BERM BREAKWATER STRUCTURES

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SUMMARY

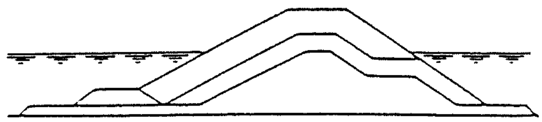
The overall objective of the research project on berm breakwater structures is to arrive at a better design basis, which will bring the design standards of berm breakwaters up to the level of design standards for other civil engineering structures. This objective will be reached by establishing an understanding of the physics of berm breakwaters, studies of problems related to practical engineering applications, and studies of three-dimensional effects. The research is a combination of theoretical work, physical model testing and numerical modelling.

The paper gives an introduction to the berm breakwater concept followed by a presentation of the main research results obtained within MAST I. Finally, the research which is carried out as part of the MAST II project on berm breakwater structures is described, including a brief presentation of the first results.

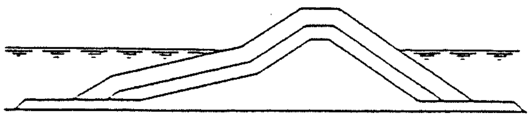
INTRODUCTION

In principle two different types of rubble mound breakwaters exist, ie conventional rubble mound breakwaters with or without a crown wall and berm breakwaters. The main armour layer of a conventional rubble mound breakwater is designed for limited damage (statically stable), whereas for a berm breakwater the berm reshapes into a flatter and more stable profile. The more stable reshaped profile of a berm breakwater is the basic idea of the S-shaped breakwater, which initially is built with a flatter statically stable slope around still water level. In **Figure 1**, typical cross-sections of the three mentioned types of rubble mound breakwaters are shown. Further, a number of hybrids of conventional and berm breakwaters exist, eg conventional rubble mound breakwaters with a small berm or increased armour layer thickness.

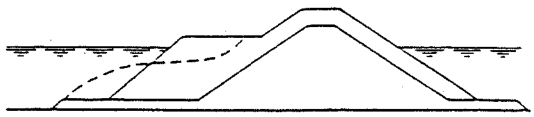
Berm breakwaters have unconsciously been known since the middle of the nineteenth century, but increasing attention has been paid to this type of breakwater during the last 10 to 15 years. Many of the early breakwater structures were constructed by simply dumping quarried stones, which were available at the site, into the sea. Material was placed until a stable breakwater profile was reached, and after severe damage repair was carried out by simply adding more stone material.



Conventional breakwater



S-shaped breakwater



Berm breakwater

Figure 1 *Typical cross-sections of three types of rubble mound breakwaters.*

In literature, various synonyms have been used for a berm breakwater, ie dynamically stable breakwater, unconventional breakwater, reshaping breakwater, naturally armouring breakwater and mass armoured breakwater. However, it is important to distinguish between berm breakwaters which reshape into a statically stable profile or dynamically stable profile.

A berm breakwater is a rubble mound breakwater with a berm above still water on the seaward side. During exposure to wave action of a certain intensity, the berm reshapes until eventually an equilibrium profile of the stones on the seaward face is reached. For each wave height, there is thus an equilibrium profile corresponding to this wave height. Just below the water level the reshaped profile has typically a slope of about 1:5. In front of this flat slope, stones are deposited with a steeper slope approaching the natural angle of repose. Wave energy is dissipated in the mass of stones in the flat slope resulting in reduced wave run-up above still water level where the natural equilibrium slope is steeper.

Berm breakwaters can be designed to be in either static or dynamic equilibrium in the long-term. For a dynamically stable berm breakwater the stones are allowed to move somewhat but with the average profile being in equilibrium. In order to ensure long-term stability, berm breakwaters should reshape into a statically stable profile where movements are only occurring in very severe and rare conditions. This requirement is due to the fact that frequent stone movements could result in abrasion and fracturing or displacement of stones finally resulting in degradation of the breakwater.

A berm breakwater trunk section exposed to oblique waves has to be designed with stones larger than a certain critical size in order to avoid continued movements of stones in the wave direction (longshore transport) which would eventually endanger the breakwater.

Singular points are of special interest for berm breakwaters, eg bends and roundheads. Stone displacements occurring at singular points result in stones being moved in the wave direction and the structure is consequently weakened. A point of special concern is whether, and under which conditions, a singular point of a berm breakwater may develop in a way that in the long-term will lead to structural failure. For a permanent structure, such features are normally undesirable as it would required maintenance from time to time in order to ensure the long-term stability.

The average armour rock size needed in a berm breakwater structure is smaller than in a traditional rubble mound structure. This is due to the flatter final slope of the seaward face on which the breaking wave plunges and dissipates energy, and the higher proportion of wave energy dissipated within the porous mound (reducing the hydrodynamic forces acting on the individual stones). Further, wave action causes consolidation of the breakwater and nesting of the stones, which increase the stability. Typically stones with a weight two to ten times smaller can be used for construction of the berm compared to the main armour layer of a conventional breakwater.

Especially when a quarry is available near the construction site and it is not possible to produce a sufficient quantity of large armour stones for a conventional rubble mound breakwater, a berm breakwater can be a feasible solution. Berm breakwaters are presently being considered for more and more applications worldwide, and several berm breakwaters are or have already been constructed. Berm breakwaters can normally be constructed with only two stone gradations as indicated in **Figure 1**. Proper design of berm breakwaters might lead to utilisation of almost 100 per cent of the quarry yield.

The smaller stones to be used for berm breakwaters have also an influence on the construction method and equipment to be used. The core can be constructed by end tipping trucks or dumping by barges, whereas the berm can be constructed by cranes with stone grabs, end tipping trucks or excavators. Generally lighter and less specialised construction equipment can be used compared to construction of conventional breakwaters. Even if the construction tolerances are wider for berm breakwaters than for conventional rubble mound breakwaters, fulfilment of the specifications to the stone material (mean weight, gradation, geometrical shape, quality, content of fines, etc), construction method and breakwater profiles is strictly required.

STATE-OF-THE-ART

The state-of-the-art before initiating MAST I was that knowledge was generally limited to: results from site specific projects, limited prototype experience, systematic two-dimensional model testing of the berm reshaping, and a few three-dimensional model tests of trunk and roundhead exposed to oblique waves.

The research on berm breakwaters during MAST I concentrated on: review of knowledge and expertise with berm breakwaters, theoretical considerations of structure response to wave climate, numerical simulations of wave action and flow processes on and in berm breakwaters, and parameter tests to supplement available data on berm breakwater profiles. The main results from the MAST I project are briefly summarised in the following with reference to papers published by the partners.

Review of knowledge and expertise with berm breakwaters

- The features of berm breakwaters including advantages and drawbacks in comparison to traditional rubble mound structures is described in Juhl and Jensen (1995). This paper also gives a review of selected practical experience with actually constructed berm breakwaters.

- A review of experience with berm breakwater roundheads and trunk sections exposed to oblique waves is included in van der Meer and Veldman (1992).
- The outcome of a review of data on wave forces and armour movements is presented in Tørum (1994) and Andersen (1994).
- Results from previous extensive testing of berm breakwaters have been analysed with respect to scale effects and rear side damage, and the outcome is presented in van der Meer and Veldman (1992).
- An extensive research on the stability of rock slopes and gravel beaches was reanalysed and focused on berm breakwaters. The effects on the seaward profile of wave height, wave period, storm duration, spectral shape, initial slope, rock size, rock shape and grading, water depth, and angle of wave attack is qualitatively described in van der Meer (1992).

Theoretical considerations of structure response to wave climate. Numerical simulations of wave action and flow processes on and in berm breakwaters

- Experimental work on the flow field on breakwater slopes was undertaken together with measurements of the flow-induced forces on a single stone in the upper layer of a reshaped berm. Water particle velocities in the waves running up and down a berm breakwater were measured for several wave heights and wave periods with a Laser Doppler Velocimeter and the results were compared with numerical simulations, see Tørum and van Gent (1992). Wave induced parallel and normal forces on an armour stone were measured and used for the calculation of Morison type force coefficients, see Tørum (1994).
- A computer simulation model for the reshaping of berm breakwaters under normally incident monochromatic waves was developed, see Norton and Holmes (1992). Rock armour units within the armour are represented by equivalent spherical particles, and a force model is used to assess armour stability and initiate displacements on the slope.

Parameter tests to supplement available data on berm breakwater profiles

- Flume tests were carried out in order to study the berm breakwater performance (with special emphasis on rear side stability) as function of wave conditions and breakwater configuration (berm width, crest height, crest width, etc). With the aim of providing improved methods for preliminary design of berm breakwaters, a parametric expression for the rear side stability is presented in Andersen et al (1992).
- The possible movement upwards and downwards of stones on a reshaped berm breakwater slope was studied in a wave flume. The results have been analysed with respect to threshold conditions, total displacement length and dispersion of stones, see Tomasicchio et al (1994). This aspect is important in the assessment of the abrasion of moving stones and initiation of longshore transport.

SCIENTIFIC AND TECHNICAL DESCRIPTION

The research on berm breakwater structures within the MAST II programme is a combination of theoretical work, physical model testing and numerical modelling, and is divided into four tasks as described in the following:

Task 1 Physics of berm breakwaters

This task includes the study of subjects related to more basic research and theoretical aspects of berm breakwaters, eg scale effects, flow on and in berm breakwaters, water particle velocities, and forces on single stones on a berm breakwater.

Task 2 Studies of profile development

The development of the profile of berm breakwaters is studied by numerical modelling applying different simulation methods. Additionally, a new set of parameter equations for the reshaped profile of berm breakwaters will be established.

Task 3 Studies of structural aspects of berm breakwaters

This task concentrates on problems directly related to practical engineering application and design. The studies include structural aspects as the influence of permeability and stone gradation, stability of toe and scour protection, and probabilistic analysis. Finally, analysis of the experience from two prototype berm breakwaters is part of the project.

Task 4 Three-dimensional effects

Physical model testing in a wave basin and numerical modelling is carried out for studying the stability of berm breakwater roundheads and trunk sections exposed to oblique wave attack.

A more detailed description of each subtask is presented in the following, including a brief presentation of the results obtained until now:

Task 1.1 Scale Effects

Scale effects in physical modelling of the flow inside a berm will influence the wave run-up and wave overtopping (and thus the rear side stability), whereas previous investigations have shown almost no influence of scale effects on the berm profile development.

Physical model tests will be carried out in two different scales, and will include measurements of the profile development, run-up, wave overtopping and transmitted wave energy. Subsequently, the results from these tests and previously performed tests will be analysed with respect to scale effects in physical modelling of berm breakwaters.

Task 1.2 Flow on and in Berm Breakwaters

Numerical simulations of the flow on and in berm breakwaters are made in order to increase the understanding of the physical processes. The simulations of the flow processes are made for a wide range of stone characteristics (diameters, gradations, energy loss factors, etc) and will help to increase the knowledge of the physics of berm breakwaters. Van Gent (1994) describes the verification of a one-dimensional model with physical model tests and presents results from simulations of flows on and in porous structures.

Task 1.3 Water Particle Velocities

The study of water particle velocities and forces on stones on berm breakwaters will be treated both theoretically and by measurements. The measurements to be made in model tests will include both particle velocities (including turbulence) above the reshaped berm and forces on single stones. The theoretical work will focus on understanding and describing the water motions and forces on single stones.

Task 2.1 Numerical modelling

The objective of this task is to make numerical modelling of the profile development of berm breakwaters. Integrated wave load/response models (a one-dimensional model and a two-dimensional model) is used in the study of the profile development of berm breakwaters.

The one-dimensional model is based on the numerical model developed in MAST I by Delft University of Technology for description of the flow on and in berm breakwaters combined with a morphological model for calculation of stone transport, see van Gent (1993). The failure mechanisms related to sliding, lifting and rolling are simulated. As observed in physical model tests, rolling appeared to be the dominant failure mechanism in most cases. An example of a simulated reshaped profile is shown in **Figure 2**, which also includes a comparison to results from a physical model test.

Despite the neglect of many hydrodynamic and morphodynamic phenomena in the presented combined model, the results indicate that these neglects do not make the approach unrealistic. Quantitative and qualitative verifications were performed with highly dynamic slopes (gravel beaches) and with berm breakwater profiles. It was found that computations of the berm reshaping compared well to a physical model test with regular waves (**Figure 2**), an empirical expression for irregular waves (van der Meer (1992)), and to a prototype case. The qualitative verification showed that the influence of the wave height, wave period, stone diameter and initial slope is simulated correctly as physical model tests show the same trends.

The two-dimensional model developed by the Danish Hydraulic Institute and Aalborg University includes full vertical resolution (xz-model) and describes both the wave load and the profile development of berm breakwaters (see Andersen (1994)). The numerical model is based on an interaction of a hydrodynamic part and a part for calculating the development of the berm. The part for calculating the profile development is based on theories and methods similar to those applied in sediment transport calculations.

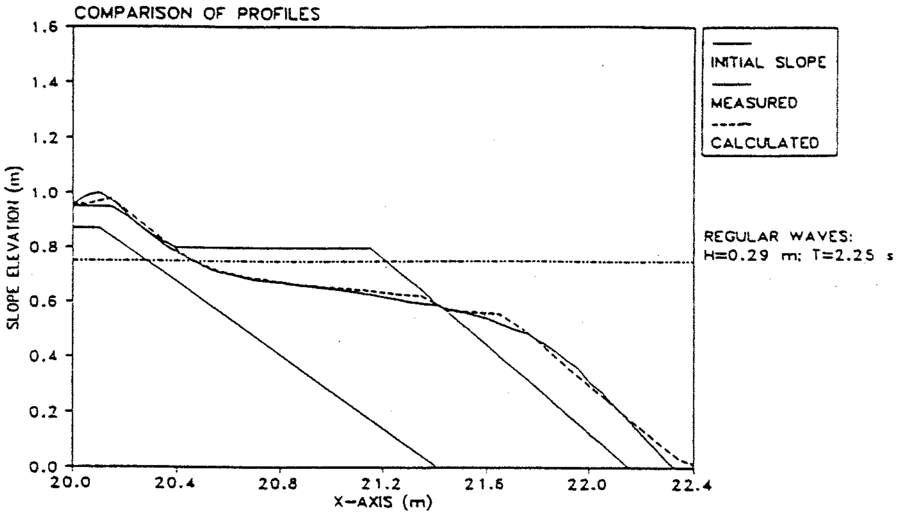


Figure 2 *Comparison between measured and simulated reshaped profile. (Figure from van Gent (1993)).*

Two different types of models describing the equilibrium berm breakwater profile have been developed: a static model based on a Shields' approach and two different dynamic models based on the theory for transfer of shear stress due to occasional encounters of moving and fixed stones. **Figure 3** includes a plot of results from simulations of the profile development for a berm breakwater. Despite the uncertainties associated with the selection of a proper set of model coefficients, several conclusions can be drawn (actually confirming observations from physical model tests):

- the model gives a S-shaped profile with a steep lower slope (angle of repose), a middle slope and an upper slope
- there is clearly a shift from static to dynamic equilibrium when the wave climate is intensified, typically the transition occurs for a value of $H/\Delta D_{n50}$ at approximately 3.25
- comparing to physical model tests, it appears that the berm recession is fairly good described for values of $H/\Delta D_{n50}$ ranging between 2.6 and 4.6 (the range used for the model tests)
- application of the model to initially straight slopes gives good results in case of an initially steep slope, whereas the lack of wave breaking in the hydrodynamic model becomes pronounced in the case of an initially flat slope

From the numerical simulations, it was found that the impact of varying the porous flow resistance parameters within realistic ranges is visible, but still within the range of uncertainty concerning the measured berm recessions.

A comparison of results from the one-dimensional and the two-dimensional model will be made in order to assess possible limitations of the two basically different models with respect to calculation of the profile development of berm breakwaters.

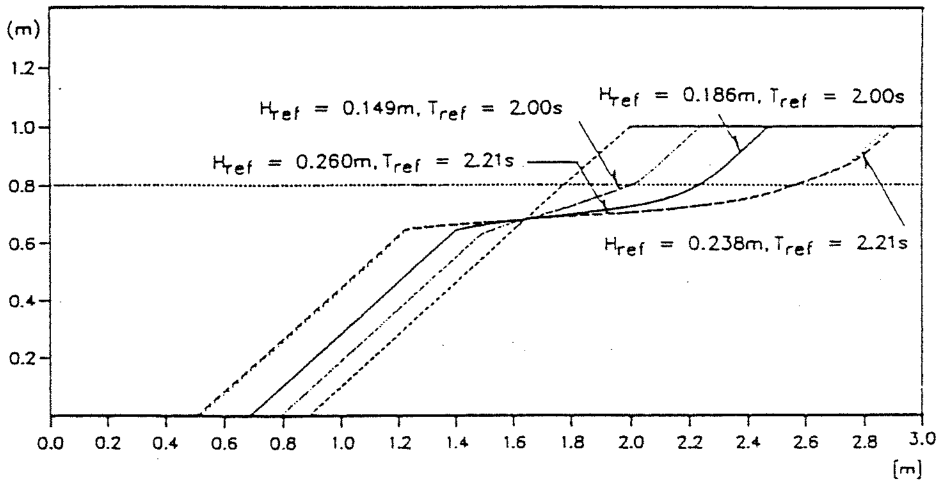


Figure 3 *Simulated profile development for four wave conditions. (Figure from Andersen (1994)).*

Task 2.2 Parameter Analysis

A new set of parameter equations for reshaped berm breakwater profiles will be developed. The input to this research will be the test results on profile developments obtained in MAST I (eg the results presented by Lamberti et al (1994)) and new data from both physical and numerical modelling being a part of the MAST II research.

Task 3.1 Influence of Permeability and Stone Gradation

The permeability of a mound of stones may be reduced by the presence of finer materials. Reduced permeability can, for example, be in the surface zone of the mound, but also in internal parts. The study will reveal the influence of reduced permeability of the surface and the internal parts of the stone mass forming the berm.

A series of model tests will be made in a wave flume for studying these structural details. Tests will be made both with gradations containing a lot of fines and with very wide gradations (reducing the permeability of the berm). The effect on the reshaping will be investigated, but attention will also be paid to the wave run-up and wave overtopping and to the rear side damage.

Task 3.2 Stability of Toe Protection and Scour Protection

For a berm breakwater constructed on a sandy seabed, local scour can occur in front of the breakwater. Scouring in front of a berm breakwater may result in berm stones to be moved into the scour hole, and thus reduce the stability of the protecting berm. Physical two-dimensional wave tests will be made for studying the scour development in front of a berm breakwater. Further, the scour development will be studied for a berm breakwater including a toe protection and a scour protection layer as for a traditional rubble mound breakwater constructed on a sandy seabed.

Task 3.3 Probabilistic Analysis

The aim of this task is to make probabilistic analysis of the stability of berm breakwaters. The results of model tests previously conducted will, in combination with knowledge of the probability distributions for the wave and stone parameters, be used for making probabilistic analysis of berm breakwaters. Compared to traditional rubble mound breakwaters and vertical breakwaters the probabilistic analysis has to be treated differently as no design formula exists for the stability of berm breakwaters.

Task 3.4 Prototype Comparisons

Two berm breakwaters have recently been built in Norway with design wave conditions of approximately $H_s=7.0$ m. The breakwater in Årviksand will be monitored in the sense that profile records have been taken and will be taken, especially after major storms during which the breakwater has been significantly reshaped. Fifty of the stone blocks have been marked and will be looked for after reshaping has taken place. The monitoring work will be carried out by the Norwegian Coast Directorate. There will be no wave measurements, however, the waves will be estimated from wave hindcast in deep water by the Norwegian Meteorological Institute and by refraction analysis by the Norwegian Hydrotechnical Laboratory.

The other berm breakwater is for a new ferry terminal at Rennesóy, Norway. This breakwater will be monitored by the Norwegian State Highway Department. The waves will be estimated in a similar way as described for the Årviksand breakwater.

In the MAST programme, the actual reshaping of the two berm breakwaters will be compared with model test results from the project, with other available model test results and with numerical simulations.

Task 4.1 Three-Dimensional Model Tests

For berm breakwaters as compared with traditional rubble mound breakwaters, special measures have to be taken for the breakwater roundhead. If stone displacements occur on a roundhead, the stones will be moved in the wave direction and will loose most of their stabilising effect. A point of special concern is whether, and under which conditions, a berm breakwater roundhead may develop in a way that in the long-term will lead to structural failure.

For a berm breakwater trunk section consisting of berm stones smaller than a certain critical size, the stones will continue to move in the wave direction (longshore transport) when the breakwater is exposed to oblique waves.

Existing data from laboratory tests carried out at Aalborg University have been reanalysed with the objective of assessing the effect of stone transport on both the roundhead and the trunk. Test results were available for two different breakwaters, one with a slender breakwater having a width of 1/6 of the wave length and a very wide breakwater with a width of about one wave length. Characteristics of the stone movements were found by photo and video recordings. Moreover, the steady mass transport along the trunk and the rate of recession of the armour crest was evaluated.

The results of this reanalysis are presented in Hald et al (1995). Considering the trunk, the mass transport clearly increases with increasing wave height, but also the wave period and the angle of wave incidence tend to influence the mass transport. For both tested roundheads the erosion rate is small up to a certain sea state after which a sudden increase is observed. In both cases, material is eroded on the seaward part and transported around the roundhead. A stable equilibrium profile is never reached as the recession rate increases linearly with time (or the number of waves).

As part of the MAST II project, a comprehensive model test programme was carried out in a wave basin for studying the stability of a berm breakwater roundhead and the adjacent trunk section exposed to unidirectional waves. A drawing of the applied berm breakwater cross-section is shown in **Figure 4**.

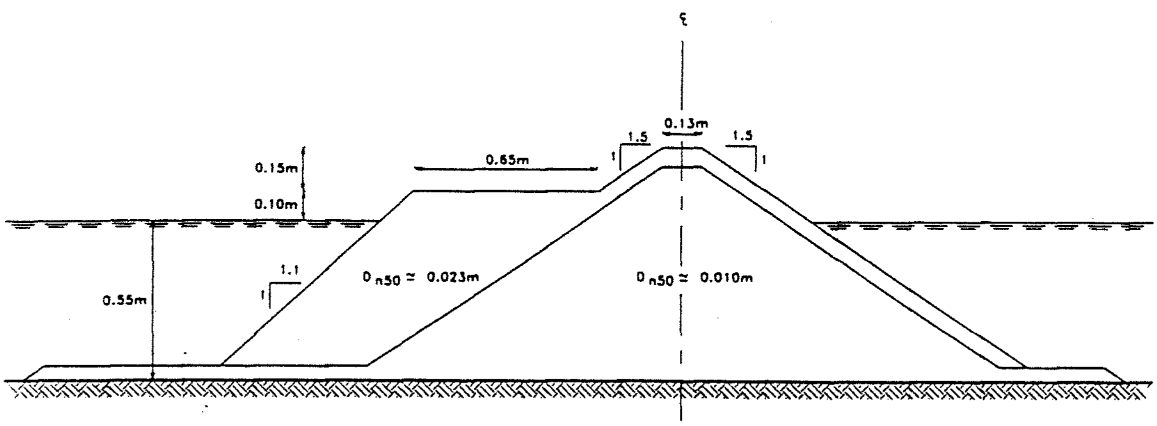


Figure 4 *Berm breakwater cross-section used in the detailed three-dimensional model tests.*

The test programme concentrated on studying the effect of the wave incidence angle on the profile development of a berm breakwater, but also the longshore transport of berm stones in the trunk section was studied in the model. The test programme included seven test series (each consisting of five to six test runs with a fixed wave steepness), covering six wave directions and two wave steepnesses for one of the wave directions.

A project team consisting of researchers from four of the participating institutes ran the tests and made the detailed measurements during the summer 1995, and subsequently analysed and reported the test results. The results will be disseminated in international journals and at conferences.

Task 4.2 Numerical Modelling

The work on a fundamental research tool was initiated in MAST I by Imperial College. The one-dimensional numerical model of a simulated berm breakwater at an individual rock unit scale is capable of predicting the evolution of berm breakwater slopes, but with a certain degree of idealisation.

This research tool will be further developed in order to include, in an idealised way, the effect of oblique waves, ie a description of the three-dimensionality of berm breakwaters by a one-dimensional model.

CONCLUSIONS

The progress in the berm breakwater research obtained in a MAST I project is continued in the described MAST II project with the overall aim to arrive at a better design basis for this type of breakwaters. Technical benefits will be gained as increased knowledge and understanding of the flow processes on and in berm breakwaters, the stability of berm breakwater trunk sections exposed to oblique waves and of berm breakwater roundheads, and in the form of improved information on design aspects.

Until now, progress has been made with respect to the numerical modelling of the flow on and in berm breakwaters and the reshaping process of the berm. Physical model tests have been carried out in a large wave basin with the aim of studying the stability of a berm breakwater roundhead exposed to waves from various directions and the profile development and longshore transport on a trunk section exposed to oblique waves.

ACKNOWLEDGEMENTS

The present paper describing the work carried out as part of a MAST I project and the planned/conducted work within the present MAST II project was prepared by the coordinator based on reports and papers made as part of the project, and discussions at the start-up workshop on 3 October 1994 and information on the work progress from the partners.

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