6. Stability of cubes, tetrapods and accropode

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SYNOPSIS. Results of an extensive research program on stability of rubble mound revetments and breakwaters were presented in recent years. In fact new stability formulae were introduced for an armour layer consisting of rock. In addition to this research Delft Hydraulics has performed basic model tests on breakwaters armoured with Cubes, Tetrapods and Accropode(R). The stability of these artificial units under random wave attack is the subject for the present paper. Finally a comparison of stability between rock and the mentioned artificial units is made.

ROCK STRUCTURES

Background

1. New practical design formulae have been developed which describe the stability of rubble mound revetments and breakwaters consisting of rock under random wave attack. The formulae were based upon a series of more than two hundred and fifty model tests. The work of Thompson and Shuttler (ref. 1) were used as a starting point. First results were published at the Breakwaters '85 Conference (ref. 2) and final results were published in ref. 3. The application of the formulae in a deterministic and probabilistic design were given in ref. 4.

Formulae for rock

2. The final formulae established for rock structures will be summarized first as it gives the basis for the investigation on stability of artificial units. The stability formulae derived are (ref. 3):

$$H_s/\Delta D_{n50} * \sqrt{\xi_z} = 6.2\ P^{0.18}\ (S/\sqrt{N})^{0.2} \qquad (1)$$

for plunging waves, and

$$H_s/\Delta D_{n50} = 1.0\ P^{-0.13}\ (S/\sqrt{N})^{0.2}\ \sqrt{\cot\alpha}\ \xi_z^P \qquad (2)$$

for surging waves

where:

H_s = significant wave height at toe of structure (m)

ξ_z = surf similarity parameter, $\xi_z = \tan\alpha/\sqrt{s_z}$ (-)
s_z = wave steepness = $2\pi H_s/gT_z^2$ (-)
T_z = zero up-crossing wave period (s)
α = slope angle (degrees)
Δ = relative mass density of stone, $\Delta = \rho_a/\rho - 1$ (-)
ρ_a = mass density of stone or unit (kg/m^3)
ρ = mass density of water (kg/m^3)
D_{n50} = nominal diameter of stone, $D_{n50} = (W_{50}/\rho_a)^{1/3}$ (m)
W_{50} = 50% value of mass distribution curve (kg)
P = permeability coefficient of the structure (-)
S = damage level, $S = A/D_{n50}^2$ (-)
A = erosion area in a cross-section (m^2)
N = number of waves (storm duration) (-)

3. The influence of dimensionless wave height, wave period and damage level on stability, computed with equations (1) and (2), are shown in Fig. 1 for a breakwater with $\cot\alpha = 1.5$, $P = 0.5$ (permeable structure) and $N = 3000$. The curves on the left side of Fig. 1 are given by equation (1) and on the right side by equation (2). Collapsing waves are present at the transition from plunging to surging waves.

4. Curves are shown for two damage levels, S = 2 for "start of damage" and S = 8 for "failure" (filter layer visible).

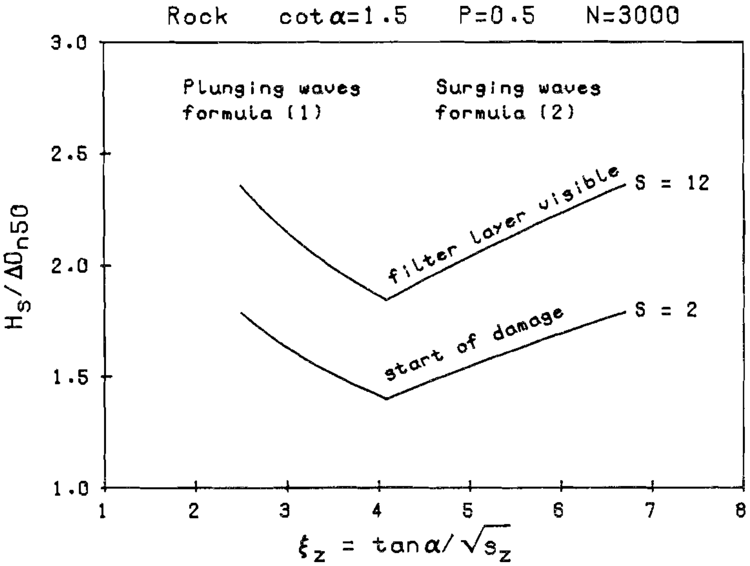


Fig. 1 Stability of rock slopes

Dimensionless governing variables

5. For armour layers consisting of rock the following conclusions were derived (ref. 3):

- Stability was determined in a dimensionless form, using:
  the significant wave height parameter: $H_s/\Delta D_{n50}$
  the surf similarity parameter: ξ_z
  the slope angle: $\cot\alpha$
  the damage as a function of the number of waves: $S/\sqrt{N}$
  the permeability of the structure: P
- Within the conditions tested the following parameters did not influence the stability:
  the grading of the armour
  the spectrum shape and groupiness of waves.

SET-UP OF RESEARCH

6. Tests on breakwaters with artificial armour units were based on above mentioned conclusions. The research was limited to only one cross-section (slope angle and permeability) for each armour unit. Therefore the slope angle, $\cot\alpha$, and consequently the surf similarity parameter, ξ_z, will not be present in a stability formula to be developed on the results of the research. The same yields for the permeability coefficient, P.

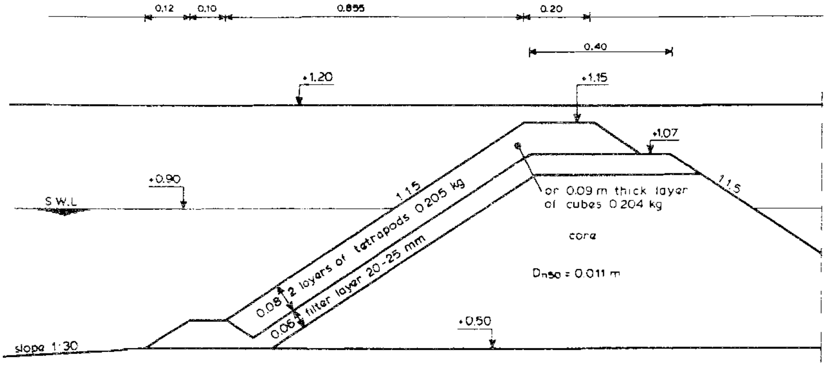
7. Breakwaters with armour layers of interlocking units are generally built with steep slopes in the order of 1:1.5. Therefore this slope angle was chosen for tests on Cubes and Tetrapods. Accropode(R) are generally built on a slope of 1:4/3, and this slope was used for tests on Accropode(R). Cubes were 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(R) were chosen as these units can be regarded as the latest development, showing high interlocking, strong elements and a one layer system.

8. A uniform 1:30 foreshore was applied for all tests. Waves were generated at a water depth of 0.90 m and the water depth at the structure amounted to 0.40 m. Each complete tests consisted of a pre-test sounding, a test of 1000 waves, an inter-mediate sounding, a test of 2000 more waves, a final sounding. Sometimes a test was extended with another 2000 waves. After each complete test the armour layer was removed and rebuilt. Fig. 2 gives the cross-sections tested.

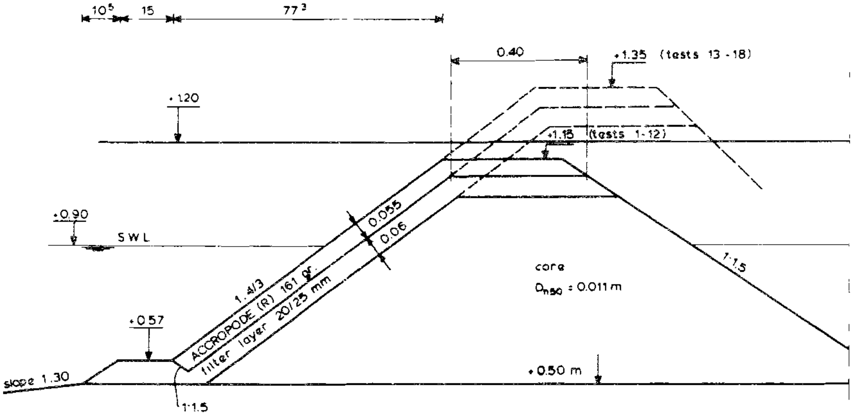
9. A tests series consisted generally of five tests with the same wave period, but different significant wave heights. Wave heights ranged from 0.10 to 0.25 m and the periods applied were: T_z = 1.4, 1.7, 2.2 and 2.9 s, covering a large part of wave steepnesses found in nature. Generally 20 tests were performed on each different armour unit which resulted in a total of about 60 tests.

10. Damage to rock structures is usually measured by means of a surface profiler. Damage, S, is then defined by the erosion area related to the nominal diameter (see Section 2). Damage to artificial armour units is often measured as the number of units displaced more than one diameter. Although damage is often given as a percentage, this definition has a lot of shortcomings. It is dependent on the slope angle and

the total number of units in the armour layer. Therefore, different investigations can hardly be compared.



a) Cross-section for Cubes and Tetrapods



b) Cross-section for Accropode (R)

Fig. 2 Tested cross-sections

11\. Another definition is suggested for damage to artificial armour units. Damage here is defined as the relative damage, N_o, which is the actual number of displaced units related to a width (along the longitudinal axis of the breakwater) of one nominal diameter, D_n. The nominal diameter is defined by:

$$D_n = (W/\rho_a)^{1/3}, \text{ where: } W = \text{mass of armour unit.} \qquad (3)$$

For Cubes D_n is the side of the cube, for Tetrapods $D_n = 0.65h$ where h is the height of the unit and for Accropode(R) $D_n = 0.7h$. The definition of the relative damage, N_o, 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 two times N_o.

12. As only one slope angle was investigated, the influence of the wave period should not be given in formulae including ξ_z, as this parameter includes both wave period (steepness) and slope angle. The influence of wave period, therefore, will be given by the wave steepness $s_z = gT_z^2/2\pi H_s$.

13. Governing variables

Sections 6-12 have reviewed the governing variables for stability of artificial armour units on the basis of the set of variables for rock structures, given in Section 5. The final governing variables are given by:

- the wave height parameter: $H_s/\Delta D_n$
- the wave steepness: s_z
- the relative damage: N_o
- the number of waves (storm duration): N

RESULTS

14. Damage curves were drawn for each period and each storm duration. An example of such damage curves is shown in Fig. 3. From these damage curves $H_s/\Delta D_n$ and ξ_z values were taken for several damage levels, according to the procedure described for rock slopes (ref. 2 and 3). These values were plotted in so-called $H_s/\Delta D_n$-ξ_z plots, showing the influence of the wave period, storm duration and damage level, as was already given in Fig. 1 for rock structures. The $H_s/\Delta D_n$-ξ_z plots for Cubes, Tetrapods and Accorpode(R) are shown in Figs. 4-6, for N = 3000 and for two damage levels: N_o = 0 (start of damage) and N_o = 1-2 (severe damage, the actual number depends on the unit considered). Results of the units will be described seperately.

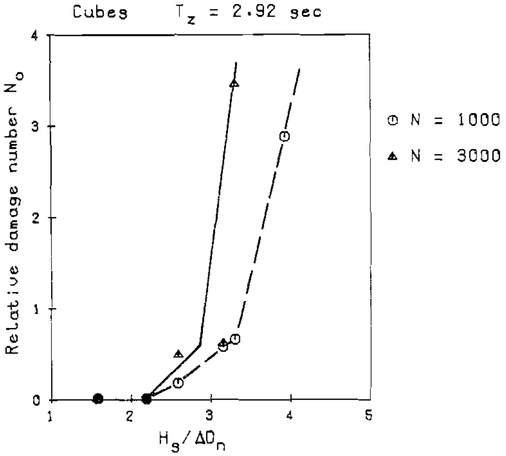


Fig. 3 Example of damage curves for Cubes

Stability of Cubes

15. Fig. 3 gives the damage curves for one wave period. From the analysis of this figure it follows that the influence of the storm duration (number of waves) is negligible for the no-damage criterion, $N_o = 0$. This can also be expected: if 1000 waves do not displace any unit it can be expected that another 1000 or 2000 waves are not able to displace more units. When some damage is considered, the damage becomes a function of the storm duration.

16. Fig. 4 shows the results for Cubes. This figure shows a slight influence of the wave period. Longer wave periods (large ξ_z values) increase the stability which is according to rock slopes, Fig. 1. No transition is found between plunging and surging waves which is probably due to the steep slope considered.

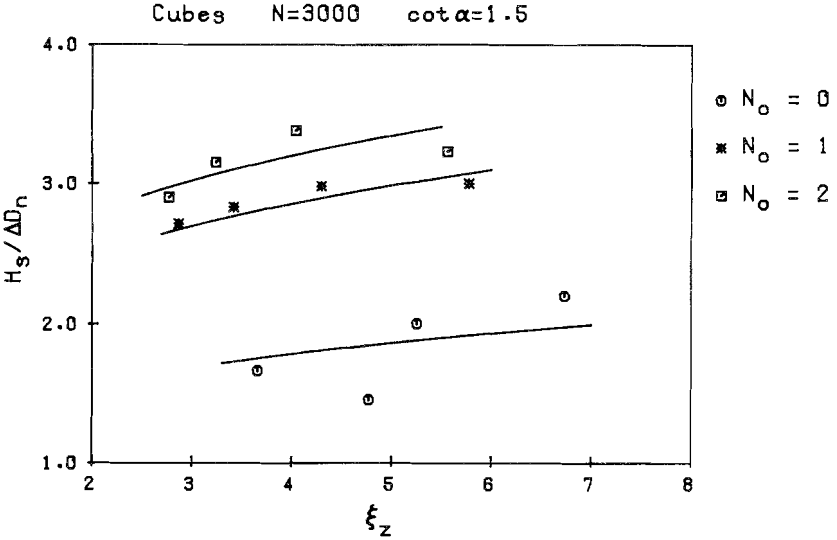


Fig. 4 Stability of Cubes

17. The final formula for stability of Cubes includes the relative damage level, N_o, the number of waves, N, and the wave steepness, s_z, and is given by:

$$H_s/\Delta D_n = (6.7\ N_o^{0.4}/N^{0.3} + 1.0)\ s_z^{-0.1} \tag{4}$$

Stability of Tetrapods

18. Figure 5 shows the $H_s/\Delta D_n$-ξ_z plot for Tetrapods. The influence of wave period on stability is more pronounced for Tetrapods than for Cubes (Fig. 4). The same conclusion of the influence of storm duration was found, however.

19. A similar formula as (4) was found for Tetrapods:

$$H_s/\Delta D_n = (3.75\ N_o^{0.5}/N^{0.25} + 0.85)\ s_z^{-0.2} \tag{5}$$

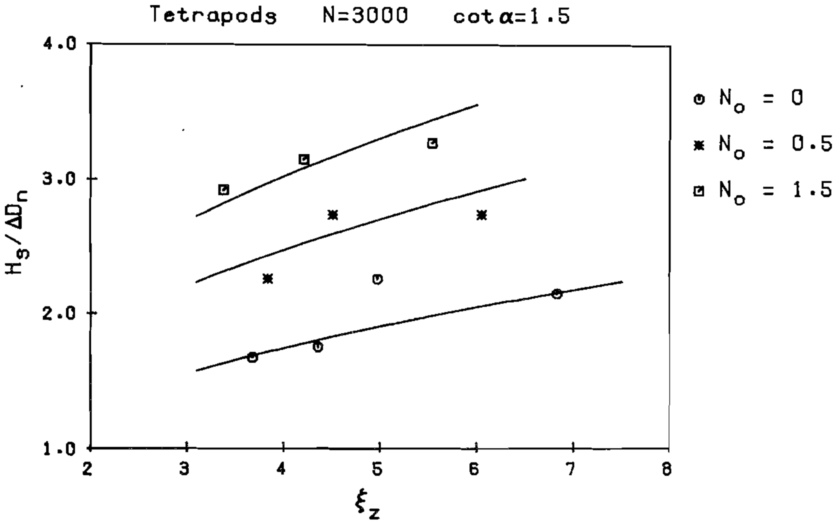


Fig. 5 Stability of Tetrapods

Stability of Accropode(R)

20. Accropode(R) are placed in a one layer system. The Accropode(R) were placed according to the specifications given by SOGREAH and described in ref. 5. The cross-sections tested are shown in Fig. 2. Both partly overtopping (10-40%) and non-overtopping (< 10%) structures were tested.

21. The results are shown in Fig. 6 for no damage (N_o = 0) and severe damage (N_o > 0.5). No influence of the storm duration was found. Furthermore, no influence of the wave period was found, as the curves in Fig. 6 are horizontal.

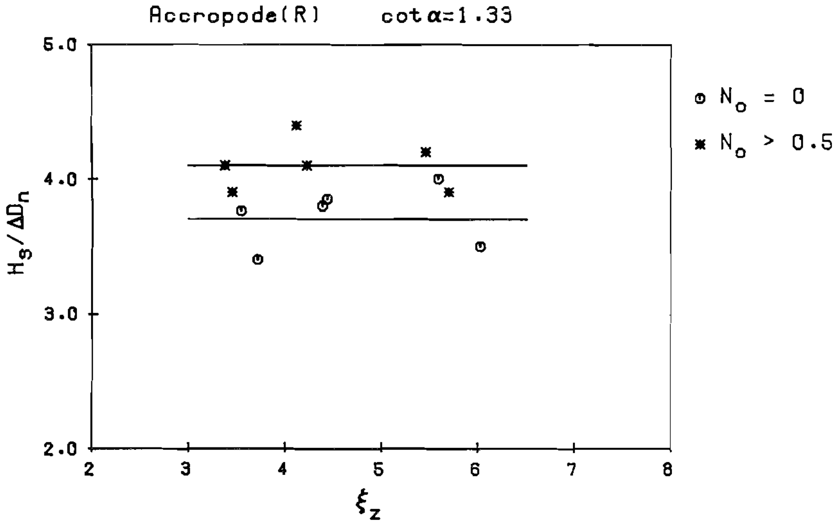


Fig. 6 Stability of Accropode(R)

22. From Fig. 6 two more and important conclusions can be drawn. The stability for start of damage is very high compared to Cubes and Tetrapods (Figs. 4 and 5). This is caused by settlement of the steep slope ($\cot\alpha = 4/3$) during the bedding in test with low waves. After settlement the armour layer acts as a "blanket" where each unit contacts several neighbours. Start of damage ($N_o = 0$) and severe damage or failure, given by $N_o > 0.5$ are very close, however. This means that the initial stability of Accropode(R) is very high, but that the structure fails in a progressive way. The results found for start of damage should not be used as design values, therefore.

23. As storm duration and wave period have no influence on the stability of Accropode(R) and as the "no damage" and "failure" criteria are very close, the stability can be described by two simple formulae:

Start of damage, $N_o = 0$: $$H_s/\Delta D_n = 3.7 \qquad (6)$$

Failure, $N_o > 0.5$: $$H_s/\Delta D_n = 4.1 \qquad (7)$$

RELIABILITY OF FORMULAE

24. In ref. 4 the formulae for rock were used in a probabilistic design, considering also the reliability of the formulae itself. This reliability (scatter) consists of a part due to random behaviour of a rubble mound structure and a part due to curve fitting. The coefficients 6.2 and 1.0 in equations 1 and 2 were treated as stochastic variables, having a normal distribution, an average equal to the values 6.2 and 1.0 respectively, and a standard deviation of 0.4 and 0.08 respectively.

25. A similar procedure can be followed for the formulae of artificial units. The coefficients 3.7 and 4.1 in equations 6 and 7 for Accropode(R) can be considered as stochastic variables. From analysis it followed that the standard deviation (assuming a normal distribution) amounded to $\sigma = 0.2$. The procedure for equations 4 and 5 is more complicated. Assume a relationship:

$$H_s/\Delta D_n = a * f\ (N_o,\ N,\ s_z) \qquad (8)$$

The function $f(N_o, N, s_z)$ is given in equations 4 and 5. The coefficient, a, can be regarded as a stochastic variable with an average of 1.0 and a standard deviation. From analysis it followed that this standard deviation is $\sigma = 0.10$ for both formulae on Cubes and Tetrapods.

COMPARISON OF STABILITY

26. Equations (1), (2) and (4)-(7) describe the stability of rock, Cubes, Tetrapods and Accropode(R). A comparison of stability is made in Fig. 7 were for all units curves are shown for two damage levels: "start of damage" ($S = 2$ for rock and $N_o = 0$ for artificial units) and "failure" ($S = 8$

for rock, $N_o = 2$ for Cubes, $N_o = 1.5$ for Tetrapods and $N_o > 0.5$ for Accropode(R)). The curves are drawn for $N = 3000$ and are given as $H_s/\Delta D_n$ versus the wave steepness, s_z.

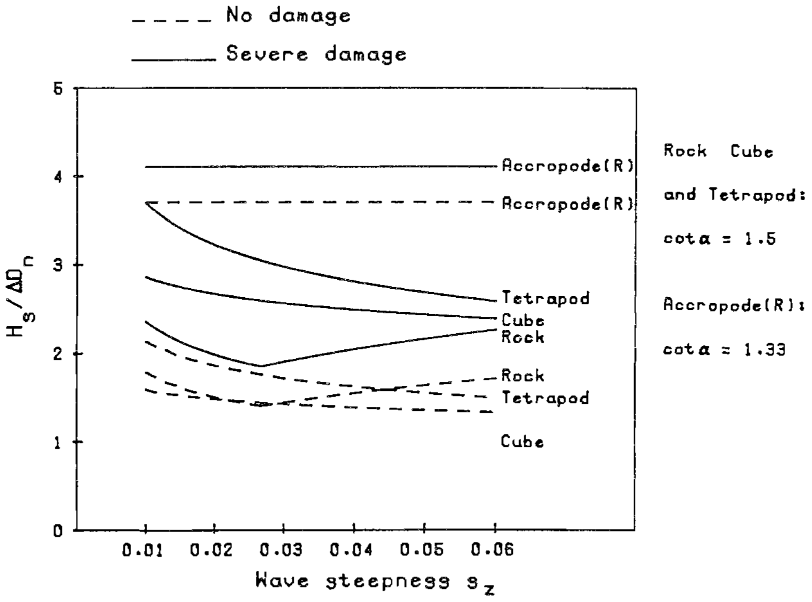


Fig. 7 Comparison of stability

27. From Fig. 7 the following conclusions can be drawn:

- Start of damage for rock and Cubes is almost the same. This is partly due to a more stringent definition of "no damage" for Cubes ($N_o = 0$). The damage level $S = 2$ for rock means that a little displacement is allowed (according to Hudson's criterion of "no damage", however).
- The initial stability of Tetrapods is higher than for rock and Cubes and the initial stability of Accropode(R) is much higher.
- Failure of the slope is reached first for rock, than Cubes, Tetrapods and Accropode(R). The stability at failure (in terms of $H_s/\Delta D_n$ values) is closer for Tetrapods and Accropode(R) than at the initial damage stage.

28. The complete investigation is described in refs. 6 and 7 for Cubes and Tetrapods and in ref. 8 for Accropode(R).

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