Part III: Coastal Structures

Groin at Fjaltring, Danish North Sea Coast

Coast Protection at Lønstrup, Danish North Sea Coast

Berm Breakwaters – Influence of Stone Gradation, Permeability and Armouring

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Abstract

The difference in reshaping of a traditional berm breakwater constructed of two stone classes and a more stable armoured type of berm breakwater with the largest berm stones used as an armour layer has been studied through physical model tests at the Danish Hydraulic Institute. A total of eight series of model tests were carried out in a wave flume with the aim of studying the effect of different armouring of the berm. The test results are described in the form of profile development, recession of the berm, waves generated by overtopping and wave reflection.

Further, four series of flume tests were carried out for studying the influence of the width of the stone gradation for the berm material and the permeability of the berm material. Two stone gradations and three permeabilities of the berm material were tested.

Finally, four test series were carried out for studying the influence of scour protection on the scouring in front of the berm breakwater and the behaviour of the berm breakwater.

Introduction

The permeability of rubble mound breakwaters is known to have an effect on the armour layer stability. An armour layer placed on an impermeable core is less stable than an armour layer placed on a core of permeable stone material. This aspect is included in the stability formulae for rubble mound breakwaters established by van der Meer (1988).

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In some cases, the stability of rubble mound breakwaters has been increased by going from two layers of stones in the armour layer to three or four layers. One of the features of berm breakwaters is the energy dissipation in the permeable berm, but this can be reduced if the permeability is reduced due to a high content of fines.

Research presented by Hall and Kao (1991) has shown that the reshaping of berm breakwaters is influenced by the stone gradation. They found, for $D_{n,85}/D_{n,15}<3$, that reducing the gradation width of the armour stones reduced the reshaping.

Experience from Iceland has shown that it is in most cases advantageous to construct berm breakwaters of more than two stone classes. The idea being that the largest stones are used where they will be most effective, ie as an armour layer protecting the berm. Armoured berm breakwaters made of several stone classes like a traditional breakwater require more sorting of stones, but at the same time the increased stability means that the overall dimensions can be reduced. Examples of the Icelandic experience with berm breakwaters are given by Sigurdarsson et al (1995) and Juhl and Jensen (1995).

Local scour can occur at a breakwater constructed on a sandy seabed and may endanger the overall stability due to sliding of the main armour layer if the toe and scour protection is failing. The scouring pattern is a function of the water depth, wave conditions, sediment characteristics, breakwater configuration, and reflection characteristics as described by Arneborg et al (1996). Further, a simultaneous current at the breakwater will influence the scouring.

Scouring in front of a berm breakwater constructed without a sufficient scour protection may result in berm stones sliding into the scour hole, which will lead to further reshaping of the protecting berm.

Model Set-up and Test Programme

Model Set-up

Physical model tests were carried out in a 23 m long and 0.60 m wide wave flume with the aim of studying profile reshaping and wave overtopping of berm breakwater profiles. A fixed bed foreshore with a slope of 1:80 was constructed in the flume.

The profiles used in the first 12 test series are shown in Figure 1. The water depth in front of the berm was 0.25 m for all tests. Profiles 1 to 8 were tested to compare the reshaping of a berm breakwater constructed of two stone classes with the reshaping of a more stable type of berm breakwater with the largest stones armouring the berm.

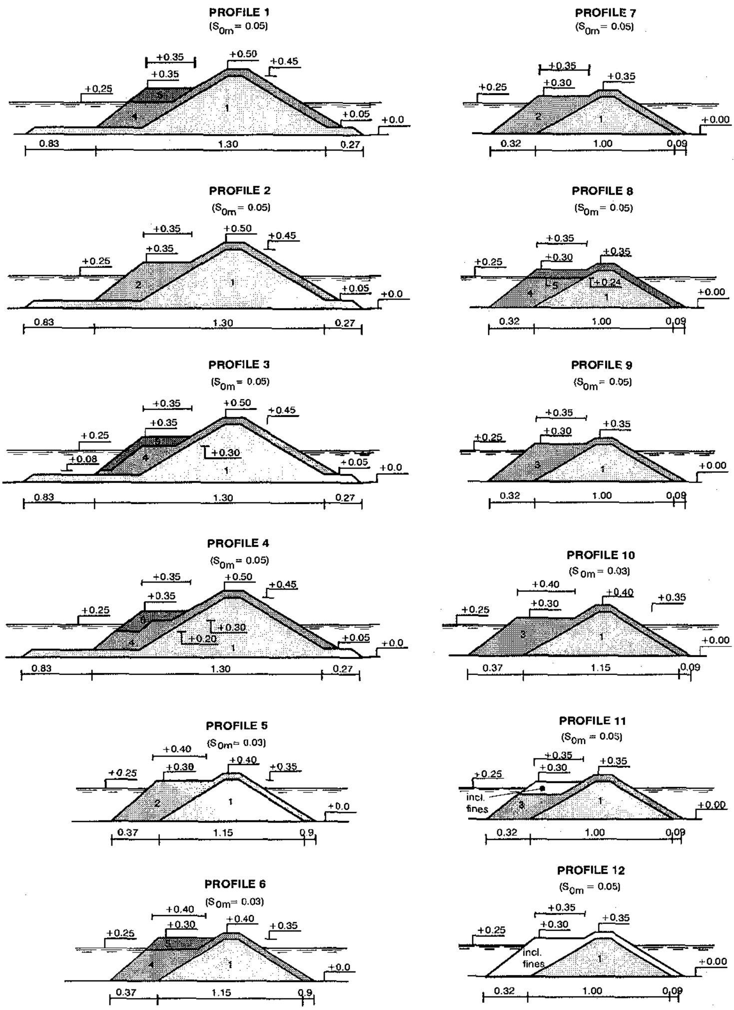

Figure 1 *Tested berm breakwater profiles. Stone class characteristics are presented in*

Profiles 1 to 4 were relatively high-crested breakwaters not allowing wave overtopping. Three alternative berm breakwaters of the armoured type (Profiles 1, 3 and 4) were tested and compared to tests with a traditional berm breakwater consisting of two stone classes (Profile 2). The subsequently tested four profiles were more low-crested breakwaters with the crest elevation and berm width adjusted to take into account different wave steepness (S_{om}=0.03 and 0.05).

The berm breakwaters were constructed of two or three stone classes, ie one for the core and scour protection and one or two for the berm, crest and rear side protection. The traditional berm breakwaters (Profiles 2, 5 and 7) were constructed of two stone classes, a relative wide stone gradation for the berm, $D_{n,85}/D_{n,15}$=1.80, having a nominal diameter, D_{n50}, of 0.022 m (stone class 2) and a core with a nominal stone diameter of 0.011 m (stone class 1). A summary of the stone classes used is presented in Table 1.

Table 1 *Summary of stone classes. The density of the stone material was measured to* ρ_S*=2.68 t/m*^{3}*.*

Stone class	Description	W_{50} (g)	$D_{n,50}$ (m)	$D_{n,85}/D_{n,15}$	Profiles
1	Core material	3.5	0.011	2.30	All
2	Berm material	30.2	0.022	1.80	2, 5, 7
3	Berm material	35.4	0.024	1.40	9, 10, 11, 12
4	Berm material	20.5	0.020	1.65	1, 3, 4, 6, 8
5	Armour layer	78.0	0.031	1.20	1, 3, 4, 6, 8

In testing of the armoured type of berm breakwaters, the berm stones (class 2) were separated into two classes, the lower fraction to be used for the berm (stone class 4) and the higher fraction to be used as an armour layer (stone class 5). This means that the same stones were used for all tested profiles.

Profiles 9 and 10 were tested using berm material with a more narrow stone gradation, $D_{n,85}/D_{n,15}$=1.40, having a nominal diameter, D_{n50}, of 0.024 m (stone class 3). Profiles 11 and 12 were tested for studying the influence of the permeability of the berm material. The permeability was reduced by adding fine material (average weight of 0.24 g) to the narrow stone gradation, either to the surface zone of the berm or to the entire berm.

Four series of model tests were carried out for studying the scouring in front of a traditional berm breakwater having a high crest and a wide berm. In order to assess the scouring, the seabed below and 1.5 m in front of the breakwater was made of fine sand with d_{50}=0.17 mm.

Test Programme

Each test series consisted of five to nine test runs each with a duration corresponding to 2,000 waves. Test runs were carried out with the following deepwater conditions: $H_o = H_{mo}/\Delta D_{n,50}$= 2.0, 2.5, 3.0, 3.5 and 4.0, where $H_{mo}(=4 \cdot \sqrt{m_0}$, where m_o is the zero'th moment of the recorded surface elevations) is the wave height, Δ is the relative density and $D_{n,50}$ is the nominal stone diameter. H_o is also called the stability number and is for the armoured berm breakwaters calculated using $D_{n,50}$ for the entire berm material (0.022 m). Further, the long-term development was studied with H_o=4.0 for Profiles 1 to 3.

The deepwater wave steepness is given by the ratio between the wave height, H_{mo}, and the deepwater wave length, L_{om}, calculated on basis of the mean wave period, T_{om}:

$$S_{om} = H_{mo}/L_{om} = 2\pi/g*H_{mo}/T_{om}^2$$

The tests were carried out in test series with fixed wave steepness in deep water, S_{om}=0.03 respectively 0.05, ie the wave steepness in front of the berm breakwater varied due to differences in wave shoaling and wave breaking on the foreshore.

Two test series were carried out to study scouring in front of a berm constructed directly on a sandy seabed. The first test series consisted of nine test runs with a wave steepness of S_{om}=0.05 and the second test series of six test runs with a wave steepness of S_{om}=0.03 and two additional test runs with S_{om}=0.02 (the last with the water depth reduced to 0.20 m).

A 0.05 m thick scour protection layer below the berm and extending 0.50 m in front of the berm was introduced in the third test series. In the fourth test series, the scour protection material was placed as a 0.10 m layer covering the front slope of the berm. The idea being that the first waves hitting the breakwater will reshape the scour protection material into a combined toe and scour protection. For both test series, four test runs were carried out with S_{om}=0.03 and two additional test runs with S_{om}=0.02 (the last with the water depth reduced to 0.20 m).

Measurements and Analysis

The waves were measured by a total of nine resistance type wave gauges, ie three in deep water, five in shallow water in front of the breakwater, and one behind the breakwater for measuring the overtopping generated waves (only Profiles 4 to 12).

A multigauge technique was used for separating the incoming and reflected waves, and subsequently determining the incoming significant wave height and the reflection coefficient both in deep water and in front of the breakwater. The waves reflected from the breakwater were absorbed by the wave generator applying DHI's AWACS system (Active Wave Absorption Control System).

The breakwater profiles were measured after each test for every 0.10 m across the flume (five profiles) before initiation of the tests and after each test run. The profiling was made by two lasers, one laser running on a bcam placed across the breakwater for measuring the vertical distance to the breakwater and another laser for measuring the horizontal position of the other laser.

Analysis of the five profiles measured after each test run (for each 0.10 m across the flume) showed that the differences were very small, and thus the five profiles were averaged for the subsequent analysis. Analysis of the recorded profiles was made for determining the recession of the berm, ie erosion of the crest of the berm as shown in Figure 2. The waves behind the breakwater caused by wave overtopping were analysed with respect to the maximum wave height, H_{max}, and the spectral wave height, H_{m0}.

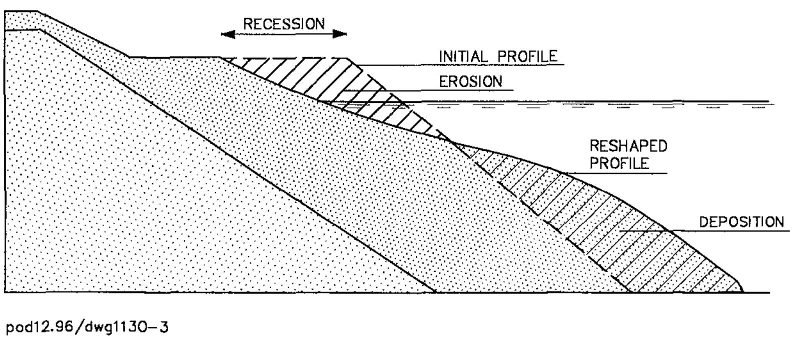

Figure 2 *Definition of berm recession.*

Presentation of Results

Profile developments, berm recessions, overtopping generated waves and reflection coefficients werc analysed for the twelve tested profiles with the aim of studying the influence of berm armouring, berm free board, wave steepness, width of stone gradation of the berm material and permeability of the berm material. Finally, the results of the four series of tests carried out for studying the scouring were analysed.

Influence of Armouring

Three alternative berm breakwaters of the armoured type (Profiles 1, 3 and 4) were tested and compared to tests with a traditional berm breakwater consisting of two stone classes (Profile 2). Figure 3 shows the berm recession as function of the stability number calculated on basis of the wave height in front of the breakwater and $D_{n,50}$=0.022 m.

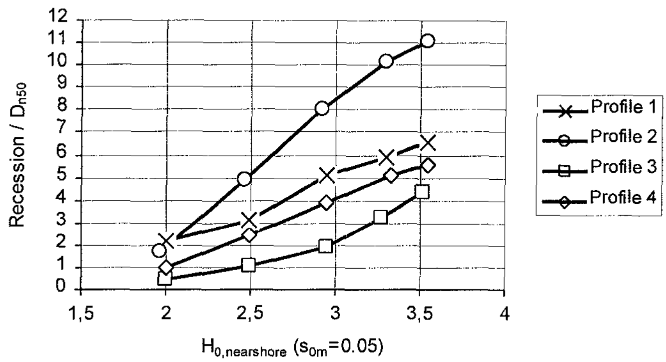

Figure 3 *Dimensionless recession (recession/$D_{n,50}$) as function of the nearshore stability number. Note: $D_{n,50}$ is for the entire berm.*

All three armoured type breakwaters showed significantly less erosion volume and berm recession compared to the traditional berm breakwater. The profile resulting in the smallest erosion volume and berm recession was Profile 3 (an armour layer at the top and at the front of the berm) followed by Profile 4 (armour layer placed as a hammer head), whereas Profile 1 (armour at the top of the berm) showed a little less effect, but has an advantage in construction.

Figure 4 shows the berm recession for the three armoured type berm breakwaters relative to the recession of the traditional berm breakwater as function of the near shore stability number. The increased stability of the armoured berm breakwaters implies that the overall dimensions can be reduced compared to a traditional berm breakwater, which will reduce the construction costs.

Comparisons of the test results for Profiles 7 and 8 (lower crest and berm elevation) also showed a significant reduction in the erosion volume and berm recession using the largest stones for armouring of the berm. The effect of the armouring was somewhat less pronounced for Profiles 5 and 6, run with a wave steepness of S_{om}=0.03.

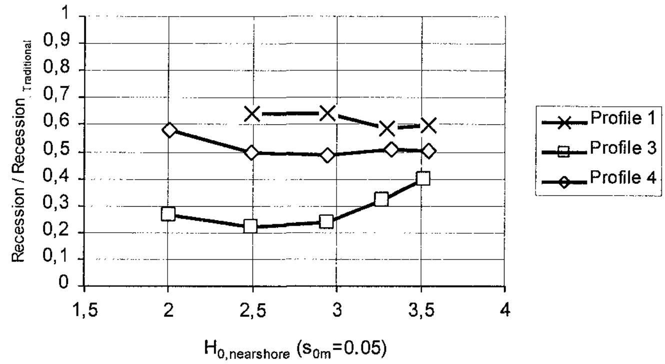

Figure 4 *Relative berm recession (recession of armoured berm breakwater/recession of traditional berm breakwater) as function of the nearshore stability number.*

Testing of Profiles 1 to 3 included long duration tests consisting of 10,000 waves with a stability number H_0=4.0. The results showed that an equilibrium profile was reached after about 8,000 waves, assuming no deterioration of the stones.

For the test series with a high crest elevation (Profiles 1 to 4), the overtopping generated waves were very small, whereas for the test series with a lower crest elevation (Profiles 5 to 8), the overtopping generated waves measured 1 m behind the centreline of the breakwater werc analysed. For wave heights up to a stability number corresponding to about 3, the waves behind the breakwater were mainly due to transmission through the breakwater, whereas for larger incoming waves, overtopping became dominant.

Figure 5 shows the transmission coefficients (including overtopping generated waves) calculated on basis of the spectral wave height behind the breakwater as function of the nearshore stability number. The overtopping wave heights were found to be smaller for the armoured type of berm breakwater (Profiles 6 and 8) than for the traditional berm breakwater constructed of two stone classes (Profile 5 and 7). The effect on the wave overtopping is mainly due to the reduced berm reshaping for the armoured berm breakwater. The maximum wave height varied only a little for the different profiles.

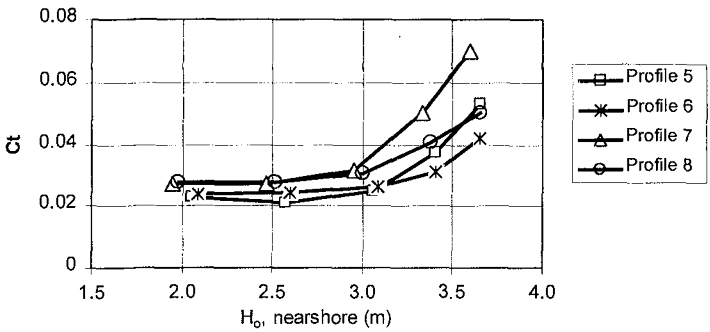

Figure 5 *Wave transmission coefficients based on the spectral wave height of the overtopping generated waves as function of the nearshore stability number.*

The reflection coefficients for the tested berm breakwaters are a function of both wave conditions and breakwater profiles. This means that the reflection conditions are changing with the berm reshaping during the test runs, and thus the results are average values over the period of each test run. The reflection coefficients were found to be higher for the armoured type of berm breakwater compared to the traditional berm breakwater constructed of two stone classes due to the reduced profile reshaping.

Influence of Stone Gradation

Tests were carried out with two stone gradations, a wide stone gradation having $D_{n,85}/D_{n,15}$=1.80 (Profiles 5 and 7) and a more narrow having $D_{n,85}/D_{n,15}$=1.40 (Profiles 9 and 10).

It was found that the wider stone gradation resulted in larger erosion volume and berm recession. Therefore, also the rear side stability was reduced for the wider stone gradation. In a wide stone gradation, the smaller stones will partly fill the voids between the larger stones resulting in a reduced permeability, which for the considered stone gradations are expected to cause increased erosion volume and berm recession due to decreased energy dissipation in the berm.

Larger overtopping generated waves were found for the tests with the wide stone gradation (Profiles 5 and 7) than for the tests with the more narrow stone gradation (Profiles 9 and 10).

A significant increase in the reflection coefficients was found for the tests with the narrow stone gradation due to the reduced berm reshaping.

Influence of Permeability

Wave run-up and overtopping conditions are significantly influenced by the presence of fine material in the berm material reducing the permeability and thus the energy dissipation, which is one of the main features of berm breakwaters. The permeability of a berm breakwater may be reduced by the presence of finer materials, which could be either in the surface of the berm or in the entire berm. The first case could occur if eg a temporary construction road on the berm is not removed after completion of construction and the latter case as an outcome of deficient design or construction.

The influence of the permeability was studied by testing of two profiles with finer material added either to the top of the berm or to the entire berm constructed from stones with the narrow gradation, $D_{n,85}/D_{n,15}$=1.40. An increase in the erosion volume and berm recession was observed by adding finer material to the top of the berm (Profile 11). Adding finer material to the entire berm (Profile 12) led to a further increase in the erosion volume and berm recession. Further, a significant increase in overtopping was found, resulting in severe damage to both crest and rear side. Figure 6 shows the influence on the berm recession by reducing the permeability of the berm.

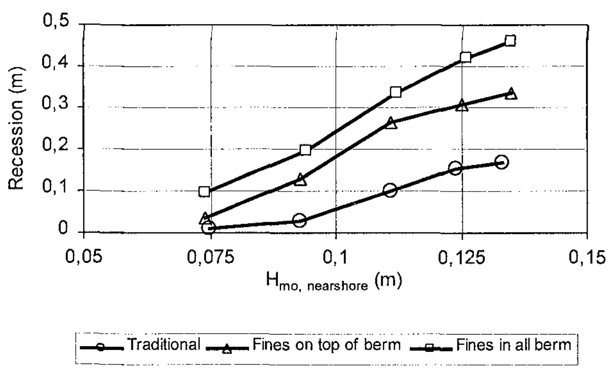

Figure 6 *Influence of permeability on berm recession.*

Scouring

A total of four test series were carried out for a qualitative study of the influence on the scour development in front of a berm breakwater and on the berm reshaping for two types of scour protection. The tests also included a study of the influence of the wave steepness.

The two profiles without a scour protection layer showed subsidence of berm stones into the sandy seabed, which resulted in larger berm recession. The tests showed the development of a larger scour hole in front of the breakwater for the tests with the smallest wave steepness.

Introduction of a scour protection layer moved the scour hole out in front of this. Further, no subsidence of berm stones into the sandy seabed was found and thus the reshaping of the berm was reduced.

Finally, a test series was carried out with the scour protection material placed as a 0.10 m layer covering the front slope of the berm, the idea being that the material under the exposure of the first waves will reshape into a toe and scour protection. During the reshaping process, some of this scour protection material was mixed into the berm material. The resulting reduced permeability led to increasing wave run-up and overtopping reducing the stability of the structure.

Conclusions

Model tests were carried out in a wave flume with the aim of studying the difference in reshaping of a traditional berm breakwater constructed of two stone classes and an armoured type berm breakwater with the largest berm stones used as an armour layer covering a part of or the berm. Further, the influence of the width of the stone gradation for the berm material and the permeability of the berm material was studied.

Finally, tests were carried out for studying the scouring in front of a breakwater without any scour protection followed by testing of two types of scour protection.

Wave conditions in front of and behind the breakwater were measured together with the profile development. All test series consisted of five test runs (H_o=2.0, 2.5, 3.0, 3.5 and 4.0, in deep water), each with a duration corresponding to 2,000 waves. However, for Profiles 1, 2 and 3, another 8,000 waves with H_o=4.0 were run for studying the long-term stability.

The main conclusions of this study can be summarised as follows:

- Comparisons between traditional berm breakwaters and berm breakwaters of the armoured type showed a reduction in the erosion volume and recession of the berm for the latter. An armour layer protecting both the top and the front of the berm (Profile 3) was found to be more effective than both the hammerhead solution (Profile 4) and a thicker layer at the top of the berm (Profile 1).
- A reduction in the berm width can be obtained by using the largest stones as an armour layer. However, the effects vary with a range of parameters, eg wave steepness, stone gradation, permeability, and breakwater geometry.
- A reduction in the wave overtopping was found for the armoured type of breakwater mainly due to the reduced berm reshaping.
- The reflection from a berm breakwater is dominated by the slope of the reshaping profile, and thus the wave reflection from the armoured type of breakwater was larger than for the traditional berm breakwater.
- An increase in the berm freeboard is associated with an increased berm volume and was found to reduce the rcshaping of the berm.
- The berm reshaping was found to increase for decreasing wave steepness, ie increasing wave period.
- Tests made with two stone gradations showed larger erosion volume and berm recession for the wider stone gradation.
- Tests with fine material added to either the top of the berm or the entire berm (reducing the permeability) showed a significant increase in the berm recession and wave overtopping.
- Subsidence of berm stones into the sandy seabed was found for the profiles without a scour protection layer
- Introduction of a scour protection layer extending 0.50 m (model) in front of the berm moved the scour hole out in front of this, and no subsidence of berm stones into the sandy seabed was found and thus thc reshaping of the berm was rcduced
- During reshaping of the scour protection material placed as a 0.10 m layer covering the front slope of the berm, some of this finer material was mixed into the berm material. This reduced the permeability and led to increased wave run-up and overtopping.

Acknowledgements

The present study was carricd out as a part of the research project on Berm Breakwater Structures co-sponsored by the European Commission under contract MAS2-CT94-0087 (1994-97).

The model tests were carried out at the Danish Hydraulic Institute, and the authors wish to thank Mr Per Vedel Brøndsted, Mr Erik Mathiesen, Ms Renata Archetti and Mr Nikolay Lissev for their assistance in carrying out the model tests and doing the initial analysis of the measurements.

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