Designing and Constructing Cubipod Armored Breakwaters in the Ports of Malaga and Punta Langosteira (Spain)

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Introduction

This paper describes the design requirements and restrictions of two different Cubipod armored breakwaters, as well as the 3D hydraulic stability, overtopping and placement tests carried out to validate the final designs. The breakwaters are located on the Mediterranean and Atlantic coasts of Spain. Double-layer and single-layer Cubipod armored breakwaters are being constructed in the Port of Malaga and the Port of Punta Langosteira, respectively. The different logistical, environmental and geotechnical conditions favored the double-layer armor in the Mediterranean Port of Malaga and the single-layer armors in the Atlantic Port of Punta Langosteira (Exterior Port of A Coruña). These two breakwaters were built with different production rates and block yard designs. Additionally, a description is given of the work in progress, production lines, handling, stacking, placement and other logistical aspects affecting the breakwater construction.

In the Port of Malaga, located on the southern Spanish Mediterranean coast, a $\cot\alpha = H/V = 2.0$ slope, double-layer 6-tonne Cubipod armor is being built to protect the new San Andrés breakwater, in an area with low soil-bearing capacity. The breakwater construction area is close to the Malaga urban area and space was the most critical issue; the five-level stacking Cubipods was necessary. On the northwestern Spanish Atlantic coast, a H/V=3/2 slope, single-layer 15-tonne and 25-tonne Cubipod armors are being constructed to protect a groin and the first phase of the secondary breakwater in the Port of Punta Langosteira. In this case, time, not space, was the critical issue and most of the 450m-long southern breakwater was close to completion in just three months working 24 hour/day cycles.

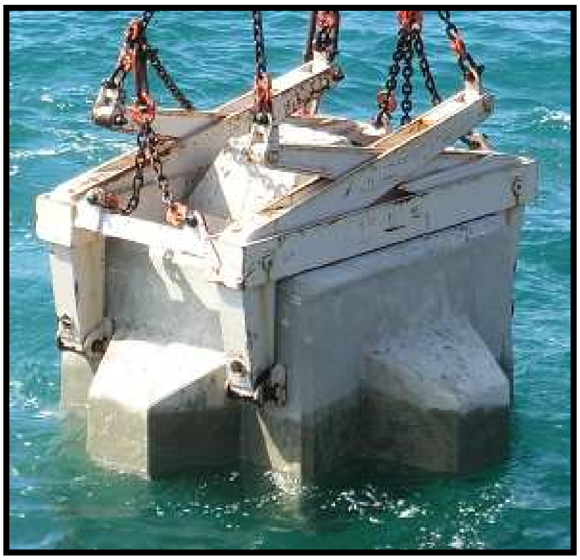

Figure 1. Double-pressure clamps handling a Cubipod armor unit.

In this paper, the design and logistical aspects of these two Cubipod armored breakwaters are analyzed and their different environmental and construction constraints are compared. Key design and logistical aspects are highlighted which may optimize single- and double-layer Cubipod armored breakwater construction when space or time is a critical restriction. Fig. 1 shows a Cubipod armor unit handled with double-pressure clamps when placed using crawler crane.

Port of Malaga

The Port of Malaga is situated on the Mediterranean Sea, on the southern coast of the Iberian Peninsula, in a natural bay (4º 25' W and 36º 43' N). The Port of Malaga is modernizing its facilities and creating new port spaces. The new San Andrés breakwater, described by Corredor et al. (2012), is located on the southern part of the Malaga harbor in an area where the sea bottom has low bearing capacity; the breakwater is being constructed by SATO/OHL JV. Single- and double-layer Cubipod armors were considered and tested, along with a variety of other concrete armor units. Uncertainty regarding breakwater settlements after construction favored the final design based on a 40 m-wide berm (h[m]=6.75), H/V=2/1 slope, double-layer 6-tonne Cubipod armor. Fig. 2 shows the breakwater cross section.

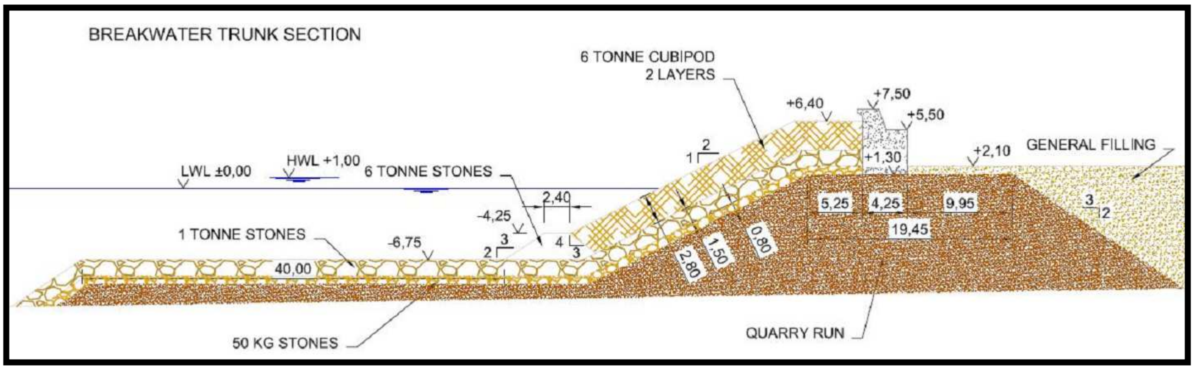

Figure 2. San Andrés breakwater cross section (trunk).

Port of Punta Langosteira

Maciñeira et al. (2009) described the construction of the 3.35 km-long Punta Langosteira breakwater. This gigantic double-layer 150-tonne cube armored breakwater is designed to withstand a design storm of Hs[m]=15 and Tp[s]=18. Water depth was h[m]=40 and maximum tidal range Δh[m]=4.5. This enormous main breakwater in the new Exterior Port of A Coruña (Spain) is located near one of the most intensively-used navigation routes and is characterized as having one of the most rough wave climates in the world.

After completing the main breakwater in 2011, two new breakwaters perpendicular to the shoreline, northern groin and southern breakwater, had to be constructed to protect the water intake of the Sabón thermal power station. This intake was affected because the littoral drift was modified by the Punta Langosteira main breakwater. The southern breakwater, nearly completed in 2012, is the first phase of the secondary breakwater which is necessary to complete the harbor shelter associated with the main breakwater.

Fig. 3a shows one of the wave propagation studies conducted by the Port Authority of A Coruña to estimate wave agitation after the completion of the main breakwater in Punta Langosteira, and Fig. 3b offers a 3D-view of the northern groin and first phase of secondary breakwater (new southern breakwater).

The roundhead of the new 450m-long southern breakwater will be the most highly exposed area of the secondary breakwater. This breakwater is situated in shallow and intermediate waters, on a sandy and rocky sea-floor, at water depths up to h[m]=8.3 (LWL) at the toe of the roundhead. Waves diffracted from the roundhead of the main breakwater in the Port of Punta Langosteira are directed to the new southern breakwater protected with H/V=3/2 slope, 25-tonne and 15-tonne single-layer Cubipod armor in the most highly exposed trunk and roundhead area. The root of the secondary breakwater is protected with a conventional H/V=3/2 slope, double-layer 5-tonne quarrystone armor.

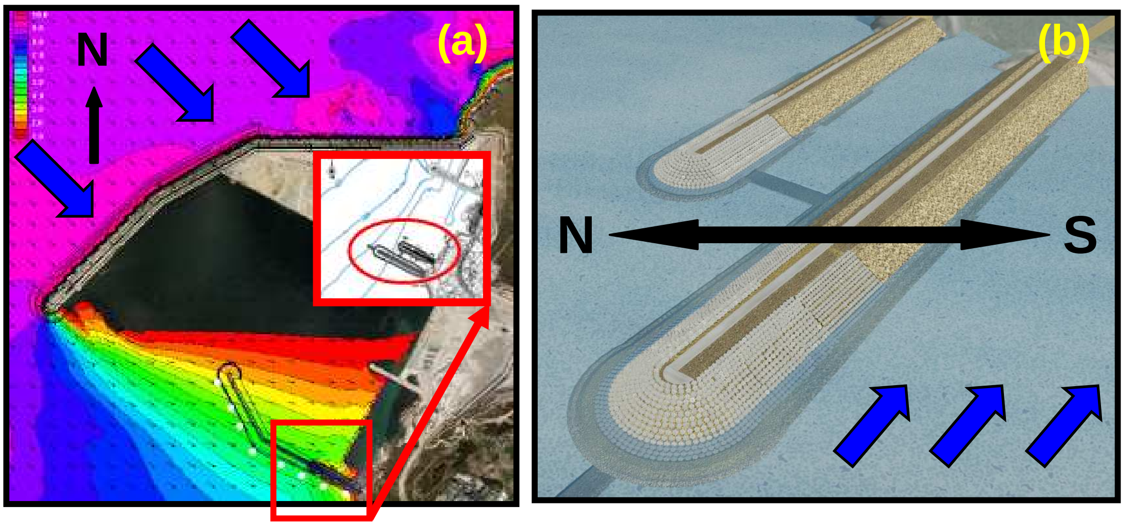

Figure 3. Punta Langosteira harbor: (a) wave agitation and (b) first phase of secondary breakwater.

Hydraulic stability, overtopping and placement tests

The San Andrés breakwater in Malaga is a double-layer Cubipod armored breakwater. The low soil-bearing capacity and the expected large settlements favored the double-layer Cubipod armor given the unit's robustness (see Medina et al., 2011) and resilient hydraulic performance. The final design was validated and the roundhead and crest elevation were optimized through 3D physical experiments with 1/36-scale models tested in a unidirectional wave basin.

By contrast, the first phase of the secondary breakwater in the Port of Punta Langosteira is a single-layer Cubipod armored breakwater. In this case, the sandy and rocky seafloor could generate some local scour problems, but not significant differential settlements. In these conditions, the H/V=3/2 slope, single-layer Cubipod armor is the most reliable and cost-efficient solution (see Medina et al. 2009). 3D physical experiments with 1/45-scale models were carried out to validate the final design.

Double-layer Cubipod armor (Port of Malaga)

3D hydraulic stability and overtopping testing was done with single- and double-layer Cubipod armors in a wave basin (45.0x6.5x2.0 meters), having unidirectional wave generation with active wave absorption, at the *Centro de Estudios de Puertos y Costas* (CEDEX, Madrid, Spain). A 1/36 scale model was used to validate the hydraulic stability and to estimate overtopping rates. The design storm characteristics were: Hs[m]= 5.1, Tp[s]=12 and $0<\Delta h[m]<0.8$. The breakwaters were subjected to partially-breaking conditions given that the water depth of the 40-m wide berm in front of the structure was h[m]=7.55 in HWL ($\Delta h[m]=0.8$). Wave obliquity and wave breaking on the berm increased the roundhead armor stability compared to non-breaking conditions (see Lomónaco et al., 2009, and Burcharth et al., 2010). Therefore, in the final design, 5000 6-tonne Cubipods were used in both the trunk and roundhead, and 250 15-tonne units were used to reinforce the breakwater root connected to an old rubble-mound breakwater.

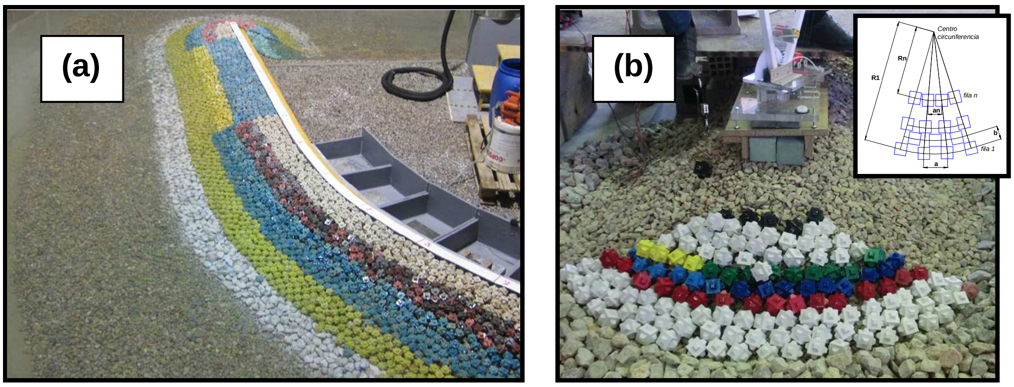

Figure 4. 1/36-scale tests: (a) hydraulic stability and overtopping and (b) placement

In order to evaluate the hydraulic stability of higher-than-design storm conditions, models were tested with Hs[m] up to 5.7, Δh[m]=0.0 and 1.0, and Tp[s]=12 and Tp[m]=14. Single- and double-layer Cubipod armors resisted the higher-than-design storm conditions with only a few units being extracted from the curved area; no damage was observed in the straight trunk or roundhead. Thus, hydraulic stability was validated and overtopping rates were measured. Following the methodology of Medina et al. (2010), 3D placement tests were conducted to obtain feasible and optimum placement grids in the Laboratory of Ports and Coasts at the *Universitat Politècnica de València* (UPV, Valencia, Spain). Figures 4a and 4b illustrate the 1/36 scale models used in the CEDEX and UPV experiments. Taking into account that the original breakwater design was a conventional 14-tonne and 21-tonne double-layer cube armor, the final 6-tonne Cubipod armor reduced concrete consumption by 30%.

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Single-layer Cubipod armor (Port of Punta Langosteira)

3D hydraulic stability tests using two parallel single-layer Cubipod armored breakwater models were conducted in the wave basin (33.0x32.0x1.2 meters) at the *Centro de Innovación Tecnológica en Edificación e Ingeniería Civil* (CITEEC, *Universidade da Coruña,* Spain). A 1/45-scale was used to model the design storm conditions (Hs[m]= 5.85 and Tp[s]=18 for T_R[years]=140) with different water levels (Δh[m]=0.0, 2.5 and 5.0) as well as higher-than-design storm conditions. The southern breakwater is the first phase of the secondary breakwater of the Port of Punta Langosteira; it is designed in partially-breaking conditions, with the roundhead toe at water depth 8.3<h[m]<13.3 while the northern groin is designed in breaking conditions with roundhead toe at 5.2<h[m]<10.2. These tests validated the use of the cost-saving 25-tonne and 15-tonne single layer Cubipod armors, compared to the original 35-tonne and 20-tonne double-layer cube armored breakwaters, which had been tested previously by the Port Authority of A Coruña in CITEEC.

Fig. 5 shows the 1/45 scale models used in the CITEEC basin after design storm using Cubipod units equivalent to W[t]=23.2 and 12.1. No units were removed at the LWL (Δh[m]=0.0) and MWL (Δh[m]=2.5), and only one unit in the southern breakwater and two units in the northern breakwater were removed at the HWL (Δh[m]=5.0). JONSWAP (γ=3.3) irregular wave runs of 1500 waves were generated for each wave step (Hs[m]= 4.0, 5.0 and 5.8) at each water level (LWL, MWL and HWL).

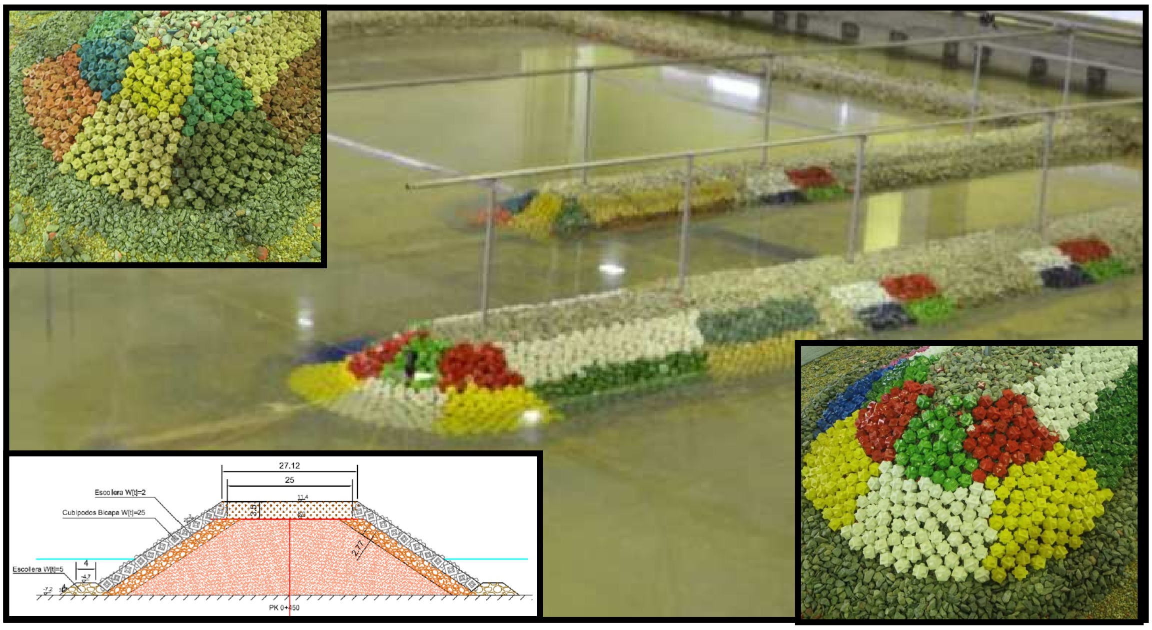

Figure 5. 3D wave basin and 1/45-scale model after design storm wave attack.

Accumulated armor damage (removed units) was recorded when significant wave height was increased above design storm. No significant damage was observed when Hs[m]=6.4 and Tp[s]=18; only one additional unit was removed from the northern breakwater. The hydraulic stability was much higher than that required for the design storm conditions. Test conditions were progressively worsened above design storm; Hs[m]= 7.0 and 7.6 and Δh[m]=5.5, 6.0 and 6.5 which caused only minor damage to the southern breakwater. The single-layer Cubipod armor showed a significant degree of resilience; when one unit was removed, the neighboring units moved slightly to close the gap. Crest elevation was Rc[m]=+11.4 (referring to LWL); it was not possible to continue worsening the wave conditions without significantly changing the test conditions in the basin. Table 1 compares the original and final breakwater design characteristics of the breakwaters described in this paper.

Area	Mediterranean Sea		Atlantic Ocean	
PORT	MALAGA (*San Andrés*)		A CORUÑA (Langosteira)	
solution	original	final	original	final
armor unit	cube	Cubipod	cube	Cubipod
# layers	2	2	2	1
trunk W[t]	14	6	20	15
head W[t]	21	6	35	25
slope H/V	2.00	2.00	2.00 to 1.75	1.50
WAVES	design storm	3D test	design storm	3D test
scale	1/1	1/36	1/1	1/45
Hs[m]	5.10	5.70	5.85	6.40
Tp[s]	12	12 and 14	18	18
h[m]	6.75	6.75	8.30	8.30
min (Δh)	0.0	0.0	0.0	0.0
max (Δh)	0.8	1.0	4.5	5.0

Table 1. Breakwater design and small-scale test characteristics.

Finally, the weight of the Cubipod units (23.2-tonne and 12.1-tonne at prototype scale) tested in the laboratory was increased by 8% and 24% to define the final 25-tonne and 15-tonne Cubipod units used at prototype scale. Although the 15-tonne Cubipod armor requires 7.4% more concrete than the 12.1-tonne armor, the cost is only slightly higher considering other logistical aspects such as the number of moulds and number of units to be placed. Compared to the original double-layer, H/V=2.0 and 1.75 slope, 20-tonne and 35-tonne cube armor, tested in CITEEC up to the design storm (Hs[m]= 5.85 and Tp[s]=18), the single-layer 15-tonne and 25-tonne Cubipod armor reduced concrete consumption over 60%.

Stacking and producing Cubipods in the block yards

The San Andrés breakwater is being constructed in an area with severe restrictions on available space. The block yard had only limited space and was very close to the urban area of Malaga. This space constraint required a five-level stacking of 6-tonne Cubipods in closed arrangement, using a wheeled crane and pressure clamps. Between January and May 2012, all the Cubipods were stacked in the block yard waiting for placement at the end of summer.

By contrast, the Port of Punta Langosteira had plenty of space and several gantry cranes available in one of the block yards used for the main breakwater, which was completed in 2011. The main restriction in this case was time, because intense storms are common in winter and the construction had to begin at the end of the summer. The 450-m long breakwater was nearly completed during the autumn of 2012. Three units/day per mould were produced in 24 hour/day work cycles.

Multi-level stacking to save space (Port of Malaga)

The block yard of the San Andrés breakwater, measured only 160mx40m to manufacture and stack Cubipod units. 8 workmen used two wheeled cranes and managed a production line of two 6.4 m^3 and twenty three 2.6 m^3 articulated vertical formworks, as described by Medina et al. (2011). Two mould bases per vertical formwork were employed. A layer of compacted gravel with excavated parallel grooves was used to stack the first layer of Cubipod units.

Four 15-tonne and forty six 6-tonne Cubipod units per day were produced (145 m^3/day with 10 hours/day work time). The average temperature (from December to May) was 14.4ºC. Unreinforced concrete HM-30 (characteristic compressive strength: 30 MPa) of plastic consistency and direct pouring, without any additives, was used to manufacture the Cubipods. The concrete was poured directly into the formworks from an elevated one-way track with the moulds on the right side.

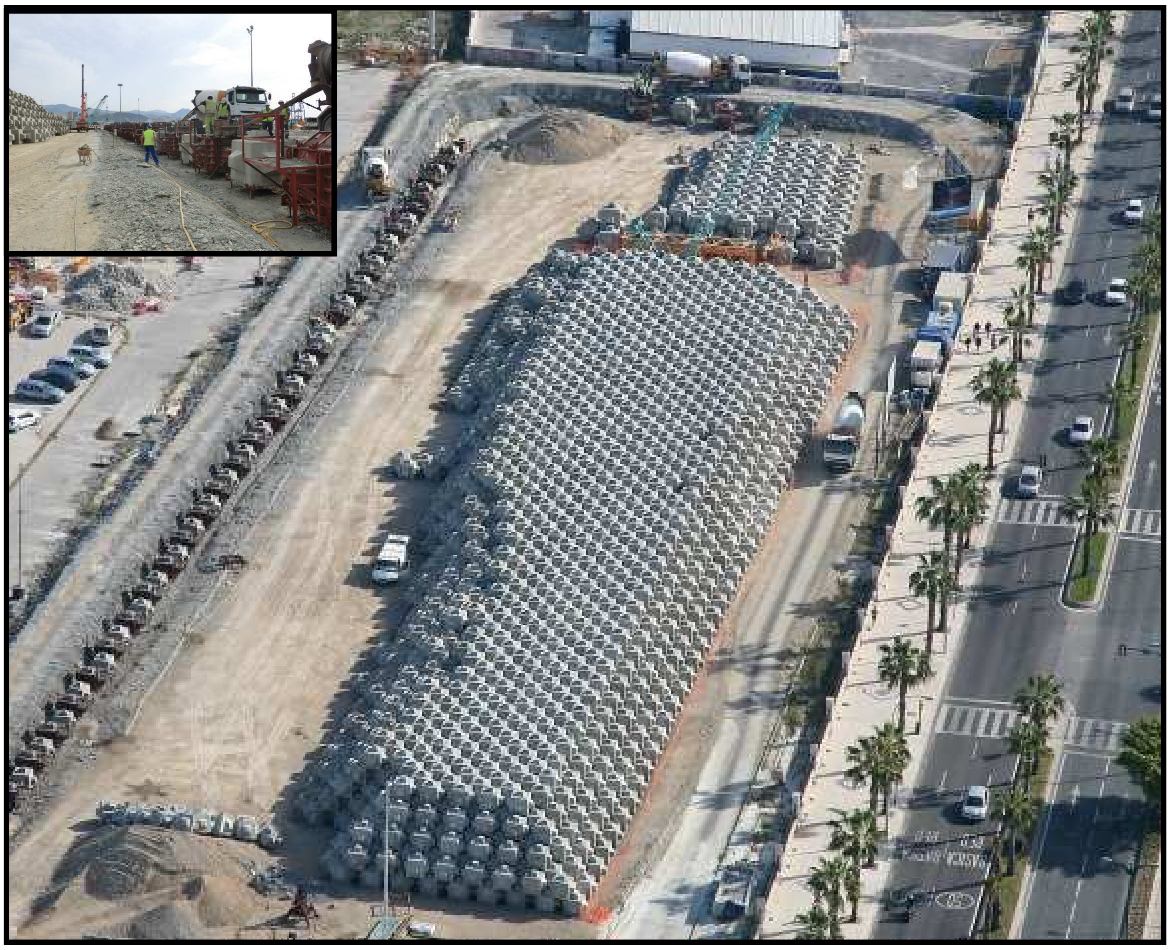

Figure 6. Port of Malaga block yard.

Optimum results were obtained using double-pressure clamps (see Fig. 1) designed to handle the Cubipod units; both 15-tonne and 6-tonne units were stacked in closed arrangement (porosity≈ 30%). A total of 5,000 6-tonne units stacked at five levels and 250 15-tonne units stacked at two levels were stored more than two months in the block yard of the San Andrés breakwater (see Fig. 5) before the placement on the slope was initiated. No unit breakage was observed during the handling and stacking process or in the placement.

High production rates (Port of Punta Langosteira)

One of the block yards of the main breakwater of the Port of Punta Langosteira was used. 80-tonne gantry cranes and plenty of space were available at the block yard to manufacture, handle and stack Cubipod units. However, time was a severe restriction, which meant 24 hours/day work cycles. 950 25-tonne and 600 15-tonne Cubipod units were required for the southern breakwater. Ten 10.6 m^3 and six 6.4 m^3 articulated vertical formworks, described by Medina et al. (2011), were used to manufacture thirty 25-tonne and eighteen 15-tonne Cubipod units per day (435 m^3/day). Three mould bases per vertical formwork were employed (see Fig. 7). A layer of compacted gravel with excavated holes was used to stack the first layer of Cubipod units.

The average temperature (from October to December) was 13.2ºC. Unreinforced concrete HM-30 (characteristic compressive strength: 30 MPa), without any additives, of plastic consistency (dry mix for the lowest temperature) was used. From an elevated one-way track, concrete was poured directly into the formworks and the moulds were placed on both sides of the track so the production line was shorter.

Double pressure clamps efficiently handled the Cubipod units; both 25-tonne and 15-tonne units were stacked at three levels in closed arrangement (porosity≈ 30%). There was not enough time (28 days) between stacking and placement to obtain 30 MPa (characteristic compressive strength), due to schedule requirements. Thus, some units were placed after stacking them for 15 days to obtain a minimum of 20 MPa. No unit breakage was observed during handling, stacking or placement.

Figure 7. Port of Punta Langosteira production line.

Cubipod placement

The San Andrés breakwater is being protected with a H/V=2/1 slope, double-layer 6-tonne Cubipod armor; however, 3D hydraulic stability tests in the wave basin proved that a single-layer 6-tonne Cubipod armor was stable enough to withstand the design storm. Adapted pressure clamps and placement grids obtained in the corresponding 3D placement tests were used to place Cubipods in the San Andrés breakwater.

The southern breakwater in the Port of Punta Langosteira has been constructed with high production rates. Pressure clamps and Cubipod placement were used following the placement grids for a single-layer Cubipod armor and H/V=3/2 slope were used. The most highly exposed part of the breakwater was protected with single-layer 25-tonne (roundhead) and 15-tonne (trunk) Cubipod armor. In this case, time restrictions meant placing some concrete units just 15 days after manufacturing, with concrete having only 20 MPa (characteristic compression strength).

Single-layer armor is placed first in the Port of Malaga

The placement of the double-layer 6-tonne Cubipod armor is being completed in three phases. The bottom layer was placed first and followed by the upper layer; however, the crown wall and upper part of the armor will be completed, after significant settlements occur. 300-tonne and 120-tonne crawler cranes were used to place the 15-tonne and 6-tonne Cubipod units. Single and double pressure clamps and conventional 4-leg multipurpose clamps were used to handle and place Cubipod units on the armor slope, the best results being obtained with the single pressure clamps specifically designed for each Cubipod size (6.4 m^3 and 2.6 m^3).

Fig. 8 shows the 300-tonne crawler crane placing a 6-tonne Cubipod unit in the San Andrés breakwater. The armor of the San Andrés breakwater was constructed with only one work cycle per day, obtaining an average placement ratio of eight Cubipod units per hour, most of these being 6-tonne units. No unit breakage was observed during the handling and placement processes.

Figure 8. 6-tonne Cubipod armor placement in San Andrés breakwater.

Single-layer armor in the Port of Punta Langosteira

The placement of the single-layer 25-tonne and 15-tonne Cubipod armor of the secondary breakwater in the Port of Punta Langosteira was completed very fast, during the autumn of 2012. A 600-tonne crawler crane was used to place the Cubipod units. Single and double pressure clamps and SATOGRAB recovery clamps were used to handle and place Cubipod units on the armor slope. To place Cubipod units on the armor, the best results were obtained using single pressure clamps specifically designed for each Cubipod size (10.6 m^3 and 6.4 m^3).

Fig. 9 shows the 600-tonne crawler crane placing 25-tonne and 15-tonne Cubipod units on the secondary breakwater in the Port of Punta Langosteira. The armor of this secondary breakwater was constructed in 24 hour/day work cycles, obtaining an average placement ratio of four Cubipod units per hour. No unit breakage was observed during the handling and placement processes.

Summary and conclusions

In the case of the Port of Malaga, the geotechnical failure modes caused by the low soil-bearing capacity and the expected large soil-induced settlements favored the design of a H/V=2.0 slope, double-layer 6-tonne Cubipod armor. In order to optimize and validate the final design, 3D 1/36-scale hydraulic stability tests were carried out in the CEDEX (Madrid, Spain). The final design was tested above the design storm conditions. The original breakwater design was a conventional double-layer 21-tonne and 14-tonne cube armor; the final 6-tonne Cubipod armor reduced concrete consumption by 30%. 3D placement tests were also carried out in the UPV basin to determine optimum and feasible Cubipod placement grids for the trunk and roundhead.

The space for the block yard in the Port of Malaga was limited to a rectangular plot near the urban area; this space constraint favored a five-level Cubipod stacking in closed arrangement. Cubipod formworks with two mould bases per vertical formwork produced forty six 6-tonne and four 15-tonne units per day, operating only 10 hours/day in the block yard. A wheeled crane was used to move the vertical formworks and stack the prefabricated units. The total of 5,000 6-tonne and 250 15-tonne Cubipods were manufactured and stacked before being placed on the breakwater. On average, the crawler crane placed 8 Cubipod units/hour. No unit breakage was observed during handling, stacking or placement.

In the case of the Port of Punta Langosteira, a sandy and rocky sea bottom favored an economically-efficient design. In order to optimize and validate the final design, 3D 1/45-scale hydraulic stability tests were carried out in the CITEEC (A Coruña, Spain). The final design was stable to higher-than-design storm conditions with the maximum water depth at the toe of the roundhead being h[m]=13.3 (HWL). The original breakwater design was a H/V= 2.0 and 1.75 slope, conventional double-layer 35-tonne and 20-tonne cube armor; the final design was a H/V=1.5 slope, single-layer 25-tonne and 15-tonne Cubipod armor which reduced concrete consumption by more than 60%. 3D placement tests carried out in the UPV basin were considered to determine feasible Cubipod placement grids in the trunk and roundhead.

Figure 9. 25-tonne and 15-tonne Cubipod armor unit placement in Punta Langosteira.

The space for the block yard in Punta Langosteira was not limited; furthermore, an extensive block yard equipped with several 80-tonne gantry cranes was available near the construction site. However, time was a major restriction; the 450m-long southern breakwater was nearly completed during autumn 2012, before the intense winter wave climate. Ten 10.6m^3 and six 6.4m^3 Cubipod moulds and three bases/mould produced thirty large 25-tonne units/day and eighteen small 15-tonne units/day, working 24 hour/day cycles. Gantry cranes were used to move the moulds and to stack the prefabricated units in three levels. The placement of Cubipods started in autumn, before completing the production of the 950 large 25-tonne and 600 small 15-tonne units required for the southern breakwater. On average, the crawler crane placed 4 Cubipod units/hour. The natural tendency of Cubipods to be randomly placed facilitated the unit placement as designed; the placement grids analyzed in the 3D small-scale tests allowed for an efficient placement at prototype scale. Concrete compression strength was not a critical issue. Due to schedule requirements, some 25-tonne and 15-tonne Cubipod units were handled and placed with only 15 days of hardening time (characteristic compressive strength of 20 MPa<30 MPa), but no unit breakage was observed during the handling, stacking or placement.

References

Burcharth, H.F., Andersen, T.L. and Medina, J.R. (2010). Stability of Cubipod armoured roundheads in short crested waves. *Proc. of 32nd Conference on Coastal Eng*ineering, ASCE, 32(2010): structures.39.

Corredor, A., Santos, M., Gómez-Martín, M.E. and Medina, J.R. (2012). Placement of Cubipod armor units in San Andrés breakwater (Port of Málaga, Spain). *Proc. of 33rd Conference on Coastal Eng*ineering, ASCE, 33(2012): structures.6.

Lomónaco, P., Vidal, C., Medina, J.R. and Gómez-Martín, M.E. (2009). Evolution of Damage on Roundheads Protected with Cube and Cubipod Armour Units. *Proc. Coastal, Marine Structures and Breakwaters 2009,* ICE, Thomas Telford Ltd., Vol 1, 169-180+186-188.

Maciñeira, E., Noya, F. and Bajo, V. (2009). Breakwater construction at new port in Punta Langosteira, A Coruña, Spain. Execution process and technical innovation. *Proc. Coastal, Marine Structures and Breakwaters 2009,* ICE, Thomas Telford Ltd., Vol 1, 532-543.

Medina, J.R., Gómez-Martín, M.E., Corredor, A., Torres, R., Miñana, J.V., Fernández, E., Menéndez, C.F. and Santos, M. (2009). Cube and Cubipod Armour Unit Drop Tests and Cost Analysis. *Proc. Coastal, Marine Structures and Breakwaters 2009,* ICE, Thomas Telford Ltd., Vol 1, 260-271+298-299.

Medina, J.R., Gómez-Martín, M.E. and Corredor, A. (2010). Influence of armor unit placement on armor porosity and hydraulic stability. *Proc. of 32nd Conference on Coastal Eng*ineering, ASCE, 32(2010): structures.41.

Medina, J.R., Gómez-Martín, M.E, Corredor, A., Torres, R., Miñana, J.V., Fernández, E., Menéndez, C.F. and Santos, M. (2011). Prototype drop tests of cube and Cubipod armor units. *Journal of Waterway, Port, Coastal and Ocean Eng*., ASCE, 137(2): 54-63.