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Preface

This manual serves to guide civil engineers in the preliminary design of mound breakwaters, focusing attention on economic, environmental and logistic factors to be considered when designing Cubipod[®] armors. The Cubipod[®] is a robust precast armor unit which can be used for single- and double-layer armoring. Efficiently manufactured with vertical molds, Cubipods are easy to handle and place with pressure clamps, and may be re-used. Economic savings and logistic efficiency are the greatest advantages of Cubipod[®] armoring when compared to other concrete armor units. SATO (OHL Group) is the exclusive licensee of the Cubipod[®] registered trademark and the patent.

The *Universitat Politècnica de València* (UPV) filed the Cubipod[®] armor unit patent at the Spanish Patent and Trademark Office (SPTO) in 2005 and the Patent Cooperation Treaty (PCT) in 2006. During 2005 and 2006, the inventors of the Cubipod[®] and authors of the *Cubipod[®] Manual 2016* carried out preliminary research in the Laboratory of Ports and Coasts (LPC) at the UPV, revealing the extraordinary hydraulic performance of Cubipod[®] armors, compared to the cube armors frequently used on the coasts of Spain. The patent was licensed exclusively to SATO-OHL in 2007 and the research project CUBIPOD (2007-2010), partially funded by CDTI (Spanish Ministry of Economy and Competitiveness), served to combine the efforts of engineers and technicians from SATO and researchers from the LPC-UPV and other institutions for the full development of the Cubipod[®] unit. SATO-OHL technicians designed an efficient vertical mold to manufacture Cubipod[®] units, whose corresponding patent was filed at the SPTO in 2007. A complete series of studies, prototype drop tests, along with 2D and 3D small-scale physical experiments, were carried out to characterize the hydraulic stability of single- and double-layer Cubipod[®] armors. In addition to SATO-OHL and LPC-UPV, other institutions collaborated in essential tasks, namely *Universidad de Alicante* (UA), *Instituto de Hidrodinámica Aplicada* (INHA), *Instituto de Hidráulica Ambiental de Cantabria* (IH Cantabria), and Aalborg University (AAU).

SATO-OHL also provided funding for the research projects CLIOMARS (2009-2011) and MMONOCAPA (2013-2014) as well as for specific studies and small-scale tests corresponding to breakwaters in which Cubipods were used (San Andrés Breakwater-Málaga, Western Breakwater-Langosteira, etc.). In addition to SATO-OHL and LPC-UPV, other institutions with different test facilities, specifically *Universidad Politécnica de Madrid* (UPM), *Centro de Estudios de Puertos y Costas* (CEPYC), *IH Cantabria*, *INHA* and *Universidade da Coruña* (UDC), provided relevant contributions. Not only have these researchers collaborated with SATO-OHL to improve the characterization of Cubipod[®] armors, but also engineers from *Puertos del Estado* (Spanish Ministry of Public Works and Transport), consulting companies, port authorities (Alicante, Málaga, A Coruña, etc.), and consortiums responsible for the construction of Cubipod[®]

armored breakwaters, such as those of the ports of A Coruña and Las Palmas de Gran Canaria in Spain.

The results of this research and development have been applied to the construction of several Cubipod[®] armored breakwaters along the Spanish Atlantic and Mediterranean coasts. Results have also been presented in three PhD thesis, published in more than forty papers in technical journals and discussed in national and international coastal engineering congresses. The most relevant publications are listed in the References of this *Cubipod[®] Manual 2016*. Regarding to the contents of the present manual, the following civil engineers and researchers deserve special mention for their relevant contribution to the research, development and design of Cubipod[®] armors: Moisés Santos, Rafael Torres, Antonio Corredor, Carlos Fermín Menéndez, Eva Smolka, Vicente Pardo and Jorge Molines. Debra Westall revised the manuscript.

Chapter 1

Introduction

1.1. Introduction

The *Cubipod[®] Manual 2016* provides the basic criteria to design and construct mound breakwaters protected with single- and double layer Cubipod[®] armors. This Introduction describes the main characteristics of rubble-mound breakwaters and Cubipod[®] armoring.

The economic cost of a mound breakwater depends on the environmental conditions and one key factor: the rock or artificial concrete units used for the armor layer. Each geometrical shape (cube, Cubipod[®], Tetrapod, Dolo, Xbloc[®], etc.) requires a specific placement pattern (random, uniform, interlocked, etc.) and each can be placed or not in a single- or double-layer. Each armor unit and placement pattern requires a given armor porosity with different breakwater performance (hydraulic stability, overtopping rates, etc.). A concrete armor unit with higher hydraulic stability (higher stability coefficient, K_D) should be smaller to withstand the design storm, reducing concrete consumption and size of cranes and handling equipment as well as stones in the filter layer.

Cubipod[®] is a massive armor unit belonging to the cube family; Cubipod[®] has a robust design for structural integrity (140-tonne Cubipod[®] units can be manufactured with $f_{ck}[f_{ct,k}]=30[2.0]$ MPa concrete). Cubipods are placed randomly in single- or double-layer armors, and they tend to self-position on the slope with homogeneous armor porosity. Double-layer Cubipod[®] armors show a high hydraulic stability ($K_D=28$); they are especially appropriate to withstand rough seas or relevant design uncertainties (differential settlements, construction quality control, etc.). The double-layer Cubipod[®]

armor is an adequate design alternative for the most adverse construction or environmental conditions given its high hydraulic stability together with its self-arrangement and self-repairing performance. Figure 1.1 shows the double-layer 6-tonne Cubipod[®] armor placed in the San Andrés Breakwater of the Port of Málaga (Spain).

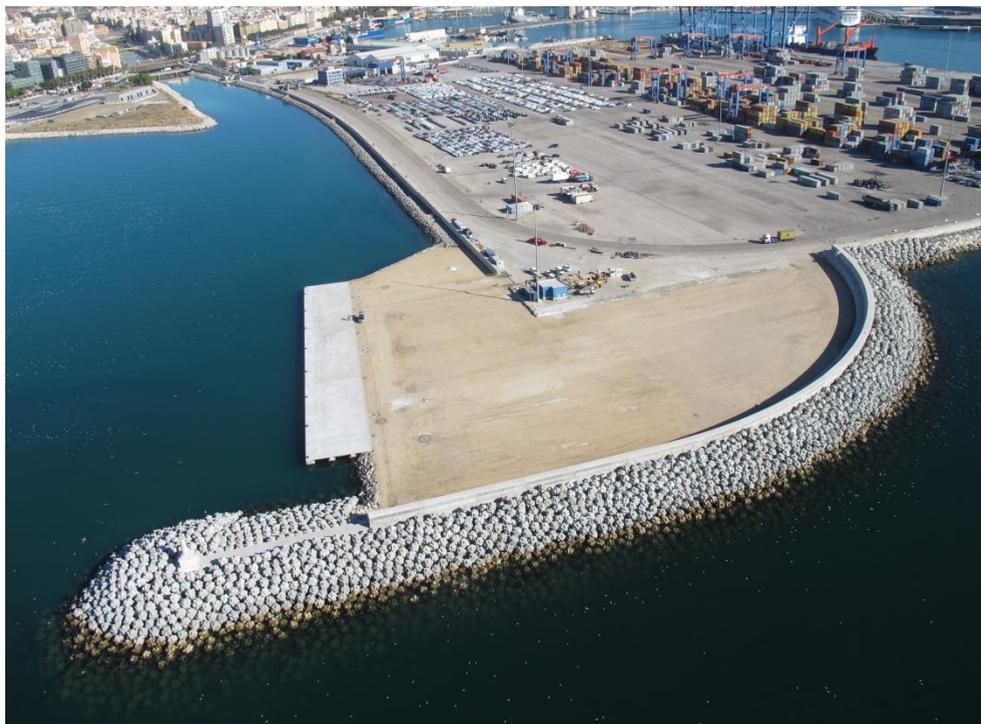


Figure 1.1 Six-tonne Cubipod[®] units in the San Andrés Breakwater of the Port of Málaga (Spain).

A single-layer Cubipod[®] armor ($K_D=12$) has a higher hydraulic stability in the trunk than a conventional double-layer cube armor ($K_D=6$), but a lower hydraulic stability than the double-layer Cubipod[®] armor ($K_D=28$). However, the single-layer Cubipod armor reduces by one-third the concrete required for the double-layer Cubipod[®] armor. For breakwaters which must withstand very rough wave storms ($H_{sd}[m]>12$), single-layer Cubipod armors usually require another single-layer Cubipod[®] armor as a secondary cover layer (using concrete units with a 5-10% mass of units in the first cover layer); the clear advantage of the single-layer is neutralized in these conditions. Figure 1.2 shows a single-layer 25-tonne Cubipod[®] armor, with a 2-tonne quarry-stone underlayer, placed in the Western Breakwater of the Outer Port of A Coruña at Punta Langosteira (Spain).



Figure 1.2 Twenty five-tonne Cubipod[®] units in the Western Breakwater of the Outer Port of A Coruña at Punta Langosteira (Spain).

Compared to slender or bulky interlocking units, the Cubipod[®] is much more robust; much larger units can be manufactured with concrete having lower characteristic compressive and tensile strengths (cheaper concrete). Cubipod[®] manufacturing (2 to 3.5 units/day) and unit stacking (multiple levels) are much more efficient, while its handling is safer and easier using pressure clamps instead of slings. The hydraulic stability of single-layer Cubipod[®] armors is slightly lower than that of armors with interlocking bulky units ($K_D=12 < 15$ or 16) and the recommended slope is less pronounced ($H/V=1.5 < 1.33$); however, the packing density ($\Phi=0.59$) is lower than most interlocking units. Compared to single-layer interlocked armors, Cubipod[®] armors usually require between -3% and +18% additional concrete, depending on the slope and unit used for comparison. This slight disadvantage in the required volume of concrete becomes a clear advantage when taking into account the quality of concrete required as well as the handling and placement of units. Slender and bulky units require concrete with a much higher characteristic tensile strength (much higher cement to volume ratio) than massive concrete armor units such as Cubipods or conventional cubes.

Compared to conventional cubic blocks, Cubipod[®] units are quite similar in terms of robustness, manufacturing, handling with pressure clamps and stacking in the block yard. Cubipods can be used in single- and double-layer armoring, these units are not prone to Heterogeneous Packing (HeP) failure mode and its hydraulic stability is much higher than cube armors. Unlike conventional cubic blocks, which tend to position one face parallel to the slope (favoring sliding) and several faces parallel to those of neighboring units, Cubipods arrange themselves in random orientations and with homogene-

ous armor porosity. For breakwaters designed to withstand low intensity design storms ($5 < H_{sd}[m] < 8$), single-layer ($K_D=12$) and double-layer ($K_D=28$) Cubipod[®] armors reduce concrete consumption by 60% and 40%, respectively. The economic savings are higher for breakwaters under intense design storms ($H_{sd}[m] > 8$) because, in addition to concrete savings in the first cover layer, no concrete is required for the secondary cover layer (depending on the type of quarry stone available at the construction site). Figure 1.3 shows 15-tonne cube and 16-tonne Cubipod[®] units, stacked in the SATO block yard at the Port of Alicante, ready to be used in the prototype drop tests carried out in April 2008 during the CUBIPOD Project (2007-2009).



Figure 1.3 Fifteen-tonne cube and sixteen-tonne Cubipod[®] units in the Port of Alicante (Spain).

1.2. Mound breakwaters

Mound breakwaters are sloping structures composed of layers of stones, protected with a cover layer of selected armor units made up of either natural quarry stones or special concrete units. These sloping structures cause waves to break on the slope, sheltering coastal areas or protecting the shoreline. The armor or primary cover layer, made of large quarry stones or precast concrete units, must withstand the forces generated by

waves breaking on the slope during wave storms. The *Cubipod[®] Manual 2016* focuses on mound breakwaters protected with Cubipod[®] armors.

In addition to the armor layer, mound breakwaters have a core made of heterogeneous and small stones (typically from 1 to 50 kg) which is the most voluminous part of the breakwater. The core must not only reduce wave transmission through the breakwater during service time, but it must also provide a work platform for the terrestrial equipment (cranes, trucks, etc.) during the construction phase. The materials required for the core are usually selected after a sound analysis of both the quarries available at the construction site and the logistics of materials supply; logistics and construction costs are highly dependent on a reliable source of materials.

The armor layer (large quarry stones or concrete units) must not be placed directly on the core because smaller stones escape through the voids of the armor layer. A secondary cover layer and perhaps an additional underlayer, following the filter criterion, should be placed between the armor and the core. These layers of stones or concrete units, with increasing size from the core to the armor, prevent smaller stones from the core being dragged out by wave currents during storms. The filter criterion commonly used for mound breakwaters is simple: the size of the units in the upper layer should not exceed 2.5 times the size of units in the underlayer (mass relation $W/10$ to $W/20$). If this filter criterion is applied, smaller stones from the underlayers are not able to pass through the voids in the outer layers, and the layers remain stable during wave storms. Figure 1.4 shows a typical cross section of a mound breakwater protected by a single Cubipod[®] layer.

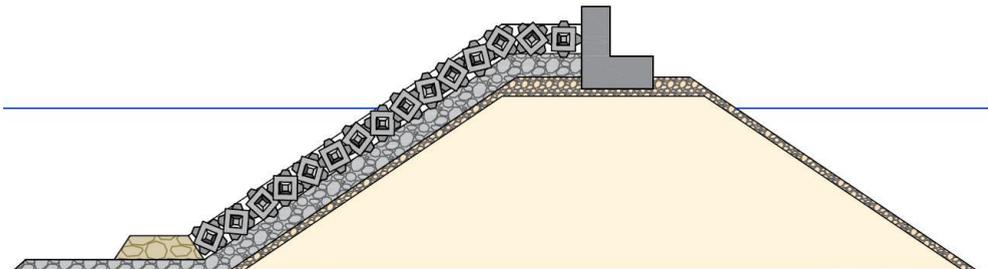


Figure 1.4 Mound breakwater protected by a single-layer Cubipod[®] armor.

The secondary cover layer and filter layer must follow the filter criterion ($W/10$ to $W/20$). Stone filter layers must be at least one meter thick and double the equivalent cube size or nominal diameter ($e_i[m] > \max[1.0, 2D_{n50i} = (W_i/\rho_i)^{1/3}]$). For breakwaters to withstand very rough wave storms ($H_{sd}[m] > 12$), it may be necessary to use a single layer of Cubipod[®] concrete units as a secondary cover layer, when very large quarry stones are not available; in this case, the recommended unit mass is $W_1 = W_0/15$, where W_0 is the mass of the Cubipods in the armor and W_1 is the mass of the Cubipods in the secondary cover layer.

Cubipods are designed to enhance the friction with the underlayer. The size of the protrusions on Cubipod[®] armor units (unit mass W_0) is similar to that of the voids in a layer of quarry stones, thus fulfilling the filter criterion (unit mass $W_1=W_0/15$). The higher friction between layers is achieved when a layer of Cubipod[®] units is placed on a layer of randomly-placed stones; to maximize the friction between layers, ordering the stones in the secondary cover layer is not recommended.

When precast concrete units are used for the armor layer, a toe berm is necessary for an adequate support and a precise placement of the first row of concrete units. A correct toe berm design and construction is relevant in single-layer armoring because the placement of the first row of concrete units affects the upper rows. In the case of interlocking units, the placement of the first row is critical and must follow strict placement criteria to guarantee the prescribed interlocking. Cubipod[®] units show a self-arranging behavior on the slope and tend to achieve homogeneous armor porosity (see Gómez-Martín, 2015). In any case, it is always recommended to place the first row of Cubipods with low error positioning to obtain homogeneous armors.

If the breakwater is placed on a sandy sea bottom with a high risk of scouring, a scour apron and a toe berm are necessary. The construction of the new breakwater tends to create new wave-induced currents along the breakwater which favor scouring near the toe of the structure. If the geotechnical conditions are poor (low bearing capacity, high liquefaction potential, etc.), it may be necessary to dredge the sea bottom and change material, to construct bottom wide berm structures, to pre-load the soil or to make use of other techniques. These techniques increase bearing capacity, reduce long-term settlements and prevent geotechnical failure modes.

Finally, the design process should also take into account the minimum core crest width for an efficient use of the terrestrial construction equipment (cranes, trucks, etc.). It is common to design a crown wall on the breakwater crest to reduce the consumption of materials, to improve accessibility to the breakwater or to reduce overtopping rates. The crown wall is the last element of the mound breakwater to be completed, as it is the most rigid part of the structure; crown walls should be initiated when most breakwater settlements have already occurred. Figure 1.5 shows an image of the construction of a mound breakwater with a voluminous core, a filter layer, a secondary cover layer, a toe berm and a single-layer Cubipod[®] armor.

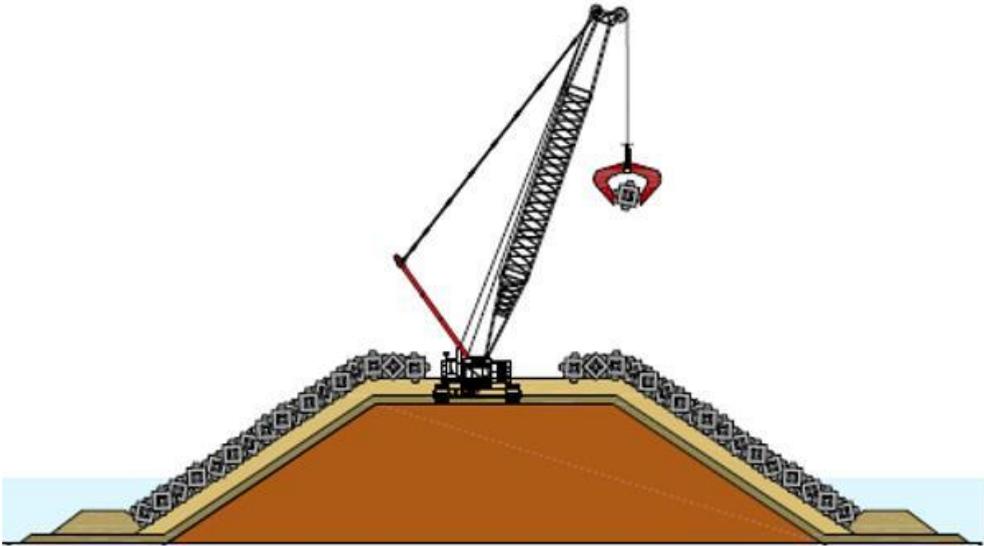


Figure 1.5 Construction of a Cubipod[®] armored mound breakwater.

1.3. Quarry materials supply

Mound breakwaters require relatively large volumes of quarry materials (quarry run, quarry stones of different size ranges, aggregates for concrete, etc.). Obtaining an adequate supply of quarry materials at a reasonable price is usually the greatest logistic challenge and it is essential to keep the overall construction cost low. The feasibility of a specific breakwater design and construction frequently depends on available quarries and equipment as well as transportation systems which can be used to extract and move quarry materials to the construction site.

Quarries located far from the construction site can be exploited to obtain the required stone size or density; however, imported stones are usually very expensive. As a general rule, only small rubble-mound breakwaters, designed to withstand very low intensity wave storms ($H_{sd}[m] < 5$), can be protected using only quarry stones. Larger breakwaters designed to resist intense wave storms usually require precast concrete units for the armor layer and also for the secondary cover layer if the design wave storm is very intense. An exception to this general rule is the statically stable Icelandic-type berm breakwater (see Van der Meer and Sigurdarson, 2014); in this case available quarries are analyzed in detail to define unconventional berm breakwater cross sections to withstand more intense wave storms using a small volume of very large quarry rocks.

The supply of quarry materials is especially relevant when designing large mound breakwaters (volume of materials), for unpopulated areas (equipment and transportation network), environmentally protected islands (available quarries) or large sedimen-

tary areas such as deltas of the largest continental rivers (no rocks available nearby). If suitable quarries are available near the construction site in an unpopulated area (cheap and large rocks but expensive equipment), the Icelandic-type berm breakwater may be a good design alternative. *Cubipod® Manual 2016* refers only to conventional mound breakwaters; berm breakwaters are not analyzed here.

The types of quarries near the construction site always condition the volumes and sizes of stones to be used in the breakwater. If the available quarries are not far from the construction site, the quarry materials supply costs will be low; the larger rock sizes which can be extracted from the quarries (sufficient volume) condition which part of the breakwater can be protected with quarry stones and which part will require concrete armor units. In these conditions, the unit cost (€/m³) of the quarry stones will be much lower than that of concrete units; therefore, the maximum rock size which a quarry can supply will determine the final construction cost.



Figure 1.6 View of a quarry at Punta Langosteira (Spain).

The mass density of quarry materials and aggregates is the first design factor affecting the hydraulic stability of a armor units (rock or concrete). The higher the mass density, the smaller the required armor units and concrete consumption. For a given construction site and wave climate, if the concrete mass density is 4% higher ($\rho_r[t/m^3]=2.40$ rather than 2.30), concrete armor unit mass decreases by 20% and concrete consumption decreases by 7%. Therefore, the mass density of quarry materials and aggregates, as well as the volumes of stones available in the quarries, are usually the two major design factors affecting the logistics and the cost of the breakwater.

In addition to the direct economic cost of the quarry materials, the terrestrial transportation of materials from the quarries to the construction site usually generates a relevant environmental impact (energy consumption, dust, traffic, noise, etc.). For large mound

breakwaters, it is convenient to avoid congestion in the road network by exploiting quarries close to the construction site or those with access to maritime transportation. In these cases, regardless of the location of the quarries, it is essential to take advantage of the high efficiency and low environmental impact of maritime transportation systems (barges) to place most of the submerged part of the breakwater (core, filter layer, etc.), reducing traffic on the breakwater crest when transporting of quarry materials and precast concrete units.

A reasonable design for a mound breakwater requires a previous detailed analysis of the available quarries to adapt the design to the volumes of each class of materials which can be supplied at an acceptable price. One of the secondary objectives of the design will be to minimize the volume of quarry materials to be extracted from the quarry but not used in the breakwater. If only a small part of the quarry materials are used in the breakwater, the economic, logistic and environmental impact will be significant. The best economic and environmental design allows all materials extracted from the quarries to be used.

Quarry availability, wave climate and seafloor at the construction site, are three factors which condition the breakwater design. Wave climate and bathymetry determine the design storm at the toe of the structure (H_{sd}). Sea bottoms (rocky, sandy, etc.) condition the breakwater foundation; a sandy seafloor will require a bedding layer or apron to prevent scour. If the bearing capacity is low, pre-load construction phases and wide bottom berms may be necessary to prevent uncontrolled settlements.

The design storm at the breakwater toe should be calculated first, and the breakwater foundation (bedding layer, berms and scour protection) is designed later. Once the wave climate and the structure foundation are defined, the available quarries determine the volume of stones of different sizes to be used in the breakwater. Core, berms, filter layer and quarry-stone main and secondary cover layers should be designed according to the quarry exploitation plan. Available quarries are relevant for construction logistics and breakwater design. This is especially true for large breakwaters (huge quarry materials volumes to be transported) and breakwaters designed to withstand intense wave storms (it may be necessary to use concrete units for the secondary cover layer if the quarries are not able to provide sufficient stones of the appropriate size).

1.4. Concrete supply

Mound breakwaters designed to withstand moderate or intense wave storms ($H_{sd}[m]>5$) usually require precast concrete units for the breakwater. *Cubipod[®] Manual 2016* refers to the use of Cubipod[®] units in the armor layer.

For any given wave climate and construction site, the volume of concrete required for the armor layer depends on decisions taken during the design process. The concrete consumption (V) is approximately proportional to $L \times H_{sd}^2$, where L is the breakwater length and H_{sd} is the design significant wave height. The volume of concrete used in

the armor layer (V) also depends on the selection of the armor unit (Cubipod[®]), number of layers (single- or double-layer) and packing density (e.g. $\phi=0.59$). The unit placement indirectly affects concrete consumption because placement conditions armor porosity. For slope cot $\alpha=1.5$, single- and double-layer Cubipod[®] armors require an approximate concrete supply given by

$$V_{\text{single-layer}}[\text{m}^3] \approx 0.9 \times L_b[\text{m}] \times H_{sd}^2[\text{m}^2] \text{ and } V_{\text{double-layer}}[\text{m}^3] \approx 1.3 \times L_b[\text{m}] \times H_{sd}^2[\text{m}^2]$$



Figure 1.7 Concrete being poured into the molds to manufacture 25-tonne Cubipod[®] units.

Concrete supply is usually a relevant economic and logistic factor affecting large mound breakwater construction, after the quarry materials supply described previously. Concrete is an artificial material which does not usually have quality or quantity restrictions; however, the unit cost ($\text{€}/\text{m}^3$) may vary significantly depending on the construction site (unit cost differs considerably from country to country), concrete characteristics and volume to be supplied. The characteristic tensile strength (f_{ctk}) is often the critical variable to design unreinforced concrete armor units, although characteristic compressive strength (f_{ck}) is the variable systematically controlled during the manufacturing process.

The compressive strength of unreinforced concrete is much higher than the tensile strength; therefore, unreinforced armor units break when flexures or torsions generate significant tensile stresses exceeding the tensile strength limit. Fragile breakage is likely to occur when the maximum tensile stress is similar to the mean tensile strength (f_{ctm}). The maximum tensile stress created within the armor unit (handling, placement, etc.) depends mainly on size and unit geometry. For a given unit size, tensile stress is higher for a slender armor unit than for a massive one. For a given armor unit and han-

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