Proceedings of the 9th International Conference on Physical Modelling in Coastal Engineering (Coastlab24)
Delft, Netherlands, May 13-16, 2024

Conference Paper, DOI: 10.59490/coastlab.2024.683

HYDRAULIC STABILITY OF THE NEW CUBILOK ARMOUR UNIT ON A 3:4 SLOPE

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ABSTRACT

The Cubilok™ (or Cubilok) is a new trademarked armour unit that has been developed in South Africa by PRDW Consulting Ports and Coastal Engineers to accommodate a wide range of breakwater designs. The Cubilok is still in its early stages of development and therefore it has not yet been applied or tested in prototype conditions. 2D Physical model tests were conducted as part of a master's research project to investigate the stability and behaviour of the Cubilok on a 3V:4H slope. From this study, it was observed that the wave steepness has a significant influence on the performance of the Cubilok, where superior stabilities were recorded during conditions with shorter wave periods. When placed on a 3V:4H slope and with a packing density of ϕ = 0.63, the stability of the Cubilok is comparable to that of other concrete armour units, however, it is susceptible to severe settlement. Some results also showed that the settlement of the armour layer can probably be significantly reduced when the armour layer is constructed on a milder 1V:2H slope or when the packing density is increased to ϕ = 0.65.

This paper is a version of the paper: Wehlitz C.F.V.M., and Schoones, J.S., (2023). Hydraulic stability of the new Cubilok™ armour unit on a 3:4 slope. Coastal Engineering, 183, Article 104313. https://doi.org/10.1016/j.coastaleng.2023.104313

KEYWORDS: Rubble mound breakwater; Concrete armour unit; Cubilok; Hydraulic stability; Physical model

1 INTRODUCTION

While rock remains the preferred construction material for rubble mound breakwaters, adequate rock is not always available or in sufficient quantities. This has been the main drive for developing various concrete armour units over the last half a century. Since the 1980s, single layer concrete armour units have become increasingly popular and is the preferred solution in many of the present-day designs (CIRIA, 2007). The use of interlocking single layer armour units is considered more economical when compared to the classic double layer or bulky armour units, since the demand for concrete is less. Many single layer armour units have been developed for placement on steep slopes with gradients up to 3V:4H (or 1V:1.33H), thus further reducing the demand for construction material.

As opposed to rock that relies mainly on its own weight, many artificial armour units are designed to obtain their stability by interlocking. This mechanism functions by placing units with complex shapes on a slope and allowing each unit to exert contact forces on the adjacent units. The motivation for using classical interlocking units was that a greater K_D value could be obtained when compared to rock of the same weight. It is generally accepted that the interaction between units fundamentally relates to the unit's shape and placement, while unit placement is directly related to the packing density. Packing density is therefore an important parameter and must be strictly maintained during armour layer construction to ensure proper interlocking of armour units. The slope onto which the armour units are placed also affects the physics of interlocking. According to the Coastal Engineering Manual (USACE, 2008), the interlocking effect is significant only for steeper slopes, however the optimum slope may vary depending on the shape of the unit. Interlocking is therefore primarily a function of the shape of the armour units, the packing density, and the slope onto which the units are placed.

The interlocking capability of armour layers are not limited to these parameters only, therefore the stability and behaviour of the slope should ultimately be determined experimentally. Given that the Cubilok is still in its early stages of development, it has not yet been applied or tested in prototype conditions. The primary objective of this study was therefore to investigate the hydraulic stability of the Cubilok in a 2D physical model setup, mainly, on a 3V:4H slope (or 1: 1.33) and using a packing density of ϕ = 0.63. Variations of these and other parameters were also investigated, however these included only limited testing and additional experimental support will be required to verify the results.

2 NEW CUBILOK ARMOUR UNIT

2.1 Armour unit properties and description

The Cubilok™ (or Cubilok) is a new trademarked armour unit that was developed in South Africa by PRDW Consulting Ports and Coastal Engineers (PRDW, 2019). It is composed of a cuboctahedron shaped core with six identical protuberances (or arms) extending from each square face. Each of the arms terminates with a pyramidal shaped end. The shape can be described as having four-fold rotational symmetry when viewed along an axis passing through two opposite arms and four mirror planes, two orthogonal and two diagonal. The Cubilok, as well as its geometric definition, is shown in Figure 1.

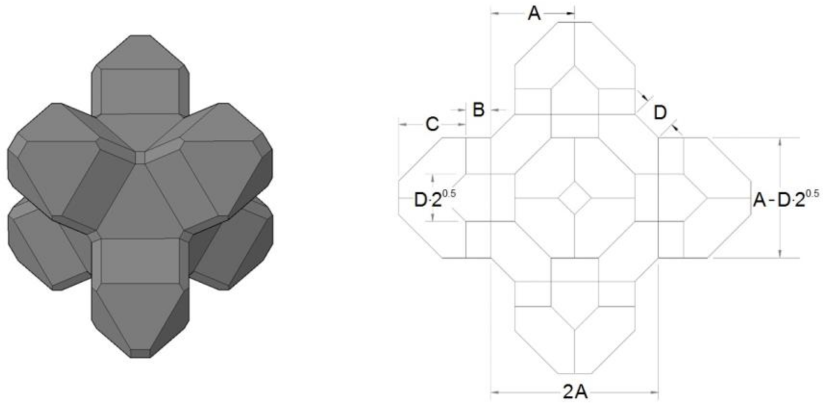

Figure 1. Cubilok armour unit.

The Cubilok will be suitable for exposed marine environments given its high structural robustness. The robustness of an armour unit is related to the slenderness of its arms, which is an indication of its ability to resist breaking during rocking. Van der Meer (1999) mentions that, for most single layer armour units, if one of the arms breaks off, about 90% of the unit's original weight is preserved. This includes most of its ability to interlock with other units. Nonetheless, a piece that has broken off would be more prone to movement during moderate wave climates and would still have sufficient weight to cause damage to other units. PRDW (2019) provides an expression for determining the slenderness ratio (H') as shown in Equation (1).

$$H' = \frac{H}{A^{0.5}} \tag{1}$$

where H is the height of the arm; and A is the base area of the arm.

According to PRDW (2019), a maximum slenderness ratio of H' = 1.085 is proposed for the Cubilok, which applies to the units used during this study. This implies that the Cubilok should have a superior structural robustness when compared to other units including Xbloc® and Accropode™. This is illustrated in Figure 2.

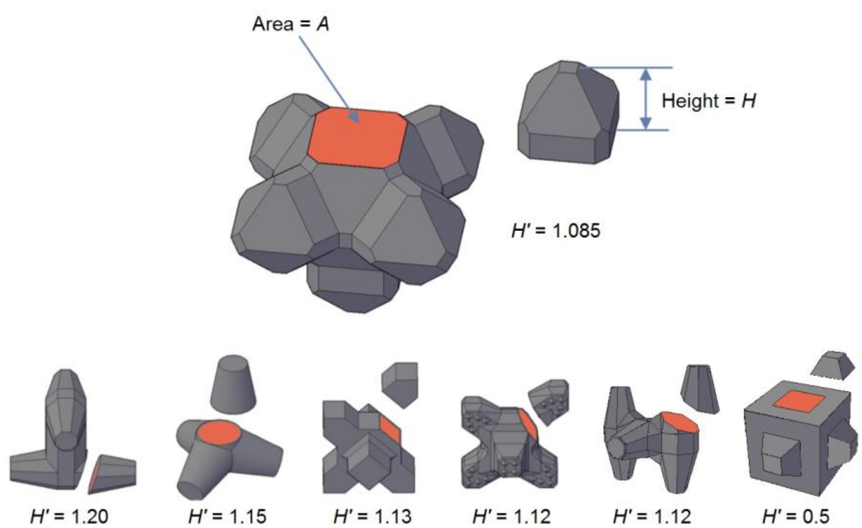

Figure 2. Slenderness ratio of selected amour units (Dolos, Tetrapod, Xbloc®, Accropode™ II, Core-loc™ and Cubipod®).

The Cubilok has been developed as a symmetrical parametric shape, which enables the shape of the unit to be changed from slender to very robust in response to a wide range of design applications. The unit's shape can therefore be modified from a highly interlocking unit to a very bulky shape that resembles the structural robustness of a cube. Depending on the size (or weight) of the units, the relative length of the arms may be varied to alter its slenderness ratio. Two variations of the Cubilok shape are shown in Figure 3.

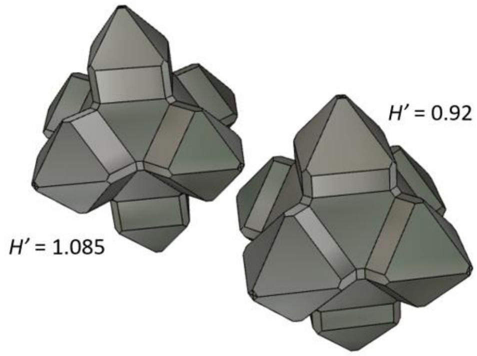

Figure 3. Two variations of the Cubilok shape.

With reference to Figure 3, the shape with H' = 1.085 was used during this study. The units were defined by shape ratios of A = 0.5, B = 0.36, C = 0.4 and D = 0.07 (see Figure 1), where the target dimensions were A = 11.5 mm, B = 8.3 mm, C = 9.2 mm and D = 1.6 mm. The more robust Cubilok shape with H' = 0.92 was proposed for a 60 tonne unit applied as a double layer during a different study (PRDW, 2019).

2.2 Armour unit placement

Armour unit placement has a major influence on the stability of the armour layer, since armour units rely on their ability to interlock with adjacent units, as well as to adhere to the underlayer. Placement parameters therefore include the placement pattern, unit orientation and packing density. The staggered grid was adopted for the Cubilok, however little was known about the packing densities to be considered for the Cubilok. Before testing commenced, multiple slopes were constructed, each with a different packing density that varied from $\phi = 0.56$ to 0.65. Voids between armour units, with a diameter greater than $0.44 \cdot D_n$, were measured to develop a sense of potential unit interlocking. This procedure was recommended by PRDW since it is used by them in the field to verify the proper placement of Core-loc™ units. Table 1 shows the three different armour layer arrangements that were selected for this study.

Table 1. Slope parameters of the three armour layer arrangements that were selected for testing.

$X = d_x / D_n$		$Y = d_y / D_n$		$\phi = 1 / (X \cdot Y)$	
Horizontal distance		**Along-slope distance**		**Packing Density**	**Measured number**
d_x	$X \cdot D_n$	d_y	$Y \cdot D_n$	ϕ	**of voids > $0.44 \cdot D_n$**
54 mm	$1.82 \cdot D_n$	27 mm	$0.91 \cdot D_n$	0.61	10
52 mm	$1.75 \cdot D_n$	27 mm	$0.91 \cdot D_n$	0.63	6
50 mm	$1.68 \cdot D_n$	27 mm	$0.91 \cdot D_n$	0.65	0

Constructing an armour layer with $\phi < 0.61$ would be impractical as it had many voids larger than $0.44 \cdot D_n$, making it more susceptible to rocking and significant settlement. On the other hand, the highest packing density tested during this study was $\phi = 0.65$, for which no gaps larger than $0.44 \cdot D_n$ were recorded. These slopes became difficult to construct, therefore slopes with ϕ greater than 0.65 were excluded as it may no longer be practical for prototype construction.

3 PHYSICAL MODEL SETUP AND TESTING

3.1 2D wave flume

The hydraulic performance of the Cubilok was studied in a 2D physical model setup at CSIR in Stellenbosch, South Africa. The flume used for this study comprises a glass panel structure measuring 30 m in length, 0.75 m wide and 1.0 m deep. The flume is equipped with a single-paddle piston-type wave generator manufactured by HR Wallingford, UK. The paddle is fitted with an integrated Dynamic Wave Absorption System that compensates for reflected waves and enables testing of reflecting structures. Figure 4 shows a schematic layout of the model setup and instrumentation inside the flume as used throughout this research.

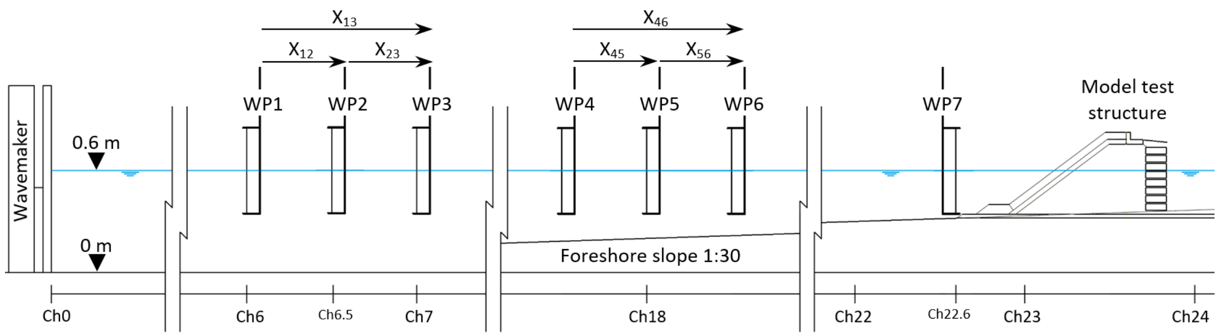

Figure 4. Schematic layout of the model setup inside the 2D flume. Reference can be made to Mansard & Funke (1980) for determining the probe spacings.

A fixed-bed model setup was used for this study and the model floor was constructed from hard, yet permeable mortar (cement-sand mix). The model seabed included a sloped foreshore with a constant gradient of 1:30. By including a sloped foreshore, several more wave processes associated with intermediate water depths were included in the model, making the system more realistic. All parameters for this model were scaled according to the Froude scaling laws, ensuring that the dominant forces acting on the system are represented in the correct proportions to the actual physical system (Hughes, 1993).

3.2 Wave measurement equipment

Wave measurements were taken using capacitance probes. The output datasets captured from the probes were analysed using GEDAP analysis software developed by the Canadian Hydraulics Centre. Two sets of three-probe array setups were used to measure the incident and reflected waves inside the flume. The total wave data from these two setups were analysed using the method developed by Mansard and Funke (1980) to separate the reflected waves from the incident waves. A single probe was installed at the structure toe to measure the total waves and the reflection parameters from the two three-probe arrays were then used to verify the incident wave height at this location.

3.3 Test structure setup

The model Cubilok units were fabricated from resin compound (material density = 2 360 kg/m^3) and the target mass of the individual units was 61.8 g. The armour layer comprised 25 rows of Cubilok, where the spacing between rows (d_y) remained constant at 27 mm ($0.91 \cdot D_n$) for all test slopes. The horizontal crest was armoured using a continuation of Cubilok (five rows), which terminated onto an L-shaped crest wall. Only single layer armour layers were tested during this study, where the armour layer thickness was around 37 mm. The nominal mass of the underlayer rock was selected to be 6.2 g, which is equivalent to one-tenth of the mass of the armour units (therefore $M_{50} = W/10$, where W refers to the mass of the armour units). The underlayer had a thickness of 27 mm, which was equivalent of two times D_{n50} (USACE, 2008). The core material was scaled using the method developed by Burcharth et al. (1999) and was composed of gravel with a standard grading of 5–12 mm, which had an M_{50} value of 1.0 g. The rock size for adequate toe stability was determined using the expression refined by Van der Meer (1998), which is presented in Equation (2).

$$\frac{H_s}{\Delta \cdot D_n} \cdot N_{od}^{-0.15} = 2 + 6.2 \cdot \left(\frac{h_t}{h}\right)^{2.7} \quad (2)$$

The stability of the toe did however, not form part of this study, therefore, to restrict excessive movement of the toe, larger rock were selected with a D_{n50} value of 30 mm. This was preferred over using a fixed toe block or gabion basket.

A summary of the materials and material properties that were used in the model test structures are provided in Table 2.

Table 2. List of materials and material properties that were used in the model test structures.

Description	Material type	Material Density	Nominal weight (M_{50})	Nominal diameter (D_{n50})
Armour layer	Cubilok	2360 kg/m^3	61.8 g	29.7 mm
Underlayer	Rock	2650 kg/m^3	6.2 g	13.3 mm
Core	Rock	2650 kg/m^3	1.0 g	7.2 mm
Toe	Rock	2650 kg/m^3	71 g	30 mm

Figure 5 shows the cross-sectional details of the model test structures. These details were requested and approved by PRDW and are supported by standard design guidelines contained in USACE (2008) and CIRIA (2007). This study focused on structures with a 3V:4H slope and all tests were conducted at a constant water depth of 0.28 m measured in front of the structure toe (or 0.60 m measured at the wavemaker paddle). All dimensions shown in Figure 5 are in millimetres (mm).

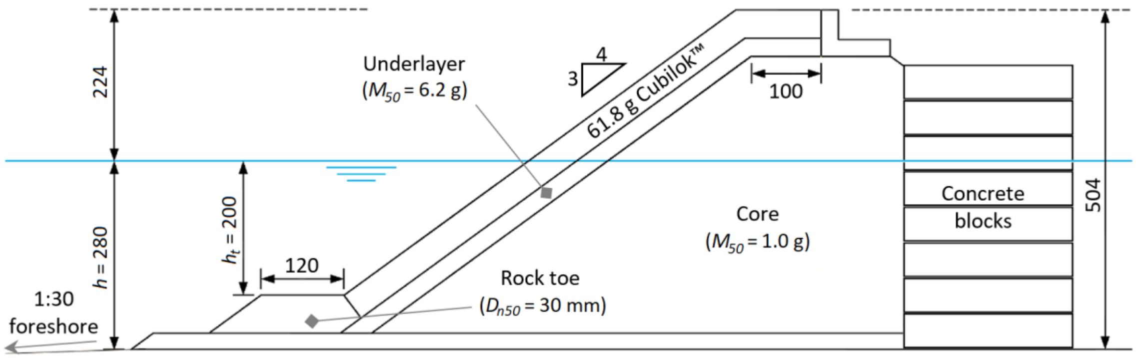

Figure 5. Typical cross-sectional detail of the model test structure.

This study was not specific to any particular project, therefore no specific model scale was applicable. When considering an indicative Froude scale of 1:42, the size of the Cubilok units is equivalent to 2 m^2 units in prototype, the water depth at the toe was 11.8 m, and the largest H_s simulated was 6.22 m.

It should be noted that wave overtopping did not form part of this study.

3.4 Hydraulic parameters for testing

Wave heights, as measured at the structure toe, were selected to start at H_{m0} = 0.10 m and were increased incrementally by 0.012 m for subsequent tests. Testing continued until reaching H_{m0} = 0.148 m or when ultimate failure of the slope occurred. Test conditions were also defined and grouped into sets with constant values of wave steepness. Wave steepness (S_{op}) is defined as the relationship between the wave height and wavelength and can be expressed as shown in Equation (3).

$$S_{op} = \frac{H_s}{L_{op}} = \frac{2\pi \cdot H_s}{g \cdot T_p^2} \tag{3}$$

where H_s is the significant wave height of the incident waves at the toe of the structure (H_s is assumed to be equivalent to H_{m0}); L_{op} is the deep-water wavelength based on the wave period corresponding to the peak of the wave spectrum, and T_p is the peak wave period.

S_{op} represents a fictitious wave steepness since it is a ratio between a statistical wave height at the structure and a representative deepwater wavelength. An S_{op} value of 0.02 typically indicates long swell and values closer to 0.06 usually represent wind seas (USACE, 2008).

The initial test schedule grouped tests depending on the wave or armour layer parameters. Variations in wave conditions included the wave steepness (S_{op}) and the number of waves (N), while differences in the slope parameters included the packing density (ϕ). Comparisons were mostly done using S_{op} = 0.04 since this represents a balance between swell and seas. All wave conditions were irregular (random) and were defined by the standard JONSWAP spectral shape with a peak enhancement factor of γ = 3.3 (refer to USACE, 2008).

3.5 Additional scenarios

By the time the initial test schedule was finalised, new insight was gained into the behaviour and limitations of the Cubilok. Several new questions were also raised, which included the following:

- What effect does the number of rows have on the stability of the slope?
- Will the behaviour of the unit be different if the material size of the underlayer is increased?
- Can the performance of the Cubilok be enhanced if the slope is milder than 3V:4H?

Based on the uncertainties listed, additional test scenarios were developed to gain more insight into the behaviour of the Cubilok. Changes to specific test parameters are discussed and motivated in the subsequent subsections. Only limited testing was done to cover these alterations, thus the outcomes may be speculative and require additional experimental support to verify the results.

3.5.1 Number of rows

The structures investigated previously comprised 25 rows of Cubilok, however armour layers generally do not exceed 20 rows (Besley and Denechere, 2009; DMC, 2018). By decreasing the number of rows on the slope, the potential for settlement may also be reduced. A single test series was conducted to check if this is applicable to the Cubilok, where the armour layer was reduced to include only 15 rows. To keep the crest elevation of the structure the same as before, the lower portion of the slope was constructed using larger alternative units placed in a ridged arrangement. The first row of Cubilok units started below the still water line.

3.5.2 Underlayer size

USACE (2008) recommends that underlayer material should have a nominal weight of one-tenth of the weight of the overlying armour units, thus $W/10$. It further mentions that M_{50} of the underlayer material should be about $W/5$ for armour units with $K_D > 12$, rather than $W/10$. The motivation is that larger stone sizes may promote increased interlocking between the armour units and the underlayer. To find out if the size of the underlayer material could influence the behaviour of the Cubilok, two test series were conducted where the underlayer material was increased from M_{50} = 6.2 g to 12.4 g.

3.5.3. Structure slope

When considering the steepness of the structure slope, the shape of an armour units also needs to be accounted for. For instance, most blocky armour units rely on their own weight for stability, and they are more susceptible to settlement as the slope becomes steeper. To determine if the slope steepness influences the stability of the Cubilok, the gradient of the slope was changed from 3V:4H to 1V:2H. Two test series were conducted using this setup and the armour layers comprised 19 rows of Cubilok. To keep to the same crest elevations as before, the same method, as mentioned above, of constructing the lower structure slope was utilised.

3.6 Test outcome

During this study, 22 test series were conducted, which made up a total of 110 individual test runs. If the armour layer failed during a particular test run, then the test series was concluded. Table 3 lists the tests completed, as well as the different parameters used to define each test series. All wave parameters listed were measured in front of the structure toe.

Table 3. List of wave conditions and grouping of different sets of tests. All tests were carried out at a constant water depth of 0.28 meter measured at the structure toe.

Test Series	ϕ	Target S_{op}	No of waves	Number of tests completed	Range of measured H_{m0} (m)	Range of measured T_p (s)	N_s	Slope failure
1	0.61	0.04	2000	4	0.10 - 0.136	1.36 – 1.75	3.37	17% into 5th test
2	0.61	0.04	2000	4	0.10 - 0.136	1.36 – 1.75	3.37	19% into 5th test
3	0.61	0.04	2000	4	0.10 - 0.136	1.36 – 1.75	3.37	17% into 5th test
4	0.61	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
5	0.61	0.04	1000	4	0.10 - 0.136	1.36 – 1.75	3.37	63% into 5th test
6	0.61	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
7	0.63	0.04	2000	4	0.10 - 0.136	1.36 – 1.75	3.37	97% into 5th test
8	0.63	0.04	2000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
9	0.63	0.04	2000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
10	0.63	0.02	2000	2	0.10 - 0.112	2.14 – 2.32	2.77	81% into 3rd test
11	0.63	0.03	2000	3	0.10 - 0.124	1.66 – 1.93	3.07	61% into 4th test
12	0.63	0.05	2000	5	0.10 - 0.148	1.21 – 1.64	3.66	No failure
13	0.63	0.06	2000	5	0.10 - 0.148	1.02 – 1.40	3.66	No failure
14	0.63	0.02	1000	3	0.10 - 0.124	2.14 – 2.53	3.07	26% into 4th test
15	0.63	0.03	1000	5	0.10 - 0.148	1.66 – 2.29	3.66	No failure
16	0.63	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
17	0.65	0.04	2000	5	0.10 - 0.148	1.36 – 1.88	>3.66	No failure
Additional test scenarios								
Increase underlayer size from $W/10$ to $W/5$								
18	0.63	0.04	1000	4	0.10 - 0.136	1.36 – 1.75	3.37	46% into 5th test
19	0.63	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
Reduce number of rows from 25 to 15								
20	0.63	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	3.66	No failure
Flatten slope from 3V:4H to 1V:2H								
21	0.63	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	>3.66	No failure
22	0.63	0.04	1000	5	0.10 - 0.148	1.36 – 1.88	>3.66	No failure

For each test series as indicated in Table 3, the wave parameters H_s and T_P were increased stepwise until the armour layer failed, or the limits of the model setup were reached. These increments were selected to maintain a constant S_{op} throughout the series. The stability of the slope (N_s) is based on cumulative damage, thus the successful completion of successive testing. This means that if the slope failed during a specific test, then the stability is based on the successful completion of the previous test. Slope failure is indicated as a percentage into testing, which refers to the time the test was stopped relative to the full test duration. The armour layer was only reconstructed at the end of each test series.

3.7 Damage assessment

Armour unit movements were analysed using the image-overlay technique, and displacements were tracked and analysed using concepts developed by the CSIR (Phelp and Tulsi, 2006). The flicker technique enables tracking of small movements by comparing one image taken before testing to one taken after. Movements were quantified as image pixels, which were then converted and scaled to actual distances using a known reference length selected on the images. By quantifying the displacement of armour units over time, movements can be defined as the relative damage (N_{od}), which represents the number of units displaced from the armour layer over a distance relative to one nominal diameter (D_n). The relative damage is defined as shown in Equation (4).

$$N_{od} = \frac{Number\ of\ units\ displaced\ over\ distance\ greater\ than\ D_n}{Width\ of\ section\ /\ D_n} \tag{4}$$

The behavioural trends and damage progression of the different test structure can be expressed in terms of N_{od} and the dimensionless stability number (N_s). N_s include parameters first introduced by Hudson (1959) and is determined using Equation (5).

$$N_s = \frac{H_s}{\Delta \cdot D_n} = \sqrt[3]{K_D \cdot \cot\alpha} \tag{5}$$

where α refers to the angle of the structure slope; $\Delta = \rho_r/\rho_w - 1$; ρ_r is the mass density of the armour unit; ρ_w is the mass density of water; K_D is the stability coefficient of the unit (needs to be determined experimentally).

Van der Meer (1988a) developed stability equations that vary depending on the type of wave breaking, which includes the wave period in the surf similarity (ξ). The surf similarity number is defined as shown in Equation (6).

$$\xi = \frac{\tan\alpha}{\sqrt{S_{op}}} \tag{6}$$

Figure 6 shows the relative damage sustained by the different test setups at the various wave heights tested. Trend lines were included to indicate the behaviour of the Cubilok based on S_{op} and ϕ, which highlights its sensitivity wave steepness and packing density respectively. The trend lines are based on the mean values of N_{od} for each setup, and the colour of the trend lines matches that of the corresponding test markers. For setups where limited testing was conducted, curve smoothing was applied to reduce the elevated scatter. The correlation coefficient (r) for the each trendline is provided, where r = 0 means there is no correlation to the data points and r = 1 means there is a perfect match.

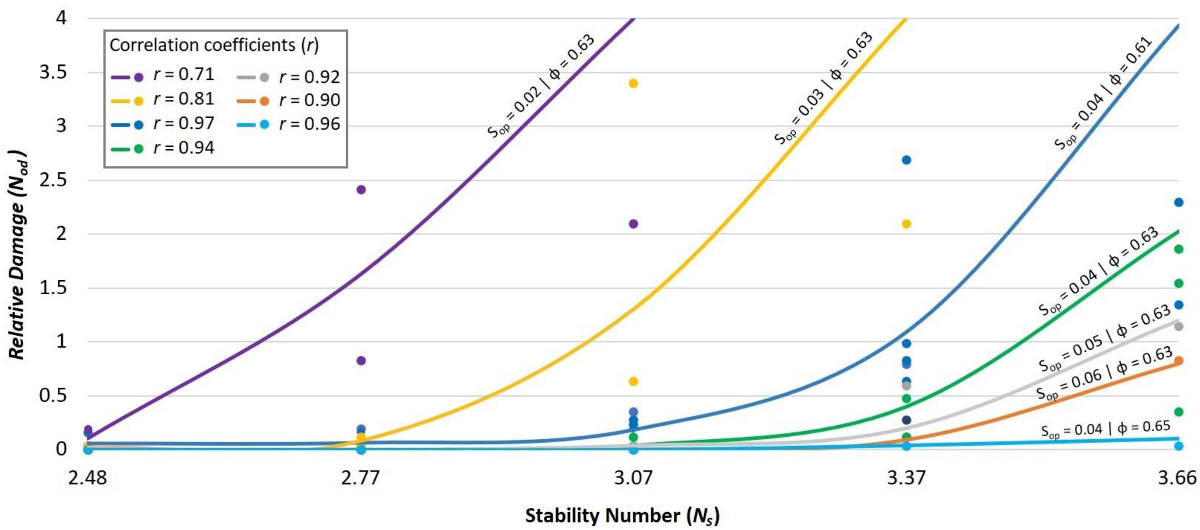

Figure 6. Behavioural trends of the Cubilok on a 3V:4H slope based on wave steepness and packing density.

Behavioural trends of the additional scenarios are not included in Figure 6 since these tests included variations to parameters that are outside the original scope of this study. The observations and outcomes of the additional scenarios are however discussed in the subsequent sections.

4 OBSERVATIONS AND DISCUSSION

4.1 Armour layer packing density

The armour layer packing density has a significant influence on the behaviour and stability of the Cubilok. During the early stages of this study, it was determined that the stability of the Cubilok cannot be guaranteed for $\phi = 0.61$. When increasing ϕ from 0.61 to 0.63, the armour layer remained susceptible to large armour unit displacement during conditions with larger wave heights and longer wave periods ($S_{op} < 0.04$). A single test series was conducted at a tighter packing of $\phi = 0.65$, which significantly improved the stability of the armour layer.

4.2 Slope response to wave steepness ($\phi = 0.63$)

The performance of the Cubilok is sensitive to changes in the wave steepness given the significant difference in the stability of the armour layer during tests with $S_{op} > 0.04$ and $S_{op} < 0.04$. Conditions with lower wave steepness (or longer wave periods) resulted in greater settlement earlier into testing and the damage progression was also faster. This caused the slope to start deteriorating sooner and it ultimately failed at lower wave heights.

4.3 Number of rows placed on a slope

A single test series was conducted for this setup to determine if the number of rows placed on a slope influences the stability of the Cubilok. While placing only 15 rows did reduce the amount of movement on the slope, using a packing density of $\phi = 0.63$ still resulted in appreciable settlement. No units were extracted from the slope by the end of the series and the damage number was therefore zero for $N_s = 3.7$. This result shows that the number of rows appears to have an influence on the stability of the armour layer, however not enough testing was done to quantify the effect. This variable also affects other single layer armour units in a similar way, therefore a maximum number of rows is usually prescribed by the developers. This still needs to be determined for Cubilok.

4.4 Influence of underlayer material

No significant improvement to the Cubilok stability was observed when the nominal mass of the underlayer material was increased from $W/10$ to $W/5$. Rather, the outcome of the two test series that were conducted showed that the use of larger underlayer material slightly reduced the stability of the armour layer. A possible explanation is that when the stone size of the underlayer is increased, the natural roughness at the layer interface is also increased. This means that the number of contact points with the Cubilok units are reduced, and consequently the interaction between the underlayer and armour layer is weakened.

The results of these two test series suggest that the stability of the Cubilok is more reliant on friction between the armour layer and the underlayer, rather than interlocking between the two layers. This suggestion is supported when considering that the ends of the Cubilok arms are pyramid-shaped, which have a lesser tendency to penetrate the underlayer material as opposed to arms with flat ends. When a Cubilok is placed in such a way that three of its arms make contact with the underlayer, then there are essentially three flat surfaces resting on the underlayer surface. This is better illustrated in Figure 7, which shows a simplified placement of the Cubilok on a 3H:4V slope, as well as the same for three other commonly used armour units.

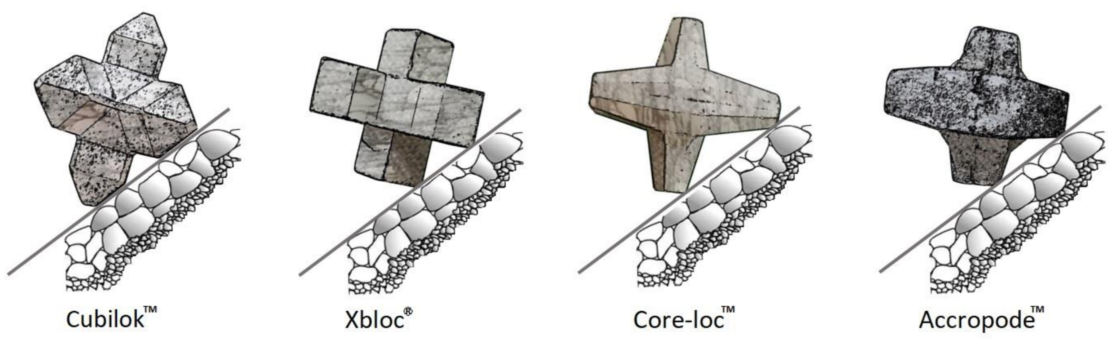

Figure 7. Simplified placement of various single layer armour units to illustrate its interaction with the underlayer.

The behavioural suggestions mentioned above are based on observations made during testing and require additional experimental support to verify the results.

4.5 Effect of structure slope

For the two test series that were completed with a milder slope of 1V:2H, both resulted in much lower cumulative settlement when compared to all previous tests. The minor settlement that was recorded is considered acceptable for design, and smaller displacements between $0.5 \cdot D_n$ and D_n affected less than 1% of the units on the slope. There were no extractions, nor unit displacements greater then D_n after the highest wave height was simulated, and therefore N_s will be greater than 3.7. The outcome of these two test series suggests that the steepness of the armour layer slope has a significant influence on the behaviour of the Cubilok, where superior stabilities can be achieved on flatter slopes. With reference to Section 4.4, the results also seem to support the idea that the Cubilok's stability is reliant on friction between the armour layer and the underlayer. This is better illustrated in Figure 8 where the fundamentals of friction on a slope are illustrated.

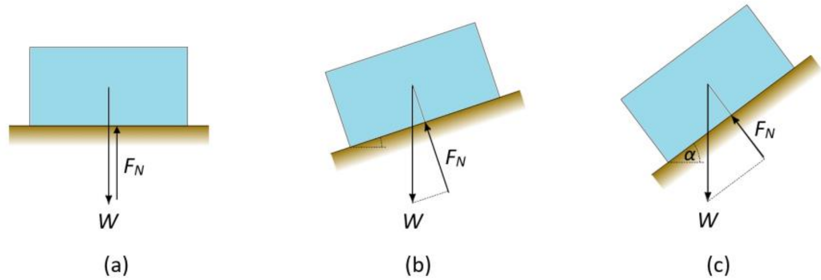

Figure 8. Fundamentals of friction on a slope.

According to Meriam and Kraige (2003), friction is the tangential forces between contacting surfaces that oppose the tendency of an object to move. Friction is proportional to the force normal to the surface (F_N), which is at its greatest when the contacting surfaces are horizontal (Figure 8 - a). When the contacting surfaces are at an inclination, F_N decreases by $\cos \alpha$ (where α is the angle of the slope), thus friction decreases as the slope becomes steeper (Figure 8 - b and c). The fundamentals illustrated by Figure 8 is a simplified representation of the Cubilok-underlayer interaction, and reference should also be made to the discussion of Section 4.4. These behavioural suggestions are from limited testing, therefore further experimental support will be required to confirm this behaviour.

4.6 Cubilok stability function for ϕ = 0.63 on a 3V:4H slope

Damage results of different test setups for ϕ = 0.63 on a 3V:4H slope were plotted on a single graph. Variability in the setups included that of the wave steepness, where S_{op} was varied from 0.02 to 0.06, as well as the number of waves, which was either 1 000 or 2000. These plots are shown in Figure 9.

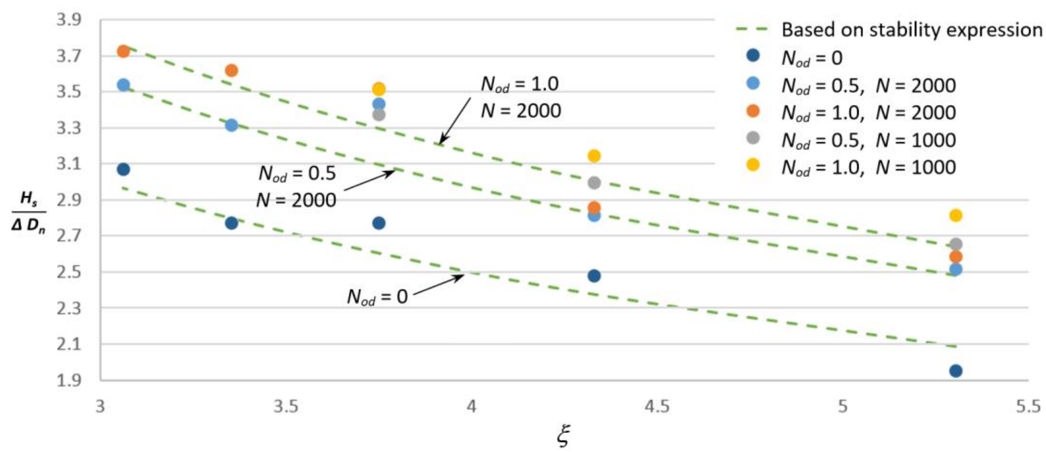

Figure 9. Cubilok damage plots for different wave steepness values and the number of waves per test. These plots are valid for ϕ = 0.63 on a 3V:4H slope.

Using the data points included in Figure 9, as well as curve fitting techniques, an expression was developed to describe the stability of the Cubilok on a 3V:4H slope and a packing density of ϕ = 0.63. Given the initial focus of this study, the stability function was limited to these parameters only. The test slope for the setups remained constant, therefore $\cot \alpha$ and consequently, the surf similarity parameter ξ, could be omitted from this expression. The stability expression therefore assumes a basic relationship between the Cubilok stability, the relative damage, wave steepness and the number of waves. This expression is given by Equation (7).

$$\frac{H_s}{\Delta \cdot D_n} = \left(13 \cdot \frac{N_{od}^{0.5}}{N^{0.25}} + 7.5\right) \cdot S_{op}^{0.32} \quad (7)$$

The stability curves included in Figure 9 were derived using Equation (7). These curves show that the stability of the Cubilok is significantly influenced by the wave steepness and thus, the wave period. The plots further show that the effect of the test duration, thus the number of waves (N), is less pronounced. Lastly, the plots for start of damage and those of more severe damage are not spaced very closely together, implying that damage progression is relatively slow and that the structure fails in a more gradual way. This behaviour is valid for ϕ = 0.63 on a 3V:4H slope, where the N_{od} value associated with initiation of damage is 0.5 and initiation of destruction is 1.5.

Figure 10 shows a comparison between the stability of the Cubilok and that of other artificial armour units. The curves shown for Cubilok are for a 3V:4H slope and a packing density of ϕ = 0.63, whereas the stability of the other units was described by Van der Meer (1988b), Bonfantini (2014) and Medina and Gomez-Martin (2016). The parameters used to determine each damage curve are also provided.

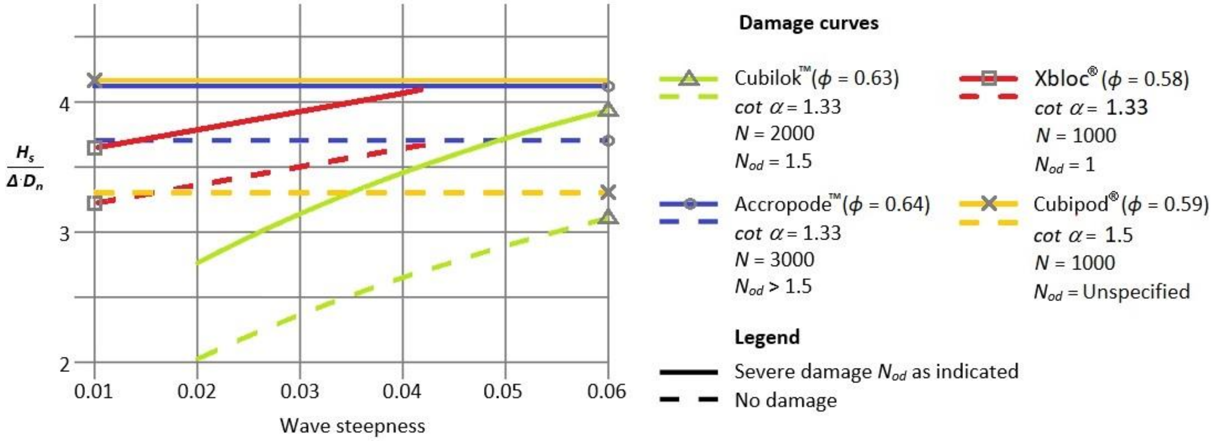

Figure 10. Comparison of Cubilok stability to that of other artificial armour units. Adapted from Van der Meer (1988b), Medina & Gomez-Martin (2016) and Bonfantini (2014).

From Figure 10, it can be seen that the stability of the Cubilok on a 3V:4H slope is dependent on the wave steepness. The plots also show an intermediate damage progression for the Cubilok, which is indicated by the spacing between the "No damage" and "Severe damage" curves. Stability numbers were determined for the Cubilok with ϕ = 0.63 based on the tests conducted in this study, which range between N_s = 2.3 to 2.6. These include a recommended safety factor of 1.25, which is the same as that for Xbloc® (Bonfantini, 2014). This safety factor was selected given the high resilience of the slope before failure and is lower than the safety factor of 1.5 recommended for Accropode™. By assuming the lower end of the stability number range for design purposes, thus N_s = 2.1, the Cubilok will have a K_D value of 12 for zero damage when placed on a 3V:4H slope with ϕ = 0.63.

The behaviour of Cubilok at ϕ = 0.65 was not included in Figure 10, since only one test series was conducted at this packing density. Nonetheless, the outcome of this test series shows that an N_s value of 3.1 was found for zero damage and the maximum damage number of N_{od} = 0.04 was reached at N_s = 3.7. Failure of the slope was never achieved since waves became depth limited when attempting to generate higher wave conditions. This outcome was compared to a study done by Bonfantini (2014) for Accropode™ and Xbloc®, and the comparison shows that the stability for Cubilok at ϕ = 0.65 was similar to that of these units. This comparison is shown in Figure 11, which includes only one outcome for the Cubilok. Given the gradual degradation of the Cubilok armour layers, failure at ϕ = 0.65 is expected for an N_s value greater than 4.0. This is also true for Cubilok on a 1V:2H slope (ϕ = 0.63) where an N_s value of 3.7 was found for zero damage.

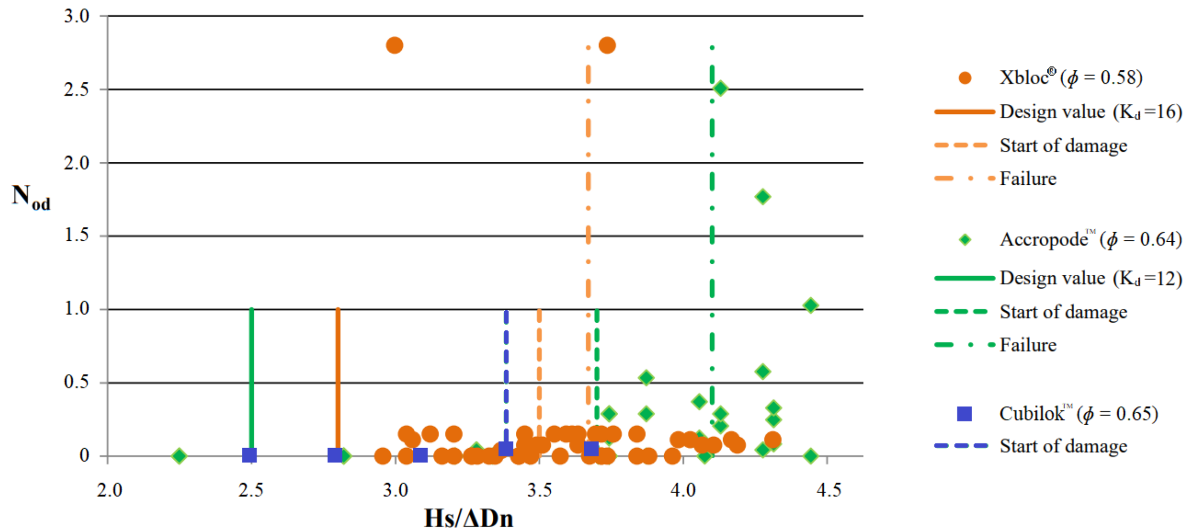

Figure 11. Stability results for ϕ = 0.65 and comparison with Accropode™ and Xbloc® (adapted from Bonfantini, 2014).

The limitation to this study was that greater wave heights could not be achieved at the structure toe owing to depth limiting conditions inside the flume. Additional physical modelling tests are therefore recommended to verify the design parameters and limitations for Cubilok at ϕ = 0.65 and on a 1V:2H slope respectively.

5 CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to investigate the behaviour of the Cubilok on a 3V:4H slope. It was observed that the wave steepness has a significant influence on the performance of the Cubilok, where superior stabilities were recorded during conditions with shorter wave periods. When placed on a 3V:4H slope, the stability of the Cubilok is comparable to that of other concrete armour units, however, it is susceptible to severe settlement. The performance of the Cubilok can probably be enhanced through denser packing, where a single test series with ϕ = 0.65 showed a damage reduction of more than 10% when compared to results of ϕ = 0.63. The stability of the Cubilok can probably also be significantly enhanced when constructing on a milder slope. When considering the results of the two test series conducted on a 1V:2H slope, both resulted in zero extractions at N_s = 3.7 and much lower cumulative settlement when compared to all tests on a 3V:4H slope. The minor settlement that was recorded is considered acceptable for design. More tests are recommended to confirm these promising findings on the improved performance. Note that using a higher packing density means that more Cubilok units must be used. Placing the Cubilok units on a milder slope, increases the area to be covered by the Cubilok units. As a result, the cost will increase; however, the stability of the armour layer is better.

This study found no evidence to support the idea that larger underlayer material will enhance the performance of the Cubilok. In contrast, the two test series conducted showed that larger stone sizes will adversely affect the armour layer stability, since the Cubilok shape does not allow the units to interlock with the underlayer in the same way as other single layer armour units. The observations made regarding the larger underlayer material, as well as for the flatter slope suggests that the stability of the Cubilok is more reliant on friction between the armour layer and the underlayer, rather than interlocking between the two layers. However, this suggestion is based on limited test results and require additional experimental support to verify this behaviour.

FOOTNOTE

This study formed part of a master's research project carried out by Carl Wehlitz at Stellenbosch University. Model testing was carried out independently by the author, and the study is regarded as an initial investigation to determine the limitations and potential of the new Cubilok unit. The content of this article is therefore focused on the unit's behaviour on a 3V:4H slope and excludes other focus areas such as the structural strength, commercial viability, etc. The findings of this research can be used to outline more refined future studies with greater in-depth focus on certain characteristics of interest.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Council for Scientific and Industrial Research (CSIR) for the use of their physical model laboratory and research facilities, as well as providing financial support for this study. PRDW Consulting Ports and Coastal Engineers is also acknowledged for their inputs and support pertaining to this research, as well as supplying the model armour units used in this study.

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