Cube and Cubipod armour unit drop tests and cost analysis

Josep R. Medina, *Universidad Politécnica de Valencia*, Valencia, Spain
M. Esther Gómez-Martín, *Universidad de Alicante*, Alicante, Spain
Antonio Corredor, Rafael Torres, Juan V. Miñana, Enrique Fernández, Carlos F. Menéndez and **Moisés Santos**, SATO (OHL Group), Madrid, Spain.

Introduction

Since the 19th century conventional concrete cubic and parallelepiped blocks have been used for armouring mound breakwaters under severe wave attack. If local quarries are not able to produce adequate armour stones, concrete armour units must be used or appropriate sized rock imported at high cost. Many types of armour units are available, from simple conventional cubic blocks, which withstand wave action by friction and gravity forces, to slender forms which generate interlocking forces as well. The Tetrapod, invented in 1950, was the first of a series of armour unit inventions designed to reduce construction and maintenance costs while increasing hydraulic stability. Hudson's formula, based on the formula given by Iribarren (1938) for regular waves, was accepted by the engineering community in the 1950s and popularized later by SPM (1984). In Hudson's formula, each armour unit shape is associated with a specific hydraulic stability coefficient (K_D); the higher the K_D, the lower armour unit weight (W) necessary to withstand a given design wave height (H).

The Dolos is an armour unit with a very high K_D as measured in different laboratories, which favoured the construction of Dolos armour breakwaters around the world until the failure of the 40-ton Dolos breakwater in the port of Sines (Portugal) in 1978. This catastrophic failure focused international attention on armour unit strength in addition to hydraulic stability. Loads are roughly proportional to the third power of armour unit size while resistance is only proportional to the second power of armour unit size. Slender armour units like Dolos may generate armour unit interlocking and a high hydraulic stability coefficient; they also withstand impacts and structural loads in small scale experiments and with small prototypes, but they break easily when prototypes are large, as in the Sines case. Conventional massive armour units, such as low K_D cubic blocks, are not very efficient against wave attack at small scale, but they are quite robust and armour units as large as 150 tonnes can be easily handled. Simple conventional cube armour units are easy to fabricate, handle, store and place on the armour slope. Thus, hydraulic stability, structural robustness and logistic requirements are essential when selecting the best armour unit for each breakwater. The world's largest breakwaters are usually armoured with randomly-placed massive, unreinforced concrete armour units or slender reinforced units. Burcharth et al. (2002) described the 150-tonne cube breakwater at La Coruña (Spain) and Hanzawa et al. (2006) reported on the 80-tonne fully reinforced Dolos in Japan.

With a few exceptions, the double-layer armour of randomly-placed conventional cubic blocks is the typology used for large mound breakwaters on the Spanish coast. The conventional cubic block is quite robust and easy to produce and handle, but the cube armour is prone to Heterogeneous Packing (HeP) as demonstrated by Gómez-Martín and Medina

(2006 and 2007). The face-to-face fitting problem of cubic blocks generates HeP and armour damage without armour unit extraction and increases overtopping. In addition, cube armour units placed on a slope of much smaller stones tend to face parallel to the slope against assumed randomness and reduce armour friction with the filter layer. Furthermore, the randomness of cube armour unit placement is relatively easy to achieve in small scale experiments with dry construction, given the excellent viewing of the placement process and easy manual correction. However, real construction is almost blind in most cases and correction is very costly. Therefore, prototype construction of double-layer armours of randomly-placed conventional cubic blocks is not so straightforward, and a significant model effect should be taken into consideration depending on the control of cubic block randomness at the construction site.

Gómez-Martín and Medina (2007 and 2008) introduced the Cubipod, a new massive armour unit designed to maintain the advantages of the conventional cubic block while preventing self-packing and increasing friction with the filter layer. The Cubipod features low sensitivity to HeP, very high hydraulic stability and high structural strength; it is almost as easy to manufacture as the conventional cube; it is easily handled with tongs, and it is much easier to place on a slope in a random position. The Cubipod is similar to a conventional cubic-shaped armour unit, but it is designed with one or more protrusions on its faces to avoid self-packing and to increase friction both with the underlayer of the breakwater and between armour units. The Cubipod armour unit manufacturing and placement processes are similar to those for conventional cubic blocks. Figure 1a shows a 3D view of Cubipod while Figures 1b and 1c show the open and closed arrangements of stored Cubipods.

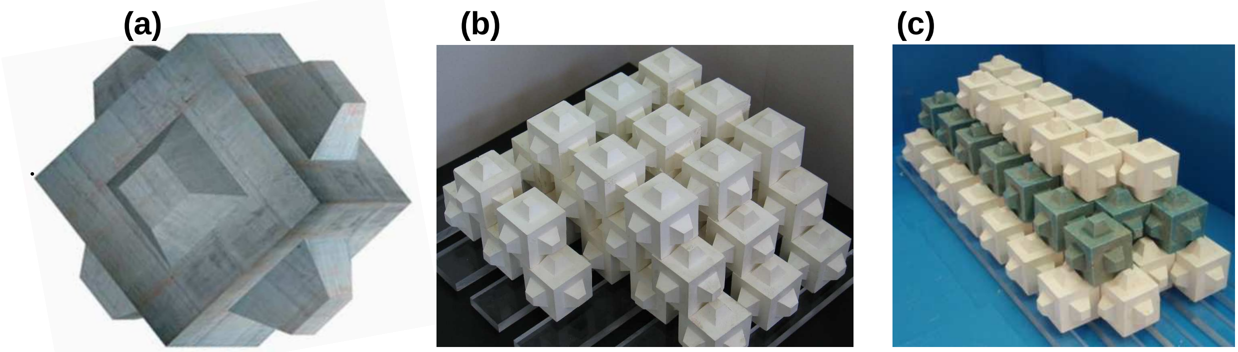

Figure 1. Cubipod: (a) 3D view, (b) open arrangement and (c) closed arrangement.

Hydraulic stability and overtopping tests

2D and 3D tests were conducted in different laboratories to assess the hydraulic stability and overtopping performance of the Cubipod armour unit.

2D and 3D hydraulic stability tests

The hydraulic stability of cube and Cubipod armours was analysed by Gómez-Martín and Medina (2008), who described 2D and 3D tests carried out in three different laboratories. Non-breaking and non-overtopping breakwater models with a 3/2 slope were tested both in 2D and 3D experiments. Core, filter layer and armour unit sizes used in the three laboratories are specified in Table 1. Similar irregular tests were conducted at the different laboratories with wave runs of 1000 waves. For each test, an Iribarren's number was fixed in the range $2.5<Irp=(2/3)Tp/(2\pi H_{m0}/g)^{0.5}<7$, and the significant wave height was increased progressively from the initiation of damage (IDa) to the initiation of destruction (IDe).

Table 1. Hydraulic stability tests with cube and Cubipod armour layers.

CUBIPOD tests: non-breaking and non-overtopping conditions								
LAB.	breakwater model			armour units		Dn50(cm)		
	test	armour unit	armour thickness	W(gr)	γ_r(gr/cm^3)	armour	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 of double-layer cube and Cubipod armours was tested in the wind and wave test facility (30.0x1.2x1.2 m.) at the *Universidad Politécnica de Valencia* (UPV). 2D trunk stability tests of single-layer and double-layer Cubipod armours were conducted in the wave flume (52.0x1.8x2.0 m.) at the *Instituto de Hidrodinámica Aplicada* (INHA). Unidirectional 3D roundhead stability tests of double-layer cube and Cubipod armours were done in the wave tank (24.8x8.5x1.5 m.) at the *Instituto de Hidráulica Ambiental* (IH Cantabria). The 2D stability results obtained by INHA and UPV for the double-layer Cubipod armour agreed, and consistent results were obtained for single-layer Cubipod and double-layer cube armours. Gómez-Martín and Medina (2008) reported stability numbers corresponding to IDa and IDe for double-layer cube and Cubipod armours (see Figure 2). For single-layer Cubipod armours, the stability numbers for IDa and IDe showed minimum values Ns(IDa)= 3.0 and Ns(IDe)= 3.7, significantly lower than Ns for double-layer Cubipod armours but much higher than Ns corresponding to double-layer cube armours. Finally, the stability numbers obtained from the unidirectional 3D roundhead hydraulic stability tests of cube and Cubipod armour layers were Ns(IDa)= 2.1 and Ns(IDe)= 2.8 for cubes and Ns(IDa)= 2.6 and Ns(IDe)= 3.2 for Cubipods in the range 3.0<Irp<4.0.

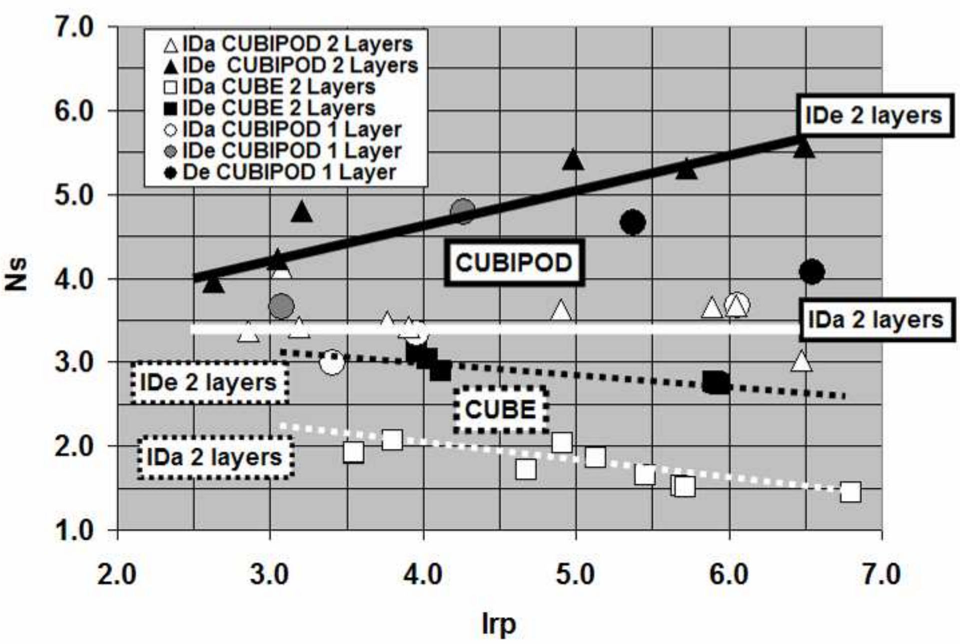

Figure 2. Stability numbers of cube and Cubipod armours in a trunk (slope 3/2).

2D overtopping tests

Gómez-Martín and Medina (2008) described the 2D overtopping tests carried out at the UPV wind and wave test facility (30.0x1.2x1.2 m.); Smolka (2008) analysed overtopping results and provided Eq. 1 to predict mean overtopping discharge, q, as a function of crest freeboard Rc, and armour elevation Ac, 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 armour unit and armour thickness (see Figure 3). The roughness factor, γ_f, for each armour unit was calculated minimizing the mean squared error: double-layer cube armour (0.50), single-layer Cubipod armour (0.46) and double-layer Cubipod armour (0.44). When compared to the conventional double-layer cube armour, both single-layer and double-layer Cubipod armours significantly reduced overtopping rates. Dimensionless overtopping discharge was negligible, $Q<10^{-7}$, when $Rc/H_{m0}>2.6$.

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

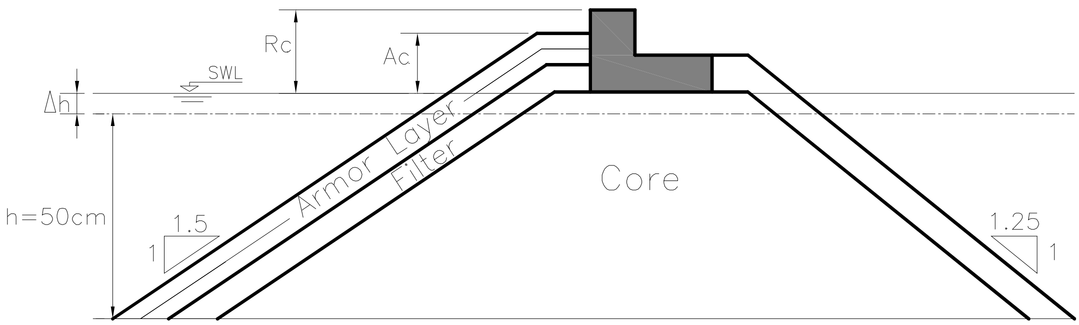

Figure 3. Breakwater cross section for 2D overtopping tests.

Prototype drop tests

In order to evaluate the structural strength of the new Cubipod armour unit, a systematic prototype drop test program was implemented using unreinforced concrete cubes and Cubipods of similar size, handling, storage and concrete characteristics. The conventional cubic block was considered *a priori* the most robust armour unit and the best reference for assessing the structural strength of any new armour unit like Cubipod. Therefore, similar armour unit sizes, the same concrete and similar drop conditions were planned for the prototype drop tests.

Production of cube and Cubipod prototypes

The engineers and technicians of the *Sociedad Anónima de Trabajos y Obras* (SATO) first designed a casting system to fabricate 7.1 m^3 (16-ton) Cubipods so as to obtain a manufacturing efficiency and handling similar to conventional cubic blocks. The tongs were also adapted for efficient Cubipod production and handling. Figure 4a shows the base and the upper part of the casting system designed by SATO. The base sustains the weight of the armour unit and the upper part can be removed vertically six hours after concrete filling and vibration. Figure 4b shows stored Cubipods and cubic blocks ready to be used in drop tests.

Cube and Cubipod formworks were filled with Standard HA-30/B/25/IIIa-Qb concrete mix totaling 350 kg/m^3 of CEM-I-42.5-R cement and using a 0.5 water/cement ratio. The measured mean values (coefficients of variation) of standard 28-day compressive strength concrete for cubes and Cubipods were 63.5(5.2) MPa and 60.1(7.8) MPa, respectively. To facilitate the lifting and removal of the upper part of the casting system, conventional cubes and Cubipods have quasi-vertical faces with an inclination of about 3% rather than perfectly vertical ones.

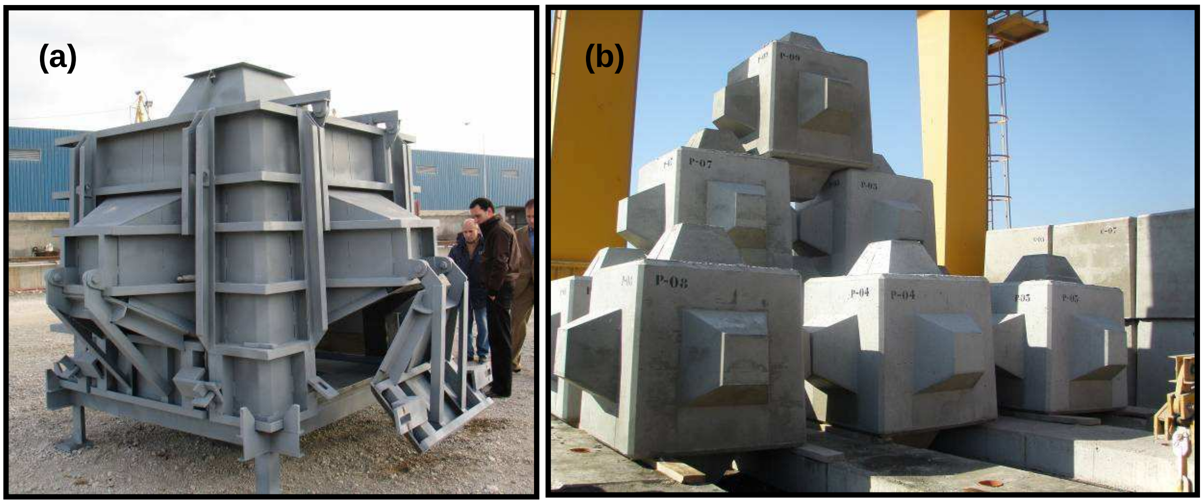

Figure 4. Cubipod casting system (a) and stored Cubipods in open arrangement (b).

SATO technicians adapted conventional tongs used for cubic blocks to create the double tongs shown in Figure 5b. Conventional single tongs for cubes and the adapted double tongs for Cubipods function and perform similarly and, during the prototype drop tests, were used to efficiently handle and drop 15-tonne cubes and 16-tonne Cubipods, respectively.

To efficiently store Cubipods during the construction phase, an optimum storage block yard for cubes and Cubipods was designed by Corredor et al. (2008). The storage of Cubipod prototypes is based on two different arrangements: “open” (see Figure 1b) with approximately 50% porosity and “closed” (see Figure 1c) with approximately 30% porosity, which may be compared to the approximately 20% porosity in a typical cubic block yard. Figure 4b shows Cubipod prototypes stacked in an open arrangement. Due to the fact that the hydraulic stability of Cubipods is much higher than that of the conventional cubic blocks, the required storage area surface is smaller for Cubipods.

Drop tests

The robustness of Cubipods and conventional cubic blocks was compared in overturning tests and free fall tests conducted during the first week of March 2008 in the SATO block yard at the Port of Alicante. The overturning tests, carried out on a 90-cm thick reinforced concrete platform (10x7.5x0.9 m.), used two 15-tonne cube and four 16-tonne Cubipod prototypes. The free fall tests, carried out on a 115-cm thick reinforced concrete platform (5.0x5.0x1.15 m.) protected with a 20-mm thick steel plate, involved seven 15-tonne cube and eight 16-tonne Cubipod prototypes. The methodology of the tests was developed from that used for bulky armour units (see Muttray et al., 2005) but adapted for much more robust armour units.

Figure 5 shows the 63/25-tonne gantry crane used to handle and drop prototypes. 20-tonne single tongs and 2x20-tonne double tongs were used to handle cubes and Cubipods, respectively. A 10-kg precision load cell was used to weigh prototypes during the tests. A wheeled excavator pushed Cubipods and tipped cubic blocks. Prototypes were weighed before and after each series of overturning strikes or free fall tests; the Relative Loss of Mass (RLM) was taken as a measurement of the structural integrity.

Figure 5. (a) 63/25-tonne gantry crane and (b) double tongs used to handle Cubipods.

Overturning tests

The possible overturning manoeuvres depend on the geometric characteristics of the armour. There is only one way to turn cubes over while Cubipods can be overturned with two different manoeuvres. The overturning tests were done on the reinforced concrete platform (10x7.5x0.9 m.) constructed on the compacted soil of the block yard.

The cubic block can only be overturned if the lateral vertical faces are maintained in the vertical position. Figure 6a shows the wheeled excavator tipping a 15-tonne cube prototype for overturning. Partial overturning is achieved when the cube is released at 15º inclination while complete overturning occurs when the cube is inclined more than 45º. One cube prototype was used for complete overturning and another for partial overturning. These two prototypes were weighed after 8, 16 and 24 overturning impacts; completely and partially overturned cubes lost 2% and 0.4% of their masses, respectively.

Two 16-tonne Cubipods were used for frontal overturning, a symmetry plane being maintained throughout the overturning manoeuvres; two additional Cubipod prototypes were used for diagonal overturning, whereby the unit was pushed laterally. Figure 6b shows the wheeled excavator pushing the Cubipod in a frontal overturning strike. After 60 overturning strikes, the maximum measured RLM of the four prototypes was 0.3%.

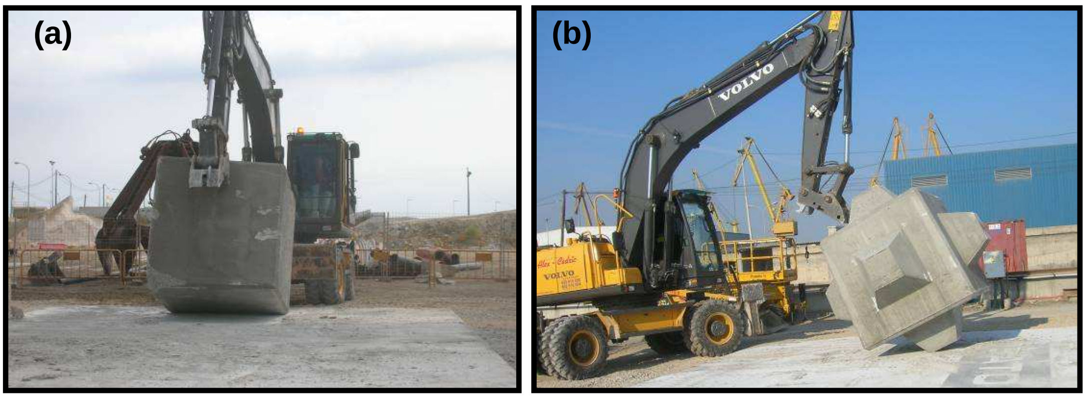

Figure 6. Overturning manoeuvres: (a) cubic block and (b) Cubipod.

Both cubes and Cubipods resisted the overturning manoeuvres quite well. Visual inspection did not reveal any serious damage. Cubipod prototypes presented only negligible damage; thus, they were used as receptor armour units in the extreme free fall tests. In these tests Cubipod prototypes were dropped from the maximum height to fall onto the four armour unit receptors placed on the overturning platform.

The reinforced concrete overturning platform (10x7.5x0.9 m.) was visually inspected throughout the overturning experiments and only negligible damage was found.

Free fall tests

The energy impacts of free fall tests were much higher than the energy corresponding to overturning tests; hence, the forces on the free fall platform and the armour units were higher as was the RLM. In the experimental design phase, the RLM in free fall tests was assumed to be dependent on prototype size (larger size, larger loss), concrete strength (higher strength, lower loss), stiffness of the free fall platform (greater stiffness, higher loss), type of impact, drop height (the higher the drop height, the greater the loss) and accumulation of internal armour unit damage.

Prototypes of 15-tonne cubes and 16-tonne Cubipods were used in the free fall tests, manufactured using a similar procedure and the same concrete mix source. Measured mean values (coefficients of variation) of standard 28-day compressive strength were 63.5(5.2) MPa for cubes and 60.1(7.8) MPa for Cubipods. Thus, one would expect slightly higher RLM for Cubipods given their slightly larger size (2.5%) and similar compressive strength.

Cube and Cubipod prototypes were dropped alternatively on the reinforced concrete free fall platform (5.0x5.0x1.15 m.) protected with a 20-mm thick steel plate; therefore, similar RLM should be expected although platform stiffness decreased during the free fall tests due to accumulative damage in the platform itself. Further, the prototypes were subjected to three different drop tests: (1) “Anvil Drop” (AD) dropping the prototype with one of its faces parallel to the platform, (2) “Edge Drop” (ED) after a 45º rotation the prototype was dropped with only one edge parallel to the platform, and (3) “Random Drop” (RD) in which the prototype was placed in an unstable position on top of a cube prototype placed on the ground, and then it was released for an unpredictable fall onto the free fall platform.

Cube and Cubipod prototypes were assigned to tests for a specific drop type (AD, ED or RD) and drop height (h). Each prototype was dropped a maximum of six times ($1 \leq n \leq 6$) and the loss of mass was measured after each drop. The drop height (h) was defined as the vertical distance from the platform surface to the lowest point of the prototype just before releasing it. Cube prototypes were AD tested from drop heights h(m)=0.5, 1.0 and 1.5. Both cube and Cubipod prototypes were AD, ED and RD tested from h(m)= 2.0. Results of the Cubipod AD test from h(m)=3.0 were not considered in this analysis because this particular armour unit specimen seriously damaged the free fall platform.

The measured RLM was related to the accumulated armour unit damage and was considered dependent on armour unit type (cube or Cubipod), drop type (AD, ED or RD), drop height (h) and number of repetitions (n). Comparing AD, ED and RD test results, Cubipods withstood over 50% higher drop heights. For both cubes and Cubipods, the AD test resulted in the highest RLM for a given drop height (h); ED tests resulted in lower RLM than the AD tests, corresponding roughly to 85% AD drop heights, and the RD tests resulted in the lowest RLM, approximately equivalent to 75% AD drop heights.

In addition to the free fall tests using the free fall platform, two extreme free fall tests were conducted by dropping two Cubipod prototypes on the four Cubipod units used previously in the overturning tests and placed on the overturning platform. The maximum drop height for the gantry crane was used and resulted in drop heights h(m)=8.5 for AD and h(m)=9.5 for ED. The four receptor Cubipod prototypes were placed on the overturning platform to receive the impact during the two extreme free fall tests; the RLM was measured weighing each prototype after each test.

Corredor et al. (2008) as well as Gómez-Martín and Medina (2008) defined an equivalent drop height (h_e) to take into account the number of repetitions (n) together with the drop height (h). Considering the results of AD tests with cube and Cubipod prototypes, the potential model for h_e given by Equation 2 minimized the mean squared error between measured and predicted RLM.

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

Both cube and Cubipod prototypes had a critical equivalent drop height (h_{ec}) which caused a RLM=4%; if the RLM was lower than 4%, the drop impacts in both cubes and Cubipods caused a small RLM which was linearly dependent on the corresponding equivalent drop height, h_e. Equations 3 and 4 estimate the small RLM of 15-tonne cube prototypes and 16-tonne Cubipod prototypes, respectively.

(3) $$RLM = 4\%\left(\frac{h_e[m]-0.5}{1.4}\right); h_e[m] < h_{ec}[cube] = 1.9 meters$$

(4) $$RLM = 4\%\left(\frac{h_e[m]-2.0}{1.1}\right); h_e[m] < h_{ec}[Cubipod] = 3.1 meters$$

If the drop height (h_e) was higher than the critical h_{ec}, massive breakage occurred which affected the core of the armour units. The critical equivalent drop heights (h_e) for cubes and Cubipods were 1.9 and 3.1 m, respectively. Figure 7 shows images of the second repetition (n=2) of an h(m)=2.0 AD test with a 15-tonne cube. As compared to conventional cubic blocks, the Cubipod armour units were able to withstand higher drops.

Figure 7. AD test of cube armour unit: h= 2 meters and n=2.

Cost analysis of cube and Cubipod armour layers

The economic viability of using Cubipods instead of conventional cubic blocks in real mound breakwaters was analysed in this study. Construction costs depend basically on breakwater geometry. In order to estimate the economic advantage of using Cubipods rather than cubic blocks, a parametric cost analysis was carried out considering six key parameters: (1) concrete supply, (2) formworks, tongs and handling equipment, (3) production, (4) casting and storage area, (5) transport and placement and (6) sensitivity analysis.

The weight of the armour unit and the length of the breakwater are the main factors to calculate the breakwater cost. In this parametric study, three breakwater lengths (L) were considered as representative of short (L=400 m), medium (L=1000 m) and long (L=2500 m) breakwaters; armour unit weight varying from 10 to 150 tonnes were considered with typical breakwater cross sections for armour layers of: (B2) double-layer conventional cubic blocks, (C1) single-layer Cubipods and (C2) double-layer Cubipods.

The number of armour units to produce and place depends on the breakwater geometry, the armour unit weight and the porosity of the armour layer. In this study, porosities of 40% and 43% were considered for cube and Cubipod armours, respectively. In order to compare cube and Cubipod armour units, a typical block yard with gantry crane and direct filling of formworks from above was assumed; this is not the optimum solution for the smallest breakwaters, but it is valid for comparative purposes.

The Cubipod casting system is more complex than the cube casting system so additional personnel and equipment were needed and production costs were higher. The double tongs for Cubipod handling were 50% heavier than those for handling cubes (single tongs); the handling costs included energy costs, equipment and labour. The placement cost was estimated taking into account both the armour unit weight and distances. In order to select the most appropriate crane for placing armour units, characteristics listed for conventional cranes, including the working cycle and the lifting force, turning speed and lifting velocity, were considered. The working efficiency of each crane was calculated for each breakwater cross section.

First the production and placement were optimized, and after that the block yard and storage system were designed. In order to produce two armour units per day, three casting bases were calculated for each Cubipod and conventional cube formwork. A conventional cubic block yard has a porosity of approximately 20%, with a handling corridor width varying between 0.5 m and 1.0 m. The closed arrangement for Cubipods (porosity≈30%) saves space with regard to open arrangement (porosity≈50%), but it can only be used for 18-tonne or larger prototypes to be handled with tongs.

Figure 8 illustrates the cost (€/m3) as function of the breakwater length (in meters) and the weight of armour units (in tons) corresponding to armour layers of: (B2) double-layer conventional cubic blocks, (C1) single-layer Cubipods and (C2) double-layer Cubipods. The heavier the unit is and the longer the breakwater, the lower the cost of the armour layer. In all cases, a fixed price (60 €/m^3) was established for concrete supply.

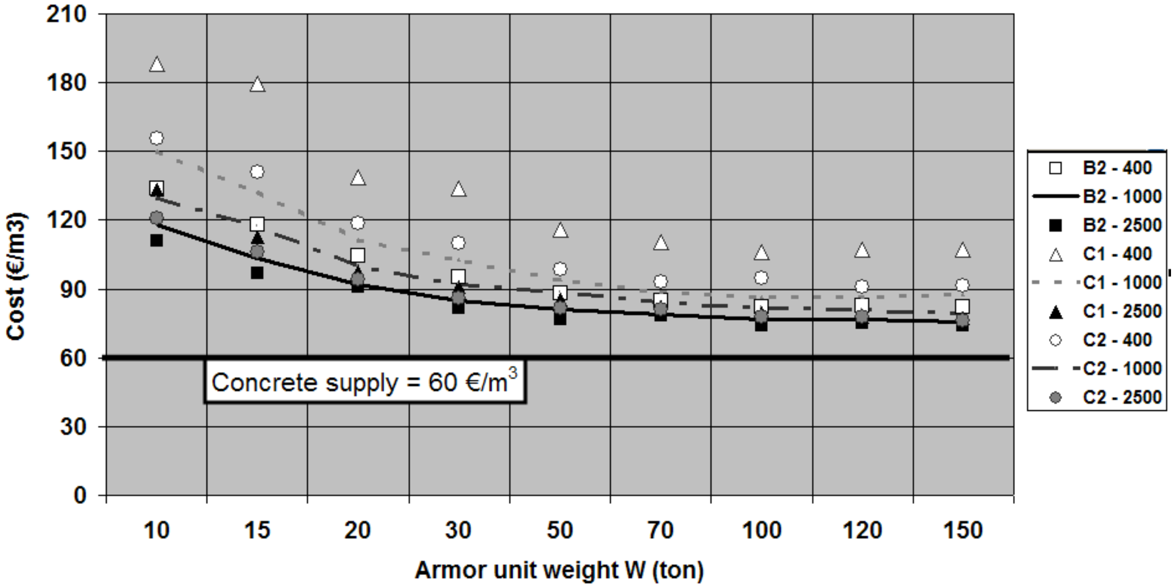

Figure 8. Cost (€/m3) depending on breakwater length (L[m]) and armour unit weight (W[ton]).

It is worth taking into consideration the hydraulic stability of cubes and Cubipods. Single-layer and double-layer Cubipod armours significantly increase safety and reduce costs as compared to conventional double-layer cube armours. Corredor et al. (2008) established reductions between 15% and 40% in armour construction for medium size breakwaters (L=1000 m). The cost savings using Cubipods are thus higher for larger breakwaters and lower for smaller ones.

Conclusions

The characteristics of the massive Cubipod armour unit are compared to those of the conventional cubic block. Results are presented from 2D and 3D hydraulic stability and overtopping tests at different laboratories. Both single-layer and double-layer Cubipod armours are much more stable than conventional double-layer cube armours in the trunk. Double-layer Cubipod armour in the roundhead is also more stable than conventional double-layer cube armour, but the advantage is not as decisive as in the trunk. Both double-layer and single-layer Cubipod armours reduce the overtopping rates obtained with conventional double-layer cube armours; the best fitting roughness factors were: γ_f=0.44 for double-layer Cubipod, γ_f=0.46 for single-layer Cubipod, and γ_f= 0.50 for conventional double-layer cube armour.

SATO's casting system to manufacture 7.1 m^3 (16-ton) Cubipods is described, the manufacturing efficiency and armour unit handling being similar to conventional cubic blocks. The base sustains the weight of the armour unit and the upper part can be removed vertically six hours after concrete filling and vibration. Conventional tongs for cubic blocks were adapted to efficiently handle 16-tonne Cubipod prototypes. In order to efficiently store Cubipods during the construction phase, optimized storage block yards for cubes and Cubipods were designed and compared.

To evaluate the structural strength of Cubipods, overturning tests and free fall tests were conducted in the block yard at the Port of Alicante (Spain). Eight 15-tonne cubes and eleven 16-tonne Cubipod prototypes were fabricated using the same concrete source and similar manufacturing procedures. The overturning tests were carried out on a 90-cm thick reinforced concrete platform (10x7.5x0.9 m.) and the free fall tests were conducted on a 115-cm thick reinforced concrete platform (5.0x5.0x1.15 m.) protected with a 20-mm thick steel plate. In addition to the reinforced concrete platforms, the specific equipment for the prototype drop tests included a gantry crane, a wheeled excavator and a 10-kg precision load cell to weigh prototypes while testing.

Overturning tests only caused minor damage to the prototypes; after 60 overturning strikes, the maximum measured Relative Loss of Mass (RLM) of the four Cubipod prototypes was 0.3%, while after 24 overturning impacts, completely and partially overturned cube prototypes lost 2% and 0.4% of their mass, respectively.

In some cases free fall tests caused breakage in the prototypes in some cases. For both cubes and Cubipods, Anvil Drop (AD) tests caused the highest RLM for a given drop height (h); Edge Drop (ED) tests caused lower RLM than AD tests, corresponding approximately to 85% AD drop heights. Random Drop (RD) tests had the lowest RLM, approximately equivalent to 75% AD drop heights. An equivalent drop height (h_e) was defined to take into account the number of repetitions (n) as well as the drop height (h). Both cube and Cubipod prototypes had a critical equivalent drop height (h_{ec}) which caused a RLM=4%; if the RLM was lower than 4%, the drop impacts caused a small RLM in both cubes and Cubipods, which was linearly dependent on the corresponding equivalent drop height. (h_e). The critical equivalent drop heights (h_{ec}) for cubes and Cubipods were h_{ec}(m)=1.9 and h_{ec}(m)=3.1, respectively; Cubipods resisted over 50% higher drops than did the conventional cubes.

Two extreme free fall tests were carried out. Two 16-tonne Cubipod prototypes were dropped from the maximum elevation of the gantry crane, h(m)=8.5 (AD) and h(m)=9.5 (ED), onto a group of four Cubipod prototypes placed on the overturning platform. The impact energy was apparently distributed between the dropped prototype and the four Cubipods which received the impact and only caused slight RLM<2.5%.

The parametric study of typical mound breakwaters on Spanish coasts compared the use of conventional cubic blocks and Cubipods in real constructions. Relevant logistic aspects were analysed: concrete supply, handling equipment (formworks and tongs), manpower and equipment for production, casting and block yard design, transport and armour unit storage. The final unit cost (€/m^3) of the armour unit depends first on the weight of the armour unit, the breakwater length and the crest elevation are secondary factors. The unit cost (€/m^3) is estimated for typical breakwater cross sections as a function of the breakwater length (in meters) and the weight of armour units (in tons) corresponding to armour layers of: (1) conventional double-layer cubes (B2), (2) single-layer Cubipods (C1) and (3) double-layer Cubipods (C2). The unit cost decreases as armour unit weight, breakwater length and crest elevation increase. Conventional B2 armour requires about 5% more armour units than C2 armour with the same armour unit weight, and C1 armour requires half the number of armour units as the C2 armour layer. Taking into consideration that Cubipods are much more stable than conventional cubes, armour unit weight is lower for a similarly designed wave climate. Total cost savings are approximately 15% for double-layer and 40% for single-layer Cubipod armours.

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Keywords
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