A Review on the Development and Applications of Single-layer Concrete Armour Units in the Design of Rubble Mound Breakwaters

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ABSTRACT

Concrete armour units can be applied to protect new reclamations, beaches or coastal structures, like rubble mound breakwaters. The design systems of concrete armour layers for breakwaters can be divided into single-layer systems and double-layer systems. In the design of rubble mound breakwaters, at present, single-layer systems using concrete armour units have become a more common practice compared to conventional two-layer systems. There are several types of artificial armour units which can be applied as single-layer armour systems. These all have different shapes and properties and improvement keeps going on by trying to develop new more effective ones. Single-layer armour system is mostly applied because of its properties, like high interlocking, high hydraulic stability of the structure, reduction of concrete use and decrease of the construction period. However, for the application of monolayer systems, different factors, like placement pattern, allowable levels of damage, additional safety for repair works and failure systems of armour layer should be treated with care. This review study highlights the development and use of single-layer concrete armour units in the design of rubble mound breakwaters. Furthermore, various important factors that need to be considered in the design of a single-layer armour are discussed in this paper.

KEYWORDS: Concrete armour unit, Rubble mound breakwater, Single-layer system, Hydraulic stability, Structural strength.

INTRODUCTION

Breakwaters are usually applied for harbours and similar structures along coasts to protect beaches and dunes from the action of waves and currents and to stop siltation in the approach channel (SPM, 1984). Rubble mound breakwaters have been mostly applied by designers among several types of breakwater. Concrete blocks of various types, shapes and sizes have been applied as main armour layer in the design of rubble mound breakwaters for more than 100 years (Jensen, n.d.). Over the years, a large number of concrete armour units have been developed and used as main armour layer either as single-layer system or double-layer system. Nowadays, single-layer systems using concrete armour units have become a more common practice compared to conventional two-layer systems in the design of rubble mound breakwaters.

This paper highlights the development and use of single-layer concrete armour units in the design of rubble mound breakwaters. Furthermore, various important factors that need to be considered in the design of a single-layer armour are discussed.

Rubble Mound Breakwaters

Rubble mound breakwaters are the most commonly used breakwaters in the world. In general, a typical

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cross-section of rubble mound breakwater is comprised of core, under-layer, armour layer, toe and crest. An armour layer of rubble mound breakwater is usually made with the use of rock armour units or concrete armour blocks in double-layer systems or in single-layer systems. CIRIA et al. (2007) stated that "rubble mound breakwaters are structures built of quarried rock, usually protected by a cover layer of heavy stones or concrete armour units". In Fig. 1, a typical cross-section of a rubble mound breakwater is presented. Rubble mound breakwaters dissipate wave energy mainly by absorption; only a small part of the wave energy is reflected. To reduce wave reflections, very often rubble mound breakwater is preferred as it has better wave energy dissipation properties compared to vertical breakwater (CIRIA et al., 2007).

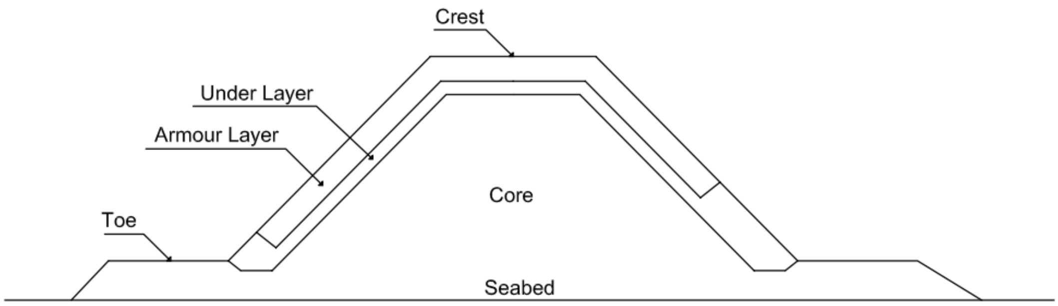


Figure (1): Conventional cross-section of rubble mound breakwater

Historical Overview of Armour Blocks

Prior to World War II, breakwater armouring was typically made with either rocks or parallel-epipedic concrete cubes, placed both uniformly and randomly (Bakker et al., 2003). The design of these types of breakwater is comprised of a gentle slope where a large number of units is deposited. One example of such breakwater armoured with large rectangular blocks is shown in Fig. 2.

Figure (2): Breakwater armoured with rectangular blocks constructed in the 1930s [Source: (Jensen, n.d.)]

The 1950s witnessed an upsurge interest in developing and using concrete armour for rubble mound breakwaters. As a consequence, after the 1950s, a large variety of concrete armour units has been invented by different consultants in different countries. For instance, in 1950, a new concrete armour unit (Tetrapod) was introduced by 'Laboratoire Dauphinois d'Hydraulique', which was first an interlocking double-layer armour unit. The main advantages of Tetrapod were better interlocking compared to a cube block and large porosity of armour layer, which results in a higher wave energy dissipation and reduction of wave run-up (Vanhoutte, 2009). However, damage of armour layer also happened with breakwater armoured with Tetrapods.

Afterwards, in the period of 1950-1970, a large variety of concrete armour units has been developed by different institutions. Nevertheless, application of most of the units from this period was very limited. Placement of these armour units was random or uniform in double layers. Their stability depends on the interlocking of units and on their own weight.

In 1978, the failure of Sines breakwater in Portugal, which was armoured with 42-ton Dolos, set an end to the rapid development of slender concrete armour units. The drastic failure of Sines breakwater showed that slender armour units designed for maximum interlocking are not sufficiently stable, because they tend to break easily and breakage of armour units may cause progressive damage (Vanhoutte, 2009). To balance hydraulic stability and structural strength, researchers then looked to develop new armour units maintaining both hydraulic stability and structural strength.

Classification of Armour Units

Breakwater armour units can be classified into different categories according to their shape, placement pattern, number of layers, structural strength, risk of progressive failure and the way they resist wave action. Bakker et al. (2003) classified breakwater armour units based on their shape as shown in Table 1.

Table 1. Classification of breakwater armour units regarding to shape

Shape	Armour Units
Cubical	Cube, Antifer Cube, Modified Cube, Grobbelar, Cob, Shed
Double Anchor	Dolos, Akmon, Toskane
Thetraeder	Tetrapod, Tetrahedron (solid, perforated, hollow), Tripod
Combined Bars	2-D: Accropode, Gassho, Core-Loc 3-D: Hexapod, Hexaleg, A-Jack
L-Shaped Blocks	Bipod
Slab Type (various shapes)	Tribar, Trilong, N-Shaped Block, Hollow Square
Others	Stabit, Seabee

Furthermore, armour units of breakwater can be grouped into 2 main categories by their placement pattern; being either random or uniform (Muttray et al., 2003). Together with placement pattern, this classification also includes criteria for shape, number of layers and way they resist wave action (stability method). single-layer concrete armour units can be placed randomly oriented or uniformly oriented. The orientation of armour units is predefined with a certain regular pattern for uniformly oriented blocks, while the orientation of armour units is irregular for randomly oriented blocks (Bakker et al., 2005). In case of a random placement, there's no concern on the orientation of the individual elements to obtain a good position; therefore, the construction is much easier compared to uniform placement. In Table 2, classification of concrete breakwater armour units regarding to placement pattern, shape and stability factor is presented. This classification has been made according to the approach proposed by Bakker et al. (2003) and Hendrikse (2014).

For massive, cube-like armour units, random placement is usually applied to ensure the porosity of the armour layers and to avoid the excess pore pressure inside the breakwater which may lift the units (Vanhoutte, 2009). However, in case of slender armour units, like Tetrapod, hydraulic stability depends mainly on interlocking and the average hydraulic stability is quite large. In contrast to hydraulic stability, the structural stability is relatively low. Therefore, slender blocks shall be considered as a series system with a large risk of progressive failure, because if they break into parts, the hydraulic stability sharply decreases, causing simultaneous loss of weight and interlocking.

For armour units bulky in shape, like Accropode, Core-Loc, Xbloc, among others, random placement in single-layer system is mostly applied. These armour units completely depend on interlocking to provide the hydraulic stability of armour layer. Nevertheless, in case of hollow blocks, like Seabee, the governing stability factor is friction, not interlocking. In some cases, these armour layers are more homogeneous than interlocking armour layers and are also very stable. However, due to difficulties in underwater placement, the application of these armour units is limited.

Table 2. Classification of armour units by placement pattern, shape and stability factor

Placement pattern	No. of layers	Shape	Stability factor		
			Own weight	**Interlocking**	**Friction**
Random	Double-layer	Massive	Cube, Antifer Cube, Modified Cube		
		Bulky	Stabit, Akmon		
		Slender		Tetrapod, Dolos	
	Single-Layer	Massive	Cube		
		Bulky		Accropode, Xbloc, Accropode II, Core-Loc II, Crablock	
		Slender		A-Jack, Core-Loc	
Uniform	Single-Layer	Massive			
		Bulky		Crablock	Seabee, Hollow Cube, Diahitis
		Slender			Cob, Shed

In the design of armour units, designers need to choose between higher hydraulic stability and higher structural strength. The hydraulic stability of armour units can be possibly increased by increasing their own weight, interlocking capacity and higher friction with the inner layer. However, interlocking and higher friction generally cause a significant reduction in the structural strength of armour layer.

Single-Layer Armour Blocks

Since 1980, single-layer randomly placed armour units have been applied in the design of breakwaters. In the eighties, Sogreah introduced a randomly placed single-layer concrete armour unit known as Accropode (CLI, 2011a). After the introduction of Accropode, it has been applied in more than 200 breakwaters (CLI, 2011b).

Single-layer concrete armour units have been developed as both pattern placed block and randomly oriented block. For example, Cob in 1969, Seabee in 1978, Shed in 1982 and Diahitis in 1998 were invented as uniformly placed single-layer armour units (Bettington et al., 2011). These are hollow blocks and placement of these blocks under water seems rather difficult; therefore, application is limited to only above low water (Muttray and Reedijk, 2009; Reedijk et al., 2003; Vanhoutte, 2009). The details on application and properties of these units are not well known. They are also more compared with placed block revetments, as applied on dikes, then with common rubble mound breakwater armour.

Next to Accropode, in the mid 1990s, another randomly oriented single-layer concrete armour unit was invented by U.S. Army Corps of Engineers (CLI, 2012); the Core-Loc. Melby et al. (1994) argued that Core-Loc provides higher stability with good interlocking and low cost solution compared to other existing irregularly oriented armour units. However, CIRIA et al. (2007) warned that although in comparison to Accropode the hydraulic stability of Core-Loc armour unit looks superior, the structural integrity of Core-Loc might be lower than that of the Accropode armour block.

Furthermore, in 2005, Cubipod was developed as a single-layer randomly placed unit to improve the low hydraulic stability of cubes with keeping advantages of high structural strength and easier placement (Vanhoutte, 2009). Recently, a new concrete armour unit (Crablock) has been invented in the UAE and applied as repair in one damaged rubble mound breakwater as a single-layer system.

The overview of the development of single-layer concrete armour units is presented in Fig. 3.

The development of single-layer concrete was then followed by the invention of other randomly oriented single-layer units; A-Jack in 1998 by Armortec, Xbloc in 2003 by Delta Marine Consultants, Accropode II in 2004 by Sogreah, followed by Core-Loc II in 2006 (DMC, n.d.).

Characteristics of Single-Layer Armour

The main reason behind the popularity of single-layer systems is its characteristics, like high interlocking, large structural stability and cost efficiency. Van der Meer (1999) found that due to high interlocking properties, single-layer armour units can better sustain under higher wave heights compared to conventional double-layer armour units. In addition to the stability of structures, a randomly placed single-layer armour system provides a better economic solution compared to a conventional double-layer system (Bakker et al., 2003; Muttray et al., 2003; Van Gent et al., 1999). Furthermore, additional maintenance in a conventional two-layer system compared to one-layer system can be reduced with appropriate design of single-layer armour (Muttray and Reedijk, 2009).

Despite of many successful applications, single-layer armoured breakwaters have also suffered damage. For example, Fig. 4 shows a damaged Core-Loc armour layer in Al-Fujeirah, UAE.

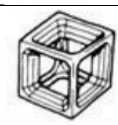
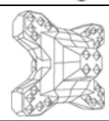
Single-layer concrete armour	**Shape**
Name: Cube (Single-layer cube)	
Name: Cob Placement Pattern: Regular	
Name: Seabee Placement Pattern: Regular	
Name: Accropode Placement Pattern: Random	
Name: Shed Placement Pattern: Regular	
Name: Core-Loc Placement Pattern: Random	
Name: A-Jack Placement Pattern: Random	
Name: Diahitis Placement Pattern: Regular	
Name: Xbloc Placement Pattern: Random	
Name: Accropode II Placement Pattern: Random	
Name: Cubipod Placement Pattern: Random	
Name: Core-Loc II Placement Pattern: Random	
Name: Crablock Placement Pattern: Both Random and Regular	

Figure (3): Development of single-layer concrete armour units [Source: (DMC, n.d.; Hendrikse, 2014; Vanhoutte, 2009)]

Figure (4): Movements of concrete armour units with large settlements [Source: Hendrikse, 2014]

Failure of one-layer systems shows much more fragile characteristics compared to double-layer systems (Besley and Denechere, 2010; CIRIA et al., 2007; Medina and Gómez-Martín, 2012; Van der Meer, 1999). Therefore, in comparison to traditional two-layer armour system design of rubble mound breakwaters, using one-layer armour systems requires additional safety factors due to their failure mechanism (Medina and Gómez-Martín, 2012).

Moreover, the maintenance and repair works of armour layer is more difficult for single-layer armour systems compared to double-layer armour systems. As the hydraulic stability of single-layer armour completely depends on the interlocking of armour unit, adding or replacing armour units does not really work. Hence, in order to keep breakwaters away from repair works, extra safety is required in the design of one-layer armour systems compared to conventional double-layer systems (Jensen, n.d.). Furthermore, the use of one-layer armour systems might increase the rate of overtopping discharge (Bruce et al., 2009; Eurotop, 2007). In addition, according to Van Gent et al. (1999), different factors, like placement pattern, allowable levels of damage and failure systems of armour layer, should be treated with care for the application of single-layer systems.

Therefore, it is necessary to understand the behaviour of single-layer systems in order to use these systems properly in the design of rubble mound breakwaters.

CONCLUSION

In the design of breakwaters, single-layer systems are becoming more and more popular due to their characteristics, like high interlocking, large structural stability and cost efficiency. They have been successfully applied in many rubble mound breakwater projects. Thus, it can be concluded that single-layer concrete armour systems are a good invention in the design of rubble mound breakwaters. However, single-layer armoured breakwaters have also suffered damage in some cases. Therefore, for the application of these systems, different factors, like placement pattern, allowable levels of damage, additional safety for repair works and failure systems of armour layer should be treated with care.

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