28th Int. Conf. Coastal Engineering*, ASCE, 1581-1593.
- Corredor, A., Torres, R., Miñana, J.V., Fernández, E., Menéndez, C.F., Santos, M., Gómez-Martín, M.E., Goumy, R., J.R. Medina, 2008. CUBÍPODO: Estudios de estabilidad hidráulica 2D y 3D, estudio del remonte y rebase, diseño del encofrado y ensayos de caída de prototipos. *Libro del III Cong. Nac. Asoc. Téc. de Puertos y Costas*, Puertos del Estado, 187-211 (in Spanish).
- Gómez-Martín, M.E., J.R. Medina, 2006. Damage progression on cube armored breakwaters. *Proc. 30th Int. Conf. Coastal Engineering*, ASCE, 5229-5240.
- Gómez-Martín, M.E., J.R. Medina, 2007. Cubipod concrete armour unit and heterogeneous packing. *Proc. Coastal Structures '07*, ASCE, (in press).
- Gómez-Martín, M.E., J.R. Medina, 2008. Erosion of cube and Cubipod armor layers under wave attack. *Proc. 31st Int. Conf. Coastal Engineering*, ASCE, (in press).
- Hanzawa, M., Kato, T., Kishira, Y., Ozawa, Y., Niidome, Y., Murakami, T., Ono, A., Hidaka, K., Yoshida, H., I. Tanaka, 2006. Fully reinforced 80t Dolos and sloping top caisson in Hososhima Port. *Proc. 30th Int. Conference Coastal Engineering*, ASCE, 4805-4814.
- IH Cantabria, 2008. *Ensayos físicos 3D de morros del Cubipodo (CUBIPODmorros)*. Report by the Instituto de Hidráulica Ambiental IH Cantabria (in Spanish).
- INHA, 2008. *Ensayos físicos 2D de estabilidad de un dique en talud de 1 y 2 capas de cubipodos*. Report by the Instituto de Hidrodinámica Aplicada INHA (in Spanish).
- Iribarren, R., 1938. A formula for the calculation of rock fill dykes. (Translation of "Una fórmula para el cálculo de los diques de escollera" in *The Bulletin of the Beach Erosion Board*, Jan 1949, 3(1):1-15).
- Muttray, M., Reedijk, J.S., Vos-Rovers, I., P. Bakker, 2005. Placement and structural strength of Xbloc® and other single layer armour units. *Proc. Coastlines, Structures and Breakwaters 2005*, ICE, 556-567.
- Smolka, E., 2008. *Estudio experimental del remonte y rebase de un dique en talud de cubipodos: Aplicación al Nuevo Dique en Punta Langosteira (A Coruña)*. Proyecto Fin de Carrera de la ETSICCP de Valencia, Universidad Politécnica de Valencia (in Spanish).
- SPM, 1984. *Shore Protection Manual*, U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.