Large scale wave run-up tests on a rubble mound breakwater

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Introduction

Large scale wave run-up tests have been performed in the project 'Research on the use of heavy rock in rubble mound breakwaters and seawalls' in the LARGE WAVE CHANNEL (GWK) of the Coastal Research Center (FZK). The large scale tests have been supported by the European Community under the Access to Research Infrastructures action of the Human Potential Programme (contract n° HPRI-CT-1999-00101). The participants of the project were Aalborg University (Denmark – co-ordinator), Ghent University (Belgium), Havnecon Consulting ApS (Denmark) and NCC Industry (Norway). The LARGE WAVE CHANNEL (GWK) is the most important facility for basic and applied research on Coastal Engineering phenomena at the Coastal Research Centre (FZK) (http://www.hydrolab.de). The LARGE WAVE CHANNEL measures 307 m long, 7.00 m deep and 5.00 m wide.

The main objectives of the project were firstly to investigate the influence of rock density on the armour layer stability and secondly to collect large scale data on wave run-up and wave overtopping.

By using high density rock for coastal protection measures, the required size and volume of rock can be reduced. The filter layer also benefits from this reduction and sections of a breakwater suffering severe wave attack can be protected more effectively with high density rock without changing the rock size used in other sections. The disadvantage of using high density rock is believed to be higher wave run-up and increased wave overtopping discharges.

Laboratory wave run-up results differ from field or large scale measurement results, both for ´very rough´ slopes (rubble mound structures armoured with artificial armour units) and ´smooth´ slopes (sea dikes). These differences are due to scale effects and modelling effects. The project allows the verification of wave run-up on a slope with an ´intermediate roughness´ (rubble mound structure armoured with rock) by providing large scale data to compare with small scale model test results.

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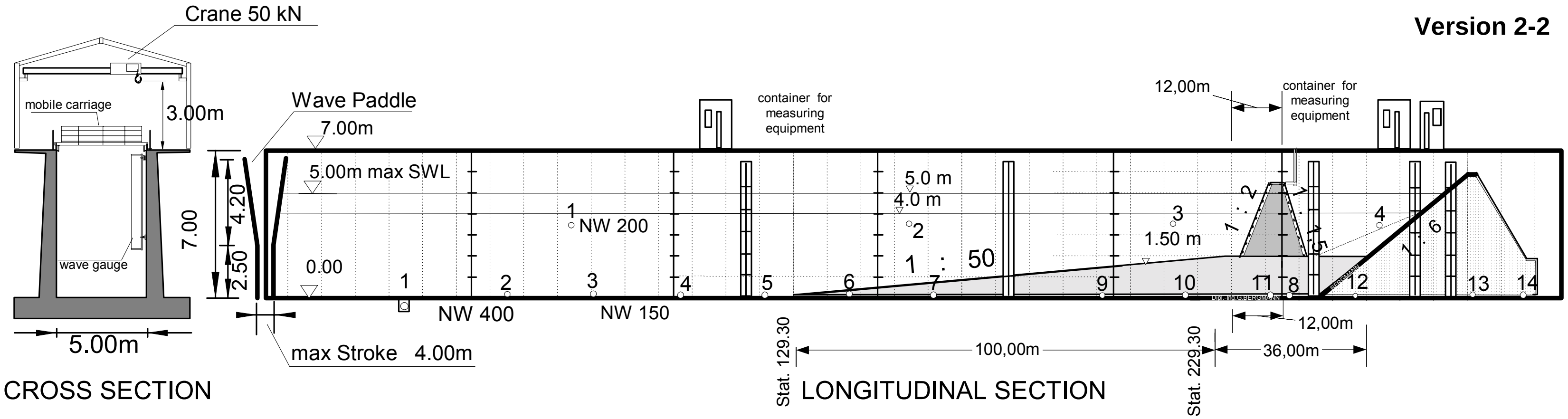

BULKHEADS	0.00	49.30	49.30	48.00	97.30	48.00	145.30	56.00	201.30	40.00	241.30	68.00	309.30

WINDOWS	0.00	113.30	177.30	249.30	273.30	281.30	309.30

SLIDE VALVES SOUTH (NW 150)	0.00	59.30	79.30	99.30	119.30	109.30	159.30	183.30	199.30	219.30	239.30	259.30	287.30	299.30	309.30

SLIDE VALVES NORTH (NW 200)	0.00	73.30	153.30	217.30	265.30	309.30

Figure 1: General view of the LARGE WAVE CHANNEL (GWK) with indication of the position of the 1:50 slope and the breakwater.

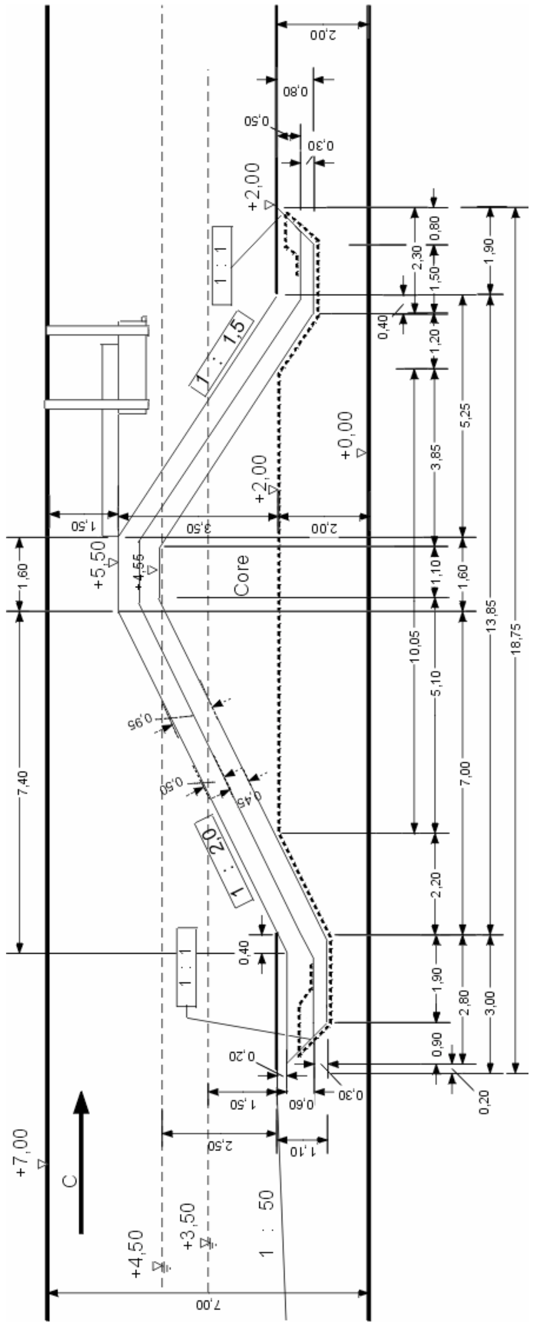

Figure 2: Geometry of the GWK rubble mound breakwater.

Model setup

A general overview of the GWK and the location of the breakwater is given in figure 1. The structure is a didactical example of a conventional rubble mound breakwater consisting of a core, a filter layer and an armour layer (figure 2).

Table 1: Characteristics of the materials of the GWK breakwater.

characteristic		core	filter	armour layer: high density rock (ρ = 3.05 t/m^3)	armour layer: normal density rock (ρ = 2.65 t/m^3)
D_{n10} [mm]		5	30	149	166
D_{n15} [mm] (W_{15} [kg])		6	32	153 (11)	180 (15.5)
D_{n50} [mm] (W_{50} [kg])		13	50	184 (19)	225 (30)
D_{n60} [mm]		15	57	193	231
D_{n85} [mm] (W_{85} [kg])		30.5	75	245 (45)	271 (53)
D_{n85}/D_{n15} [-]		5.23	2.34	1.60	1.50
D_{n10}/D_{n60} [-]		0.31	0.53	0.77	0.72
gradation	narrow or 'single sized'				
	wide		•	•	•
	very wide ('quarry run')	•			
uniformity	very uniform		•	•	•
	uniform	•			
	inuniform				
	very inuniform				

The structure was built on a 2 m thick sand bed forming a sloping foreshore of 1:50. To prevent sand migration a geotextile was placed between the sand bed and the structure.

The characteristics of the core and filter material are given in table 1. For a first series of tests, the breakwater was protected with high density rock (ρ = 3.05 t/m^3; D_{n50} = 184 mm, W_{50} = 19 kg). Once these tests had finished, a part of the armour layer, i.e. the seaward slope between toe and landward end of crest, was removed and replaced by an armour layer consisting of normal density rock (ρ = 2.65 t/m^3, D_{n50} = 225 mm, W_{50} = 30 kg). For every type of armour layer rock, two samples have been withheld and stored separately from the other rock mounds when removing the armour layer. One sample was taken from the upper part of the breakwater and another sample from the lower part of the breakwater. Each rock of the samples has been weighed manually. The cumulative weight distribution curves of the high density rock, resp. normal density rock are given in figure 3.

Figure 4 shows the breakwater built in the wave channel. The run-up gauge (see further on) is seen on the front slope of the breakwater.

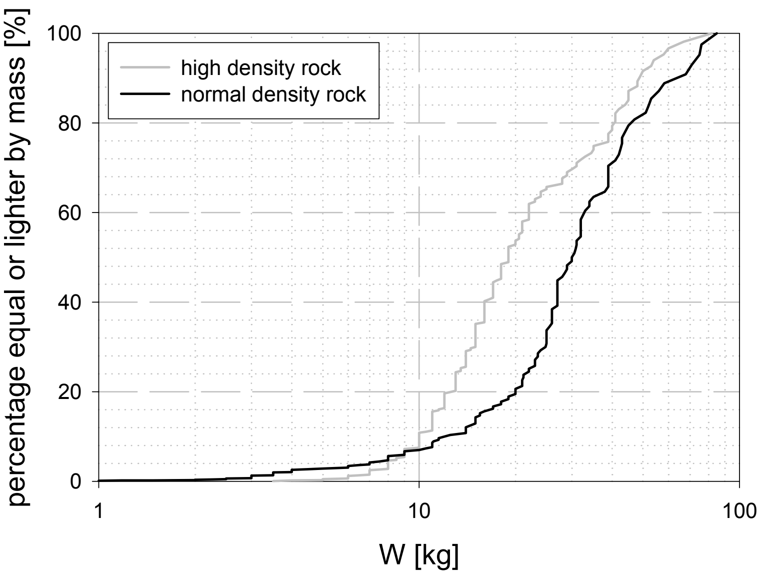

Figure 3: Cumulative rock weight distribution curve of the high and normal density armour layer rock.

Figure 4: View on the front slope of the breakwater with the run-up gauge.

Measuring equipment

Wave gauges. Twenty two capacitance wave gauges have been placed along the wave channel.
Run-up gauge. Wave run-up has been measured by a digital wave run-up gauge. The gauge consisted of three parts mounted on the seaward slope of the breakwater. Each part measures 2.40 m long and has 24 electrodes. The distance between two electrodes is 10 cm. The gauge detects wave run-up each 4.5 cm in vertical distance. The gauges are similar to the run-up gauges used for full scale wave run-up measurements and a small scale version has been used for wave run-up measurements in the laboratory (De Rouck et al. (2001), De Rouck et al. (2004)). The step gauges are attached to the armour layer by clamps and reinforcement bars driven into the core of the breakwater (figure 5(a)). The three gauges are connected to each other by cables which are protected by a piece of garden hose. During the second series of tests, a shield (figure 5(b)) was placed on the run-up gauges in order to protect the connection of the cables to the gauges.

(a) (b)

Figure 5: (a) Clamps to fix the run-up gauges to steel bars driven into the core of the breakwater and (b) shield protecting the connection of the cables to the gauges.

The gauges have been placed in such a way that the upper parts of the electrodes are as good as possible in the upper surface of the armour layer. Therefore, the gauges had to be sunken down a bit in between the armour stones. It must been said that this was not an easy task to complete.

The digital step gauge did not have to be calibrated in the same way as all other sensors. The step gauge detects the number of wet electrodes. By measuring the exact elevation of the top of the lowest and highest electrode of each gauge with a leveller and a levelling rod, the position of all intermediate electrodes can be calculated very easily.

Wave overtopping tank. The wave overtopping tank available at the LARGE WAVE CHANNEL has been used for wave overtopping measurements. However, wave overtopping measurements will not be discussed in this paper.

Other. A grid is drawn on one side wall to help visual interpretation of wave measurements. A video camera was directed towards the breakwater and visualised wave run-up and wave overtopping on the breakwater on a small tv screen which was placed in the measurement container. Video images have been taped.

Test matrix

A broad range of wave characteristics has been investigated (table 2). To study the influence of the water depth on wave run-up, tests have been carried out with three different water levels (water depths d = 3.50 m, d = 4.00 m and d = 4.50 m at the wave paddle and d_t = 1.50 m, resp. d_t = 2.00 m and d_t = 2.50 m at the toe of the structure). The tests carried out with a water depth of 4 m were only intended to measure wave run-up. For the other water depths, d = 3.5 m and d = 4.5 m, 'damage tests' have been carried out to study the stability of the armour layer rock under wave attack. During these damage tests, the wave height was gradually increased until the armour layer was severely damaged. For results concerning stability of armour layer rock, reference is made to Helgason (2004). Tests for wave run-up measurements have been carried out before the tests in which wave heights exceeded the non-damage wave height calculated by Hudson's formula have been run. The density of water was ρ_w = 979.63 kg/m^3 (at 18°C, determined at Aalborg University). For the used densities $\rho_{s,1}$ = 3050 kg/m^3 and $\rho_{s,2}$ = 2650 kg/m^3, the critical wave height is $H_{s,1}$ = 0.64 m, respectively $H_{s,2}$ = 0.63 m for a K_{RR} value of 2.2 (breaking waves) and an average weight W_{50} = 19 kg for the high density rock and W_{50} = 30 kg for the normal density rock (see table 1). The Iribarren number ξ_{op} varied between 1.71 and 5.30. JONSWAP wave spectra (with peak enhancement factor γ = 3.3) have been generated. The parameters are the significant wave height H_s and the peak period T_p. Tests with standard JONSWAP spectra have been run as long as it took to have at least 1000 waves measured. The time estimated to have one thousand waves was 1000 T_m. By a theoretical model of the JONSWAP spectrum, the mean wave period T_m was calculated from the peak period T_p. The ratio T_p/T_m for a JONSWAP spectrum is about 1.2. Further, field spectra, measured at the German coast in shallow water, have been used for the run-up tests, but all results in this paper will only deal with the Jonswap spectra. Only limited tests with regular waves have been carried out. Active wave absorption has been used during all tests.

Results

Waves and wave run-up data have been sampled at f_s = 100 Hz. All data have been subsampled to 10 Hz. Waves measured near the wave paddle but outside the 'near field' area, just before the foreshore slope and at the toe of the breakwater have been considered. Waves have been analysed both in time and in frequency domain. The number of data points per data window was taken 1028 by which the spectral band width is b = 1.21.10^{-2} Hz.

Table 2: Range of investigated parameters.

Rock density ρ [kg/m^3]	Water depth at wave paddle d [m]	Significant wave height H_s [m]	Peak wave period T_p [s]	Wave steepness s_{op} [-]	Iribarren number ξ_{op} [-]
2650 3050	3.50 4.00 4.50	0.30 – 1.00 with ΔH_s = 0.10	1.5 – 6.0	0.009 – 0.085	1.71 – 5.30

A comparison between the significant wave height measured near the wave paddle, at the toe of the foreshore slope and at the toe of the breakwater has been made. Only very small differences have been observed between the significant wave height measured near the wave paddle and the significant wave height measured just before the foreshore slope (on average 2.6% difference). The significant wave height at the toe of the breakwater differed significantly from significant wave height measured near the wave paddle (on average 9.0% difference). If waves are Rayleigh distributed, the ratio H_{mean}/H_s equals 0.626. The average relative difference to this value is 2.9% for the waves measured just before the foreshore slope and 3.4% for the waves measured near the toe of the breakwater. It is concluded that the change in water depth nor wave breaking had a significant influence on wave height distribution.

Wave run-up time series have been analysed with the zero down crossing method. The number of wave run-up events is referred to the number of (total) waves determined as the total length of the analysed time series divided by the mean wave period T_{01}. Dimensionless wave run-up values are always referred to the significant wave height measured close to 'the toe of the structure'. The wave gauge at the toe of the structure could have been used for this purpose. However, a single wave gauge measurement technique has been used. According to Klopman et al. (1999), the minimum distance between the toe of the breakwater and the position of the (only) wave gauge needs to be at least the double of the peak wave length. In case of a peak wave period of T_p = 6 s, is the peak wave length L_p = 56.20 m. The minimum distance would be 112.40 m. So, the wave gauge located at the toe of the breakwater is found in the critical area in which the determination of the significant wave height is very difficult. Instead, the wave data measured by the wave gauge just before the slope of the sand bed have been used. The distance between this wave gauge and the toe of the breakwater equals 117.7 m and is sufficient for a single wave gauge method.

Wave run-up results $Ru_{2\%}/H_{m0}$ have been plotted versus the Iribarren numbers ξ_{om} in figure 6. The full symbols (●) represent the results of the tests with the high density rock as armour rock. The open symbols (○) represent the results of the tests with the normal density rock as armour rock. Wave run-up results of the two series of tests, have been compared. The regression lines of both series of results are also shown. A statistical t test (Taerwe (1996)) has been performed on the two series of data. Since the observed value of t is outside the critical interval (Van de Walle (2003)), it is concluded that the results of both series of tests do not differ significantly (level of significance $\alpha < 0.05$) from each other. Though the difference in nominal diameter of the stones with different density is limited to about 20%, the performed tests have indicated that wave run-up on slopes covered with high density rock is the same as wave run-up on a rubble mound slope covered with normal density rock. By this conclusion, the disadvantage of using high density rock for slope protection measurements is undone. For the remaining part of the discussion, no further distinction has been made between the results of the tests with either high density rock or normal density rock as armour layer rock.

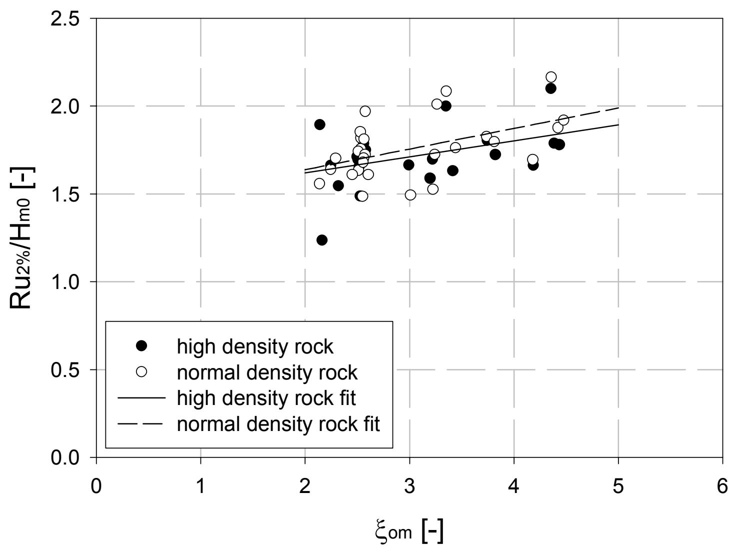

Figure 6: Comparison of wave run-up results of tests with a JONSWAP spectrum on a rubble mound breakwater armoured with either high density rock (●) or normal density rock (○).

A straight line has been fitted to the measurement results of all tests carried out with JONSWAP spectra. Following equation has been derived, valid for $2.1 < \xi_{om} < 4.5$:

$$\frac{Ru_{2\%}}{H_{m0}} = 0.1\xi_{om} + 1.42 \qquad (1)$$

Two tests in which regular waves attacked the breakwater have been run at the very beginning of the project. The armour layer consisted of high density rock. The average of all measured wave run-up levels has been calculated. The results are summarised in table 3. These wave run-up values are lower compared to the results of the tests with irregular waves.

Table 3: Regular wave run-up test results.

test n°	water depth at paddle *d* [m]	wave height *H* [m]	wave period *T* [s]	Iribarren number ξ [m]	number of waves *N* [-]	*Ru/H* [-]	*Rd/H* [-]
1	3.50	0.50	4.0	3.5	125	1.00	-0.38
2	3.50	0.70	3.5	2.6	141	0.97	-0.20

The wave run-up signals have been analysed for wave run-down as well. The results are shown in figure 7. Increasing Iribarren numbers yield increasing (absolute) dimensionless 2% wave run-down values.

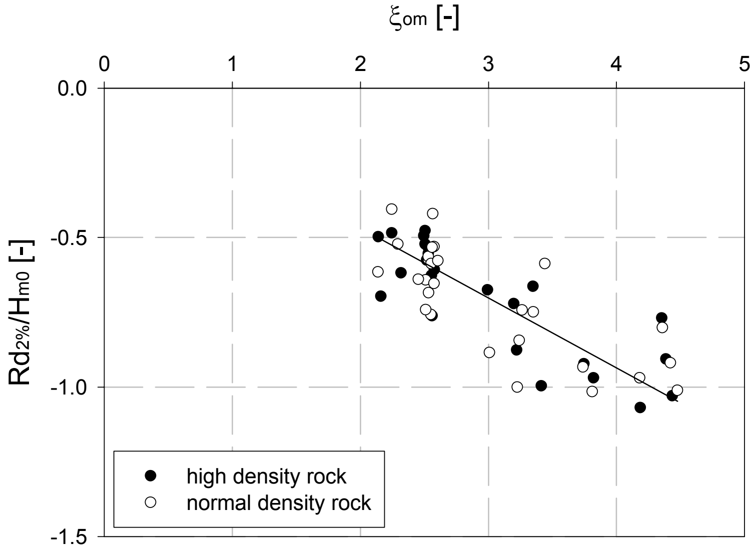

Figure 7: Dimensionless 2% wave run-down values versus the Iribarren number for all wave run-up tests.

A statistical *t* test has been performed to check whether wave run-down on the high density armour layer is different to wave run-down on the normal density armour layer or not (Van de Walle (2003)). It is concluded that there is no significant difference (level of significance $\alpha < 0.05$) between wave run-down measured on the high density armour layer and wave run-down measured on the normal density armour layer.

The equation of the regression line through all wave run-down results, valid for $2.1 < \xi_{om} < 4.5$ reads:

$$\frac{Rd_{2\%}}{H_{m0}} = 0.24\xi_{om} \tag{2}$$

A comparison of these large scale wave run-up results with other wave run-up results and a comparison of these results with the van der Meer et al. (1992) formula for wave run-up estimation on rubble slopes are found in Van de Walle et al. (2004).

Conclusions

A conventional rubble mound breakwater has been built in the LARGE WAVE CHANNEL (GWK) in Hannover. The total height of the structure was 5.5 m. The front slope of the breakwater was 1:2. The breakwater rested on a sand bed 2 m thick with a sloping foreshore (1:50). Two different types of armour layer rock has been tested successively: high density rock (ρ = 3.05 t/m^3) and normal density rock (ρ = 2.65 t/m^3). Both wave run-up tests and stability tests have been combined. Standard JONSWAP spectra have been used to generate irregular wave trains. Tests have been carried out at three different water levels (water depth at the wave paddle: d = 3.50 m, d = 4.00 m and d = 4.50 m).

Twenty two wave height meters have been placed along the channel. A three part wave run-up gauge designed and constructed at Ghent University has been placed on the front slope of the breakwater.

An increase in dimensionless wave run-up is noticed when Iribarren number increases. Statistical t tests have been applied to prove whether tests with different armour layer rock density yield significant differences in results. It is concluded that wave run-up on both armour rock types does not differ significantly from each other. By this finding, the economical advantage of using high density rock is proven.

Wave run-down has been measured and analysed. Increasing Iribarren numbers yield increasing (absolute) dimensionless 2% wave run-down values $Rd_{2\%}/H_{m0}$. No significant difference has been found between wave run-down on high density rock and wave run-down on normal density rock.

Acknowledgements

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