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COMPARISON BETWEEN OVERTOPPING DISCHARGE IN SMALL AND LARGE SCALE MODELS

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The present paper presents overtopping measurements from small scale model test performed at the Hydraulic & Coastal Engineering Laboratory, Aalborg University, Denmark and large scale model tests performed at the Large Wave Channel, Hannover, Germany. Comparison between results obtained from small and large scale model tests show no clear evidence of scale effects for overtopping above a threshold value. In the large scale model no overtopping was measured for wave heights below $H_s = 0.5m$ as the water sunk into the voids between the stones on the crest. For low overtopping scale effects are presented as the small-scale model underpredicts the overtopping discharge.

1. Introduction

Overtopping occurs when the run-up level exceeds the crest height of a coastal structure. The amount of wave overtopping is one of the important factors influencing the design of breakwaters and other coastal structure. Overtopping can cause severe damage or injuries to persons, buildings or structures, cf. figure 1 or cause great inconvenience and hamper operations in the harbour or on the quay, .

Wave overtopping and spray on breakwaters are caused by combined effects from wind and waves. The physical phenomenon of wave overtopping can be considered as a two phase flow with low dens media and a upper dens media. Mound breakwaters have a outer layer of rock or other large units and resulting in relatively large air filled pores above SWL, depending on the type and size of outer units. If the velocity of the wave uprush is large enough, the pores of the armour layer will be air filled resulting in a

Figure 1. Example of damage due to heavy overtopping. Photo from a walkway at Ananaust, Reykjavik, Iceland. Due to overtopping the pavement has been damaged and rock fill behind the structure has eroded.

two phase flow with a mixture of air and water. This mixture has a lower density than the water alone and as it hits the rough surface of the armour units the water is thrown in the air. Then the wind will carry the water drops or the spray over the structure onto the rear side.

Numerous studies have been performed to give guidelines on admissible overtopping discharge and how to determine overtopping discharge. Most studies are based on small scale model tests but in recent years, more and more attention has been given to prototype measurements and large scale model test.

Most applicable overtopping prediction formulae are based on small scale model tests, e.g. Owen (1980), Juhl and Sloth (1994), Van der Meer and Janssen (1994), Hebsgaard, Sloth, and Juhl (1998) etc.. The outcome of these formulae is the average overtopping discharge in cubic meter per seconds for a unit width of the structure.

The main complexity arises due to the fact that overtopping discharge from wind generated waves is very unevenly distributed in time and space. Furthermore only a small fraction of waves in a storm causes the major part of overtopping discharge. The local overtopping discharge in m^3/s

per. unit length of structure from a single wave can be more than 100 times the average overtopping discharge during the storm.

Burcharth and Huges (2002) gives a guideline for critical values for overtopping discharge. Such guidelines must be considered as rough guidelines as the intensity of water hitting a specific location is very much dependent on the geometry of the structure and the distance from the structure to the delicate object.

Recent comparisons between prototype field measurements and small scale model test results indicate that scale effects are present for small overtopping discharges on sloping rubble mound structures, Geeraerts, Troch, De Rouck, Willems, Franco, Bellotti, and Briganti (2004). Comparisons between prototype measurements and small scale model tests are difficult due to model effects as for example missing wind in the models. Moreover, it is sometimes difficult to obtain high quality information on incident waves in prototypes. Better controlled scale effect studies, not including wind effect, can be done by comparison of small and large scale model test results.

2. Experimental Set-up

Small-scale tests were performed at the Hydraulic & Coastal Engineering Laboratory, Aalborg University. In these tests wave induced overtopping was measured simultaneously with the incident wave parameters.

In order to verify results based on small-scale model, a large-scale model geometrically similar to the small-scale model was tested in the Large Wave Channel in Hannover (Großen Wellenkanal), Germany. The small-scale model was approx. 4.9 times smaller than the large scale model. The main purpose of the model tests was to investigate the influence of rock armour mass density on the stability of rubble mound breakwaters, but overtopping discharge was measured throughout the tests in order to compare the two models.

2.1. *Small Scale Model Tests*

Figure 2 shows the experimental setup for the small-scale model. The model was a conventional rubble mound breakwater without superstructure. The front-side slope was 1:2.0 and the rear-side slope was 1:1.5. The model was built in a 25 meter long and 1.5 meter wide flume at the Hydraulic & Coastal Engineering Laboratory, Aalborg University.

Water depth at the structure were $0.35m$ and $0.52m$. Only tests with water depth $0.52m$ gave measurable overtopping.

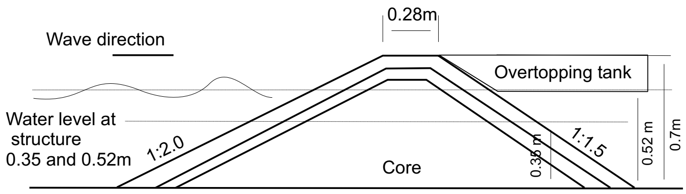

Figure 2. Cross-section of the small scale model.

Two types of armour stones were tested: stones with high density and normal density. The core and filter was kept the same for both types of armour. Table 1 gives the details of the materials used in the model tests.

Table 1. Specifications of materials in the small scale model.

Type	Weight W_{50}	Size D_{50}	Density	Grading $\frac{D85}{D_{15}}$	Porosity
Rock armour, High Density	158 g	37 mm	$3.05t/m^3$	1.10	0.4
Rock armour, Normal Density	230.5 g	46 mm	$2.65t/m^3$	1.27	0.4
Filter	-	16 mm	$2.70t/m^3$	2.1	0.4
Core	-	2.8 mm	$2.70t/m^3$	3.0	0.37

The waves were generated according to a JONSWAP- spectrum. The range of wave heights was $H_s = 0.05 - 0.2m$, and the range of periods $T_p = 1.2 - 2.0s$. Each test included 1000 waves. Incident wave parameters were determined on the basis of eight wave gauges.

Overtopping was measured by gathering overtopping water in a tank placed behind the structure. During the test it was observed that the gathering tank was not accurate enough to measure small amount of overtopping. Small amount of overtopping means individual drops and irregular splash. It was found necessary to us a different system to quantify this small amount of overtopping. Hence, low amount of overtopping was measured by placing a steel try at the inner edge of the crest. The overtopping was quantified by weighing the try before and after each test.

Converting the low overtopping values into prototype values showed the necessity of this action. The converted amount of overtopping balances on the threshold values for safety of pedestrians behind the structure (Burcharth and Huges 2002).

2.2. *Large Scale Model Tests*

Figure 3 shows the experimental setup in the Large Wave Channel. The model was a conventional rubble mound breakwater without superstructure geometrically similar to the small scale model. The channel is 300 meter long, 5 meter wide and 7 meter deep. The breakwater was constructed approx. 240 meters from the wave generator on a 2 meter thick sand pad forming a foreshore of slope 1:50. The water depths in the flume was 3.5, 4.0 and 4.5m at the wave generator, and 1.5, 2.0 and 2.5m at the structure. Only tests with the highest water level gave measurable overtopping.

As in the small scale model both high density rock and normal density rock were tested. The rocks were supplied by NCC Industries Norway. The high density rock came from NCC quarry at Valberg, Kragerø Norway; the normal density rock came from NCC quarry at Skien, Norway. Two samples from the breakwater model for each type of rock were weighed and measured to determine the statistical properties, including the porosity.

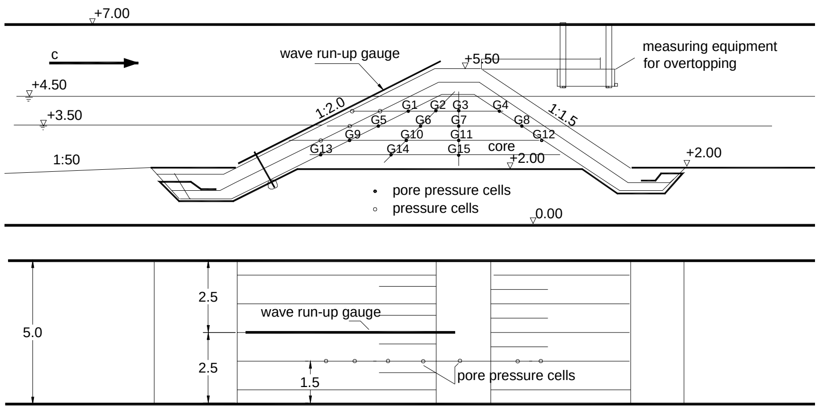

Figure 3. Cross-section of the large scale model (measures in metres).

The sand pad material had a mean diameter of 0.33 mm. The core and filter materials consisted of crushed granite from a local quarry. The core and the filter was the same for both types of armour. Table 2 gives the details on the materials used in the model.

A total number of 22 wave gauges were used, 20 placed in front of the structure and 2 behind. Wave induced run-up was measured using a run-up gauge developed at Gent University. Overtopping discharge was measured

Table 2. Specifications of materials in the large scale model.

Type of stone material	Weight W_{50}	Size D_{50}	Density	Grading $\frac{D85}{D_{15}}$	Porosity
Rock armour, High Density	19 kg	184 mm	$3.05t/m^3$	1.59	0.40
Rock armour, Normal Density	30 kg	225 mm	$2.65t/m^3$	1.51	0.42
Filter	-	50 mm	$2.65t/m^3$	2.5	0.45
Core	-	16 mm	$2.65t/m^3$	4.6	0.35

Figure 4. Installation of the overtopping tank in GWK. The tank was placed behind the structure and consisted of an inner and outer tank.

using the standard measuring equipment of GWK. A overtopping gathering tank was placed behind the structure. A $35cm$ wide channel was placed at the inner edge of the crest connecting the gathering tank and structure. The gathering tank had an inner tank which was placed on four weighing cells. Before running the tests the four weighing cells were calibrated by adding small amount of water and hence associating the reading from the weighing cell to added amount of water. The outer tank was closed with a lid in order to prevent splash and overtopping waves from disturbing the measurements, cf. figure 4.

The test program consisted mainly of irregular waves generated according to a JONSWAP-spectra. The range of wave heights were $H_s = 0.3 - 1.0m$, and the range of wave periods $T_p = 1.5 - 6.0s$. The program also included tests with spectra measured in the field (along the German coastline). All tests with JONSWAP spectra contained 1000 waves. Only few tests with regular waves were performed.

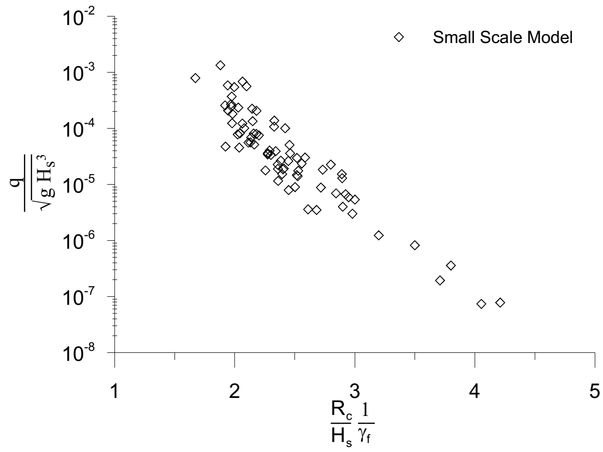

Figure 5. Results obtained in small scale model tests for non-breaking water depth conditions in front of the structure corresponding to the high water level shown in figure 2.

3. Experimental Results

For both small and large scale model tests the total overtopping volume were measured. For the small scale model two different method where applied to gather and measure overtopping volumes depending on the amount of discharge. In the large scale model only one measuring method was applied.

For low amount of overtopping in the small scale model a steel tray was placed behind the structure to enable gathering of water drops and spray. For moderate and heavy overtopping the overtopping volume were gathered in a tank placed behind the structure. The total overtopping volume in the tank was monitored using a simple gauge.

The average overtopping discharge per unit crest width were determined by dividing the total overtopping volume by the length of the test and with regard to the channel width. Results obtained from the model tests are plotted for the dimensionless freeboard vs. dimensionless overtopping discharge.

Figure 5 shows a plot for results obtained in the small scale model tests. Majority of the tests show overtopping above $q/\sqrt{gH_s^3} \times 10^{-6}$ and only few tests are in the lower section. q is the average overtopping discharge per second and unit width of the structure, H_s the significant wave height, R_c the freeboard and $\gamma_f = 0.55$ is the roughness coefficient, cf. the formula by

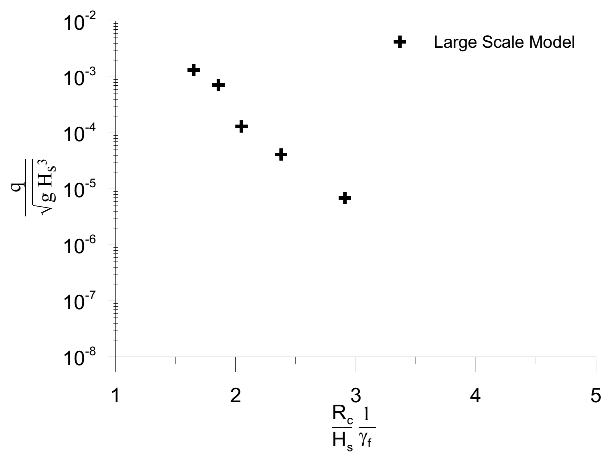

Figure 6. Results obtained in large scale model tests for non-breaking water depth conditions in front of the structure corresponding to the high water level shown in figure 3.

(Van der Meer and Janssen 1994).

Figure 6 shows a plot for recorded overtopping discharges in the large scale model tests. All the tests show overtopping above $q/\sqrt{gH_s^3} \times 10^{-6}$ or approximately $q > 0.01l/s/m$.

Figure 7 shows a plot for comparison between results obtained in the small and large scale model.

4. Discussion

Figure 7 shows a comparison between recorded overtopping discharges in the small and large scale models.

The results from the two models fit very well together indicating no scale effect on overtopping discharge, q. However, no overtopping in the large scale model could be observed for values of smaller than 6.9×10^{-6} corresponding to lowest data point given in figure 7. The related wave height was $H_s = 0.60m$. For smaller wave heights ($H_s = 0.50m$) no overtopping reached the overtopping tank as the overtopping water sank into the crest of the porous structure before reaching the tank, cf. figure 8.

Converting of this result to typical prototype conditions indicates that no model scale effect seems present for q approximately $1 - 2 \times 10^{-1}l/sm$ and higher. Overtopping rates exceeding $1 - 2 \times 10^{-1}l/sm$ can provoke damage on structures, hamper traffic and be dangerous for pedestrians.

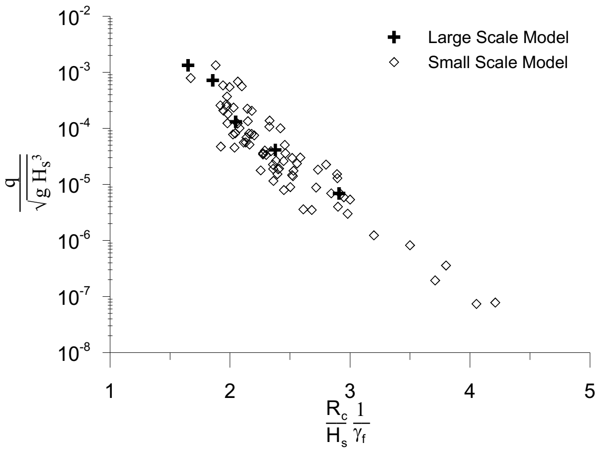

Figure 7. Comparison of results obtained in small and large scale model tests for non-breaking water depth conditions in front of the structures corresponding to the high water levels shown in figure 2 and 3.

Figure 8. The momentum of the water is too little to cross the width of the crest. The water sinks almost immediately between the stones.

For smaller values significant scale effects are present as small scale models underpredicts the overtopping discharge. This threshold value relates to the type of crest structure shown in figures 2 and 3.

Similar scale effects occur in wave run-up on sloping impermeable structures. These scale effects can be related to the inability to scale the roughness effects in small scale models.

A theoretical approach by Burcharth (2004) relates scale effects in overtopping of rubble mounds to the surface flow and surface tension. In both cases small scale models give smaller rates of overtopping due to large flow resistance caused by increase in drag coefficients with lower Reynolds numbers. Furthermore, scale effects are more educed for smaller overtopping rates.

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