CHAPTER 152

Influence of rock shape and grading on stability of low-crested structures

Jentsje W. van der Meer[1]
W.H. Tutuarima[2]
G. Burger[3]

Abstract

The stability of low-crested rubble mound structures has been treated before by various researchers. In the first phase of this study two data sets from different laboratories were combined to one homogeneous data set. Re-analysis of these data resulted in a design diagramme for the stability of the seaward side, the crest, the rear and the total armour layer of the structure. Secondly, model tests were performed on carefully selected rock with different rock shapes (angular, flat and rounded) and different gradings, all for a low-crested structure. Results show that the differences between the various rock types were small, especially for the start of damage. The influence of the length/thickness ratio showed even no infuence at all which means that the sometimes strict requirements in construction may be released.

Combination of existing results

Low-crested rubble mound structures were treated by Van der Meer and Pilarczyk (1990) and were divided into three types: reef type structures and conventional structures with, respectively, the crest above or below the still water level. For all three types design formulas were given, based on a limited number of tests. In fact the division between structures with the crest above or below still water is not really practical as both situations can happen for the same structure.

Vidal et al. (1992) treated low-crested structures in three parts: the front

---

[1] Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands

[2] Delft University of Technology and Royal Boskalis Westminster nv, Papendrecht, The Netherlands

[3] Delft University of Technology and Grabowsky & Poort Consulting Engineers, The Hague, The Netherlands

slope, the crest and the rear slope. Their tests were complementory to the available data of Van der Meer and Pilarczyk (1990). The first part of the present study was to analyse both data sets in the same way and bring them together. All data were submitted by Vidal.

Vidal et al. (1992) accounted for the development of damage onto the entire structure, where Van der Meer and Pilarczyk (1990) only looked at the stability of the front side including a small part of the crest. In addition, Vidal et al. divided the damage in three segments: the front, the crest and the rear.
The division in these three segment, used for the present re-analysis, is given in Fig. 1.

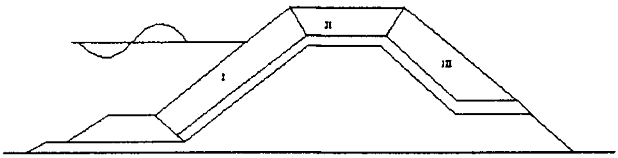


Figure 1. Division of armour layer in three segments

The damages to the structures of Van der Meer and Pilarczyk (1990) and of Vidal et al, were re-established according to Fig. 1. All data and the analysis have been described in Burger (1995). The damage is defined according to Van der Meer (1988):

$$S = A_e / D_{n50}^2 \tag{1}$$

Where: S = damage; A_e = surface of eroded area; D_{n50} = nominal diameter (cubical size) of the rock. S-values between 1-3 mean start of damage and values higher than 8-12 give "failure", this means holes in the armour layer and visible underlayer or core. With steep slopes and small areas subjected to wave attack, the smaller S-values should be used.

Parameter	**Van der Meer**	**Vidal**
D_{n50} (m)	0.0344	0.0249
Δ (-)	1.61	1.65
H_s (m)	0.073-0.229	0.047-0.152
T_p (s)	1.96 and 2.56	1.4 and 1.8
s_p (-)	0.010-0.036	0.010-0.049
B/D_{n50} (-)	8	6
R_c/D_{n50} (-)	-2.9 to 3.0	-2.0 to 2.4

Table 1. Test conditions for Van der Meer and for Vidal

The stability number is given by $N_s = H_s/\Delta D_{n50}$, where H_s = the significant wave height and Δ = the relative buoyant density. The stability of low-crested structures will be dependent on the relative crest freeboard. This is defined by R_c/D_{n50}, the number of rock sizes that the crest is above (positive) or below (negative) the still water level. Other used parameters are the peak wave period T_p, the wave steepness s_p, and the crest width B. Table 1 gives the test conditions for both Van der Meer (1990) and Vidal et al. (1992).

Re-analysis of existing results

The parameters used by Vidal et al. are not fully the same as those by Van der Meer and Pilarczyk. Vidal et al. used a front slope with an angle of 1:1.5, whereas Van der Meer and Pilarczyk used 1:2. The comparison between the two test series was carried out as follows: from the damage curves various fixed damage levels S were chosen and the corresponding stability numbers were determined. Then figures were drawn of stability number against crest freeboard for the various damage levels. Fig. 2 gives an example of the front slope.

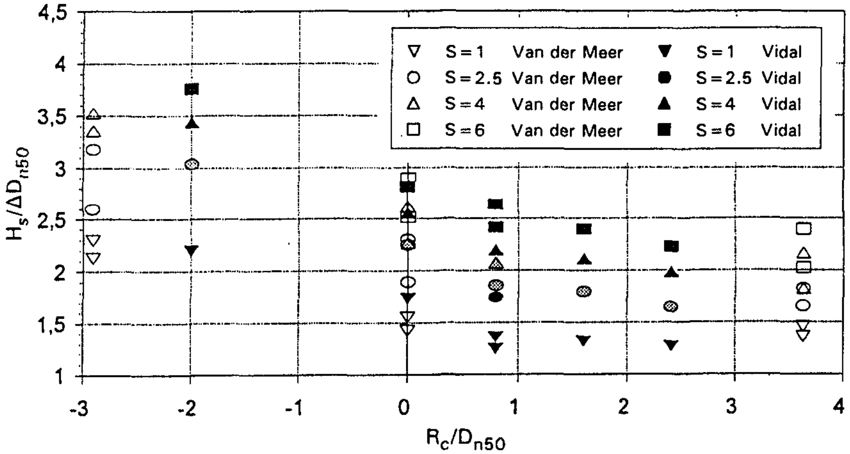


Figure 2. Stability at the front for fixed damage levels S

This figure shows that the two different data sets give a fairly good agreement, although some scatter is present. In order to make the analysis easier, in the following only start of damage will be considered. For the whole structure start of damage is given as S = 2. In order to remain consistent start of damage to the different segments seperately should be lower, but in total again S = 2. The following distribution was chosen for start of damage: front 50% (S = 1), crest 25% (S = 0.5) and rear 25% (S = 0.5). The real distribution of the damage will vary with the freeboard. Fig. 3 gives the same data as Fig. 2 for the front, but now only for start of damage S = 1.

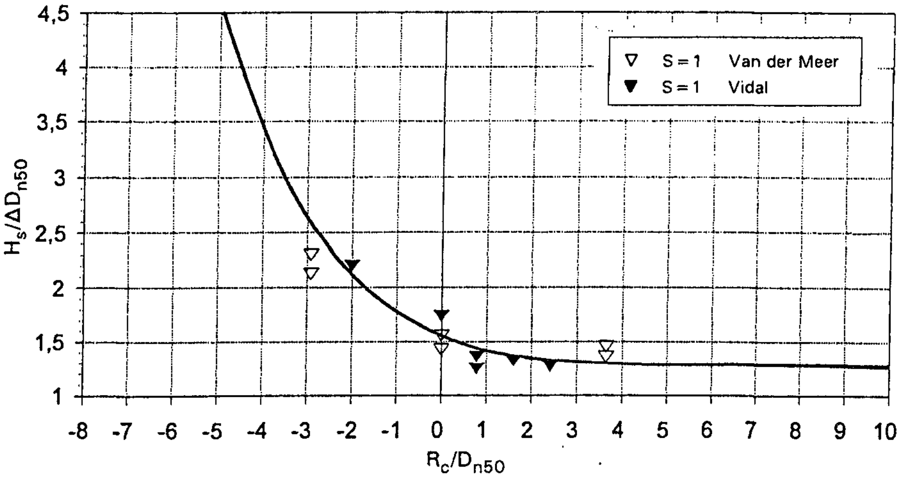


Figure 3. Stability front for start of damage

A curve is drawn trough the data points and this curve is also extended beyond the range of test data. For positively increasing freeboard the value of the stability number can be determined easily. Because as the freeboard increases there will not be any more overtopping and the structure will behave according the formulas by van der Meer (1988). The accompanying stability with the damage S = 1 is then $H_s/\Delta D_{n50}$ = 1.3. For negitively decreasing freeboard the development is less easy to predict. However, it is evident that the stability will increase with a freeboard decreasing.

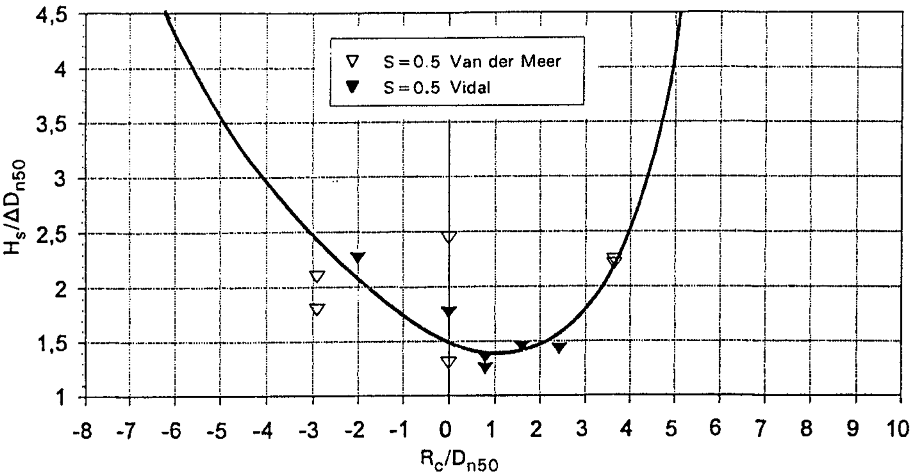


Figure 4. Stability of the crest for start of damage

Fig. 4 gives the data points for start of damage of the crest. Although some scatter is present, especially for the crest at the still water level, the trend is clear. The crest is most vulnerable for freeboards around the still water level. For high crest heights there will be hardly any or no overtopping and the curve will raise sharply. For negative freeboards the stability will increase with decreasing freeboards, more or less according to the front. Although the crest for large negative freeboards will show more damage than the front due to the wave attack directly on the crest for (very) low structures.

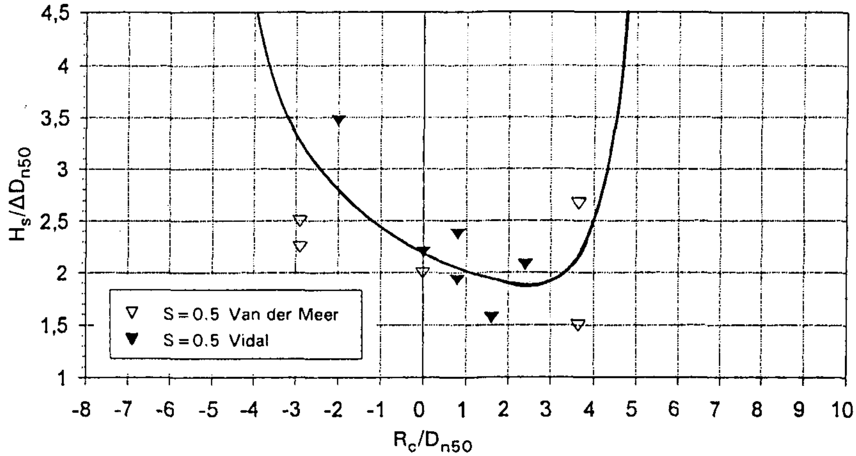


Figure 5. Stability rear for start of damage

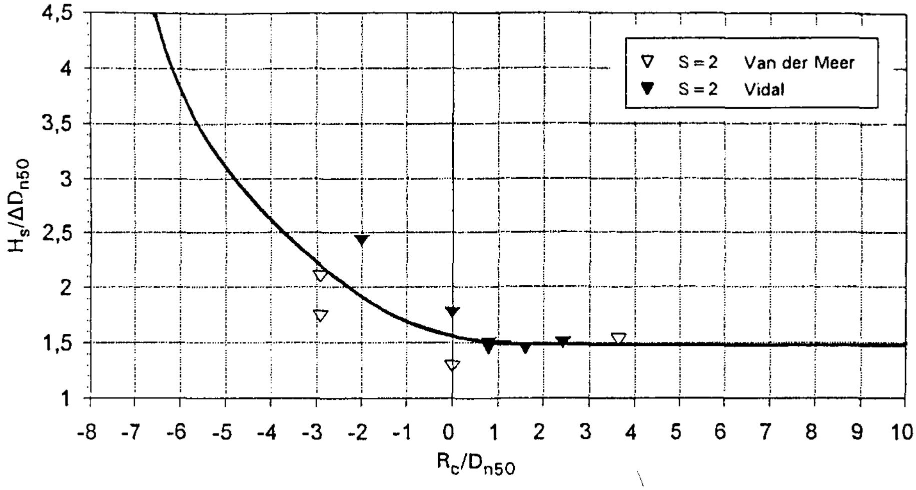


Figure 6. Stability of entire structure

Fig. 5 gives the data points for start of damage (S=0.5) for the rear. Considerable scatter is present. For increasing positive freeboards stability should increase as soon as overtopping waves can hardly reach the rear. Therefore, the curve should go up quite steep. Again the stability of the rear should increase for very low structures, according to front and crest.

The total stability is shown in Fig. 6 where the curve is similar to the one for the front side. All four graphs together give a design graph for stability of low-crested rubble mound structures at start of damage. This design graph is given in Fig. 7. The crest and front slope are always normative in this figure. The crest is normative for a crest under water up to a crest height of 1 to 2 D_{n50}. Above that level the front is the least stable segment.

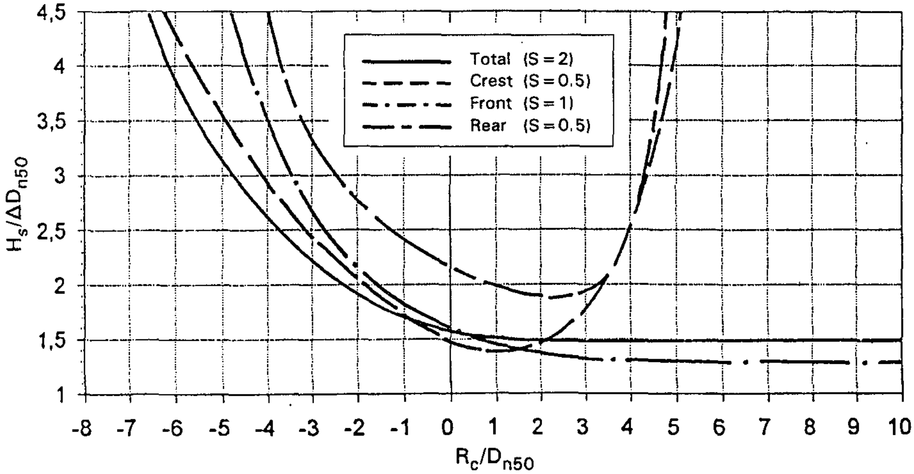


Figure 7. Design graph for low-crested rubble mound structures, for start of damage of various segments, front, crest, rear and entire structure

The design graph in Fig. 7 can be used in various ways. If the structure will be always under water it could be possible to use the armour layer only on the crest and to reduce the size at front side and rear. It is also possible to place the heaviest rock from the quarry at the least stable segment, which is determined from Fig. 7. Or one can design front, crest and rear with different rock gradings according to their required stability number. This may benefit the output yield curve of a quarry.

Tests on rock shape and grading

Requirements on rock shape and grading for constuction of rubble mound structures are often fairly strict, see the CUR\CIRIA-manual (1991). The rock shape can roughly be determined by the L/D-ratio and by a description of the shape (angular, round, etc.), see Figs. 8 and 9. Here L is the largest dimension and D the smallest. L/D=1 is a sphere or cube, L/D=3 is a fairly long and/or flat rock. In many cases values larger than 2 are not permitted, which in reality is difficult to obtain. Furthermore, such requirements are hardly based on testing. Also one is often strict as regards the demands for grading. The value of D_{85}/D_{15} may not exceed 2.0, implying that the quarry must produce uniform material.

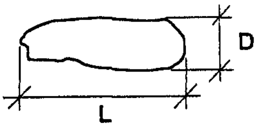


Figure 8. Rock shape L/D

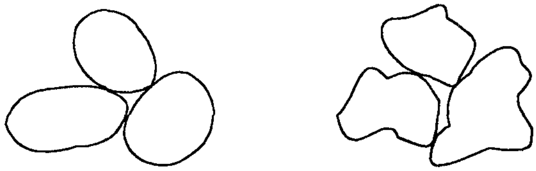


Figure 9. Round and angular rock

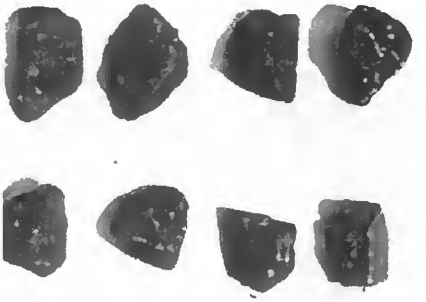
The above requirements give both delay as wel as an increase of the costs of building the structure. It is remarkable, though, that none of these requirements have been tested sufficiently so as to substantiate them. However, a number of researchers have already determined (Van der Meer, 1988; Bradbury et al. 1990) for the grading that, within reasonable limits ($D_{85}/D_{15} < 2.5$), the grading has a negligible impact on the stability, but for low breakwaters this has not yet been investigated.

Tests were performed at Delft Hydraulics with six categories of rock which were very carefully prepared. Each individual rock was weighed and all three length dimensions were measured. These rocks were placed in fractions of 5 mm size difference (25-30 mm, 30-35 mm, etc.) and then further in three fractions with different shape: L/D < 2; 2 < L/D < 3; and L/D > 3. These fractions were put together to form a predesribed grading and shape.

Table 2 shows the six different types of rock gradings and shapes. Three categories were used with angular rock, the same L/D-distribution, but with different gradings: D_{85}/D_{15} = 1.25 (uniform rock); 1.75 (normal grading); 2.5 (very wide grading). Two other categories were also made of angular rock, but had different L/D-ratio's. One of these categories had 40% rock with L/D>3 (type 5). The sixth category was made of shingle which is very rounded rock. Fig. 10 shows a picture of each of the six different types of rock gradings.

Rock type	**Shape**	**D_{85}/D_{15} (-)**	**L/D>2 (%)**	**L/D>3 (%)**
1	angular	1.25	20	0
2	angular	1.75	20	0
3	angular	2.50	20	0
4	angular	1.75	50	15
5	angular/flat	1.75	80	40
6	rounded	1.75	50	15

Table 2. Rock types tested on a low-crested breakwater



Type 1. Angular; $D_{85}/D_{15} = 1.25$
L/D > 2: 20% L/D>3: 0%

Type 2. Angular; $D_{85}/D_{15} = 1.75$
L/D > 2: 20% L/D>3: 0%

Type 3. Angular; $D_{85}/D_{15} = 2.50$
L/D > 2: 20% L/D>3: 0%

Type 4. Angular; $D_{85}/D_{15} = 1.75$
L/D > 2: 50% L/D>3: 15%

Type 5. Angular/flat; $D_{85}/D_{15} = 1.75$
L/D > 2: 80% L/D>3: 40%

Type 6. Rounded; $D_{85}/D_{15} = 1.75$
L/D > 2: 50% L/D>3: 15%

Figure 10. Pictures of the six tested gradings

Tests were performed on a cross-section as given in Fig. 11. The prepared rock was placed on the upper sections only, as for the lower sections (shaded) no damage was expected. The seaward slope was 1:2, the rear 1:1.5. The water depth for all tests was 0.6 m, the structure height 0.67 m (crest freeboard of 0.07 m). The nominal diameter of the rock was around 0.035 m. Tests were performed with a Jonswap spectrum. The significant wave heights varied from 0.07 to 0.18 m. For each rock type two test series were done, one with a wave steepness of s_p = 0.02 (fairly long waves) and one with s_p = 0.04 (storm waves). A test series consisted of 6 to 7 test runs with different wave height in order to establish the damage curve (damage versus wave height). The structure was reconstructed after each test run (6 or 7 times during each test series). This procedure gives damage data that are independent and have no cumulative effect.

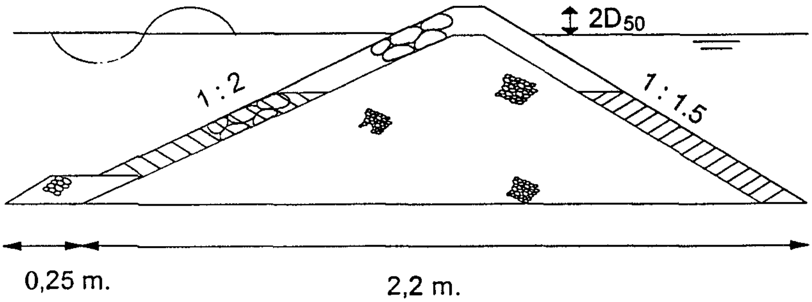


Figure 11. Tested cross-section

After each test run (of 1000 waves) the profile was sounded. Each time four cross-sections were measured with a sounding rod and a recording was taken every 0.039 m. Then the average profile was calculated and compared with the original profile. The final result was the damage area A_e and the damage S. The underside of the sounding rod had a circle shaped bulge with a radius of 0.5 D_{n50}. The test data are given in Burger (1995).

For each test series a damage curve can be drawn. This gives two damage curves for each rock type, one for low and one for high wave steepness. With certain combinations of rock types in one graph the influence of rock shape and grading can be established. Figures 12 - 14 give all these combinations for the influence of:

- rock shape L/D
- rock shape angular/rounded
- rock grading D_{85}/D_{15}

Influence of rock shape L/D

Fig. 12 gives the results of rock types 2, 4 and 5, which have similar gradings, but have different shapes of L/D. Rock type 2 is almost cubical, where rock type 5 has many long and flat stones (see also Fig. 10). The upper graph of Fig. 12 gives the results for a steepness of 0.02 and the lower graph for 0.04.

The influence of the rock shape L/D can hardly be traced in Fig. 12. In particular at the wave steepness of 0.04 the three rock types virtually overlap; the

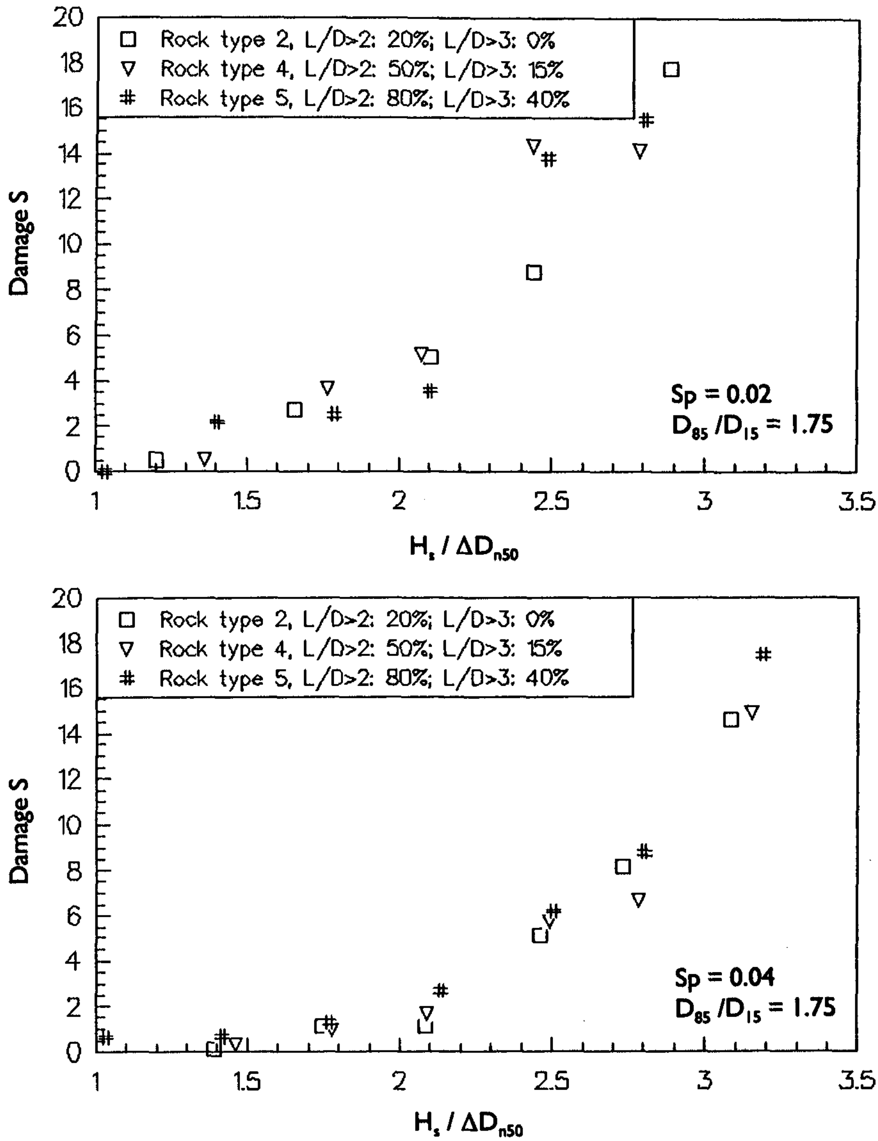


Figure 12. Influence of rock shape L/D on stability

results are virtually all on one line. With $s_p = 0.02$ there is no difference until a damage of $S = 4$; a little beyond that the more uniform material is more stable. At a yet higher stability number this is, remarkably enough, the least stable material.

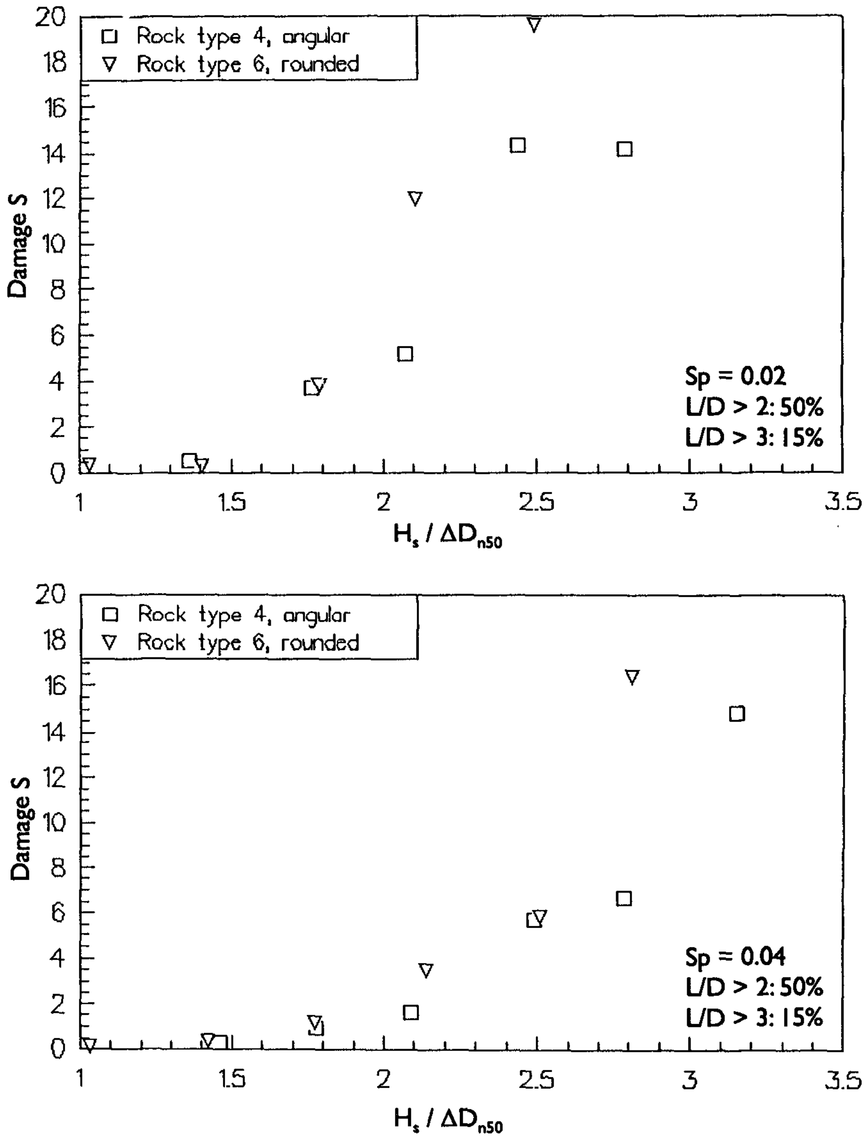
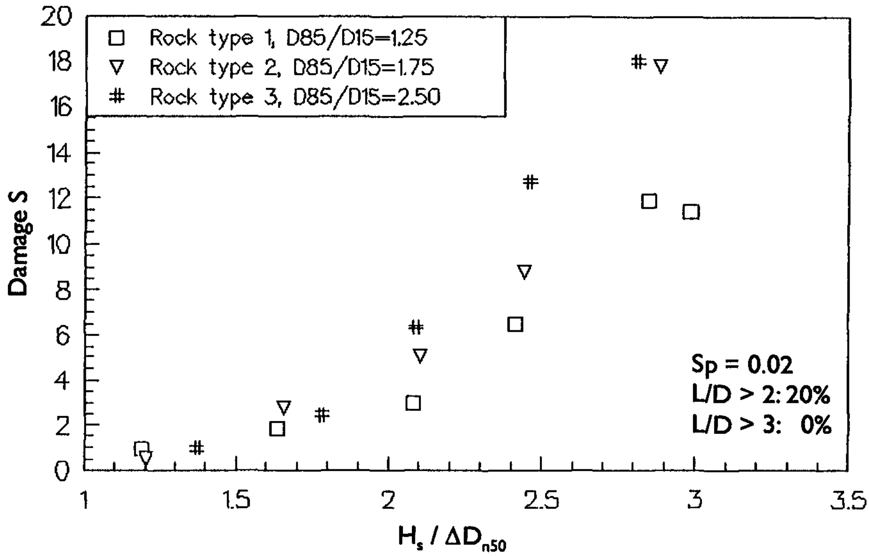


Figure 13. Influence of angularity on stability



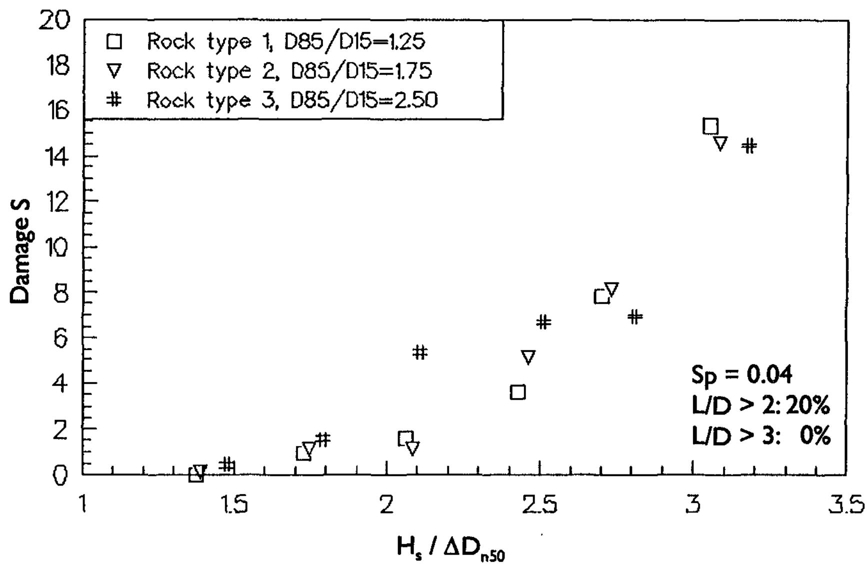


Figure 14. Influence of grading on stability

Influence of rock shape: angular/rounded

In Fig. 13 the results of the angular and rounded rock are given. Rock type 6 is composed of round shingle. For a wave steepness of s_p = 0.02 the data points up to a damage of S = 4 overlap one another exactly. The damage curves for $s_p = 0.04$ are similar up to $S = 6$. Apparently the rounded material does not roll that easily as one would expect. However, when it does start rolling, the development of damage will occur progressively in comparison to the angular material.

Influence of grading D_{85}/D_{15}

Fig. 14 gives the damage curves for the first three rock types which all have the same shape, but different gradings. Up to start of damage, $S = 2$, there is hardly any difference between damage development. Beyond that and with a wave steepness of 0.02 one can recognise a difference in damage development. There is hardly difference for the wave steepness of 0.04. The scatter in results is largest for the widest grading with $D_{85}/D_{15} = 2.5$. This is similar to tests performed at HR Wallingford, for a very wide grading with $D_{85}/D_{15} = 4.0$ (CUR/CIRIA-manual, 1991, page 271). There it is recommended not to use gradings with $D_{85}/D_{15} > 2.5$. The results in Fig. 14 show that upto this value the differences are small.

Conclusions

The existing test results of Vidal et al. (1992) and Van der Meer and Pilarczyk (1991) are reasonably in agreement, certainly if the differences in slope angle and crest width are considered. A design graph for start of damage was composed for stability of low-crested rubble mound structures (stability number versus relative crest freeboard). This design graph contains four curves: for the entire structure, the front slope, the crest and the rear.

Material factors of rock such as shape and grading appear to be of little influence on the stability of the armour layer of low-crested rubble mound structures. The length-width ratio L/D of the rock showed no influence at all on stability. A rock type with relatively many elongated/flat rocks is just as stable as a more uniformly shape rock type. There was hardly difference between the angular and rounded (shingle) shaped rock up to a damage of $S = 4$-6. After that the rounded rock showed a more progressive development of damage. Still the conclusion can be that also more rounded rock can be used for design of low-crested structures.

The grading has only little influence. It has no influence if the grading D_{85}/D_{15} is smaller than about 2. With $D_{85}/D_{15} = 2.5$ the stability can be the same, but the reliability of the results is smaller (the scatter is larger), probably due to unsorting of the grading, etc. It is recommended not to use gradings with $D_{85}/D_{15} > 2.5$.

The material factors as described above give hardly cause for the rejection of amounts of rock during construction. Hence, in future it is recommendable to be less strict as to the requirements for constructing (low) breakwaters than was customary up to now. In particular, for the differences in length/width ratios of the rock this will yield gains in time and material to be used. This will benefit both principal and contractor.

Acknowledgements

Prof. Vidal of the University of Stantander, Spain, is acknowledged for the release of all his test data.

References

Bradbury, A.P., Latham, J.P. and Allsop, N.W.H. (1990). Rock armour stability formulae influence of stone shape and layer thickness. ASCE, 22nd ICCE, Delft, The Netherlands

Burger, G. (1995). Stability of low-crested breakwaters. Stability of front, crest and rear. Influence of rock shape and gradation. MSc. thesis Delft University of Technology and Delft Hydraulics Report H1878/ H2415.

CUR/CIRIA-manual (1991). Manual on the use of rock in coastal and shoreline engineering. CUR-report 154, Gouda, The Netherlands. CIRIA special publication 83, London, United Kingdom.

Van der Meer, J.W. (1988). Rock slopes and gravel beaches under wave attack. PhD-thesis Delft University of Technology. Also Delft Hydraulics Publication No. 396

Van der Meer, J.W. and K.W. Pilarczyk (1990). Stability of low-crested and reef breakwaters. ASCE, 22th ICCE, Delft, The Netherlands.

Vidal, C., M.A. Losada, R. Medina, E.P.D. Mansard and C. Gomez-Pina (1992). A universal analysis for the stability of both low-crested and submerged breakwaters. ASCE, 23rd ICCE, Venice, Italy.