CHAPTER 86

Wave Overtopping of Breakwaters under Oblique Waves

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Abstract

A series of hydraulic model tests has been carried out in a wave basin with the aim of studying the effect of oblique waves on the wave overtopping of traditional rubble mound breakwaters without superstructure. The model tests concentrated on measuring the mean overtopping discharge for wave attacks varying from 0° (perpendicular to the structure) up to 50°. Analyses of the overtopping results were made with respect to the significant wave height, wave steepness, crest free board, crest width and angle of wave attack. The paper describes the influence of these parameters on the mean overtopping discharge for a traditional rubble mound breakwaters with an armour layer slope of 1:2.0.

Introduction

Wave overtopping of coastal structures is influenced by a large number of parameters related to breakwater geometry, construction materials, and hydrographic data. Some of the main parameters are listed below:

Geometrical parameters:
free board, crest configuration and width, slope of armour layer (irregular slope), and water depth

Construction material parameters:
porosity, stone shape and diameter (artificial blocks)

Hydrographic parameters:
wave height, wave period, angle of wave attack, wave steepness, spreading, wave sequences, wind conditions, and water level

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Wave overtopping is normally studied under perpendicular wave attack in wave flumes. Jensen and Juhl (1987) have shown overtopping data from model testing of rubble mound breakwaters and sea dikes. The paper mainly concentrates on mean overtopping discharges, but also includes a description of the horizontal distribution of the overtopping behind a breakwater, individual wave overtoppings and the influence of wind on wave overtopping, and a comparison to prototype measurements.

Franco et al (1994) have established a formula for the mean overtopping discharge for vertical breakwaters exposed to perpendicular wave attack. The influence of various geometrical types of breakwaters is taken into account using influence factors in connection with the general formula for a fully vertical breakwater. Further, a prediction formula for the probability distribution of individual overtopping volumes is presented. The effect of overtopping volumes on persons and cars behind a crown wall of a vertical breakwater was assessed by Franco (1993), and a set of critical overtopping discharges were proposed (safety criteria).

Only a little research has been made to study the influence of the angle of wave attack on the amount of overtopping water. De Wall and Van der Meer (1992) have carried out tests on the influence on wave run-up and overtopping on smooth slopes. The angle of wave attack, β, was varied from 0° up to 80°, and tests were performed with both long-crested and short-crested waves. For long-crested waves, a few tests showed larger run-up for angles between 10° and 30° than for perpendicular waves, but on average no increase was found. This also applies to the average measured overtopping discharges. For perpendicular wave attack, no difference in wave overtopping was measured between tests with long-crested and short-crested waves, whereas for oblique waves the influence of the angle of wave attack was less for short-crested waves. A reduction in the mean overtopping discharge of about 40 per cent was found for long-crested waves with an angle of 50° and of about 15 per cent for short-crested waves.

Galland (1994) has measured the number of waves overtopping rubble mound breakwaters exposed to oblique wave attack. The model tests were made with four different types of armour units, ie quarry stones, accropodes, antifer cubes and tetrapodes. In the case with quarry stones, the test results for long-crested waves showed a significant decrease in the percentage of waves overtopping the crest by increasing the angle of wave attack. For a dimensionless free board, R_c/H_s, higher than 2.0, no overtopping waves were measured, and for R_c/H_s = 1.0 the percentage of overtopping waves was about ten per cent for perpendicular waves which was reduced to no overtopping waves for an angle of 75°.

Model Set-up and Test Programme

Physical model tests have been carried out in a wave basin at the Danish Hydraulic Institute with the aim of measuring mean overtopping discharges defined as the volumes of wave overtopping per unit length of the breakwater per unit time. The basin was equipped with a movable wave generator in order to study the effect for different angles of wave attack, see **Fig 1**. The tests were carried out using long-crested irregular waves generated on basis of a Pierson-Moskowitz spectrum.

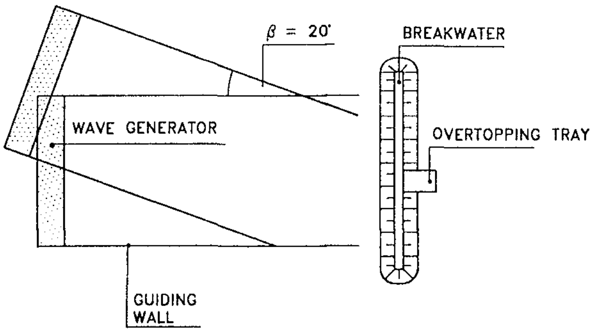


Fig. 1 Model plan for the basin tests showing the set-up for perpendicular and 20° wave attack.

The modelled structure had a total length of about seven metres and was constructed as a traditional rubble mound breakwater with a core, filter layer and armour layer of quarry stones, see **Fig. 2**. The size of the armour stones was selected not to allow for significant damage during testing, ie a nominal diameter, $D_{n,50}$, of about 0.04 m. The model consisted of a horizontal seabed which together with the use of a fixed breakwater height of 0.45 m means that variations in the crest free board were obtained by changes in the water level.

The wave conditions in the model were measured by seven resistance type wave gauges located in front of the breakwater. For perpendicular wave attack, the incident wave conditions and the reflection coefficients have been calculated using a multi-gauge technique. The significant wave height was calculated as $4 \times \sqrt{mo}$, where mo is the zeroth moment of the spectral energy density function.

The overtopping water was collected in a 0.6 m wide tray located immediately behind the breakwater in a level corresponding to the crest elevation of the breakwater. This means that the recorded wave overtopping refer to water passing the rear edge of the breakwater crest. By measuring the total amount of overtopping water after each test with a duration of 600 to 1800 seconds, the mean overtopping discharge, q, was calculated.

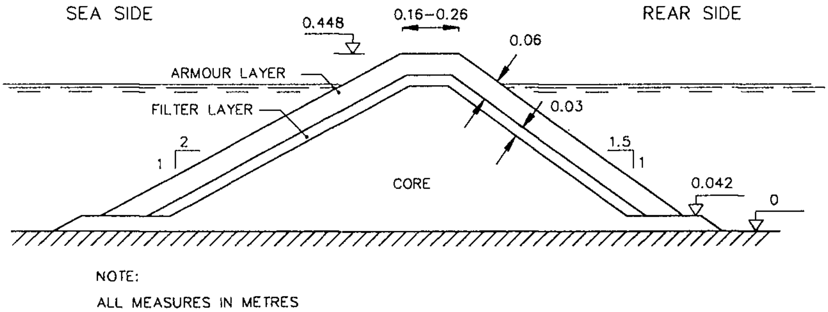


Fig. 2 Typical cross-section of breakwater used in the overtopping tests.

The following ranges of parameters were tested in the model study (all measures are in model measures):

- Significant wave height, H_s: 0.05 to 0.11 m
- Peak wave period, T_p: 0.8 to 2.0 s
- Wave steepness, s_{0p}: 0,018, 0,025, 0,030 and 0,045
- Crest free board, R_C: 0.050, 0.075 and 0.100 m
- Width of crest, B: 0.16 ($4 \cdot D_{n50}$), 0.21 and 0.26 m
- Slope angle, $\cot\alpha$: 2.0
- Angle of wave attack, β: 0° to 50° in steps of 10°

The wave steepness is given by the ratio between the significant wave height and the deep water wave length calculated on basis of the peak wave period:

$$s_{0p} = H_s/L_{0p} = 2\pi/g \cdot H_s/T_p^2$$

A parameter often used in the research on coastal structures is the surf similarity parameter given as:

$$\xi_{0p} = \tan\alpha/\mathrm{sqrt}(s_{0p})$$

The model tests were run in test series with fixed wave steepness, ie a fixed ratio between the significant wave height and the deep water wave length. Thus all tests were made with a surf similarity parameter larger than 2 (two), which means that the wave conditions can be characterised as non-breaking waves.

The dimensionless free board, defined as R_c/H_s, varied between 0.5 and 2.0, which means that the tests covered both low and high crested breakwaters.

Test Results

This section includes analyses of the influence of the various tested parameters (wave height, wave steepness, crest free board, crest width and angle of wave attack) on the mean overtopping discharge. The influence of each of the parameters is described in the following.

Previous studies and the analysis of the test results showed that it is important to distinguish between situations with a large amount of water passing the breakwater crest, 'green water', and situations with a small amount of water passing the crest, 'spray'. Observations in the model showed that a rule of thumb to distinguish the two types of wave overtoppings is the dimensionless free board, R_c/H_s. It was found that for R_c/H_s larger than unity, the major part of the wave overtopping will occur as spray, whereas for R_c/H_s less than unity green water is dominant.

Influence of Wave Height

Previous research on wave overtopping has shown that the wave overtopping increases almost exponentially with the wave height, which is confirmed by the present model tests. An example of the influence of the significant wave height on the overtopping volume is shown in **Fig. 3** for an angle of wave attack of 40°. It should be noted that also the wave period changes due to the fixed wave steepnesses. It is observed that for perpendicular waves, the wave steepness has some influence on the overtopping. This influence became smaller for oblique waves, and for 40° no influence is found.

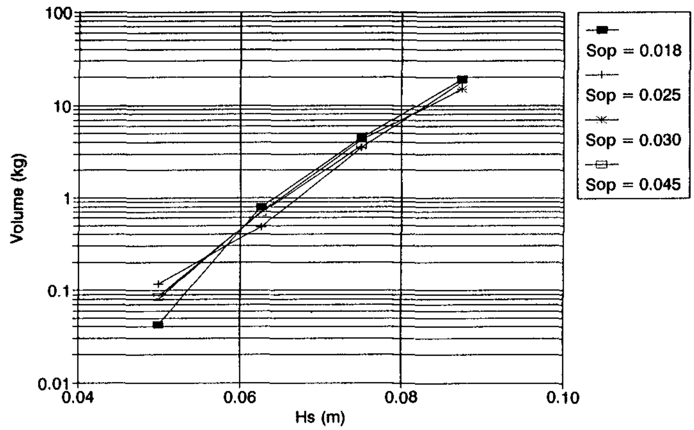


Fig. 3 Plot of the overtopping volume as function of the significant wave height, H_s. Crest free board, R_c=0.05 m. Crest width, B=0.16 m. Angle of wave attack, β=40°.

Influence of Wave Steepness

The influence of the wave steepness is shown in **Fig. 4** for two crest free boards, ie a low-crested and a high-crested breakwater. From the results, it is found necessary to distinguish between two different cases, ie $H_s > R_c$ and $H_s < R_c$. There is a tendency for decreasing overtopping volumes by an increase in the wave steepness for the case of $H_s > R_c$, whereas there is a tendency for increasing overtopping volumes for the case of $H_s < R_c$. The test results show that the influence of the wave steepness is decreasing for oblique waves, and generally no influence is found for an angle of wave attack of 30° as shown in **Fig. 7**.

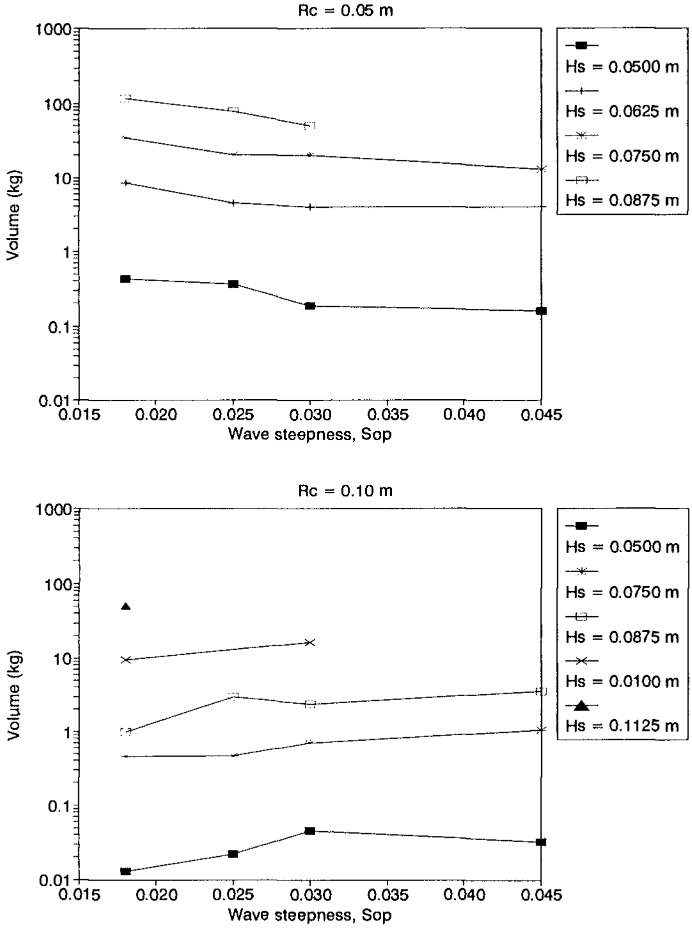


Fig. 4 Plots of the overtopping volume as function of the wave steepness, s_{0p}. Crest width, B=0.16 m. Angle of wave attack, β=0°.

Influence of Crest Free Board

Tests were made with three different crest free boards, which resulted in a dimensionless freeboard, R_c/H_s, ranging from 0.5 up to 2.0. The crest freeboard together with the significant wave height are the major parameters governing the amount of water overtopping a breakwater. Examples of the influence of the crest free board are shown in **Fig. 5**. Comparison of the result for perpendicular wave attack and for an angle of 20° shows that the influence of an increase of the crest free board is larger for the latter case, which is due to an increased distance from the intersection of the still water level with the main armour layer to the rear side of the crest (the location of the measuring tray).

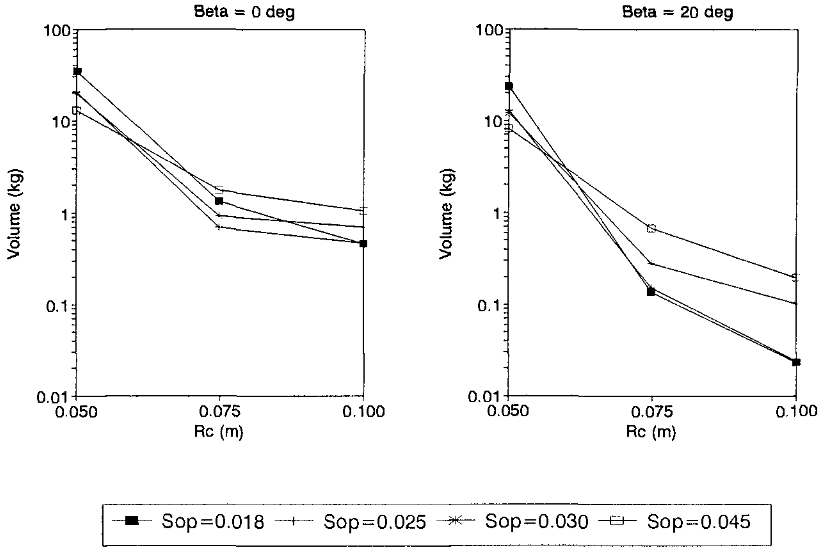


Fig. 5 Plots of the overtopping volume as function of the crest free board, R_c. H_s=0.075 m. Crest width, B=0.16 m.

Influence of Crest Width

Three crest widths were studied for perpendicular wave attack. Generally, it was found that the overtopping volume is decreasing with increasing crest width. However, the influence is smaller than the influence of the significant wave height and the crest free board. An example of the test results is presented in **Fig. 6**.

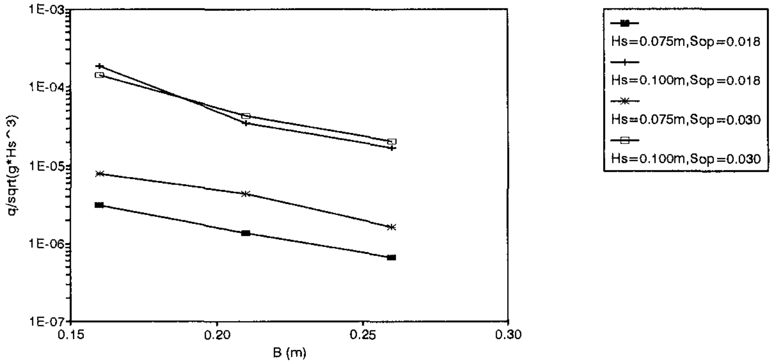


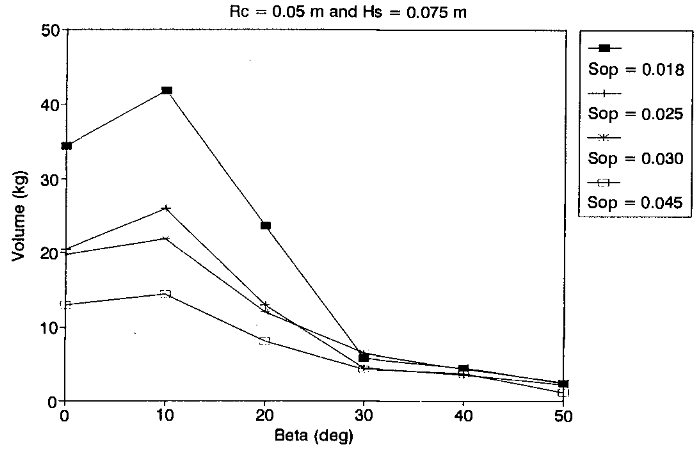
Fig. 6 Plots of the overtopping volume as function of the crest width, B. Crest free board, R_c=0.10 m. Angle of wave attack, β=0°.

Influence of Angle of Wave Attack

Test were carried out with angles of wave attack varying from 0° (perpendicular waves) up to 50° in steps of 10°. Typical examples of the influence of the angle are shown in **Fig. 7**, which includes the dependency of the wave steepness (it should be noted that the overtopping volumes are plotted in a linear scale). A pronounced characteristic in some of the cases is a maximum in the amount of wave overtopping for an angle of 10°.

In order to study in more details the influence of the angle of wave attack, dimensionless plots of the test data are shown in **Fig. 8**. These plots present the ratio between the overtopping volume for oblique waves and for perpendicular waves as function of the angle of wave attack for each of the three tested crest free boards. This ratio corresponds to a reduction factor taking into account wave obliquity. The plots show some scatter, but general trends can be recognised.

In the case with the smallest tested free board (R_c=0.05 m), the average of the tests shows a maximum in the mean overtopping discharge for an angle of 10°. A pronounced decrease in the overtopping is found increasing the angle of wave attack to 20° and 30°. For an angle of about 50°, the amount of overtopping water is on average reduced by 90 per cent compared to perpendicular wave attack, ie a reduction factor of 0.1. This reduction in the wave overtopping for an angle of wave attack of 50° is significantly higher than the reduction of about 40 per cent found for smooth slopes in De Wall and Van der Meer (1992).



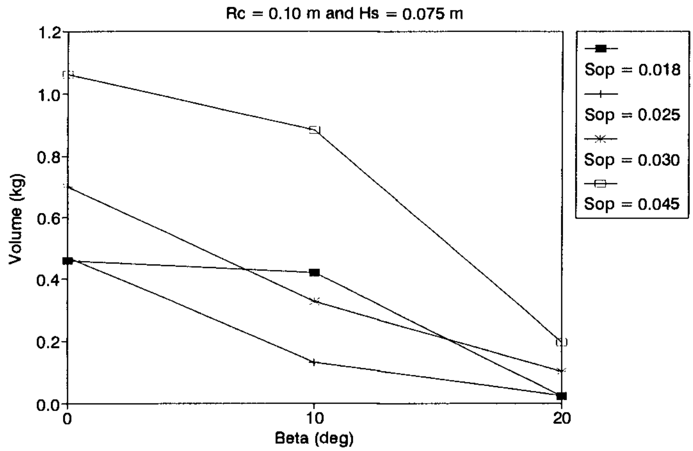


Fig. 7 Plots of the overtopping volume as function of the angle of wave attack, β. The plots include the influence of the wave steepness, s_{0p}. Crest width, B=0.16 m.

For the cases with higher free boards, only a few tests show a maximum in the overtopping for an angle of 10°, and on average a decrease is found. Comparing the three plots, it is found that the influence of the angle is getting more pronounced for the cases with the higher free boards. For the highest tested free board (R_c=0.10 m), a reduction factor of about 0.2 is found for an angle of 20°.

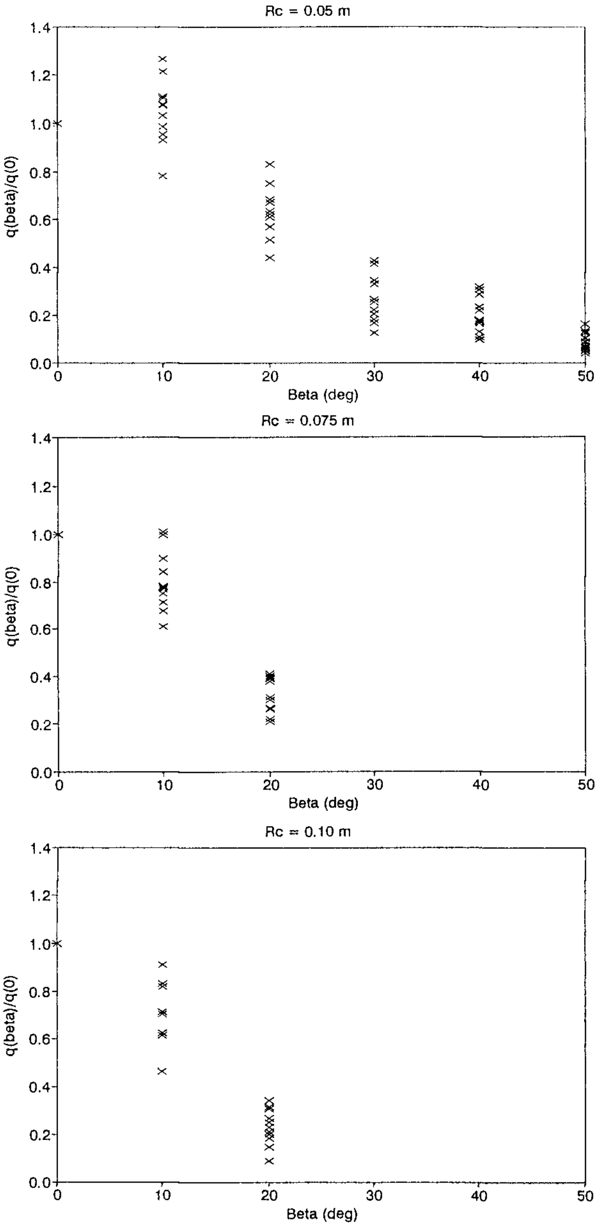


Fig. 8 Plots of the ratio between the overtopping discharge for oblique waves, q_β, and for perpendicular waves, q_0, as function of the angle of wave attack.

The overtopping volumes in De Wall and Van der Meer (1992) refer to the amount of water passing the crest of a slope, which is a relevant measure in the case of an impermeable slope. In the case of a permeable rubble mound breakwater, the amount of overtopping water will be dependant on the location of the measurement, ie the volume will be different when measuring at the front side edge or rear side edge of the crest due to the porous crest of the breakwater. The difference in the reference location of the overtopping measurements will have an effect on the influence of the angle of wave attack, as the distance from the front edge to the rear edge of the breakwater will increase with the angle of wave attack. Further, in the case of a rubble mound breakwater, the permeable layers will result in a faster decrease of the overtopping volume than for an impermeable slope.

Dimensionless Presentations

Through the years, overtopping results have been presented in numerous ways, including dimensionless plots. The most used dimensionless parameters are the dimensionless overtopping discharge, $Q=q/\mathrm{sqrt}(g \cdot H_s^3)$, and the dimensionless free board, $R=R_c/H_s$.

Examples of dimensionless plots of the test results obtained for perpendicular waves and for waves with an angle of 50° are shown in **Fig. 9**. The plots show that the test data for dimensionless free boards less than about 1.5 can be fitted to a straight line, ie Q can be described by an exponential function of R_c/H_s.

The model tests carried out with different crest widths showed that this parameter has an influence on the overtopping, and it is found that a combination of the crest free board and width can be used for describing the combined influence of these two parameters. For a fixed wave steepness, the dimensionless mean overtopping discharge can be fitted to an exponential function using $(2R_c+0.35B)/H_s$ as parameter.

The test results show that the influence of the wave steepness is small compared to the influence of the other tested parameters, and that it is decreasing for oblique waves. A dimensionless plot excluding the influence of the wave steepness is presented in **Fig. 10** for all the tests made with perpendicular waves. The overtopping data are found to fit reasonable to the dimensionless parameter, $(2R_c+0.35B)/H_s$, ranging between about 1.5 and 4.0.

Dividing the dimensionless overtopping discharge with average reduction factors for wave obliquity (see the plots presented in **Fig. 8**), all the overtopping data are presented in a dimensionless plot in **Fig. 11**. The figure presents the dimensionless overtopping discharge divided by the influence factor as function of the established dimensionless parameter, $(2R_c+0.35B)/H_s$, taking into account both the crest free board and width. It is concluded that the influence of oblique waves on the wave overtopping discharge can be described by an influence factor for wave obliquity. A slight increase in the scatter is found including the data for oblique waves, see **Figs. 10 and 11**.

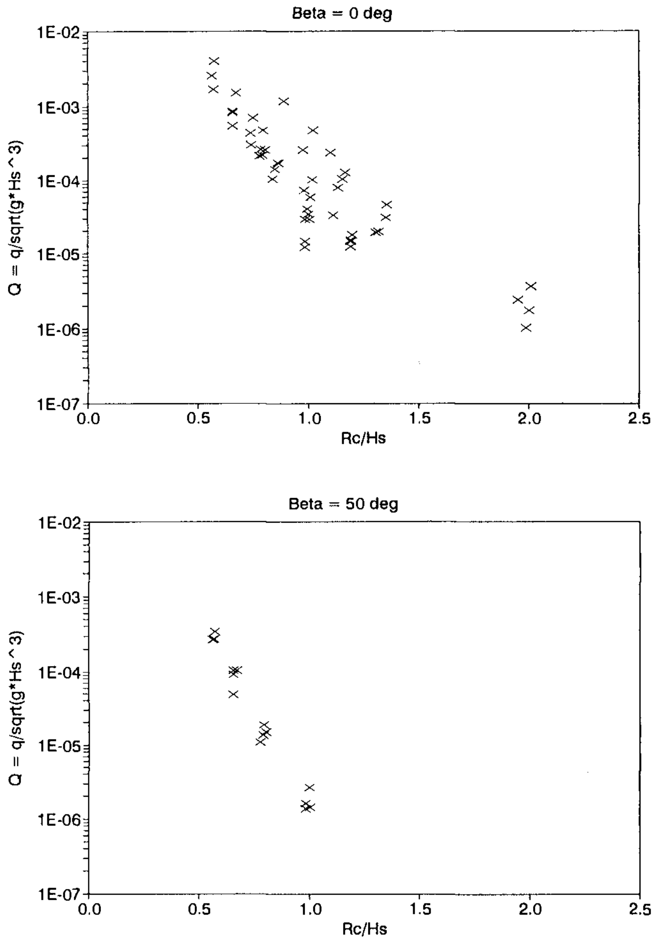


Fig. 9 Dimensionless overtopping discharge, Q, as function of dimensionless free board, R_c/H_s. Crest width, B=0.16 m.

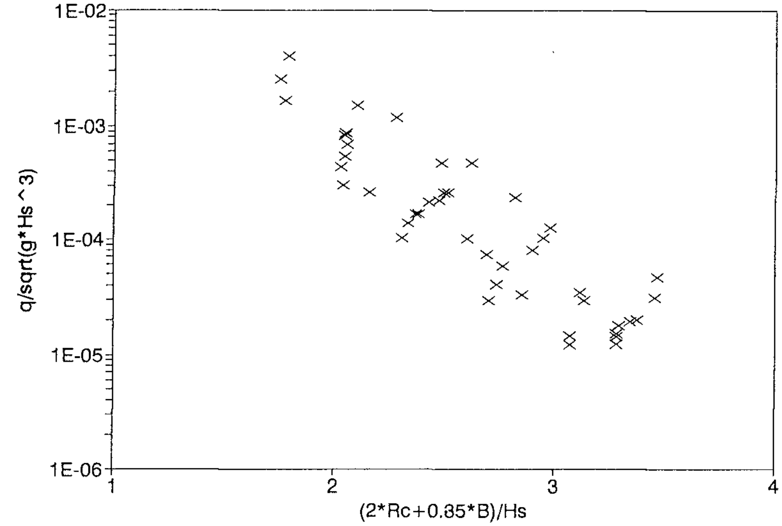


Fig. 10 Dimensionless overtopping discharge, Q, as function of the dimensionless parameter, $(2R_c+0.35B)/H_s$. Angle of wave attack, $\beta=0°$.

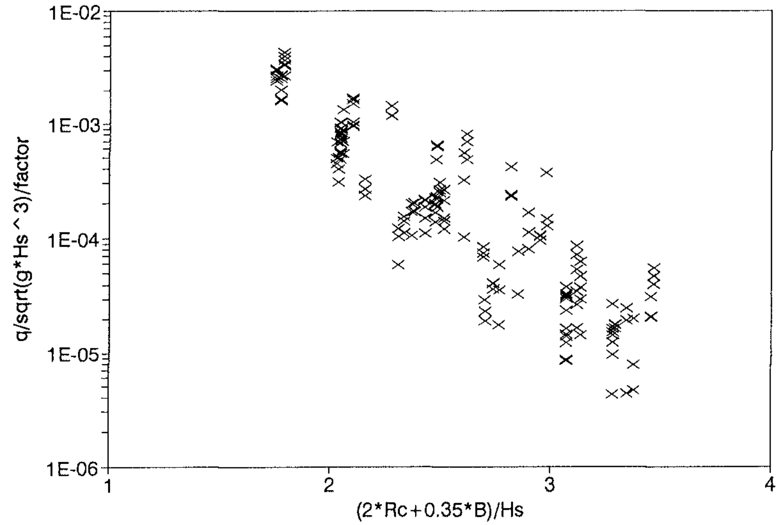


Fig. 11 Dimensionless overtopping discharge including an influence factor to take into account wave obliquity, Q/factor, as function of the dimensionless parameter, $(2R_c+0.35B)/H_s$.

Conclusions

A wide range of parameters influence wave overtopping of coastal structures. The present research study on overtopping of a traditional rubble mound breakwaters with an armour layer slope of 1:2.0 has concentrated on the angle of wave attack, the crest free board, crest width, and the general wave parameters (H_s, T_p, and s_{0p}).

Model tests were carried out in a wave basin for measuring the mean overtopping discharge, q ($m^3/m/s$), and covered angles of wave attack ranging from 0° (perpendicular waves) up to 50° in step of 10°.

The significant wave height and the crest free board are the most important parameters with respect to wave overtopping. The crest width is found to have some smaller influence.

Testing with four wave steepnesses show that this parameter has an influence on the wave overtopping for perpendicular waves, whereas the influence is decreasing for oblique waves. However, the influence is small compared to the influence of the other tested parameters.

From analyses of the test results, it can be concluded that the reduction factor for wave obliquity (described by the ratio between the overtopping for oblique waves and perpendicular waves) is dependent on the crest free board. In case of a low-crested breakwater, the average of the tests show a maximum in the mean overtopping discharge for an angle of 10°. A pronounced decrease is found increasing the angle to 20° and 30°. For an angle of 50°, an average reduction factor of 0.1 is estimated. For breakwaters with a higher crest free board, the influence of the angle is larger, eg for the high-crested breakwater a reduction factor of about 0.2 is found for 20°.

The dimensionless overtopping discharge data for perpendicular waves (including all four wave steepnesses) show to fit well when plotted against a dimensionless parameter combining the influence of the crest free board and width $(2R_c+0.35B)/H_s$. Dividing the dimensionless overtopping discharges with average reduction factors for wave obliquity, it is found that the same dimensionless parameter gives a reasonable fit also for oblique waves. This means that for rubble mound breakwaters with a slope of 1:2.0, the dimensionless overtopping discharge including a reduction factor for wave obliquity can be described by an exponential function of $(2R_c+0.35B)/H_s$.

In order to establish a general overtopping formula for rubble mound breakwaters, it will be required to include the influence of, for instance, alternative breakwater geometries, water depth, artificial armour units, and superstructures.

Acknowledgement

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