Design of concrete armour layers

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ABSTRACT: Most rubble mound breakwaters in the world have an armour which consists of two layers of units. Well known examples are rock, cubes, tetrapods and dolosse, but there are many more. The Accropode is the first unit that has been used in many applications as a randomly placed one-layer system. Recently the Core-loc has been added as a similar system. Also cubes in one layer have been tested and gave a similar behaviour with respect to damage development. Stability formulae have been presented for all these units and advantages and disadvantages discussed.

General stability formulae for cubes and tetrapods will be treated first. The influence of crest height on stability was investigated recently by changing the crest height of a breakwater with tetrapods. This influence can be described by an exponential function and can be added to the existing stability formula. Another influence on stability is the packing density. This influence has also been investigated for tetrapods, leading to an addition to the general formula. In fact, the additions for crest height and packing density can also be added (as a first guess) to the stability formula for cubes.

One-layer systems are discussed, starting with a stability formula for the accropode. A comparison is made with the Core-loc. Recent interest has been focussed on armour layers with a single layer of cubes or tetrapods. The tests for tetrapods showed very low stability, but the tests on cubes were very promising.

Finally, all the concrete units have been compared.

1 INTRODUCTION

The Hudson formula, written as a function of the stability number, is very often a part of a more recent stability formula containing more parameters. It is described by:

$$H_s / \Delta D_n = K_D (\cot\alpha)^{1/3} = f(\cot\alpha) \qquad (1)$$

The stability formulae for rock layers, given by Van der Meer (1988a and b), give the following relationship:

$$H_s / \Delta D_{n50} = f(\cot\alpha, T_m (or \xi_m), N, P, S) \qquad (2)$$

where: H_s = significant wave height in front of structure, Δ = relative mass density, D_{n50} = nominal diameter (cubic size), α = slope angle, T_m = mean period, ξ_m = surf similarity or breaker parameter, N = number of waves, P = notional permeability factor and S = damage level (for rock).

Extended research by Van der Meer (1988c) on breakwaters with concrete armour units was based on above governing variables found for rock stability. The research was limited to only one cross-section (i.e. one slope angle and permeability) for each armour unit.

Therefore the slope angle, cotα, and consequently the breaker parameter, ξ_m, are not present in the stability formulae developed on the results of the research. The same holds for the notional permeability factor, P. This factor was P = 0.4.

Breakwaters with armour layers of interlocking units are generally built with steep slopes in the order of 1:1.5. Therefore this slope angle was chosen for tests on cubes and tetrapods. Accropode are generally built on a slope of 1:1.33, and this slope was used for tests on accropode. Cubes were chosen as these elements are bulky units which have good resistance against impact forces. Tetrapods are widely used all over the world and have a fair degree of interlocking. Accropode were chosen as these units could be regarded as the latest development at that time, showing high interlocking, strong elements and a one-layer system. A uniform 1:30 foreshore was applied for all tests. Only for the highest wave heights which were generated, some waves broke due to depth limited conditions.

Damage to rock armour was measured by considering the eroded area around the water level. It is not usual to measure profiles for concrete armour layers. Very often damage is based on an actual number of units. Therefore, another definition has been suggested for damage to concrete armour units. Damage there can be defined as the relative damage, N_{od}, which is the actual number of units displaced related to a width (along the longitudinal axis of the structure) of one nominal diameter D_n. For cubes D_n is the side of the cube, for tetrapods D_n = 0.65 D, where D is the height of the unit, for accropode D_n = 0.7D and for Dolosse D_n = 0.54D (with a waist ratio of 0.32).

The definition of N_{od} is comparable with the definition of S, although S includes displacement and settlement, but does not take into account the porosity of the armour layer. Generally S is about twice N_{od}. Further, N_{od} can be easily related to a percentage of damage. If the number of units in a cross-section is known with a length of 1 D_n, the percentage of damage to a structure is simply the ratio of N_{od} and this number. N_{od} gives the actual damage, where a percentage is always related to the actual structures. A similar damage may, therefore, give different percentages of damage if the cross-sections are different.

The following example may illustrate this. Suppose a breakwater with 15 ton cubes with a D_n of 1.84 m and consider a stretch 100 m long.

Damage N_{od}	number/100 m
0.2	11 units
0.5	27 units
1.0	54 units
2.0	109 units

If a cross-section, one nominal diameter wide, consists of 20 units, N_{od} = 0.5 gives 0.5/20*100% = 2.5% damage. A longer cross-section consisting of 40 units gives only 1.25% damage.

As only one slope angle was investigated, the influence of the wave period should not be given in formulae by ξ_m, as this parameter includes both wave period (steepness) and slope angle. The influence of wave period, therefore, will be given by the wave steepness $s_{om} = 2\pi H_s/(gT_p^2)$.

General formulae for stability of concrete units include the relative damage level N_{od}, the number of waves N, and the wave steepness, s_{om}. It is given by:

$$H_s/\Delta D_n = f(s_m, N, N_{od}) \tag{3}$$

The next chapters give stability formulae for some types of concrete units. Traditional designs are treated as two-layer systems and the new units as one-layer systems.

2 TWO-LAYER SYSTEMS

2.1 *Cubes and tetrapods*

Basic research was described by Van der Meer (1988c). The formula for cubes is given by:

$$\frac{H_s}{\Delta D_n} = \left(6.7\frac{N_{od}^{0.4}}{N^{0.3}} + 1.0\right)s_{om}^{-0.1} \tag{4}$$

For tetrapods:

$$\frac{H_s}{\Delta D_n} = \left(3.75\left(\frac{N_{od}}{\sqrt{N}}\right)^{0.5} + 0.85\right)s_{om}^{-0.2} \tag{5}$$

For the no-damage criterion N_{od} = 0, equations 4 and 5 reduce to:

$$\frac{H_s}{\Delta D_n} = 1.0\, s_{om}^{-0.1} \tag{6}$$

$$\frac{H_s}{\Delta D_n} = 0.85\, s_{om}^{-0.2} \tag{7}$$

No damage at all is a very strict criterion and armour layers designed on this criterion will get large concrete units. For rock layers some settlement and small displacement is included in the "start of damage" definition S=2-3. For N_{od}=0.5 a similar situation is found and this is a more economical criterion than no damage at all.

Equations 4 and 5 give decreasing stability with increasing wave steepness. This is similar to the plunging area for rock layers. Due to the steep slopes used, no transition was found to plunging waves. De Jong (1996), however, analysed more data on tetrapods from tests performed at Delft Hydraulics and he found a similar transition as for rock. His formula for plunging waves should be considered together with equation 5, which now acts for surging waves only, and becomes:

$$\frac{H_s}{\Delta D_n} = \left(8.6\left(\frac{N_{od}}{\sqrt{N}}\right)^{0.5} + 3.94\right)s_{om}^{0.2} \tag{8}$$

Both equations 5 and 8 are shown in Figure 1 for three different damage levels of N_{od}. It is possible, and it might even be expected, that a similar transition can be found for cubes. No data are available, however, on that aspect.

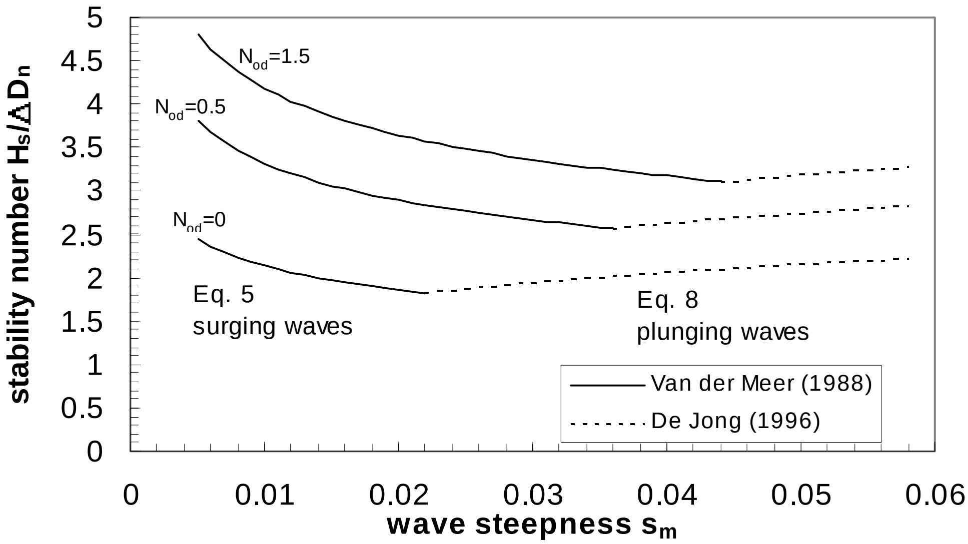

Figure 1 Stability formulae for tetrapods

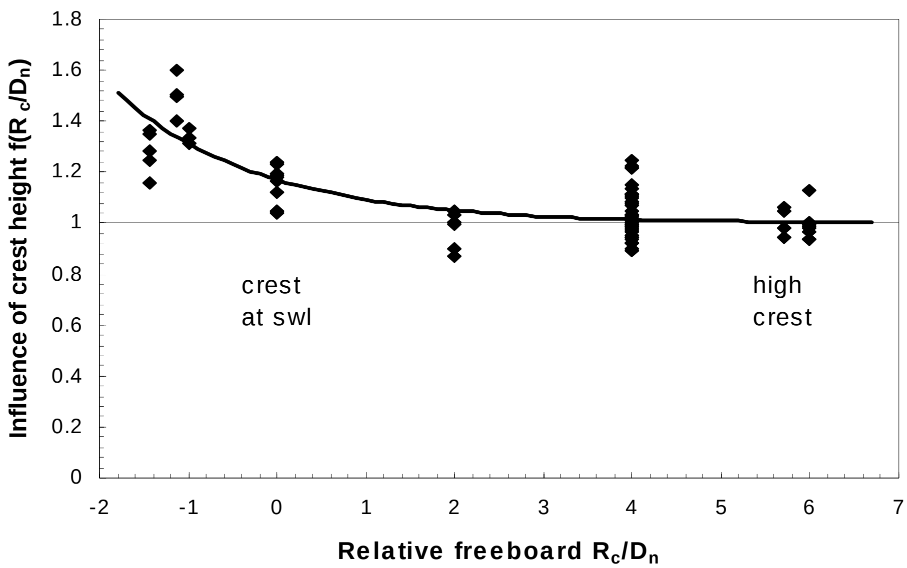

Figure 2 Influence of crest height on stability of tetrapods

2.2 *Influence of crest height*

De Jong (1996) also investigated the influence of crest height and packing density on stability of tetrapods. Equations 5 and 8 regard to an almost non-overtopped structure (less than 15% overtopping). Stability increases if the crest height decreases. With the crest freeboard defined by R_c, he found that the stability number in equations 5 and 8 could be increased by a factor $f(R_c/D_n)$, with respect to a lower crest height. The crest height is then defined by the number of nominal diameters above or below still water level. Also the packing density, described in the next section, can be involved in the equations by a factor $f(\phi)$.

The general stability formulae for tetrapods become then:

for surging waves:

$$\frac{H_s}{\Delta D_n} = \left(3.75 \left(\frac{N_{od}}{\sqrt{N}} \right)^{0.5} + 0.85 f(\phi) \right) s_{om}^{-0.2} f(R_c / D_n) \quad (9)$$

for plunging waves:

$$\frac{H_s}{\Delta D_n} = \left(8.6 \left(\frac{N_{od}}{\sqrt{N}} \right)^{0.5} + 3.94 f(\phi) \right) s_{om}^{0.2} f(R_c / D_n) \quad (10)$$

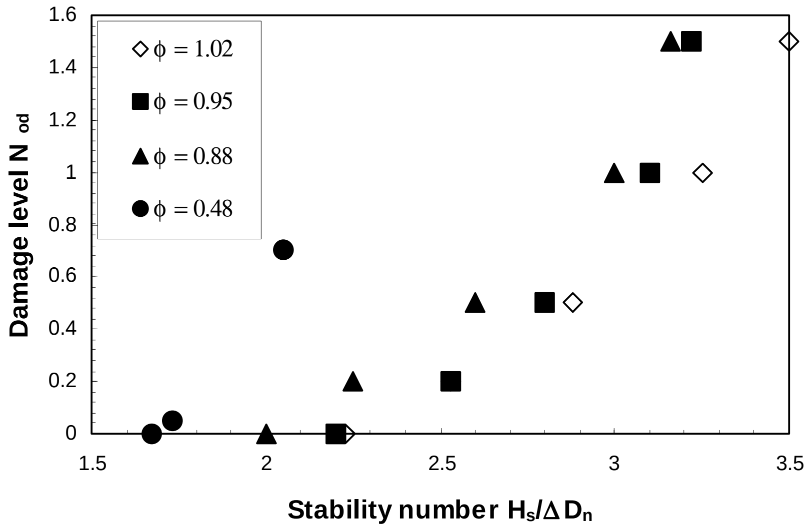

Figure 3 Stability of tetrapods for various packing densities

The factor $f(R_c/D_n)$ is shown in Figure 2 as a function of the crest height R_c/D_n. This factor can be described by:

$$f(R_c/D_n) = 1 + 0.17\exp(-0.61 R_c/D_n) \qquad (11)$$

If the crest is at the still water level, ie. $R_c/D_n = 0$, $f(R_c/D_n) = 1.17$. It means that the stability number increases by a factor 1.17, or that the nominal diameter required can be decreased by a factor 1/1.17 = 0.85. On the required weight this is a factor $0.85^3 = 0.62$. Similar factors were found for rock structures, see Van der Meer (1993). The factor on the nominal diameter there was 1.25 and on the weight 0.51.

2.3 *Influence of packing density*

The packing density can be described in its simplest way as a number of placed units per square nominal diameter:

$$N_a / A = \phi / D_n^2 \qquad (12)$$

where: N_a = the number of units; A = surface area and ϕ = the packing density. Packing densities are given in the Shore Protection Manual (1984). The normal packing density used in the tests amounted to $\phi = 1.02$. Lower packing densities of $\phi = 0.95$ and 0.88 were used to investigate the influence of ϕ. The packing density given in the Shore Protection Manual (1984) is $\phi = 1.04$ for tetrapods (and 1.17 for cubes). It indeed appeared that a lower packing density leads to lower stability, see Figure 3. The damage level is given as a function of the stability number. The wave steepness was the same for all tests. According to Van der Meer (1988c) each data point is an independent test (no cumulative damage by increasing the wave height in consecutive test runs).

Three points are added to Figure 3. d'Angremond et al. (1999) performed tests on armour units in a single layer. One of these units was the tetrapod. It appeared that tetrapods in one layer are not stable at all. The stability results are shown in Figure 3. The packing density was only $\phi = 0.48$. Nevertheless, the data are very useful to find an expression for the influence of the packing density on stability, the factor $f(\phi)$.

First of all general curves through the data points in Figure 3 would have more or less the same shape. In order to describe the packing density, the average shift with respect to no damage $N_{od} = 0$ is taken into account. This is the reason why in equations 9 and 10 $f(\phi)$ is placed behind the numbers 0.85 and 3.94. Finally the packing densities given in the Shore Protection Manual (1984) were taken as reference: ϕ_{SPM}. The actual packing density is then described by ϕ/ϕ_{SPM}, which gives unity if the packing densities of the Shore Protection Manual are used.

Figure 4 gives the results. The factor $f(\phi)$ is given as a function of ϕ/ϕ_{SPM}. Including the results of a single layer of tetrapods, a straight line is the only correct interpretation of the results. The influence of the packing density on stability can be described by:

$$f(\phi) = 0.40 + 0.61\phi/\phi_{SPM} \qquad (13)$$

In conclusion, equations 9 and 10, in combination with equations 11 and 13, give the stability of an armour layer of tetrapods, including the influence of crest height and packing density.

It might be possible that equations 11 and 13 can also be applied to the stability formula 4 for cubes, but more research is required to prove that. In order to give a first guess of the influence of crest height and packing density on the stability of cubes, equation 4 becomes:

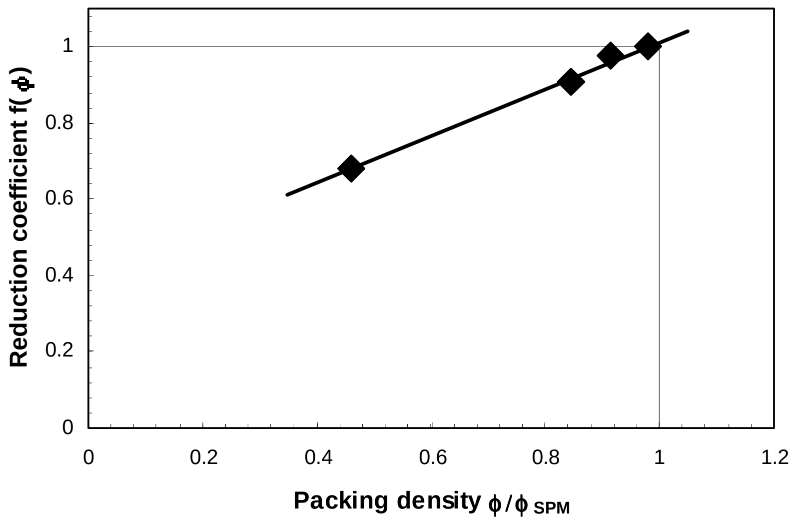

Figure 4 Influence of packing density on stability (of tetrapods)

$$\frac{H_s}{\Delta D_n} = \left(6.7\frac{N_{od}^{0.4}}{N^{0.3}} + 1.0\, f(\phi)\right) s_{om}^{-0.1}\, f(R_c / D_n) \qquad (14)$$

2.4 *Cumulative damage*

With regard to cumulative effects of multiple events, the slope in each test of all the research described above was rebuilt after each test. Cumulative damage for different wave heights was not measured. In practice, however, a structure like a breakwater is very often tested in a wave flume or basin by consecutive test runs with increasing wave conditions. If damage starts at a certain wave height, a next test run will increase this damage.

The formulae can also be used to calculate such cumulative damage. The procedure is as follows:

- calculate the damage for the first wave condition
- calculate for the second wave condition how many waves would be required to give the same damage as caused by the first wave condition
- add this number of waves to the number of waves under the second wave condition
- calculate the damage under the second wave condition with the increased number of waves
- calculate for the third wave condition how many waves would be required to give the same damage as caused by the second wave condition, etc.

Actually, the influence of the number of waves on stability has been described in a very simple way. In fact the formula are only valid for numbers of waves between about 700 and 5000. One may improve the range in the following way, also based on extensive experience with rock slopes (Van der Meer, 1988a): The influence of the number of waves is according to above given formulae in the range N = 1000 – 7000. Between N = 0 – 1000 the damage increases linearly from 0 to the damage found for N = 1000. Further, for N > 7000 the damage is limited to the damage found for N = 7000. This procedure should be used in combination with the above procedure for calculating cumulative damage.

3 ONE-LAYER SYSTEMS

3.1 *The system*

The conventional two-layer system has been used for many years and is still very popular. A first layer is placed with on top another layer. The units have more or less interlocking, depending on the shape, but in fact the stability of such a layer depends mainly on stability of individual units. If damage starts, this damage will increase if the wave height increases. The problem with very heavy units (say heavier than 20-30 tons) might be that placing and rocking may lead to breakage of the units and consequently to large damage to the structure. Dolosse and tetrapods are fairly sensitive for breakage if they become too large.

The best known unit in a one-layer system is the accropode. More recently the core-loc was invented. Generally they have similar behaviour although some differences exist. Accropode are randomly placed in one layer, but on a very strict placing pattern. The units are placed as close as possible to each other. Core-locs are placed less strict and are even proposed to be used for repair of damaged layers with dolosse. Both accropode and core-loc are strong units. Even if a leg breaks, still 90% of its original weight is left, including most of its interlocking with other units.

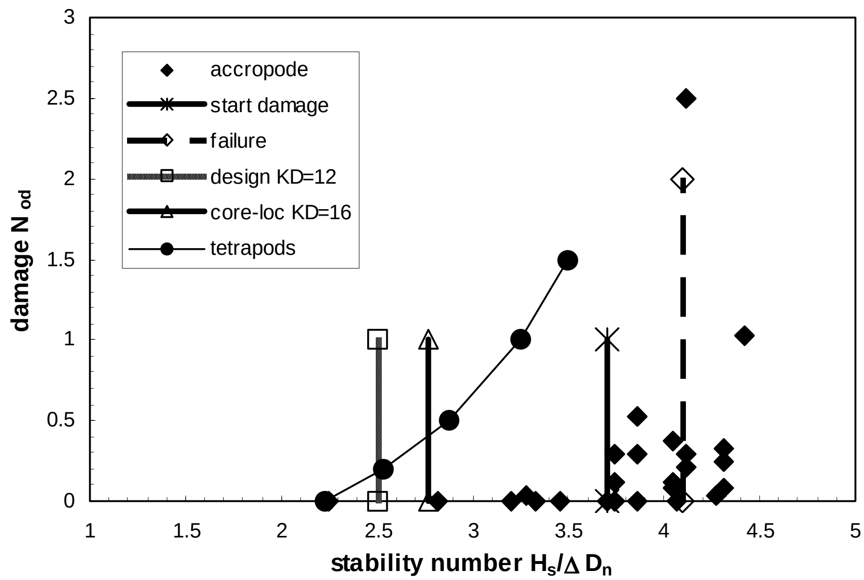

Figure 5 Stability of accropode

The behaviour of these units under wave attack is different from conventional two-layer systems. First wave attack after construction will give some settlement to the layer. This causes a complete packed layer where every unit makes contact with some neighbours. In fact loose units do not exist anymore and rocking can hardly be observed. In fact a one-layer system reacts as an integral layer, where a two-layer system reacts on stability of individual units.

Stability tests show (results are discussed later) that accropode and core-locs are stable to a very high wave height. As soon as damage starts for these high wave heights a fairly sudden failure of the whole structure occurs. In first instance, such a progressive failure may look quite dangerous. But this behaviour may turn into an advantage if a proper safety factor is used for design. If a safety factor of 1.3 is used on the stability number for start of damage, it means that if the design wave height is underpredicted by 10 or 20%, nothing will happen! This in contrast to two-layer systems, where damage increases with increasing wave height.

One of the main reasons to choose for a one-layer system is an economical factor. A one-layer system means a large saving in concrete for the armour layer. It should be noted that the difference in volumes of concrete required for both systems is not really the actual saving in costs. As the dimensions of the breakwater will be more or less similar, the saving in volume of concrete has to be substituted by (cheaper) rock. Still a substantial saving is possible.

One of the main arguments against a new unit has always been the lack of experience. But with more than 100 breakwaters built with accropode, this is not longer a valid argument. For core-locs it is still valid as only a few structures have been built with these units. But core-locs and accropode are quite similar and their behaviour is similar too.

All together one may conclude that a one-layer system with accropode or core-locs gives cheap and reliable structures. Therefore, it is recommended to compare a conventional design always with a one-layer system.

3.2 *Accropode*

Figure 5 gives the test results for accropode as found by Van der Meer (1988c). Tests are only valid for a slope of 1:1.33, but a similar behaviour is expected for 1:1.5. The storm duration and wave period showed no influence on the stability of accropode and the "no damage" and "failure" criteria were very close. The stability, therefore, can be described by two simple formulae, ie. a fixed stability number:

start of damage, $N_{od} = 0$:

$$\frac{H_s}{\Delta D_n} = 3.7 \tag{15}$$

failure, $N_{od} > 0.5$:

$$\frac{H_s}{\Delta D_n} = 4.1 \tag{16}$$

Comparison of equations 15 and 16 shows that start of damage and failure for accropode are very close, although at very high $H_s/\Delta D_n$-numbers. It means that up to a high wave height accropode are completely stable, but after the initiation of damage at this high wave height, the structure will fail progressively. Therefore, it is recommended that a safety coefficient for design should be used of about 1.5 on the $H_s/\Delta D_n$-value. This means that for the design of accropode one should use the following formula, which is close to design values of cubes and tetrapods:

for design:

$$\frac{H_s}{\Delta D_n} = 2.5 \tag{17}$$

This is also a value that is used by Sogreah to design accropode layers (K_D = 12). Although accropode may fail in a progressive way for high wave heights, use of a safety coefficient changes it to a safe structure which has the following advantage with respect to other units. If the design wave height for cubes or tetrapods is under-estimated, a higher wave height than expected may lead to increased and undesirable damage. If the wave height for an accropode layer is under-estimated up to 50%, in fact nothing happens. No damage is expected as the stability number is still lower than the one for start of damage. The 50% is of course based on ideal testing conditions. But in practice one may rely at least on 20-30% safety beyond given design conditions.

3.3 *Core-locs*

The recently developed core-loc has a similar stability behaviour as accropode, although limited test results have been published. It might be that the core-loc is even a little more stable than the accropode. This was discussed at the conference after the presentation of this paper. Some researchers had tested both accropode and core-locs and found that core-locs showed less movement in the layer (after settlement) than accropode. Results have not yet been published.

The design value given for core-locs is K_D = 16 which is a little higher than for accropode. The stability number for a 1:1.33 slope becomes:

for design:

$$\frac{H_s}{\Delta D_n} = 2.78 \tag{18}$$

This value is given in Figure 5 too. Although the difference with accropode (equation 17) looks small, the difference in weight is a saving of 27%.

The main advantage of accropode at this moment is the large experience in construction of breakwaters. Only a few structures have been built with core-locs. But core-locs may be more suitable for less strict placing which means that repair of local damages could be easier with core-locs.

3.4 *Cubes*

The experience of many researchers, who have built test sections of breakwaters with a double layer of cubes, is that it is not easy to place these two layers randomly. The main reason is that, due to the shape of a cube, cubes "like to lay in one layer". Bhageloe (1998) tested one-layer systems with rock, tetrapods and cubes. The results have also been published by d'Angremond et al. (1999). The main conclusion was that a single layer of cubes was remarkably stable. Research was continued with cubes. The final results can be found in this proceedings, the paper by Van Gent et al. (1999).

The tested structure had a slope of 1:1.5. One remark should be made as a warning: a single layer of cubes is stable on the seaside, but can not withstand heavy wave attack on the crest. A single layer of cubes should only be considered if the overtopping is limited to say less than 10%.

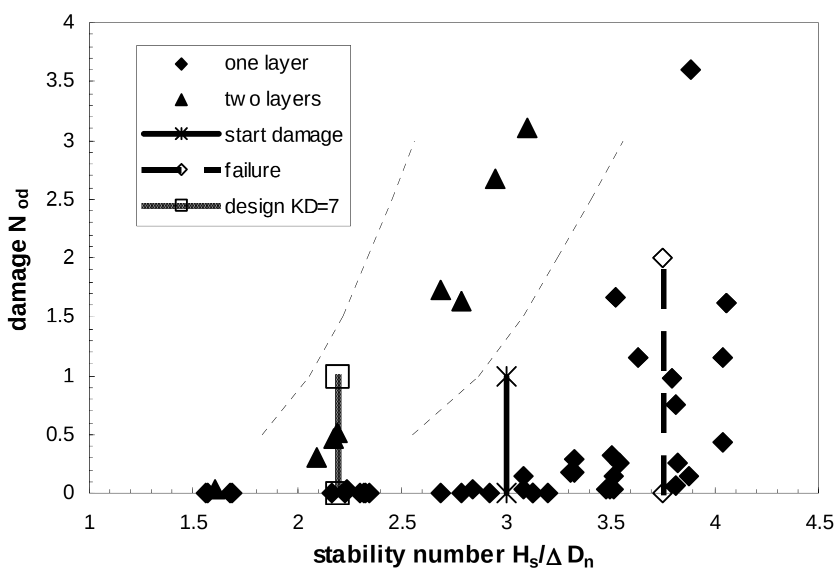

Figure 6 Stability of a single layer of cubes

For influence of packing density, water depth and size of under layer one is referred to Van Gent et al. (1999). The final results are summarized in Figure 6. A similar behaviour is found for a single layer of cubes as for accropode and core-locs. The structure is stable up to a fairly high stability number, but fails for only little higher wave heights. This behaviour can be described by:

start of damage:

$$\frac{H_s}{\Delta D_n} = 3.0 \tag{19}$$

failure:

$$\frac{H_s}{\Delta D_n} = 3.75 \tag{20}$$

Both values are given in Figure 6. The main item to be decided on is the required safety factor for design purposes. Figure 6 gives also results for a conventional double layer of cubes (from Van der Meer, 1988c), including 90% confidence bands. It is clear that a single layer is more stable than the conventional structure. On the other hand, one can not accept a lot of damage to a single layer of cubes as under layer rock will disappear after initial damage: there is only one layer!

A conventional double layer of cubes will often be designed for limited damage, say N_{od} = 0.5. In Figure 6 this is for about $H_s/\Delta D_n$ = 2.2, which is similar to K_D = 7. If a single layer of cubes will be designed for this value it means that a conventional double layer and a single layer will require the same weight.

The safety factor with respect to actual start of damage is for the single layer of cubes 3.0/2.2 = 1.36. This is lower than the factor 1.5 found for accropode. The safety factor with respect to failure is 3.75/2.2 = 1.70, which is a little higher than for accropode: 4.1/2.5 = 1.64. In average similar safety factors are found.

Therefore it is concluded that above proposed design value for a single layer of cubes gives similar safety as for accropode. This means:

for design:

$$\frac{H_s}{\Delta D_n} = 2.2 \qquad (21$$

4 OVERALL COMPARISON

The brochure of accropode gives a table with some characteristics of a few units. That table has been extended to include all the units treated in this paper and has been extended by a few more characteristic values. Table 1 gives a good comparison of various concrete units which are available to protect breakwaters under wave attack. The table is based on units with a weight around 30 ton.

Table 1 shows that conventional layers are designed for some damage, where the single-layer system uses no damage. On the other hand less damage should be accepted for the these single layers.

With the packing density ϕ it is possible to calculate the required volume of concrete per m^2 on the slope as a function of the significant wave height H_s, using a mass density for concrete of 2400 kg/m^3.

The relative volume of concrete can be calculated if the different slopes are taken into account. Here 100% is equal to the required volume for accropode. It is clear that accropode and core-locs give large savings in required volumes of concrete. One should remember, however, that generally the concrete volume saved should be substituted by (cheaper) rock. The relative saving in volume of concrete is not equal to the actual saving in total costs.

Table 1. Comparison of various concrete units for design of armour layers

	Accropode	**Core-Loc**	**Tetrapod**	**Cube**	**Cube**
number of layers	1	1	2	2	1
slope	1:4/3	1:4/3	1:1,5	1:1,5	1:1,5
K_D (breaking waves)	12	16	7	7	7
$H_s/\Delta D_n = N_s$	2,5	2,8	2,2	2,2	2,2
damage N_{od}	0	0	0,5	0,5	0
damage %	0	0	5	5	0
packing density ϕ	0,61	0,56	1,04	1,17	0,70
concrete per m^2 on slope	$0{,}182H_s$	$0{,}148H_s$	$0{,}350H_s$	$0{,}370H_s$	$0{,}236H_s$
relative volume of concrete	100%	81%	208%	220%	140%

The single layer of cubes is also an attractive solution. The production of moulds for cubes is easier and probably cheaper than for the complicated unit shapes of accropode and core-loc. It may also be easier to place a single layer of cubes, although practical experience is lacking. The main limitation of a single layer of cubes is that only non-overtopping structures can be designed.

REFERENCES

Bhageloe, G.S. 1998. Golfbrekers met een enkele toplaag (breakwaters with a single-layer). *MSc-thesis, Delft University of Technology*, also Delft Hydraulics Report H3356.

d'Angremond, K., E. Berendsen, G.S. Bhageloe, M.R.A. van Gent and J.W. van der Meer 1999. Breakwaters with a single-layer. *Proc. COPEDEC-V*, Capetown.

De Jong, R.J. 1996. Wave transmission at low-crested structures. Stability of tetrapods at front, crest and rear of a low-crested breakwater. *MSc-thesis, Delft University of Technology*.

Shore Protection Manual 1984. US Army Corps of Engrs, CERC, *US Govt. Printing Ofice*, Washington, DC

Van der Meer, J.W. 1988a.. Rock slopes and gravel beaches under wave attack. *Doctoral thesis, Delft University of Technology*. Also DELFT HYDRAULICS Publication no. 396.

Van der Meer, J.W. 1988b.. Deterministic and probabilistic design of breakwater armour layers, *Proc. ASCE, Journal of WPC and OE*, Vol. 114, No. 1.

Van der Meer, J.W. 1988c. Stability of Cubes, Tetrapods and Accropode, *Design of Breakwaters, Thomas Telford. Proc. Breakwaters '88 Conference*, Eastbourne.

Van der Meer, J.W., Conceptual design of rubble mound breakwaters, *DELFT HYDRAULICS Publication number 483*.

Van Gent, M.R.A., S.E. Plate, G.B.H. Spaan, J.W. van der Meer & K. d'Angremond 1999. Single-layer rubble mound breakwaters. *Proc. Coastal Structures 99*, Santander.