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ON 3-DIMENSIONAL STABILITY OF RESHAPING BREAKWATERS

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INTRODUCTION

The paper deals with the 3-dimensional stability of the type of rubble mound breakwaters where reshaping of the mound due to wave action is foreseen in the design. Such breakwaters are commonly named sacrificial types and berm types. The latter is due to the relatively large volume of armour stones placed in a seaward berm. However, as also conventional armoured breakwaters sometimes do contain a berm it is assumed that a better and more ambiguous designation would be "reshaping" mound breakwaters.

The principle of reshaping breakwaters is to use relatively fine rock material which will then be eroded to S-shape profiles if sufficient amount of material is provided, Fig. 1. This type of breakwater can be constructed and maintained without the use of expensive specialized equipment. For a detailed discussion see Baird et al., 1984.

If sufficient material is provided to prevent the top of the mound to be eroded in its full width a reshaping breakwater will always be dynamically stable in head-on waves (2-dimensional case). This principle holds for all sizes of stone materials since even a sand beach stabilizes though with a very flat profile.

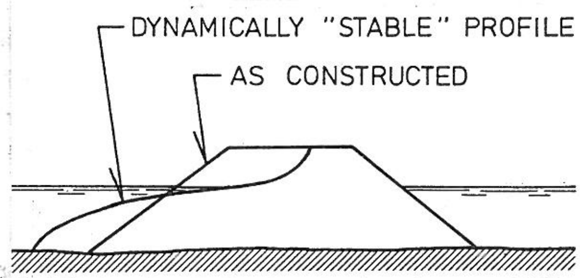


Fig 1. Reshaping breakwater.

However, in reality there are two important 3-dimensional effects which must be included in the design criteria, namely the rate of erosion (recession) of the roundhead and the rate of erosion of the trunk caused by oblique waves. The latter might cause unacceptable removal and transport of stones along the structure and thereby constitute a more restricting design criteria than head-on waves.

The paper discusses the trunk stability in oblique waves and the stability of berm roundheads and presents results from model tests.

The tests were conducted in a 3-dimensional model at The Hydraulics Laboratory, Department of Civil Engineering, University of Aalborg.

MODEL TEST SET-UP

Geometry of the model

Fig. 2 shows the cross sections of the model (before each test) and the lay-out of the model in the wave basin.

Two different lay-outs were used in order to examine the stability of breakwaters with different widths.

To avoid too many parameters a simple breakwater geometry and only one class of stones were used.

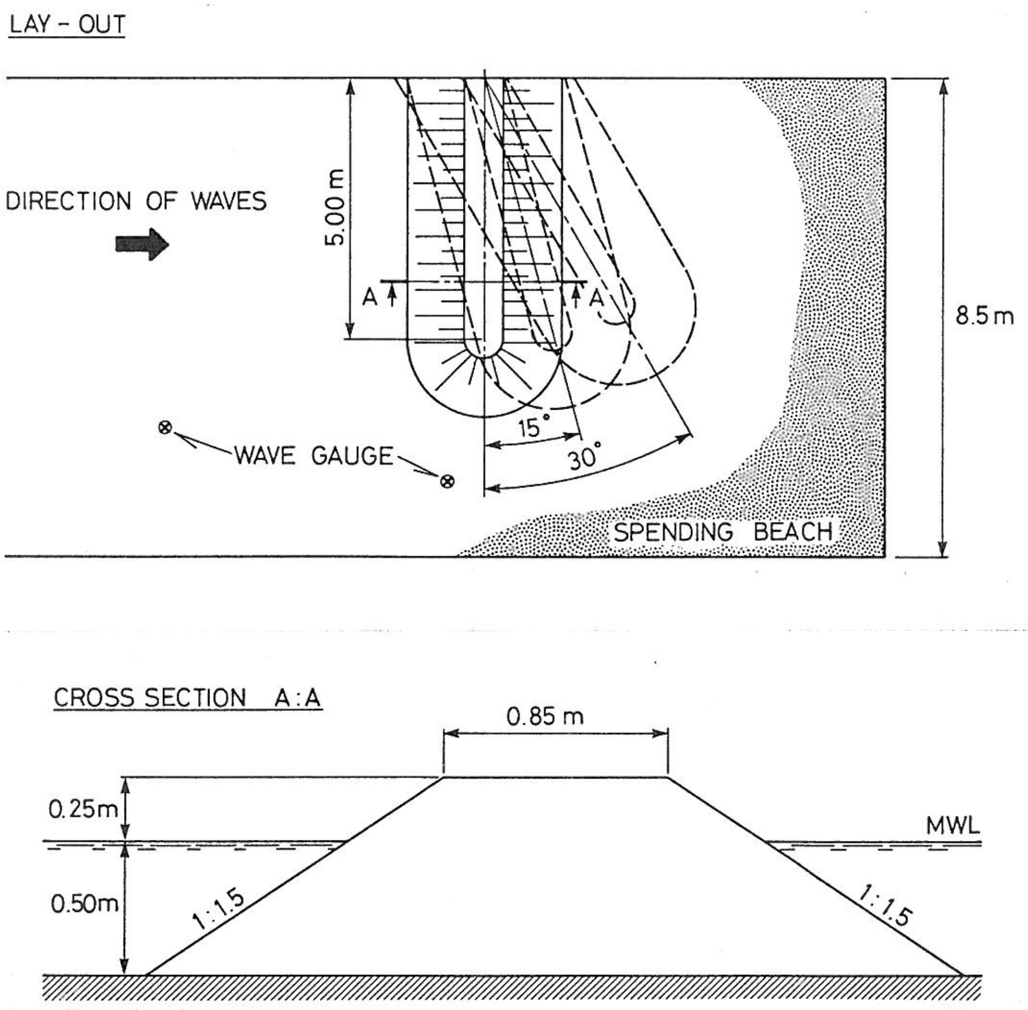
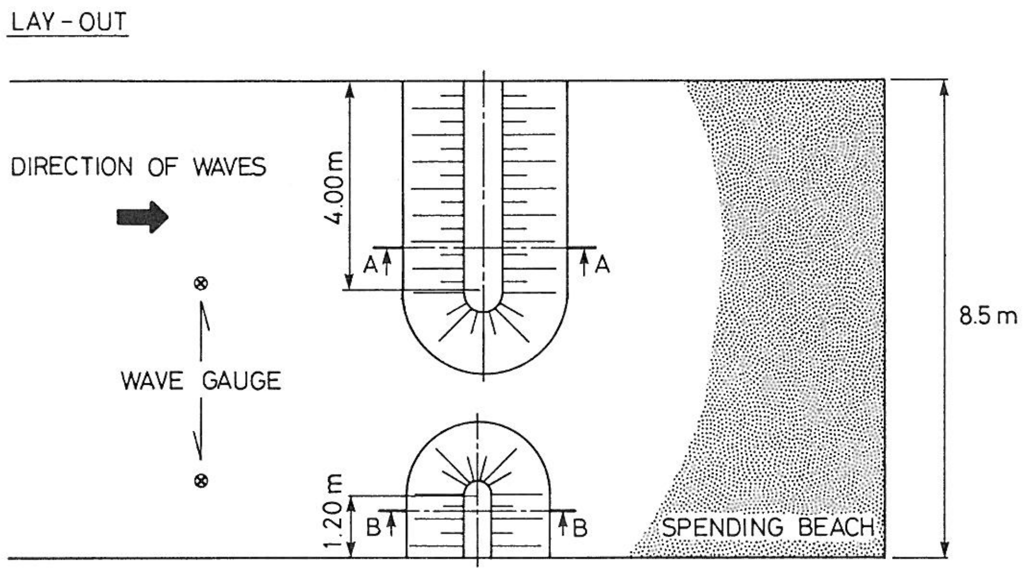


Fig 2. Lay-out and cross section of the model. (Continuied on next page).



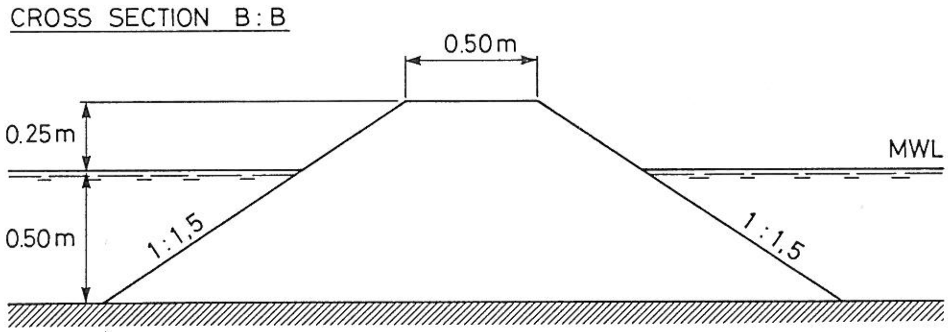


Fig 2. Lay-out and cross section of the model.

The stone material

The model consisted of one grading of crushed stones with a density $\rho_s = 2.65$ t/m^3 (metric ton) and a gradation as given in Figs. 3 and 4. No special core material was used.

It was found that the relationship between the sieve diameter (quadratic sieve) d and the stone volume V and stone weight w is

$$V = 0.7d^3 = \frac{w}{\rho_s}$$

d is regarded a characteristic diameter of the stones.

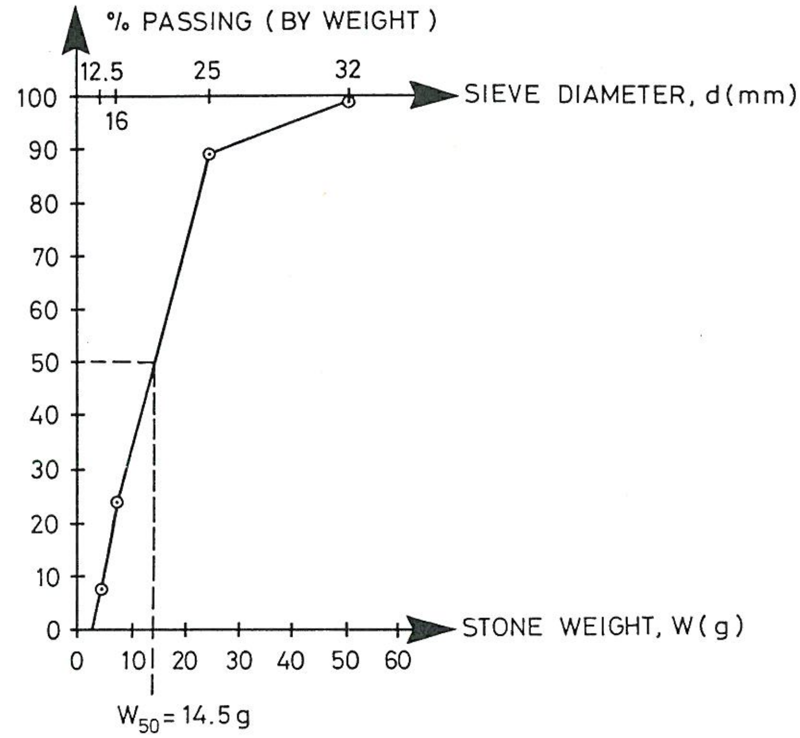


Fig 3. Gradation of model stones (Linear representation).

As seen from Fig. 3 w_{50} is found to be 14.5 g. However, it is most likely that an extra point on the gradation curve in the sieve interval 16-25 mm would have shifted the graph to the left and thereby given a w_{50} smaller than 14.5 g. This is investigated by Fig. 4.

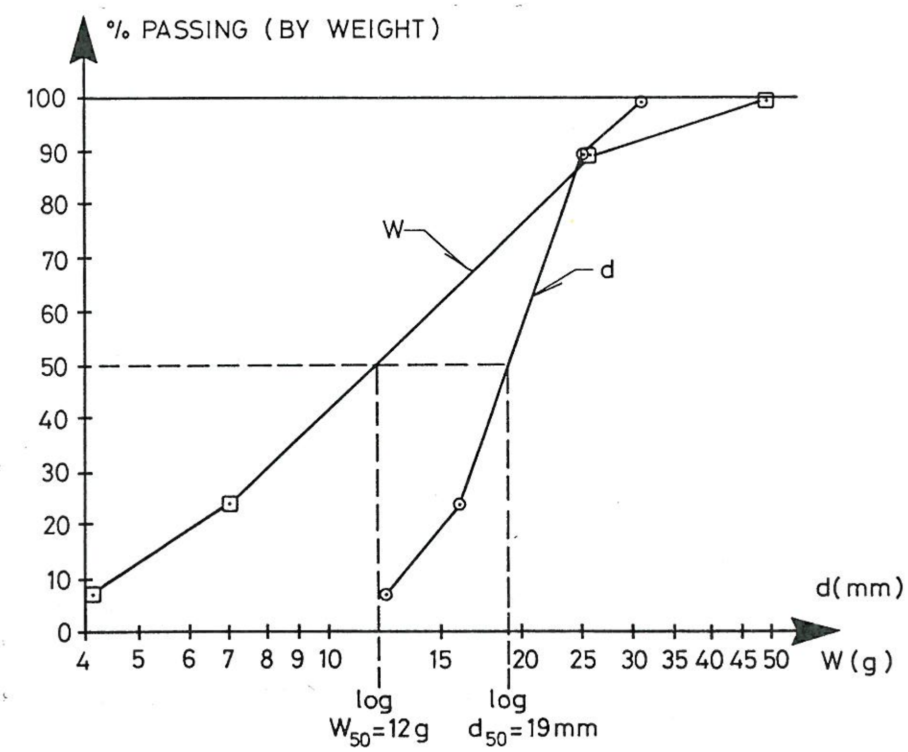


Fig 4. Gradation of model stones (Log-linear representation).

The stone weight corresponding to d_{50}^{log} = 19 mm is $w_{d_{50}} = \rho_s \cdot 0.7 d^3 = 2.65 \cdot 0.7 \cdot 1.9^3 = 12.7g \geqslant w_{50}^{log} = 12$ g.

The log representation confirms that w_{50} is somewhat less than 14.5 g.

Based on the various figures a w_{50} of 12.7 g corresponding to d_{50}^{log} = 19 mm is chosen as the most correct value.

D_{n50} is a nominal diameter defined as $D_{n50} = (w_{50}/\rho_s)^{1/3} = 16.9$ mm.

It should be noted that for the investigation of longshore transport in oblique waves samples of stones without diameters less that 16 mm were used. For these samples d_{50}^{log} = 22 mm and $w_{d_{50}}$ = 20.3 g.

Waves

All waves were irregular waves generated in accordance with a random phase JONSWAP-type spectrum (peakedness parameter $\gamma = 3.3$ and width parameters $\sigma_f = 0.10$ for $f \leqslant f_p$ and $\sigma_f = 0.50$ for $f > f_p$).

All tested sea states are stated in Tabel 1.

Spectrum no.	H_s (m)	T_p (sec.)	$H_s/\Delta \cdot D_{n50}$
A	0.10	1.50	3.5
B	0.10	2.00	3.5
C	0.15	1.80	5.4
D	0.15	2.50	5.4
E	0.20	2.50	7.1
F	0.10	1.70	3.5
G	0.13	1.80	4.6
H	0.13	2.50	4.6
I	0.15	2.00	5.4
J	0.15	2.20	5.4
K	0.15	2.50	5.4
L	0.175	2.50	6.3

Tabel 1. Tested sea states.

Two different methods of producing the wave generator control signals were used.

Control signals for the tests using spectrums A through E were calculated by use of FFT-transformation, while all other control signals were based on the method of filtering white noise.

The following three angles of wave attack were tested: $\alpha = 0°$ (head-on waves), $\alpha = 15°$, and $\alpha = 30°$.

MODEL CONSIDERATIONS

The sea states were chosen in the range from very little erosion to fast erosion of the profile under oblique wave attack.

An indication of the relative stability of the profiles can be given by the dimensionless parameter $H_s/\Delta \cdot D_{n50}$, where $\Delta = \rho_s/\rho - 1$. It is seen that $H_s/\Delta D_{n50}$ equals the stability number $N_s = (K_D \cot\alpha)^{1/3}$, where K_D is the Hudson stability coefficient and α is the slope angle. (Note that the influence of the wave period is lacking in the parameter).

According to extensive testing of rock slopes in head-on waves by DHL(Pilarczyk and Van der Meer) the values of the dimensionless parameter can be related to various types of rock slopes as follows:

$H_s/\Delta D_{n50}$	
1 – 3	Conventional breakwater layer, start of damage
2 – 5	Conventional breakwater layer, failure
3 – 7	Reshaping breakwater (Berm breakwater)
5 – 50	Rock beaches

In the present tests we have

$$\Delta = \left(\frac{\rho_s}{\rho} - 1\right) = 1.65$$

$$D_{n50} = \left(\frac{12.7}{2.65}\right)^{1/3} = 1.69 \text{ cm}$$

$$\Delta \cdot D_{n50} = 2.79 \text{ cm}$$

and consequently the range of tests corresponds to

$$3.5 < H_s/\Delta \cdot D_{n50} < 7.1$$

which is the interval considered for reshaping breakwaters.

SCALE EFFECTS CONSIDERATIONS

Provided that the grading of the stones is not too wide, say $\frac{d_{85}}{d_{15}} < 3$, and provided that the amount of fine material cannot block the pores (which is usually the case if $\frac{d_{85}}{d_{15}} < 3$) it is relevant to define a Reynolds' number with the characteristic length D_{n50}

$$Re = \frac{D_{n50}\sqrt{gH_s}}{\nu}$$

ν is the kinematic viscosity = 10^{-6} m²/s at 20°C.

With H_s = 0.10 - 0.20 m we get

$$1.7 \cdot 10^4 < Re < 2.4 \cdot 10^4$$

Juul Jensen and Klinting analysed the scale effects and found that no significant viscous scale effect is to be expected if in the outer part of the structure $Re > 0.6 \cdot 10^4$. Van der Meer found no scale effects for rock slopes with characteristic stone size of 20 mm, which is approximately the stone size in the present tests. This is also the experience of the Hydraulics Laboratory at the University of Aalborg.

However, although it is believed that a viscous scale effect is present it will be either negligible or will cause the results (in terms of amount of damage) to be on the safe side.

STABILITY OF ROUNDHEAD AND TRUNK IN HEAD-ON WAVES

Test procedure

The initial cross sections profiles of the model are shown in Fig. 2.

In the rough wave conditions only the model with the large crest width was used. In tests with calmer sea conditions both models were used.

The waves were recorded throughout all the tests. Wave height, wave period and shape of spectrum were controlled. The breakwater profile was measured after 3000 waves in all tests, and in most of the tests the waveseries were repeated once or twice and then the breakwater profile was measured again.

The wave basin was equipped with two cameras and contour plots of the breakwater was made after all tests using Photogrammetry.

Moreover, the characteristics of the stone movements were found from video recordings of the movements of coloured stones.

Test results for profiles in head-on waves

In agreement with results from several other authors, i.e. Van der Meer and Pilarczyk 1986, the shape of the profiles was found to be governed by the wave heigth and the wave period. The influence of the number of waves was found to be very little for profiles exposed to more than 3000 waves. After 6000 waves the profiles seem to have reached a "state of equilibrium".

Also, it was observed that most of the reshaping took place within approximately 200 waves.

It is characteristic that a very wide range of sea states (from mild to severe) produce only slightly different trunk profiles in head-on waves.

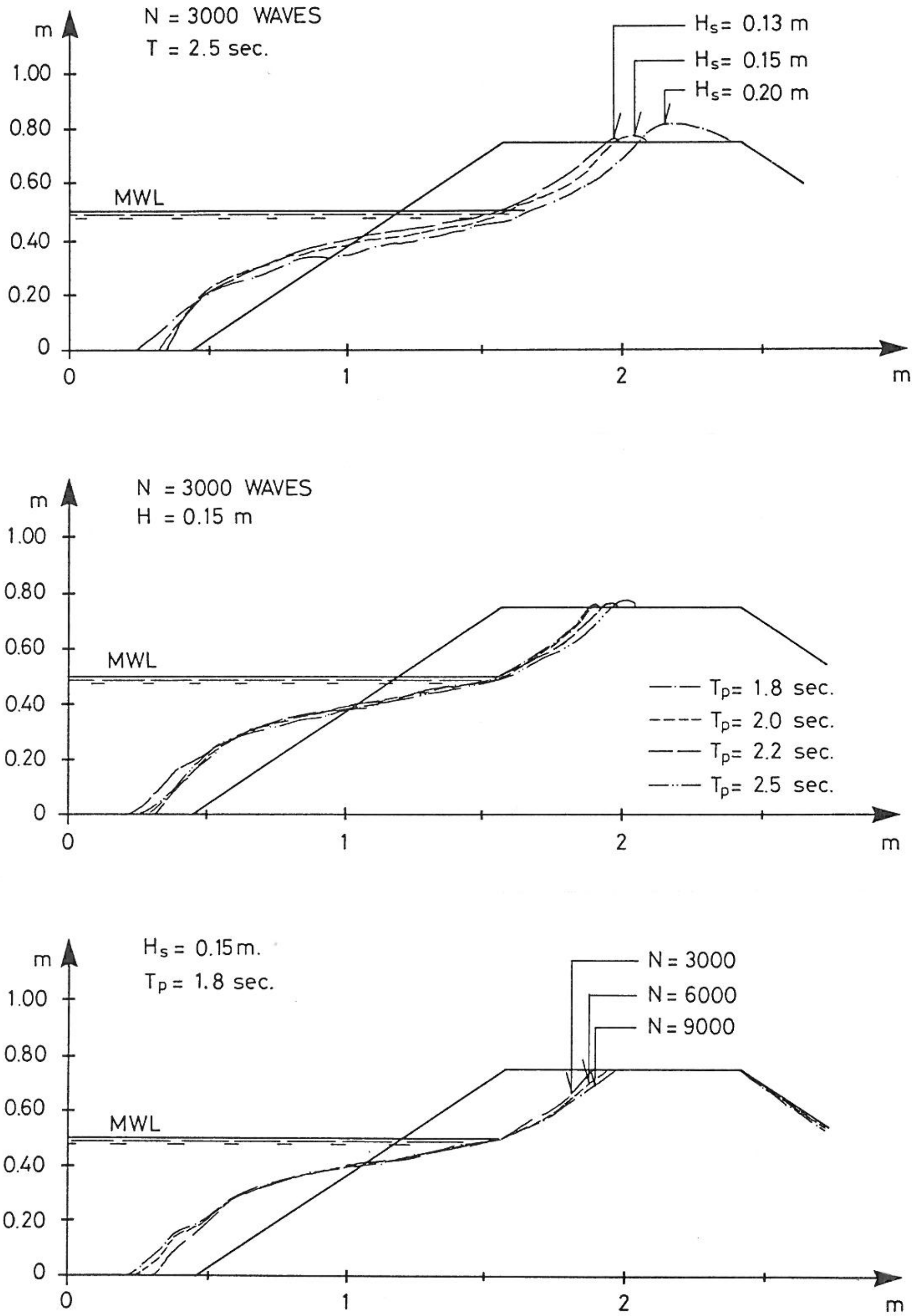


Fig 5. Examples of profiles in head-on waves
- influence of wave heigth
- influence of wave period
- influence of number of waves

The material deficit is due to settlements caused by wave compaction and material transport across the crest.

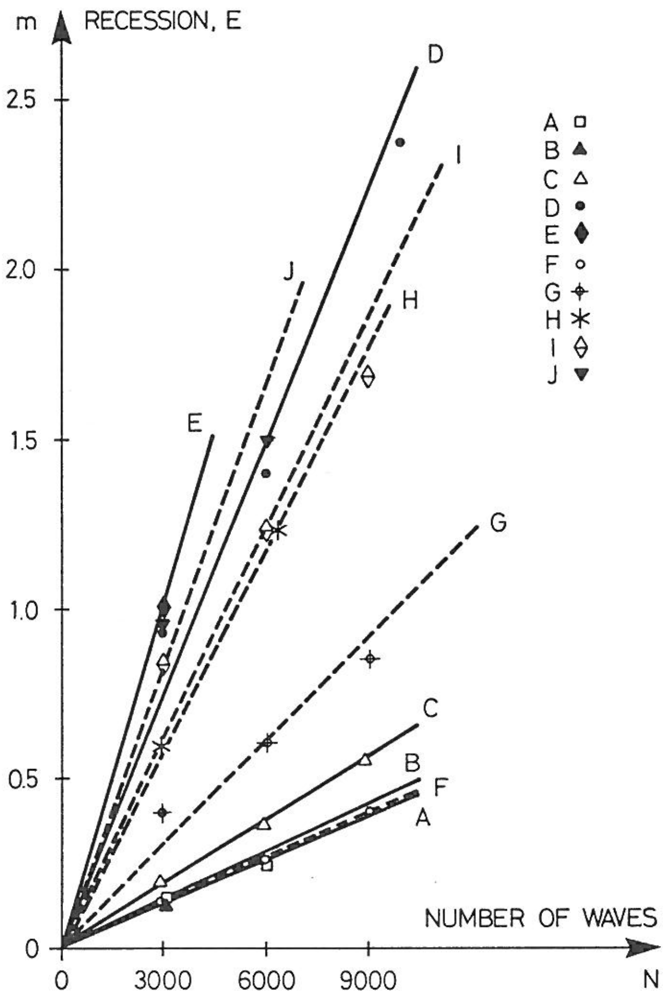


Fig 6. Recession (erosion) rate of the roundhead.

The erosion of the roundhead is expressed in terms of recession of the crest end measured along a longitudinal line parallel to the centerline of the breakwater, see Fig. 7.

Fig. 6 shows the recession as function of the number of waves. Note that the rate is almost constant for a certain sea state, i.e. a linear relationship between the recession of the central crest end and the time (or number of waves).

In spite of the almost linear relationship between the recession of the roundhead and the time for each sea state. Fig. 6 shows a large amount of scatter. Notice that wave spectrum G (H_s = 0.13 m and T_p = 1.80 sec.) gives larger erosion than spectrum C (H_s = 0.15 m and T_p = 1.80 sec.). It is believed that the scatter is due to different grouping in the waves caused by different methods of generating the wave control signals.

Fig. 6 shows that the roundhead erosion rate is small up to a certain sea state, characterized by both wave heigth and wave period. When this sea state is exceeded, erosion is fast and the sea state now seems to be characterized by the ability of practically every one of the waves to erode some of the stones from the roundhead and to displace (shift) them all the way across the roundhead.

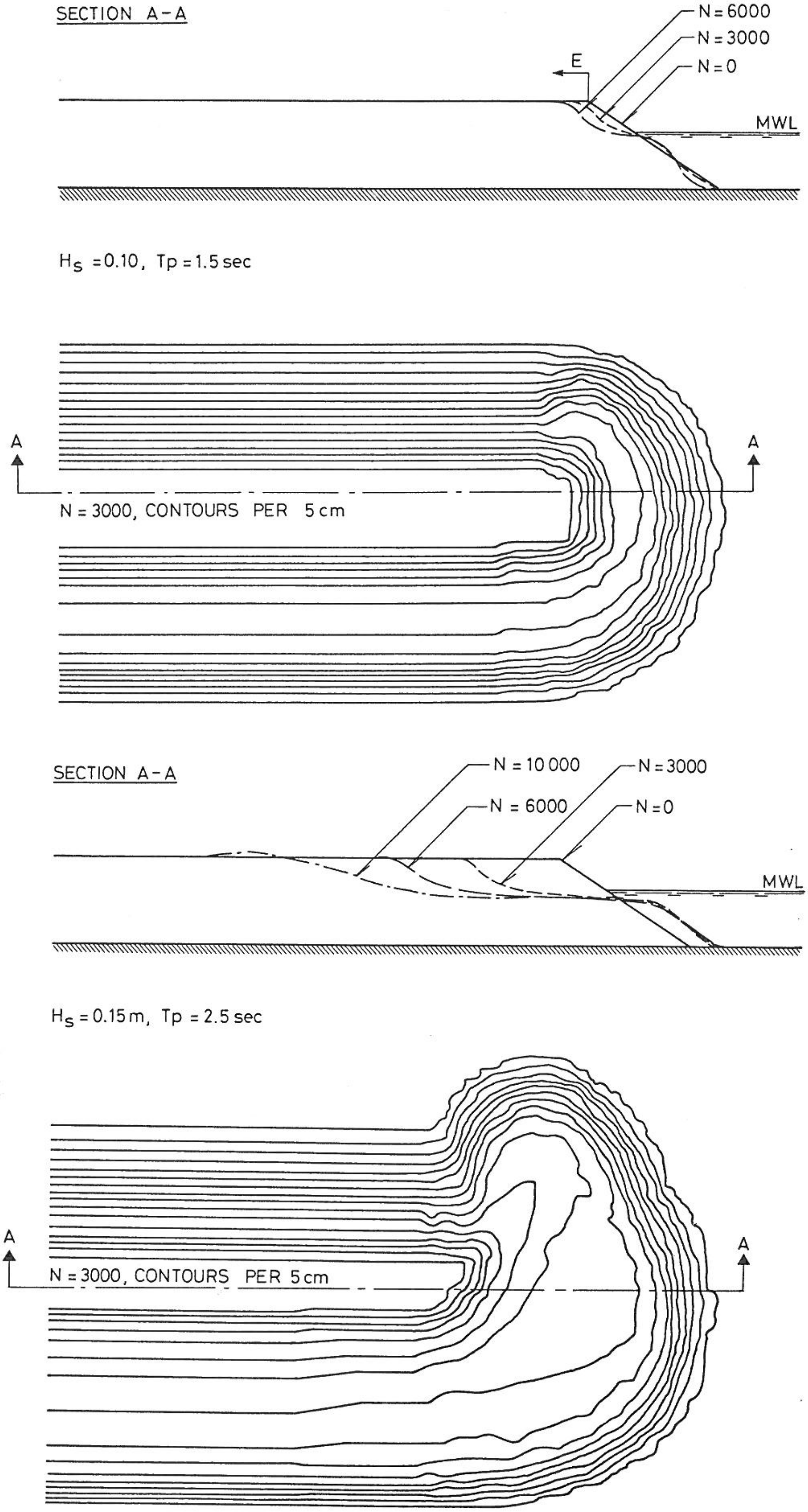


Fig 7. Examples of erosion of roundhead.

Simultaneous tests with the two lay-outs, Fig.2, indicate that erosion of the narrow breakwater will start at less severe sea states than for the wide breakwater.

Having observed in the tests that the erosion reached a level of approximately $H_s/2$ below the still water level the eroded cross sections can be evaluated.

The ratio of erosion of the breakwaters seems to have the same value as the ratio of the eroded cross sections until the sea state reaches the level where practically every one of the waves erodes some stones.

Seastate	H_s	T_p	Number of waves	Ratio cross section	Ratio recession
F	0.10	1.70	3000	1.5	1.7
F	0.10	1.70	6000	1.5	1.6
F	0.10	1.70	9000	1.5	1.5
G	0.13	1.80	3000	1.5	1.6
G	0.13	1.80	6000	1.5	1.5
H	0.13	2.50	2000	1.5	1.9
H	0.13	2.50	3000	1.5	> 2.0

Tabel 2. Ratio of recession between the narrow crested breakwater and the wide crested breakwater.

Fig. 8 shows that the maximum width of the eroded breakwater seems to be almost independent of the width of the non-eroded structure.

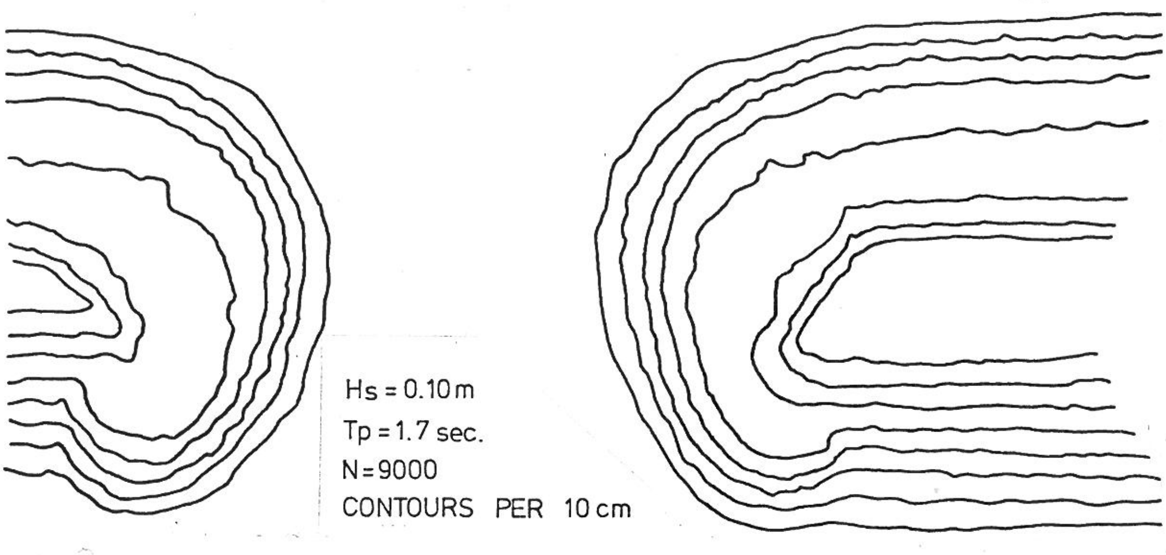


Fig 8. Example of erosion of a narrow crested breakwater and a wide crested breakwater.

The area on the breakwater where the erosion starts was found to be on the seaward side of the roundhead. The location is different from what is observed for conventional breakwaters where the erosion normally starts on the lee side of the breakwater, app. 135 degree angle with wave direction.

This difference might be explained by the larger width and larger roundhead diameter of the reshaping breakwater, which cause the stones on the leeward roundhead slope to be less exposed due to the diffraction of the waves along the relatively wide end of the roundhead. Moreover, the larger diameter provides a relatively better support of the stones in the direction of a wave attack.

Enlargement of the roundhead diameter has been used as a means of improving the stability of conventional breakwater roundheads, e.g. the Mohammedia breakwater in Morocco.

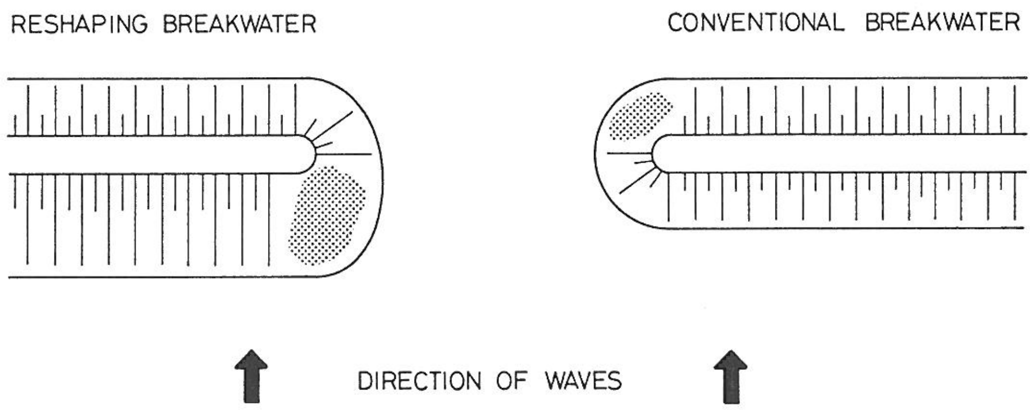


Fig 9. Area for start of erosion.

The breakwater develops into a characteristic banana shape as the erosion proceeds. Fig. 10 shows an example of the changing of the bathymetry of the roundhead.

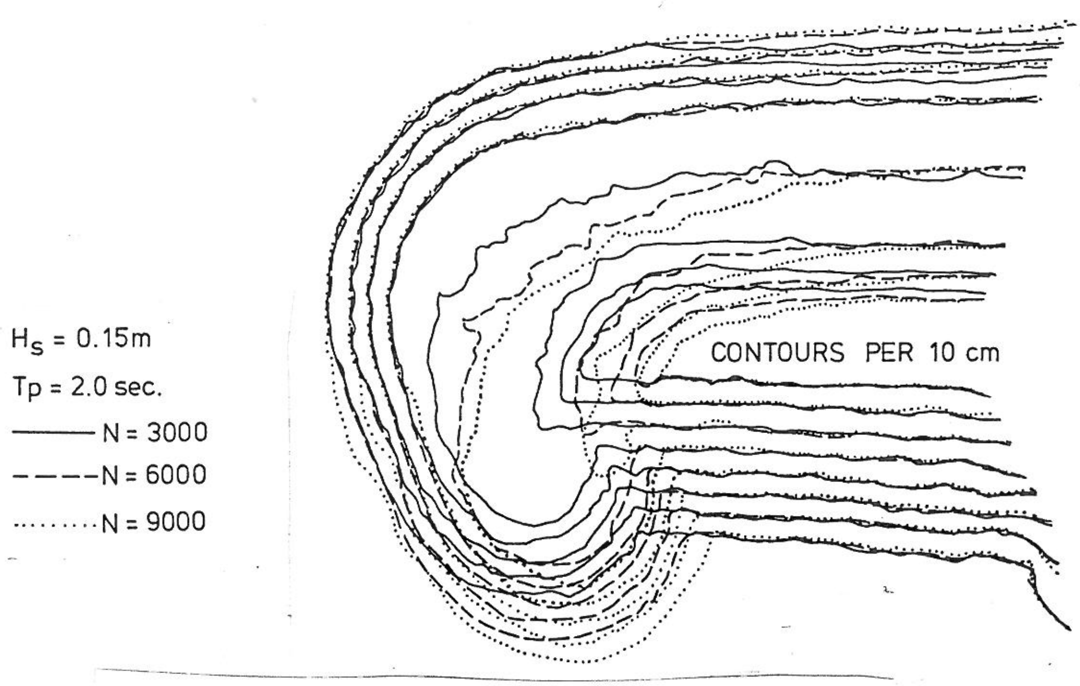


Fig 10. Time dependent development of roundhead.

STABILITY OF TRUNK AND LONGSHORE TRANSPORT IN OBLIQUE WAVES

In a trial test series it was found that for a given H_s, T_p the dynamically stable profiles in oblique waves within the tested range $\alpha \leqslant 30°$, cf. Fig. 2, were almost identical to the profiles in head-on waves.

Thus in every test with oblique waves the initial profile was chosen as the one found after 3000 head-on waves.

The longshore transport was found from video recordings of the movements of coloured stones placed in three bands over the profile. Moreover, after a specific number of waves (or time) the number, the positions and the total weight of each type of coloured stones were recorded.

The band width and the number of waves N were adjusted to the sea state in such a way that within the test period the non-coloured stones upstream the coloured bands did not pass the downstream coloured band. In this way the average transport per second (or per wave) through a cross section could be found. Moreover, by studying the distribution of the coloured stones over the profiles the maximum erosion depth (i.e. the number of stone layers within which displacements take place) could be estimated. The number of waves in each test varied between 250 waves and 900 waves.

Test results

The steady state transport of stones along the trunk was studied for two angles of wave attack, $\alpha = 15°$ and $\alpha = 30°$, c.f. Fig. 2.

Sea state	H_s (m)	T_p (sec.)	Average mass transport, Q (g/sec.) $\alpha = 15°$	$\alpha = 30°$
A	0.10	1.50	0.45	0.74
B	0.10	2.00	0.68	0.92
G	0.13	1.80	3.55	2.02
H	0.13	2.50	7.18	4.29
C	0.15	1.80	11.7	16.3
I	0.15	2.00	9.13	8.0
J	0.15	2.20	9.45	13.4
K	0.15	2.50	12.2	14.2
D	0.15	2.50	7.1	17.5
L	0.175	2.50	20.2	22.9
E	0.20	2.50	32.0	35.7

Tabel 3. Steady state mass transports along the trunk.

Notice that the sea states A and B only cause very small mass transports corresponding more or less to the onset of long-structure transport. Also notice that the more severe sea states L and E result in a significant transport, which in typical prototype situations will change the geometry of the structure significantly and might endanger the stability.

From the tests it is found that the average stone weigth of the transported stones varied significantly. The range was from 14.3 g/stone (sea state H, H_s = 0.13 m, T_p = 2.50 sec., α = 15°) to 20.5 g/stone (sea state I, H_s = 0.15 m, T_p = 2.00 sec., α = 30°).

It was found that a small average stone weight corresponded to a relative large transport. Because the same stone sample was used in all the tests the observed sorting must be regarded as natural scatter of the process. The large scatter is a consequence of the relatively short duration of each test.

The results look homogeneous in the sense that the trend is that the transport increases with wave height, wave period and angle of incidence in the tested ranges. However, the large scatter in the results, makes it impossible to quantify the sediment transport accurately.

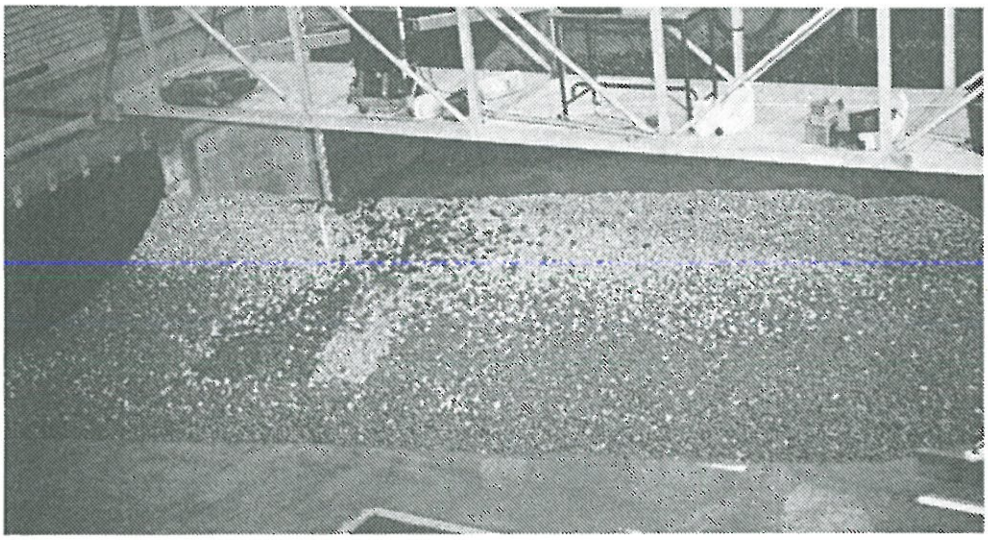


Fig 11. Example of the breakwater after longshore transport tests in oblique waves.

CONCLUSIONS

It is characteristic that a very wide range of sea states (from mild to severe) produce only slightly different trunk profiles in head-on waves, but very large differences in roundhead erosion and trunk erosion in oblique waves.

The roundhead erosion and the erosion of the trunk in oblique waves have a very strong non-linear dependency on the sea state. Below a certain sea state threshold value the erosion rates are very small, but excess of this value causes a drastic increase in the erosion. Consequently identification and consideration of this threshold value are of great importance in the design process.

Based on the presented model tests and the behaviour of some prototype breakwaters the following somewhat premature recommendations valid for permanent designs with accepted moderate damage are proposed:

	$H_s/\Delta D_{n50}$
For trunks exposed to steep oblique waves	< 4.5
For trunks exposed to long oblique waves	< 3.5
For roundheads	< 3

These values should be used as guidelines *only* if no other more qualified information is available. This is because the parameters $H_s/\Delta D_{n50}$ is insufficient as among other things it does not contain the effect of wave length and the effect of the duration of the sea. Moreover, the influence of the breakwater geometry and the relative water depth are not included.

A study of a general parametric representation of the mass transport (erosion) based on a "shields approach" using characteristic wave parameters has been tried without much success.

It is believed that in additional investigations of erosion of reshaping breakwaters it will be necessary in principle to examine and summarize the respons from every single wave instead of using characteristic parameters like H_s to characterize the sea state. This is because the character of the flow kinematics in the erosion zones is strongly dependent on the size and the steepness of the single waves.

ACKNOWLEDGEMENT

The help of Mr. Van der Meer in estimating cross section profiles during the planning of the test is gratefully acknowledged. Also many thanks to the Laboratory for Photogrammetry and Surveying, University of Aalborg, for working out the photogrammetry and the contour plots of the bathymetry of the roundhead.

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