Influence of Core Permeability on Accropode Armour Layer Stability

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by

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INTRODUCTION

Hedar (1960 and 1986) and van der Meer (1988a) studied the influence of core permeability on the stability of two layer rock armour. In both cases a significant influence was found. However, it is to be expected that for single layer armour there will be an even larger influence of the core permeability. This is because the dissipation of wave energy in single layer armour will be smaller than in double layer armour, thus giving room for larger flow velocities in and over the armour layer. On this background a laboratory study of single layer Accropode® stability was undertaken at Aalborg University in 1995. The test results as well as a comparison with results of other researchers are presented in the paper. The expected sensitivity of Accropode armour stability to core permeability was confirmed.

Test set-up and test programme

Tests were performed in a 1.2 m wide and a 1.5 m deep wave flume. Two types of core material were used in the cross section shown in Fig. 1. The *fine* core material was sharp sand with gradation 2-3 mm, while the coarse material was crushed stones with gradation 5–8 mm. The Accropodes were 111 g having an equivalent cube length of $D_n = 0.036$ m and mass density $\rho_s = 2330$ kg/m^3.

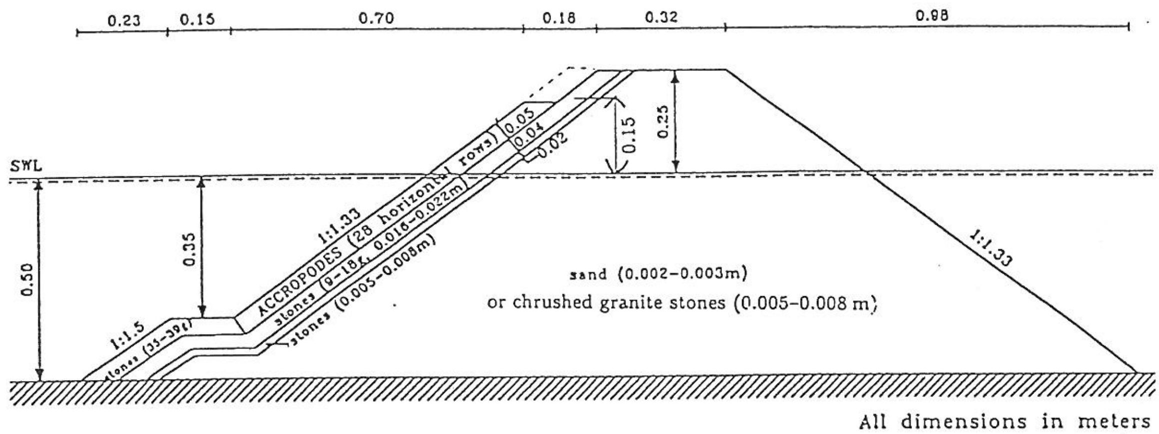

Fig. 1. Cross section of model.

The Accropode armour layer was built corresponding to the recommendation laid out by SOGREAH (1991) and guidelines given by M. Denechere, Manager of the Accropode Division at SOGREAH. Hence the armour layer consisted of a total of 504 armour units placed in 18 columns and 28 rows. As recommended by SOGREAH (1991) the distance between two horizontal rows was $0.6H_{B,Acc}$ and the horizontal mesh was $1.24H_{B,Acc}$, where $H_{B,Acc} = 0.052$m is the block height. See SOGREAH (1991) for further details.

Irregular waves (JONSWAP-type) corresponding to Iribarren numbers $\xi_P = \frac{tan\alpha}{\sqrt{H_{mo}/L_p}} =$ 3.75 and 5.00, with increasing wave heights within the range $H_{mo} = 0.08$–0.20 m were used. Each seastate contained app. 1,000 waves. The target values for the applied sea states in one test are presented in Table 1. It is seen that one test is composed of seven seastates of increasing severity, so that the loading history on the test structure represents the build up of a natural storm. This test procedure also allows the armour layer to settle during the smaller wave heights ($H_{mo} = 0.08$ m and $H_{mo} = 0.10$ m) and thereby obtain its natural stability . The damage level D was defined as percentage of units displaced a distance D_n or more, and was determined by photo overlay technique.

Table 1. Target values for the applied sea states in each test.

H_{mo} [m]*	0.08	0.10	0.12	0.14	0.16	0.18	0.20
fp [Hz] for $\xi_p = 3.75$	0.85	0.73	0.64	0.57	0.51	0.46	0.42
fp [Hz] for $\xi_p = 5.00$	0.57	0.47	0.40	0.35	0.31	0.28	0.26

* H_{mo} is the estimate on the significant wave height derived from the wave spectrum.

To prevent boundary effects along the sides of the flume, the damage analysis was carried out within a 0.75 m wide test section. This corresponds to 12 columns of Accropode units, i.e. the total number of Accropode units in the test section was 336.

After the end of each test (i.e., when the armour layer has failed) the test structure was totally rebuilt and prepared for the succeeding test.

Incident and reflected waves were separated by surface elevation analysis, Mansard and Funke (1980). Each test series was repeated minimum 5 times in order to evaluate the scatter.

A wave gauge was placed along the face of the armour layer in order to measure the run–up levels. The armour layer was extended to the top of the breakwater while recording run–up.

Surface Armouring of the fine core material

Little attention is in general paid to scaling of soil strength in hydraulic model tests with rubble mound breakwaters. This is mainly bacause soil mechanics failures in prototype structures are very rare and consequently not considered a problem. Moreover, correct scaling of soil strength is very difficult. In models with steep slopes and fine core materials the mound will be close to instability even without wave action. In the present case was used sharp sand with a narrow gradation, $2\,\mathrm{mm} \leq d \leq 3\,\mathrm{mm}$, in order to model the porous flow in a rather impermeable prototype structure. However, in the first test series a surprisingly low armour stability was observed. A closer investigation revealed that geotechnical sheet slip failure had occurred in the surface of the core material. Being very difficult to observe, especially in 3–dimensional models where cross section development cannot be studied through a glass wall, such failure can be misinterpreted as armour instability. To prevent further geotechnical problems it was chosen to reinforce the core with 90 steel wire spears placed in a mesh with a width of 15–16 cm. This method proved successful and it did not change the permeability of the core or caused bias of the stability of filter and armour layers.

Hydraulic stability of Accropode armour

Figs. 2, 3, and 4 show the test results given as the damage level D as function of the stability number $N_S = \frac{H_{mo}}{\Delta D_n}$, where $\Delta = \frac{\rho_s}{\rho_w} - 1 = 1.33$.

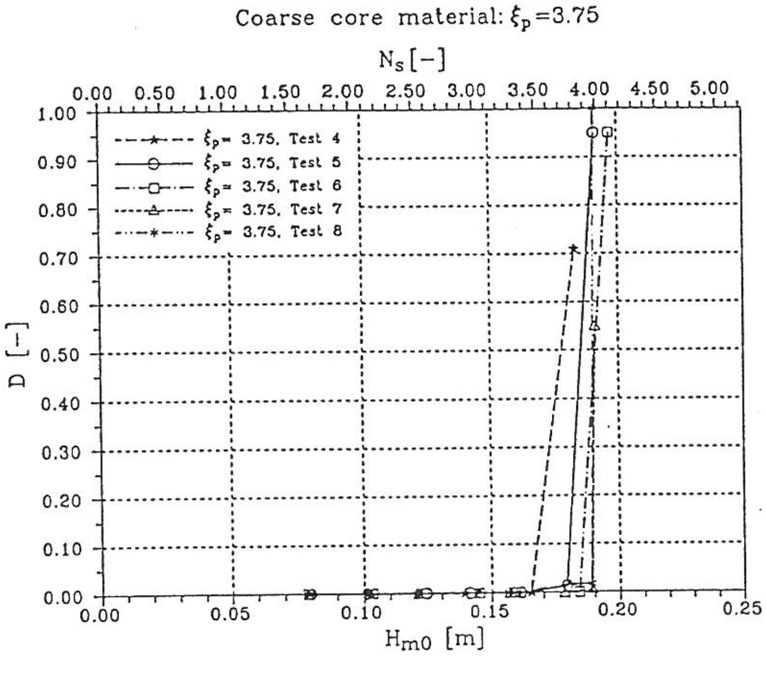

Fig. 2. Damage level (D) versus H_{mo} and N_S. Coarse core material and $\xi_p = 3.75$.

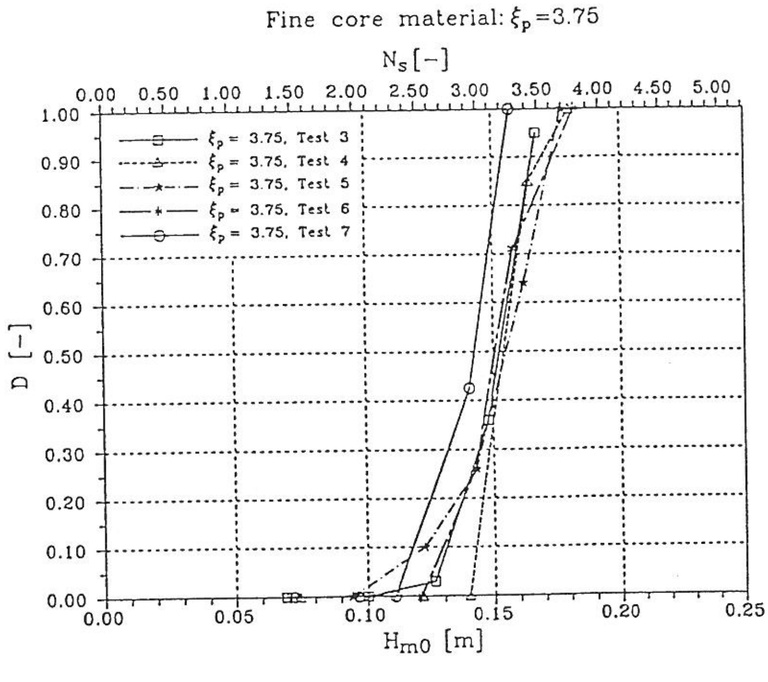

Fig. 3. Damage level (D) versus H_{mo} and N_S. Fine core material and $\xi_p = 3.75$.

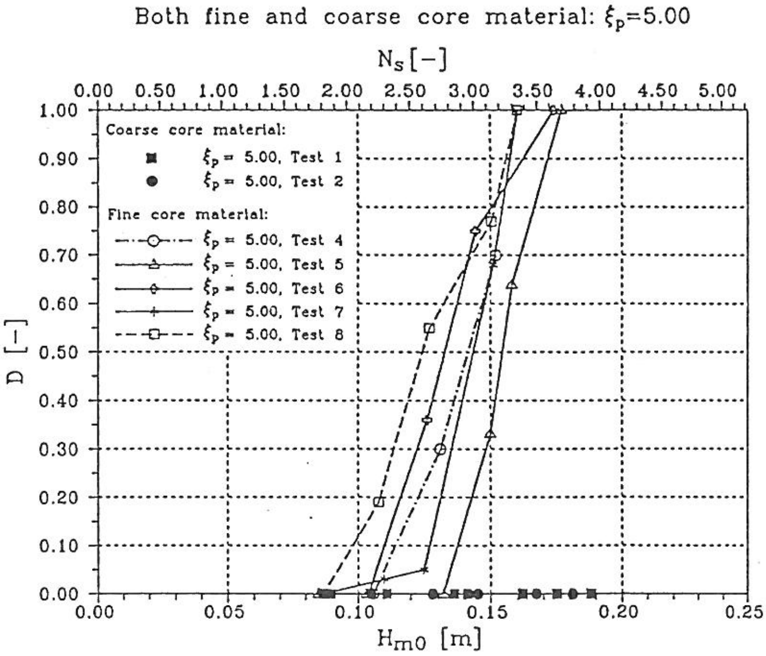

Fig. 4. Damage level (D) versus H_{mo} and N_S. Fine and coarse core materials and ξ_p = 5.00.

Figs. 5, 6, and 7 show the expected value μ and the 90% confidence levels of N_s based on the assumption of a Gaussian distribution for a certain damage level, i.e. $\mu \pm 1.64 \cdot \sigma$ where σ is the standard variation. The figures also show the coefficient of variation, $V = \sigma/\mu$.

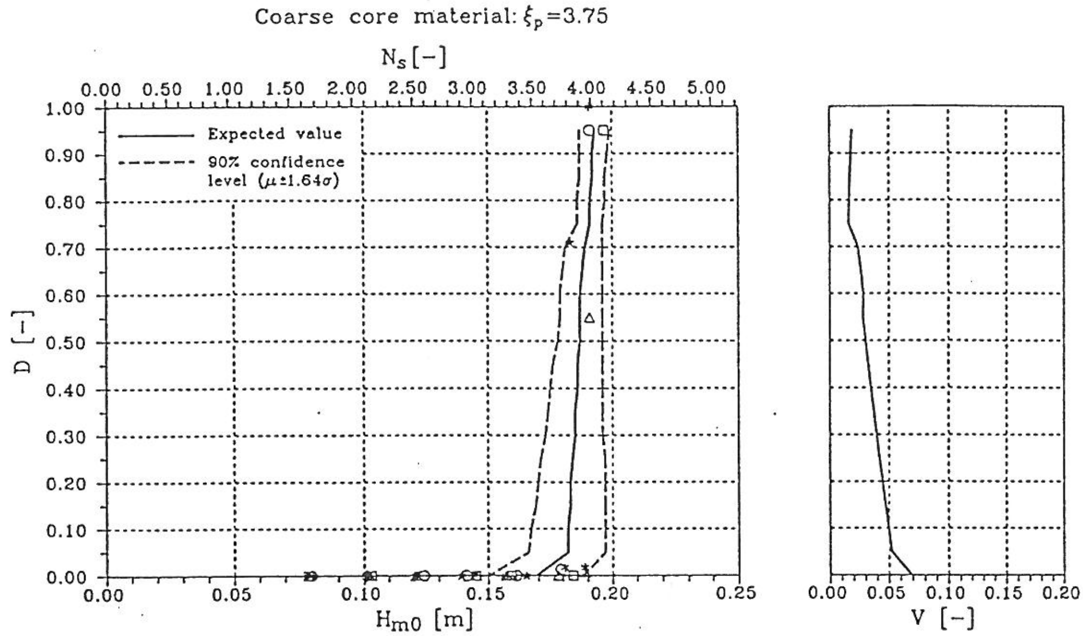

Fig. 5. Expected values and 90% confidence intervals of N_s. Coarse core material and $\xi_p = 3.75$.

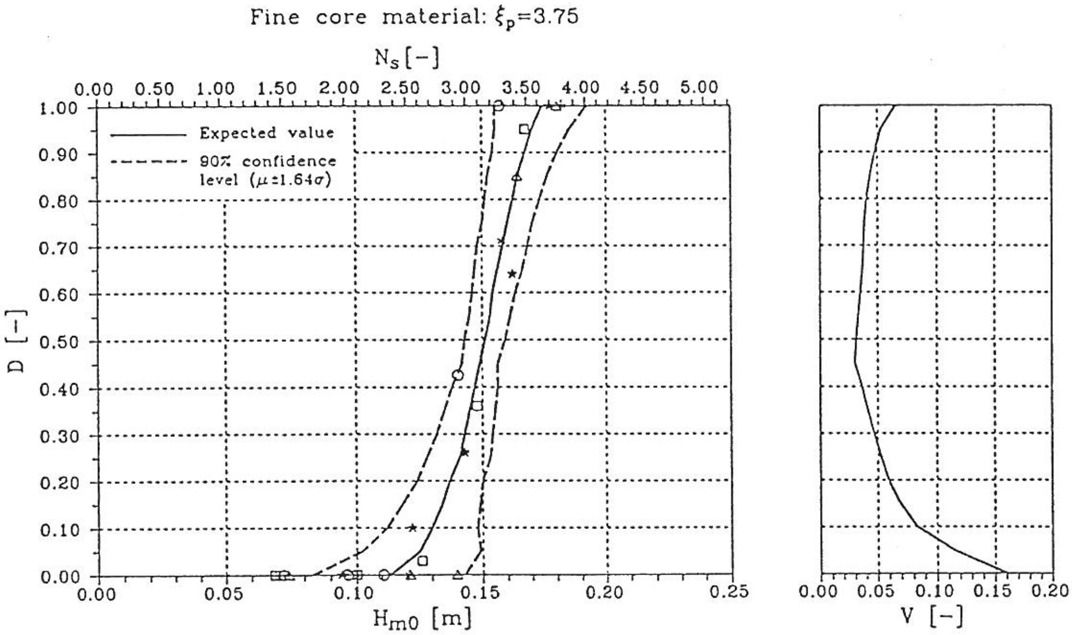

Fig. 6. Expected values and 90% confidence intervals of N_s. Fine core material and $\xi_p = 5.00$.

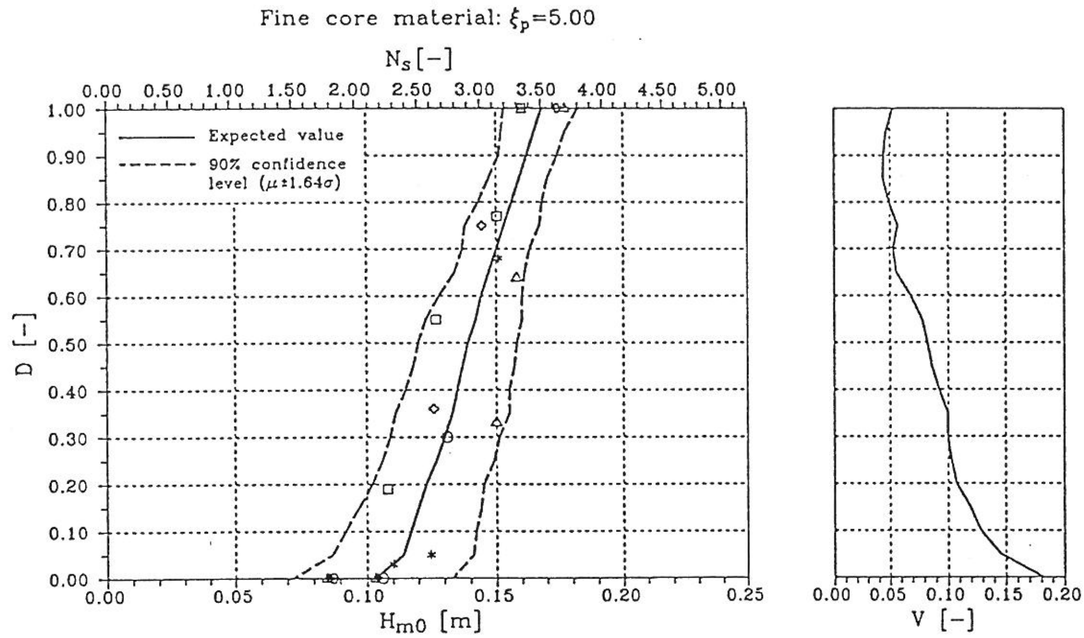

Fig. 7. Expected values and 90% confidence intervals of N_s. Fine core material and $\xi_p = 5.00$.

Tables 2 and 3 summarize the test results by giving the N_s–values corresponding to damage levels $D = 0\%$ and $D = 5\%$.

Table 2. Statistics of the stability number N_s corresponding to zero and 5% damage. Coarse core material.

	Coarse core material					
Iribarren number, ξ_p	3.75			5.00		
Statistical parameter	$\mu - 1.64\sigma$	μ	$\mu + 1.64\sigma$	$\mu - 1.64\sigma$	μ	$\mu + 1.64\sigma$
Stability number corresponding to zero damage, $N_{s,0\%}$	3.1	3.5	3.9	-	> 3.9*	-
Stability number corresponding to 5% damage, $N_{s,5\%}$	3.5	3.8	4.1	-	-	-

* As it appears from Fig. 4 no damage occurred for the coarse core material and $\xi_p = 5.00$. Therefore the highest N_s-value obtained during the test is presented. The actual $N_{s,0\%}$ is of course larger than this value.

Table 3. Statistics of the stability number N_s corresponding to zero and 5% damage. Fine core material.

	Fine core material					
Iribarren number, ξ_p	3.75			5.00		
Statistical parameter	$\mu - 1.64\sigma$	μ	$\mu + 1.64\sigma$	$\mu - 1.64\sigma$	μ	$\mu + 1.64\sigma$
Stability number corresponding to zero damage, $N_{s,0\%}$	1.7	2.4	3.0	1.5	2.1	2.8
Stability number corresponding to 5% damage, $N_{s,5\%}$	2.1	2.6	3.1	1.8	2.4	2.9

Influence of core permeability on Accropode stability

For rather massive single layer armour like Accropode armour with relatively small pore volume it is expected that low porosity core material has a significant negative influence on the stability. The present test results confirm this.

Not only the magnitude of the stability number seems to be influenced by the permeability of the core, but also the evolution of the damage differs significantly in the two cases. The stability is significantly higher in the case of coarse core material. However, the structure fails very suddenly, almost as a collapse in the case of coarse core material, whereas the failure of the structure with fine core material develops less rapidly.

For the short waves ($\xi_p = 3.75$) the expected value of $N_{s,0\%}$ is 3.5 for the coarse core material and only 2.4 for the fine core material, i.e. almost a difference of 50%. For the long waves ($\xi_p = 5.00$) the significance of the core permeability is even larger, since the difference is in the order of 100%, still with the coarse core material yielding the highest stability numbers. This large difference in hydraulic stability is magnified by the apparently opposite influence of the Iribarren number for the coarse and the fine core material.

The reason for the generally smaller stability in the case of fine core material is, that because of the relatively impermeable core the water cannot percolate into the voids of the core, and therefore the flow velocities over and in the armour layer become larger.

The same reasoning can be used to explain the opposite influence of the Iribarren number for the fine and the coarse core material. In the case of impermeable core it is obvious that if no water is allowed to percolate into the voids of the structure, the long waves ($\xi_p = 5.00$) will be more damaging than the short waves, since each wave carry more water onto the structure than for short waves. On the other hand, in the case of coarse core material, the long waves have time enough to penetrate deep into the structure, and thereby reducing the flow in the very armour layer. The short waves have less time to penetrate into the core, and hence a larger amount of the flow is situated in the armour layer, and thereby reducing its stability. The tendencies described above supports the *reservoir effect* presented by Burcharth & Thompson (1982).

Comparison with results from other researchers

A few papers dealing with the hydraulic stability of Accropode armour have been published during the recent years. The most important are Kobayashi and Kaihatsu (1994), Holtzhausen and Zwamborn (1991) and van der Meer (1988b). The results found by these researchers are presented in Table 4 together with the results of the present study and a previous study at Aalborg University (1995).

Table 4. Results obtained by other researchers and results from the present and a previous study at Aalborg University.

Researchers	Reported Stability number for a slope 1 : 1.33		Reported (N_s, ξ_p)-relationship
Kobayashi and Kaihatsu (1994)	$N_{s,0\%} = 3.5$ - 4.0	$(\xi_p \approx 2.4$ - $3.9)$	Decreasing N_s with increasing ξ_p for gravel filter layer. No influence of ξ_p for a filter layer of concrete blocks.
Holtzhausen and Zwamborn (1991)	$N_{s,1\%} = 3.0$	$(\xi_p \approx 4.3)$	Increasing N_s with increasing ξ_p (this was reported on basis of tests on other slopes than 1 : 1.33)
van der Meer (1988b)	$N_{s,0\%} = 3.7$	$(\xi_p \approx 2.6$ - $4.5)$	No influence of ξ_p
Aalborg University (1995) *	$N_{s,0\%} \approx 2.0$ - 2.5	$(\xi_p \approx 4)$	Nothing reported
Present study (Coarse core material)	$N_{s,0\%} = 3.5 \pm 0.4$ $N_{s,0\%} > 3.9$	$(\xi_p = 3.75)$ $(\xi_p = 5.00)$	Increasing N_s with increasing ξ_p
Present study (Fine core material)	$N_{s,0\%} = 2.4 \pm 0.6$ $N_{s,0\%} = 2.1 \pm 0.6$	$(\xi_p = 3.75)$ $(\xi_p = 5.00)$	Decreasing N_s with increasing ξ_p

* Same structural layout as in the present study with fine core material.

However, due to differences in the experimental set-up and especially in the test procedure it is difficult to perform a proper comparison to the results of the present study. For example the other researchers performed their tests with constant peak period, whereas the present tests were performed with constant Iribarren number. This means that the loading history varies in the different tests, making a proper comparison of the test results difficult. The significant influence of core permeability, which has been verified in the present study, is another perfect example on why different experimental set-ups yield different results. To enable a comparison of the permeability of the different structures, their cross sections have been sketched in Figure 8. From this it is also seen that the crest height relative to the Accropode size (D_n) differs significantly. This certainly influences the stability as larger overtopping increases the front armour stability. Moreover, the height of the armour layer (i.e. number of rows of Accropodes) varies considerably. This also influences the stability because prestressing due to the weight of the blocks is significant on steep slopes like the 1:1.33 slope.

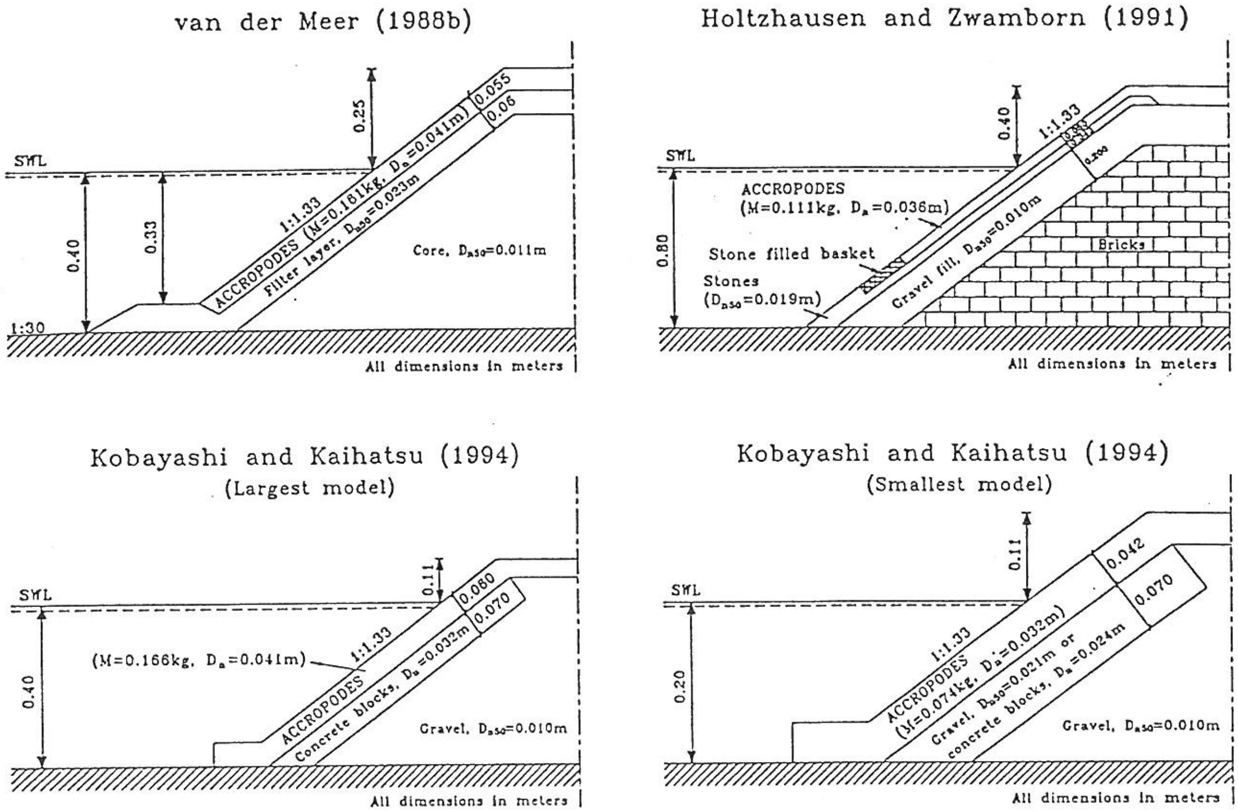

Fig. 8. Cross sections of models by other researchers. Drawings not to scale.

Run–up

Selected run-up data have been plotted in Figs. 9 and 10 for the case of coarse core material and fine core material, respectively. $R_{u,2\%}$ is the run-up level corresponding to an exceedence probability of 2% and h= 0.50 m is the water depth in front of the structure.

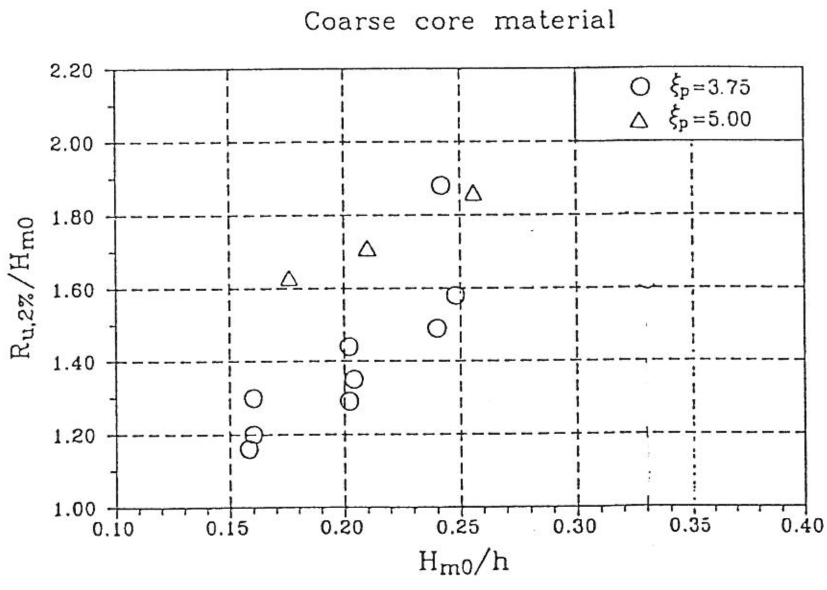

Fig. 9. Run–up in the case of coarse core material.

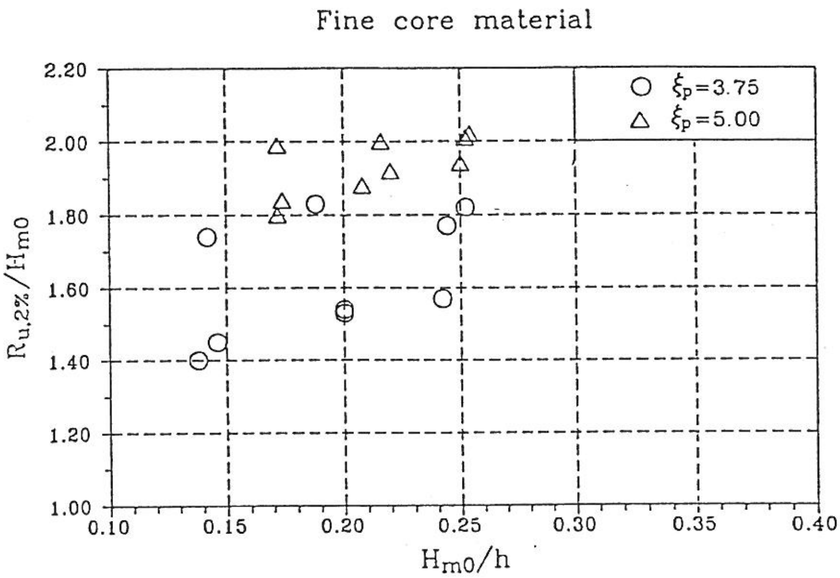

Fig. 10. Run–up in the case of fine core material.

It is seen that the relative run–up $R_{u,2\%}/H_{mo}$ increases with H_{mo} for constant ξ_p. Moreover, the relative run–up is 5–15% larger for $\xi_p = 5.00$ than for ξ_p= 3.75, and 10–15% larger for the fine core compared to the coarse core.

Prototype interpretation of model test results

The significant influence of the core permeability on the armour stability and the run–up makes it important to consider porous flow scale effects when designing a model of a prototype or, the other way around, when converting model test results to prototype conditions.

Generally, in order to avoid bias in the hydraulic response at the surface of the breakwater it is necessary to ensure similarity between the flow fields in the prototype and model cores. This again requires the hydraulic gradient I to be the same in geometrically similar points, i.e.

$$I_P = I_M \tag{1}$$

in which subindex P and M refer to prototype and model, respectively.

I can be estimated from the Forchheimer equation, for example the formulation for the one–dimensional, steady flow case, given by Burcharth et al. (1995)

$$I = \alpha \left(\frac{1-n}{n}\right)^2 \frac{\nu}{g\,d^2} \left(\frac{U}{n}\right) + \beta \frac{1-n}{n} \frac{1}{g\,d} \left(\frac{U}{n}\right)^2 \tag{2}$$

in which

n = porosity
ν = kinematic viscosity of water
d = characteristic diameter of grains
U = discharge velocity, $\frac{U}{n}$ = pore velocity
g = gravitational constant
α and β = coefficients dependent on Reynolds' number $Re = \dfrac{U\,d}{\nu}$, and on grading and shape of the grain material.

For given length scale ratio $\dfrac{\ell_P}{\ell_M} = \lambda$ the velocity scale is $\dfrac{U_P}{U_M} = \sqrt{\lambda}$ in a Froude model. Given f.ex. the prototype values of n_P, ν_P, d_P, α_P, β_P and U_P and the model values of n_M, ν_M, α_M, β_M, $U_M = U_P/\sqrt{\lambda}$ it is possible by the use of eqs (1) and (2) to calculate d_M.

For the presented two cases of core material the characteristic pore velocities U under design conditions were estimated to be $\frac{1}{50}$ and $\frac{1}{200}$ of a characteristic surface velocity $U_W = \sqrt{g\,H_s}$, for the coarse and fine core materials, respectively. The following values of α and β estimated from information given in Burcharth et al. (1995) were applied, Table 5.

Table 5.

Gradation	Re	α	β
narrow	< 5	650	0
narrow	5–600	360	3.6
wide	> 600	13,000	3.6
very wide	> 600	13,000	4.0

The length scale in the present study was $\lambda = 54.6$.

The relationship between model and prototype core characteristics is as follows:

Coarse core. $N_s = 3.34$
Prototype $d_{50} = 0.200\,\text{m}$, $\dfrac{d_{85}}{d_{15}} = 3.3$
1:54.6 model $D_{50} = 0.0060\,\text{m}$, gradation 0.0050–0.0080 m

Fine core. $N_s = 2.50$
Prototype $d_{50} = 0.050\,\text{m}$, $\dfrac{d_{85}}{d_{15}} = 5.5$
1:54.6 model $D_{50} = 0.0025\,\text{m}$, gradation 0.0020–0.0030 m

Comparison with core permeability influence on rock armour stability

van der Meer (1988a) investigated the sensitivity of conventional two–layer rock armour stability to core permeability. Generally the same trends, also with respect to influence of ξ, were observed. A quantitative comparison of the two sets of results can be made if it is assumed that van der Meer's stability formulae can be expanded to cover also a 1:1.33 slope.

The van der Meer formulae for rock reads:

$$N_s \cdot \sqrt{\xi_m} = 6.2 \cdot P^{0.18} \left(S/\sqrt{N}\right)^{0.2} \qquad \text{plunging waves} \tag{3}$$

$$N_s = 1.0 \cdot P^{-0.13} \xi_m^P \left(S/\sqrt{N}\right)^{0.2} \sqrt{cot\alpha} \qquad \text{surging waves} \tag{4}$$

The intersection between eqs (3) and (4) is given by

$$\xi_m = \left(6.2 \cdot P^{0.31} \sqrt{tan\alpha}\right)^{1/(P+0.5)} \tag{5}$$

The Accropode test conditions correspond to:

$$\begin{aligned} N &= 1,000 \text{ , number of waves} \\ \cot\alpha &= 1.33 \\ S &= \begin{cases} 2 & \text{for } D = 0\% \\ \simeq 8 & \text{for } D = 5\% \end{cases} \quad \text{damage level} \\ \xi_m &= \begin{cases} 3.00 & \text{for } \xi_P = 3.75 \\ 4.00 & \text{for } \xi_P = 5.00 \end{cases} \\ P &\simeq \begin{cases} 0.2 & \text{fine core material} \\ 0.4 & \text{coarse core material} \end{cases} \end{aligned}$$

By the use of eqs (3)–(5) we get the following N_s–values for rock slopes, Table 6:

Table 6. Approximate values for rock armour on 1:1.33 slope.

	fine core		coarse core	
ξ_P	3.75	5.0	3.75	5.0
$N_{s,D=0\%}$	1.54	1.33	1.75	1.52
$N_{s,D=5\%}$	2.04	1.77	2.31	2.01

By comparing with the accropode results given in Tables 2 and 3 it is seen that the sensitivity to core permeability is much higher for Accropode armour than for conventional rock armour. This conclusion also holds for rock armour on 1:2 slopes.

Conclusions

- Stability factors and related statistical uncertainties are given for Accropode® armour on 1:1.33 slope based on model tests with coarse and fine core materials.
- The large sensitivity of Accropode armour stability to core permeability is demonstrated.
- An example of scaling core material between model and prototype is given.
- Fine core material reduces the stability considerably. However, the failure develops more gradually than in case of coarse core material.
- The large sensitivity makes it very important to scale the core permeability in Accropode models correctly with respect to the porous flow.
- It is equally important to control the core permeability during construction of prototype structures.

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