Design of Concrete Armour Layers

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Introduction

Rubble mound breakwaters and seawalls have been built for centuries and are still commonly applied. The outer slopes of these structures force storm waves to break and dissipate wave energy. Rubble mound structures are favourable as they can be constructed with limited equipment, resources and professional skills, damage will mostly increase gradually, repair works can be easily executed and due to their flexibility they are not sensitive to differential settlements.

Rubble mound breakwaters are mostly built of quarried rock. Larger armour stones are generally used for the outer layer to protect the structure against wave attack. The wave loads during a design storm may show the need for an armour rock size, which cannot be economically produced and transported to the site. Concrete armour units then become a competitive alternative.

Various design formulae are available for the more common types of concrete armour units. Secondary effects that are not considered in these design formulae may have significant influence on the armour layer stability. The designer's experience and insight into the functioning of armouring systems is therefore essential for a proper armour layer design. This article is intended to provide some guidance for the choice of armour unit type and for the design of concrete armour layers.

Concrete Armour Unit Types

The first artificial armour units were parallel-epipedic concrete blocks (cubes). Various attempts have been made to improve the stability and porosity of cube armouring and to reduce the concrete demand, which finally led to two basic armouring concepts for concrete armour units: Randomly placed interlocking armour units and uniformly placed friction type armouring. A variety of concrete armour units is presently available (see Table 1).

For *randomly placed armour units* the governing stability factors are own weight and interlocking (Table 1). Armour units with a simple bulky shape as Cube, Antifer Cube and Modified Cube are mainly stabilised by their own weight and only to a limited extend by interlocking. The armour unit development after 1950 went from slightly interlocking armour units with relatively simple shape (as Tetrapod and Akmon) to more economical highly interlocking armour units with a more complex shape (as Dolos and Stabit). The increase in interlocking capacity has been achieved by an optimised block shape with increased slenderness. The safety concept for breakwater armouring has been reconsidered after the failure of the Sines breakwater (Portugal) in 1978. Armour units had been placed in two layers in order to cover the uncertainties with respect to hydraulic stability and structural integrity of individual armour units. Since 1980 armour units have been placed in a single layer with higher safety margins for the hydraulic design and increased structural strength of individual units. The Accropode™ was the first randomly placed single layer armour unit introduced in 1980 and was followed by Core-loc® and Xbloc®.

Uniformly placed armour units are typically parallel-epipedic hollow blocks with either simple (as Seabee and Diahitis) or complex shape (as Cob and Shed). The placement is uniform in a single layer (cobblestone-concept). The governing stability factor between neighbouring blocks is friction (Table 1).

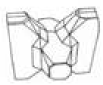
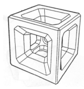
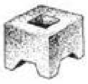
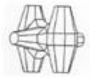
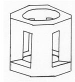
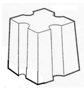
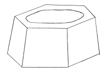
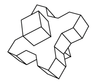
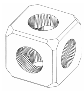
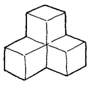
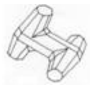
Randomly placed armour units			**Uniformly placed armour units**
Double layer placement		Single layer placement	
Stability factor: Own weight	Own weight and interlocking	Interlocking	Friction
Cube 	Tetrapode France, 1950 	Accropode France, 1980 	Cob UK, 1969 
Modified Cube USA, 1959 	Akmon NL, 1962 	Core-loc® USA, 1996 	Diahitis Ireland, 1998 
Antifer Cube France, 1973 	Tribar USA, 1958 	A-Jack USA, 1998 	Seabee Australia, 1978 
Haro Belgium, 1984 	Stabit UK, 1961 	Xbloc NL, 2003 	Shed UK, 1982 
Tripod NL, 1962 	Dolos South Africa, 1963 		

Table 1: Overview of breakwater armour units

Choice of Armour Units

A rule of thumb for preliminary design: For moderate design wave conditions and at sites where rock material of sufficient quality, size and quantity is available the first choice for armouring will mostly be rock for economical and possibly also for esthetical reasons. Artificial armour units may be required for more severe design conditions or at sites where rock is not available at sufficient size and quality. The most efficient and economical type of armouring shall be selected with respect to (i) structural and hydraulic stability (including the risk of progressive damage), (ii) fabrication, storage, handling and placement of armour units and (iii) maintenance and repair of armour layers.

Uniformly placed armour units - hollow blocks

The stability of uniformly placed hollow blocks is based on friction between neighbouring blocks and depends primarily on layer thickness and partly also on unit weight. The friction between uniformly placed blocks is less variable than the interlocking between randomly placed blocks. Friction type armour layers are therefore more homogeneous than interlocking armour layers and very stable. Hudson stability coefficients K_D up to 100 have been determined in model tests. The required safety margins for the hydraulic design of hollow block armour layers are smaller than for interlocking armour layers. Other advantages of hollow blocks are single layer placement, relatively small armour blocks, placement of multiple blocks and a relatively high porosity of the armour layer (advantageous with respect to concrete savings and hydraulic performance, see Figure 1).

The hollow block units can be manufactured either on site or in a factory. Fibre reinforcement is recommended for slender armour units as Shed and Cob to improve the handling stress resistance.

Figure 1: Shed armouring at Burj al Arab Hotel, Dubai, UAE

The placement of hollow block armour on slopes with complex geometry (curved section, roundhead etc.) requires spacers. The underwater placement of hollow blocks requires final placing by divers and a pre-fabricated concrete toe. In a harsh environment underwater placement will be almost impossible. Therefore it has to be checked from case to case if friction type armour units are applicable. If so, it might be a cost efficient alternative for conventional concrete armour units. However, this will be the case mostly for revetments; friction type armour is not recommended for exposed breakwaters.

The design scheme for hollow block armour units is completely different from a conventional armour layer design. Generally accepted design procedures are not available. The transition stability at toe and lateral boundaries and the risk of progressive failure have to be addressed. The developers of the various armour units will advise on preliminary design. The final design shall be tested extensively in hydraulic models.

Randomly placed armour – double layer armouring

Cube armour units are normally placed in two layers. The second layer acts as a separator for the blocks of the first layer. Otherwise settlements could rearrange the Cubes of the first layer whereby it will finally form an almost solid layer. Random placement of Cubes is a tedious procedure as the blocks are commonly gripped with clamps, the block orientation does not vary and the risk of unwanted uniform placement is inherent (Figure 2). A random placement is important for Cubes in order to guaranty the porosity of the armour layer and to prevent Cubes from being lifted by excess pore pressure that develops inside the breakwater.

Most double layer concrete armour units as Tetrapod, Dolos, Tribar, etc. are placed according to a positioning plan with either randomly varying or predefined block orientation. The second layer is necessary to create interlocking. Thus, the second layer shall be considered as integral part of the armouring system; it does not provide extra safety. The armour units of the second layer tend to rock and have an aggravated risk of breaking.

Figure 2: Beakwater roundhead with Cubes, Port of Scheveningen, NL

The structural stability of several commonly used double layer armour units has been extensively studied after the failure of the Sines Breakwater (1978). Possible reasons for breakage of armour units are static failure and construction related breaks. However, most of the breakages are induced by movements. Armour units with slender shape as Dolos and Tribar, with a relatively slender central section and long legs will face high stresses in central part of the armour block and have a relatively high risk of breaking in the central part (Figure 3). Broken armour units have little residual hydraulic stability; an adequate reinforcement of slender armour units is uneconomical.

Double layer randomly placed armour is sensible for compact armour blocks, which provide large structural stability and which are stable mainly due to their own weight (as Cube, Antifer Cube etc.). However, such a design will be most probably uneconomical with respect to (a) the total volume of concrete and (b) the equipment for the placement of these large blocks (including the necessity of a wider breakwater crest). An improved design with more slender, interlocking double layer armour units will probably reduce the construction cost and increase the costs for maintenance because slender blocks as Dolos, Tetrapod and Tribar tend to rock and to break. Hence, frequent monitoring and regular replacing of broken armour units will be necessary. The placement of double layer armouring on flat slopes is mostly uneconomical.

Figure 3: Breakage of armour units: Cubes (left) and Dolos (right)

Randomly placed armour – single layer armouring

Single layer randomly placed armour units have been applied since 1980. The Accropode™ was the first block of this new generation of armour units and became the leading armour unit worldwide for the next 20 years. Core-loc® (1994) and Xbloc (2003) are further examples of this type of armour unit that have been developed subsequently (Figure 4). Single layer armour units are economically and technically advantageous with respect to the total number of armour units per unit area of slope and to the lower susceptibility to rocking.

Figure 4: Single layer armour units: Accropode™ (6.2 m^3, Scarborough, UK), Core-loc® (15 m^3, Kaumalapau Harbor, Hawaii) and Xbloc (4 m^3, Port Oriel, Ireland)

The *Accropode*™ was intended to balance hydraulic stability by interlocking and structural strength. The latter is excellent; no significant breakage of Accropode™ armour units during placement or service has been reported. Accropodes™ are placed in a single layer in a predefined grid whereby the orientation of the blocks has to be varied; the latter is typically specified. Various sling techniques are recommended for placement. However, sling techniques and grid placing do not guarantee a proper interlocking. The hydraulic stability is very sensitive to placement and therefore rather conservative stability coefficients are recommended for design. The best interlocking of Accropodes™ can be achieved on steep slopes.

The *Core-loc*® is a further development of the Accropode™. It is more slender and the shape of the legs is a true copy of the Dolos; Core-loc® can therefore be applied as repair units for Dolos armour layers (Figure 5). The hydraulic stability of Core-loc® armour units is better than that of Accropode™; however the recommended stability coefficients for design are close to those for Accropode™. The structural integrity of Core-loc® is less than that of Accropode™. Higher quality concrete or fibre reinforcement have been applied to improve the structural integrity. The placement procedures for Core-loc® and Accropode™ are similar; various sling techniques are applied for both types of armour units.

Figure 5: Repair of Dolos armouring with Core-loc® (Jetties at Manasquan Inlet, New Jersey, USA)

The *Xbloc* is a compact armour unit with large structural strength (similar to Accropode™). The hydraulic stability of Xbloc armour layers is similar to that of Accropode™ and Core-loc® armouring. Xbloc units are placed on a predefined grid; the orientation of individual blocks varies randomly and is thus not prescribed. The latter is the main difference between Xbloc and other single layer interlocking armour units.

Application of Cubes in a single layer has been studied in hydraulic model tests (Van Gent et al, 1999). Single layer Cubes form an armour layer with a relatively smooth surface and little porosity. Wave overtopping will be therefore most probably increased.

Randomly placed single layer concrete armour units are the most advanced breakwater armour units. They are applicable for exposed breakwaters, can be placed in deep water and can withstand severe wave loads. Single layer placement is significantly more cost efficient than double layer armouring. A properly designed single layer armouring requires less maintenance than double layer armour. A relatively large safety margin is typically applied for the hydraulic stability of single layer armour units. It is further essential that the structural integrity of armour units is guaranteed either by selecting armour blocks with a compact shape or by preventing rocking of armour units.

Design of armour layers

Hollow blocks

No generally accepted approach for the design of hollow block armouring has been developed yet. For the application of hollow block armouring it is recommended to request design guidelines from the developers. Reference is made to Allsop and Jones (1997) for the design of Cob and Shed armouring.

Armour unit	Country	Year	Developer
Cob	UK	1966	Coode & Partners, London
Seabee	Australia	1978	University New South Wales
Shed	UK	1982	Shephard Hill Civil Eng. Ltd.
Haro	Belgium	1984	University Ghent
Diahitis	Ireland	1998	University Cork & Ascon

Table 2: Development of hollow block armour units

Randomly Placed Armour Units

The basic design formulae for armour layers with randomly placed concrete units as well as the conversion of governing geometric parameters are summarised in Table 3.

The required armour unit size (nominal diameter D_n) can be assessed by a stability formula, for example the Hudson formula:

$$\frac{H_D}{\Delta D} = \sqrt[3]{K_D \cot\alpha} \quad ; \quad \Delta = \left(\frac{\gamma_c}{\gamma} - 1\right)$$

with design wave height H_D, Hudson stability coefficient K_D, specific density of water γ and concrete γ_c, breakwater slope angle α and stability number $H_D/\Delta D$. It should be noted that the effect of slope angle α will be limited for interlocking armour units.

Armour unit volume, nominal diameter and characteristic length:	$V = \left(\frac{W}{\rho_c}\right) = D_n^{\ 3} = k_s\, C^3$
Centre to centre distance between armour units:	$\Delta x = X_c\, C = X\, D_n \quad ; \quad X = X_c\, / \, k_s^{1/3}$ $\Delta y = Y_c\, C = Y\, D_n \quad ; \quad Y = Y_c\, / \, k_s^{1/3}$
Area covered by one armour unit:	$A = \frac{\Delta x\, \Delta y}{n} = \frac{X_c\, Y_c\, C^2}{n} = \frac{X\, Y\, D_n^{\ 2}}{n} = \frac{1}{N}$
Armour layer thickness:	$t = n\, k_\Delta\, D_n = n\, k_C\, C \quad ; \quad k_C = k_\Delta\, k_s^{1/3}$
Packing density:	$N = \frac{t\,(1-p)}{V} = \frac{n\, k_\Delta\,(1-p)}{D_n^2} = \frac{k_p}{D_n^2} = \frac{k_p}{k_s^{2/3}\, C^2} = \frac{1}{A}$ $k_p = n\, k_\Delta\,(1-p)$
Armour layer porosity:	$p = 1 - \frac{k_s^{2/3}}{X_c\, Y_c\, k_\Delta} = 1 - \frac{1}{X\, Y\, k_\Delta} = 1 - \frac{V}{A\, t}$
Concrete volume:	$V_c = N\, V = t\,(1-p)$

with:			
	V	armour unit volume = $D_n^{\ 3}$	[m³]
	D_n	nominal armour unit diameter	[m]
	C	characteristic armour unit length	[m]
	W	armour unit mass	[kg]
	ρ_c	specific density of concrete	[kg/m³]
	Δx, Δy	horizontal & upslope centre to centre distance between units	[m]
	X, Y, X_c, Y_c	dimensionless horizontal & upslope distances	[-]
	A	area covered by one armour unit	[m²]
	N	packing density (number of armour units per unit area)	[1/m²]
	t	armour layer thickness	[m]
	p	armour layer porosity	[-]
	n	number of layers	[-]
	k_s	shape coefficient	[-]
	k_Δ	layer coefficient	[-]
	k_C	modified layer coefficient	[-]
	k_p	packing density coefficient	[-]
	V_c	concrete volume per unit area	[m³/m²]

Table 3: Basic design formulae for randomly placed armour layers

The damage to armour layers of randomly placed concrete units can be quantified by the damage numbers N_d and N_{od}:

- Damage number N_{od}: Number of displaced armour units within a strip of breakwater slope of width D_n (nominal diameter of armour units);
- Damage number N_d: Number of displaced armour units referred to the total number of armour units placed within a certain range from design water level (a range of ±1.5 H_D (design wave height) is typically considered).

Typical values of N_{od} and N_d for certain damage levels are listed in Table 4.

Armour type	Damage number	Start of damage	Intermediate damage	Failure
Cube	N_{od}	0	–	2
Tetrapod		0	–	1.5
Accropode™		> 0	–	> 0.5
Cube	N_d	–	4%	–
Dolos		0% – 2%	–	≥ 15%
Accropode™		0%	1% – 5%	≥ 10%

Table 4: Characteristic damage levels for various types of concrete armour units (CEM, 2003)

Stability formulae for various types of armour units have been developed a.o. by van der Meer (1988), Burcharth and Liu (1992) and Burcharth (1998) (see Table 5). The empirical coefficients c_1 to c_6 are also listed in Table 5 for various types of armour units. The proposed stability formula bear significant uncertainties (standard deviations for $H_s/\Delta D_n$ of about 20% for Accropode™ and Dolos and 10% for Cube and Tetrapod) and are not necessarily applicable for design. The stability numbers listed in Table 8 are therefore recommended for design.

stability number: $$\frac{H_s}{\Delta D_n} = c_1 + \left(c_2 + c_3 \frac{N_{od}^{c_4}}{N^{c_5}} \right) s_{0,m}^{c_6}$$

with: N storm duration (number of waves, typically 1000 – 3000)
$s_{0,m}$ wave steepness $H_s\, 2\pi/(g\, T_m)$

	Cube	Tetrapod	Accropode™	Dolos	Accropode™
	van der Meer (1988)			Burcharth & Liu (1992)	Burcharth (1998)
c_1	0	0	3.7 2)	0	3.5 3)
c_2	1.0	0.85	0	0	0
c_3	6.7	3.75	0	7.67 1)	0
c_4	0.4	0.5	0	0.33	0
c_5	0.3	0.25	0	0.1	0
c_6	-0.1	-0.2	0	0	0

1) may vary with waist to height ratio and packing density
2) corresponds to no damage (failure: c_1 = 4.1); design values see Table 8
3) corresponds to no damage (failure: c_1 = 3.8); design values see Table 8

Table 5: Empirical coefficients of stability formula for concrete breakwater armour units

Double Layer Armouring

Table 6 gives some guidance on the hydraulic stability of the most commonly applied double layer armour blocks. For further details reference is made to CEM 2003, BS6349 Part 7 and SPM 1977/84.

Armour unit	Country	Year	Hudson stability coefficient K_D				Slope
			trunk		head		
			breaking waves	non-breaking	breaking waves	non-breaking	
Cube	–	–	6.5	7.5	n.a.*)	5	1:1.5 – 1:3
Tetrapod	France	1950	7	8	4.5	5.5	1:2
Tribar	USA	1958	9	10	n.a.	8.5	1:2
Stabit	UK	1961	10	12	n.a.	n.a.	–
Akmon	NL	1962	8	9	n.a.	n.a.	–
Dolos	RSA	1963	16	32	8	16	1:2
Antifer Cube	France	1973	7	8	n.a.	n.a.	–
Haro	Belgium	1984	8	9	n.a.	n.a.	–

*) not available

Table 6: Hydraulic stability of double layer armour units

Figure 6: Double layer armouring: Cubes (left) and Tetrapods (right)

Cube: Typical parameters of Cube armour layers (2 layers, randomly placed, see Figure 6) are given in Table 7. The stability number for Cube armouring is increasing with the level of acceptable damage N_d (or N_{od}) and is slightly decreasing with increasing wave steepness. It may be further affected by the slope; however the effect of the slope is uncertain. Typical stability numbers for Cubes with a damage level of about 0 – 5% (initial damage) are listed in Table 8. Modified cubes might be more effective with respect to interlocking (as the Antifer Cube) or with respect to armour layer porosity and packing density (as the Haro).

Tetrapod: Typical parameters of Tetrapod armour layers are presented in Table 7 (further details on Tetrapod shape can be found in SPM, 1984). The stability of Tetrapod armouring is increasing with the level of acceptable damage N_d (or N_{od}) and is slightly decreasing with increasing wave steepness. It may be further affected by the slope; however the effect of slope is uncertain. Typical stability numbers for Tetrapode armour with a damage level of less than 5% (initial damage) are listed in Table 8.

Dolos: The shape of Dolos armour units may vary with size. The waist (diameter in centre part) to height ratio for Dolos is typically 0.32; an increased waist to height ratio is recommended for larger units (0.34 for units of 20 t and 0.36 for units of 30 t). The waist to height ratio *r* for larger Dolos units (≥ 20 t) can be assessed by:

$r = 0.34\ (W / W_{20})^{1/6}$ with block weight W [t] and W_{20} = 20 t.

The unit weight of Dolos shall not exceed 30 t (see Figure 7). Typical parameters of Dolos armour layers are listed in Table 7 (further details on Dolos shape can be found in SPM, 1984).

The stability of Dolos armouring is decreasing approximately linearly with increasing waist ratio. It is further increasing with the acceptable damage level N_d (or N_{od}). The packing density and the slope may also affect the stability, however the effect of packing density and slope is uncertain and shall be tentatively neglected.

Typical stability numbers for Dolos armouring on a 1V:2H slope with a damage level of about 2% (initial damage) are listed in Table 8. Increased storm duration of 3000 waves (instead of 1000 waves) will reduce the stability number by about 10%.

Figure 7: Transport and placement of Dolos units (30 t), Coega Port, South Africa

Armour units		layer coefficient	shape coefficient	distance between units				porosity	packing density coefficient	modified layer coefficient
				horizontal	slope-parallel	horizontal	slope-parallel			
type	size [m³]	k_Δ [-]	k_s [-]	$\Delta x/C$ [-]	$\Delta y/C$ [-]	$\Delta x/D_n$ [-]	$\Delta y/D_n$ [-]	n_v [-]	k_p [-]	k_C [-]
Cube (2 layers)		1.10	1.0	1.70	0.85	1.70	0.85	0.37	1.38	1.10
Tetrapod		1.02	0.280	1.295	0.650	1.98	0.99	0.50	1.02	0.667
Dolos (*r* = 0.32)[1)]		0.94	0.16	1.19	0.595	2.19	1.10	0.56	0.83	0.51
Accropode™	< 5	1.29	0.341	1.24	0.600	1.77	0.86	0.491	0.656	0.9012
	5 – 12			1.27	0.635	1.82	0.91	0.531	0.605	
	> 12			1.30	0.650	1.86	0.93	0.552	0.578	
Core-loc®	< 5	1.516	0.2236	1.11	0.555	1.83	0.91	0.606	0.598	0.9201
	5 – 8.5			1.12	0.560	1.85	0.92	0.613	0.587	
	8.5 – 12			1.125	0.565	1.85	0.93	0.618	0.580	
	> 12			1.135	0.570	1.87	0.94	0.624	0.569	
Xbloc	< 5	1.40	0.333	1.30	0.64	1.87	0.92	0.587	0.578	0.97
	5 – 12			1.33	0.655	1.92	0.94	0.606	0.552	
	> 12			1.36	0.67	1.96	0.97	0.623	0.528	

[1)] r = waist to height ratio (waist of central section and total height of unit)
[2)] packing density

Table 7: Characteristics of concrete armour layers (randomly placed blocks)

Single Layer Armouring

Single layer armouring is generally designed for no damage; even low damage levels of 0–5% are not accepted. In order to guaranty the functioning of the armour layer even during a design storm the hydraulic design of single layer armouring has a relatively large safety margin. Under design conditions single layer armouring should show no damage and only minor rocking. The armour layer should be further able to withstand an overload of about 20% (design wave height exceeded by 20%) without significant damage. For a properly designed single layer armouring a damage progression and a resulting failure of the armour layer will be associated with a significant exceedence of the design conditions.

Note: There is no generally agreed definition for rocking, start of damage and failure of single layer armour units. The following values are proposed as guidance for hydraulic model testing: minor or significant rocking shall refer to less or more than 3% of rocking units, respectively; start of damage and critical damage (failure) shall refer to 0.5% and 3% displaced units. The percentage of rocking and displaced units shall be defined with respect to the total number of units placed within a range of $\pm H_D$ (design wave height) from design water level.

Interlocking single layer armour units (i.e. Accropode™, Core-loc® and Xbloc) are typically applied on slopes 1:1.33 – 1:1.5. They can be applied efficiently on slopes 1:1.25 – 1:2. The stability is not affected by the slope angle (i.e. no increase of stability on flatter slopes). Characteristic design parameters are summarised in Table 7. The stability numbers listed in Table 8 are recommended for preliminary design and correspond to no damage.

Figure 8: Single layer armouring: 6.3 m^3 Accropode™ (Scarborough, UK) and 4 m^3 Xbloc (Port Oriel, Ireland)

Accropode™: Accropodes™ should show only minor rocking under design conditions and should be able to withstand an overload of about 20%. Minor rocking is acceptable for Accropodes™ as these units are not susceptible to breakage (for further details see Sogreah, 2000). For breaking waves (depth induced breaking) and at the roundhead stability numbers shall be reduced by about 10%. A further reduction of stability numbers by about 10% is recommended for situations with depth limited wave heights in combination with steep foreshore slopes.

Core-loc®: As Core-loc® units are more slender than Accropodes™ there should be virtually no rocking under design conditions. The safety margin for the hydraulic stability of Core-loc® armour units is large enough to cover the effect of breaking waves; no reduction of stability numbers is recommended for breaking waves (see Table 8, for further details see Melby & Turk, 1997). The stability numbers shall be reduced by about 10% for steep foreshore slopes and in a roundhead.

Xbloc: The safety margin of the Xbloc design values is large enough to cover the effect of breaking waves (as for Core-loc®). Minor rocking will be accepted for Xbloc armouring under design conditions (as for Accropodes™). The armour layer should further withstand an overload of 20% without damage. As for other single layer armour units the stability numbers shall be reduced by about 10% for steep foreshore slopes and in a roundhead (see also Xbloc, 2003).

		stability number $H_s/\Delta D_n$				
		trunk		roundhead		
Armour type	damage level	non-breaking waves	breaking waves	non-breaking waves	breaking waves	references / remarks
Cube (2 layers)	0% (onset)	1.8 – 2.0		–		Brorsen et al. (1974) slope: 1:1.5 and 1:2
	4% (moderate)	2.3 – 2.6		–		
	0% (N_{od}=0)	1.5 – 1.7		–		van der Meer (1988) 1) slope 1:1.5
	5% (N_{od}=0.5)	2.0 – 2.4		–		
	< 5%	2.2	2.1	1.95	–	SPM (1984) slope 1:1.5
		2.45	2.35	2.15	–	slope 1:2
		2.8	2.7	2.5	–	slope 1:3
Tetrapod	0% (N_{od}=0)	1.7 – 2.0		–		van der Meer (1988) 1) slope 1:1.5
	5% (N_{od}=0.5)	2.3 – 2.9		–		
	< 5%	2.3	2.2	2.1	1.95	SPM (1984) slope 1:1.5
		2.5	2.4	2.2	2.1	slope 1:2
		2.9	2.75	2.3	2.2	slope 1:3
Dolos	*r* = 0.32 4)	2.7		–		Burcharth & Liu (1992) 2)
	r = 0.34 4)	2.5		–		
	r = 0.36 4)	2.3		–		
	r = 0.32 4)	3.2		–		Holtzhausen (1996) 3)
	r = 0.32 4)	3.2	2.5	2.5	2.0	SPM (1984)
Accropode™		2.7 (15)	2.5 (12)	2.5 (11.5)	2.3 (9.5)	recommended for design 5)
Core-loc®		2.8 (16.0)		2.6 (13.0)		recommended for design 5)
Xbloc		2.8 (16.0)		2.6 (13.0)		recommended for design 5)

1) storm duration = 1000–3000 waves; wave steepness = $s_{m,0}$ = 0.01–0.06
2) packing density k_p = 0.83; storm duration = 1000 waves
3) packing density k_p = 0.83
4) thickness to waist ratio *r*
5) in brackets: corresponding Hudson stability coefficient for a 3V:4H slope

Table 8: Stability of concrete armour layers (randomly placed blocks)

Note: The stability numbers for concrete armour units as presented in Table 8 provide guidance for preliminary design. Hydraulic model tests are strongly recommended for detailed design in order to check the hydraulic stability of the proposed armouring.

Concrete armour units in a roundhead

The armour layer stability at the roundhead is critical with respect to the exposure of the breakwater head and to the reduced interlocking of armour units:

- The breakwater head typically faces deeper water and larger design waves then the other breakwater sections. Parts of the roundhead are exposed to severe overtopping; the most critical section of the roundhead is at an angle of about 135° from the direction of wave incidence.
- Randomly placed armour units are typically placed on a grid in order to guarantee reasonable interlocking. However at the breakwater head the placement pattern will deviate significantly from a regular grid. The placement at the head is characterised by varying distances between

neighbouring amour blocks, varying packing density and mostly also by larger gaps in the armour layer. The interlocking at the head is further reduced by the convex shape of the underlayer.

The radius of the roundhead measured at design water level shall not be less than 3 times the design wave height for single layer armour units (as Accropode™, Core-loc® and Xbloc) in order to limit the convex shape of the underlayer and to prevent a significant reduction of interlocking. The design of the distorted placement grid in a roundhead requires special attention to minimise the adverse effects respect to interlocking.

Toe protection for concrete armour units

The design of the breakwater toe depends on the characteristics of the sea bottom, on the hydrodynamic loads and on the proposed construction method. For concrete armour units it is mostly more favourable to install the toe berm (of rock) after placing the armour units on the slope. Otherwise, a proper alignment of armour layer, under layer and toe berm might be difficult to achieve. An embedded toe is recommended for breaking waves and for steep foreshore slopes. The installation of the toe berm after the placement of the armour units is also the preferred construction method for an embedded toe.

For single layer randomly placed armour units (as Accropode™, Core-loc® and Xbloc) a double row of armour blocks can be applied as toe protection in shallow water (for breaking waves). The armour blocks shall be placed on a filter layer to prevent erosion of the seabed. A scour protection consisting of a top layer of larger rock (minimum width of 3 stone diameters) and a filter layer might be necessary to prevent displacement of armour blocks at the toe.

Rubble mound structures are relatively flexible structures that are able to deform and settle. Rigid toe structures are not in line with the design philosophy of rubble mound structures and might have adverse influence on the armour layer stability.

Figure 9: Placing the first row of Accropodes™ against a toe structure of concrete piles (Scarborough, UK)

A specific toe unit called Xbase was developed for Xbloc armouring. In contrast with a rock berm the Xbase units are interlocking with the armour layer. Xbase units can be more easily positioned on a rocky seabed or underlayer than conventional armour units (with a more symmetrical shape) and form a flatter toe. The latter is favourable with respect to the wave loading.

Figure 10: Xbloc toe units in a model and in prototype (Lagos, Nigeria)

Concluding remarks

Breakwater armour layers are primarily designed for hydraulic stability. Confirmative model tests are also targeted on the hydraulic stability of the proposed design. Structural integrity of armour units is not specifically addressed in the design process. Nonetheless, breakage of armour units can be disastrous for the armour layer stability and may result in severe damage and progressive failure of the armour layer.

It is strongly recommended that repeated rocking of armour units and settlements of the armour layer are recorded during hydraulic model tests. Rocking and settlements may indicate a significant risk of armour unit breakage.

It may be further advisable to apply larger armour units than required with respect to hydraulic stability, if these larger units can be handled with the available equipment. The safety margin for the armour layer will be increased by a larger block size. The additional costs for a slightly larger amount of concrete (with regard to the increased layer thickness) will be mostly compensated by savings in production, handling and placement, as the total number of armour units will be reduced.

The safety margins of an armour layer design should be carefully considered in case of depth limited wave conditions. A moderate storm in combination with an exceptional water level may result in overload conditions. The breakwater may be further frequently exposed to near-design conditions (offshore wave conditions with return periods of only a few years can result in near-design conditions at the structure). The structural integrity of armour units may be at risk due to frequent rocking. Depth limited wave heights are mostly associated with (a) frequent occurrence of near-design conditions and (b) increased risk of armour unit breakage. Both will increase the risk of damage and progressive failure of the armour layer.

A steep foreshore in combination with breaking waves (i.e. depth limited wave conditions) may further aggravate the wave loading on the armour layer. The breaker type on the foreshore may change (depending on foreshore slope and wave steepness) and result in more severe wave loads in case of a steep foreshore slope. A steep foreshore slope will further result in larger breaker heights at the structure (as compared to a gentle slope), which have to be considered in the armour layer design.

The occurrence of combined sea states (for example the joint occurrence of sea and swell waves) and the seabed characteristics in close vicinity to the structure may result in a local increase of wave loads that is not addressed in 2-dimensional hydraulic model tests. The safety margin of an armour layer should account for these effects.

It should be finally noted that armour unit placement in deeper water and in harsh conditions can be a difficult operation. Especially swell conditions may affect the placement speed and the accuracy of placement. The quality of placement in prototype (i.e. positioning and interlocking of armour units) may deviate from the placement pattern in a laboratory. Such deviations should be also covered by the safety margin of the design.

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