



WAVE FORCES ON STORM WALLS, SMALL AND LARGE SCALE EXPERIMENTS

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Abstract: Storm walls are effective measures to control wave overtopping and flooding of sea dikes with low crest heights. If the storm wall is not built directly on the crest, but some meters behind it, it is not subjected to direct impacting waves but to an overtopping water layer which hits this storm wall. No design formulae for these forces exist, which was the trigger for an experimental research project. Small scale testing was carried out in the laboratory of Ghent University. To decrease the uncertainties related to scale effects, two test campaigns have been carried out on full scale. First with the use of the Wave Overtopping Simulator, followed by a test campaign in the Grosser Wellenkanal (Hannover). This paper gives an overall view of the approaches used throughout the whole project: small scale testing, large scale testing, measuring pressures versus forces, etc.

Keywords: wave overtopping, impact force, impact pressure, storm wall, resonance, scale model testing.

INTRODUCTION

For many years, coastal engineers have been investigating wave-structure interaction. Experimental research has led to formulae to estimate wave overtopping discharges over a structure and wave impact forces on that structure. However, the results of overtopped waves on strength of water defenses has only been investigated in recent years, e.g. at the lee side of an overtopped grass dike using the Wave Overtopping Simulator (Van der Meer et al., 2009).

To reduce wave overtopping along the Belgian coastline and in the harbors, storm walls are being built at several locations. These storm walls are built at a certain distance from the “crest” of the quay or dike which is overtopped during storms (see fig 1).

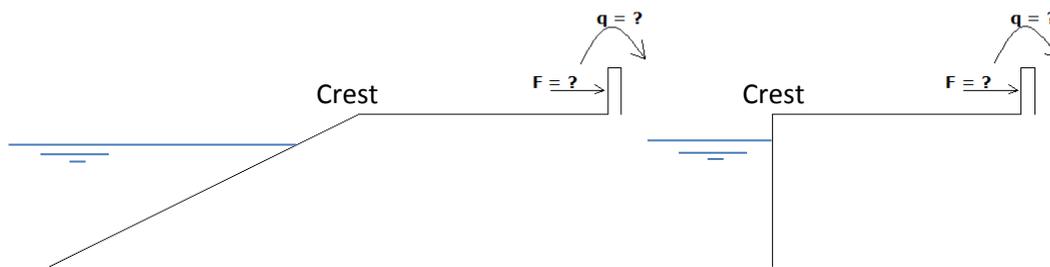


Figure 1. A storm wall at a certain distance from the dike (left) or quay wall (right)

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The impact forces on these walls cannot be determined using the theoretical formulae for impacting waves, since no waves, but an overtopped water layer with a certain flow depth and velocity hits the structure. Also the overtopping discharge over these storm walls cannot be determined using the existing overtopping formulae or neural network prediction tool (see EurOtop Manual, 2007), due to the combination of a berm (promenade) and a vertical wall.

Experimental research in the wave flume of Ghent University has been carried out to determine wave overtopping over and impact forces on a storm wall of different heights, placed at different distances from the dike or quay wall. The scale of these tests varied from 1/20, 1/15 to 1/10.

Apart from small scale experiments, tests at large scale have been carried out as well, focusing on the impact forces on the storm wall. A first test campaign at large (full) scale was carried out in Tielrode (Belgium) using the Wave Overtopping Simulator. A second test campaign was carried out in Hannover, in the Large Wave Flume (Grosser Wellenkanal, GWK) of Forschungszentrum Küste (FZK). A third and final test campaign is scheduled in the CIEM large-scale flume at Barcelona (CIEM, Universitat Politecnica de Barcelona), as a part of the HYDRALAB IV program.

This paper gives an overall view of the experimental research in small and in large scale and some preliminary conclusions of each individual test campaign will be made. At this stage, the comparison between different scales and approaches can't yet be made. Further analysis will be carried out.

SMALL SCALE EXPERIMENTS

The small scale experiments were carried out in the wave flume of Ghent University (30m long, 1m wide, 1.2m high) at a scale varying from 1/20 to 1/10.

Both the geometry with a dike (Figure 1, left, and Figure 2) and a quay wall (Figure 1, right) were tested. A berm of variable length (0.5m to 1.5m) was built, with a storm wall of 6 to 12cm high.

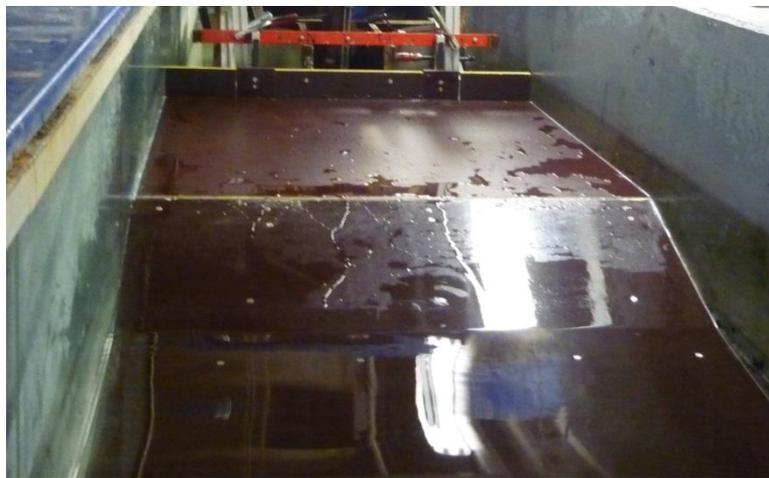


Figure 2. A dike (slope 1/3) with berm 1m and storm wall 8cm (length scale 1/15)

On top of this storm wall, overtopping water was captured in a tray and weighed on a balance to determine the overtopping discharges. The reducing effect of the berm and the storm wall has been described in Van Doorslaer et al. (2010) for the geometry with a dike. Two reduction coefficients, γ_b (berm) and γ_v (vertical wall), are introduced at the right-hand side of the classic overtopping formula:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = A \cdot \exp\left(-B \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_x}\right) \quad (1)$$

In Van Doorslaer et al. (2010) it is stated that the combined effect of both a berm and a storm wall, γ_{bv} , gives better reduction of overtopping discharge than predicted by multiplying γ_b and γ_v .

The storm wall in the wave flume at Ghent University was attached to a force sensor (load cell) and the impacts were recorded at 1000Hz. A classic church-roof shaped signal was recorded (Figure 3).

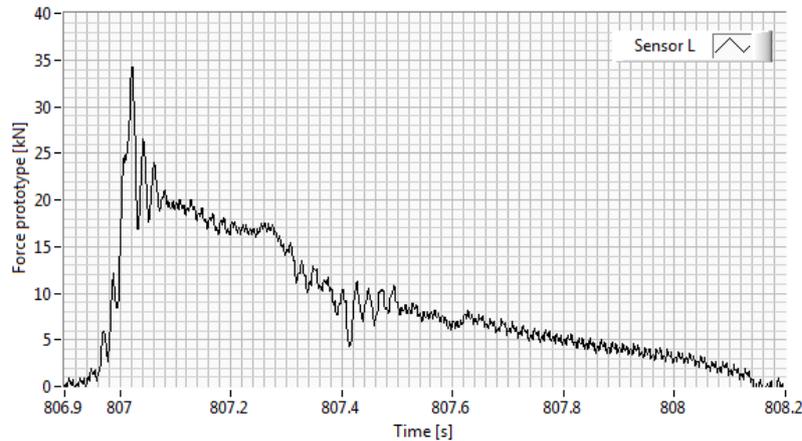


Figure 3. A typical force record over time (church roof)

After analyzing the signals, a few impacts showed very high peak values which had a very short duration (Fig 4). Even more, these values were out of line compared to the distribution of impacts ordered by magnitude. These signals also showed an oscillation which even reaches negative values.

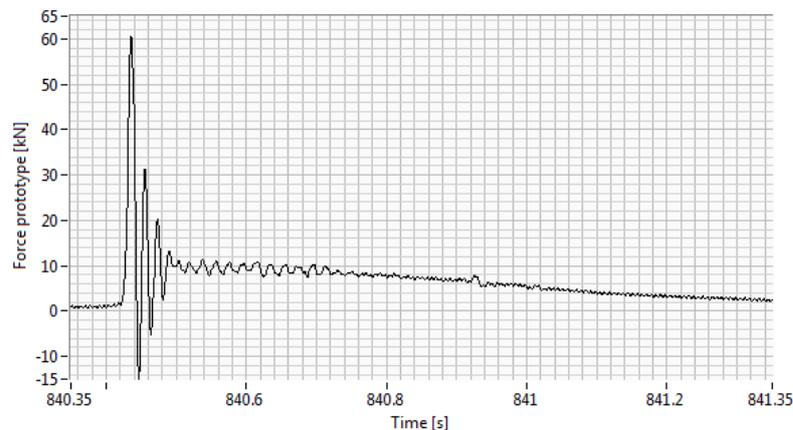


Figure 4. An impact with a high peak value and negative oscillations, recorded at 1000Hz.

A literature study showed that similar oscillations and negative values occurred when overturning waves, with a large air pocket, hit a structure (see Bullock et al., 2007). The oscillations then came from the implosion of the air pocket under the overturning wave. In our tests, a turbulent water layer flowed over a berm with a certain flow depth and flow velocity. The oscillations in Figure 4 were not caused by the implosion of such a large air pocket.

The oscillation has a frequency close to the natural frequency of the storm wall which was built in the wave flume. Resonance could be the explanation of that few very high peaks. A filter, with filter frequency (20Hz) clearly below the natural frequency (~ 70 Hz) of the structure, was used for analyzing the signals. The high peak values were filtered out, and a smooth signal was obtained (Fig 5). The exact value of the impact can never be obtained in this way, but an order of magnitude is now closer to reality than the unfiltered force signals over time.

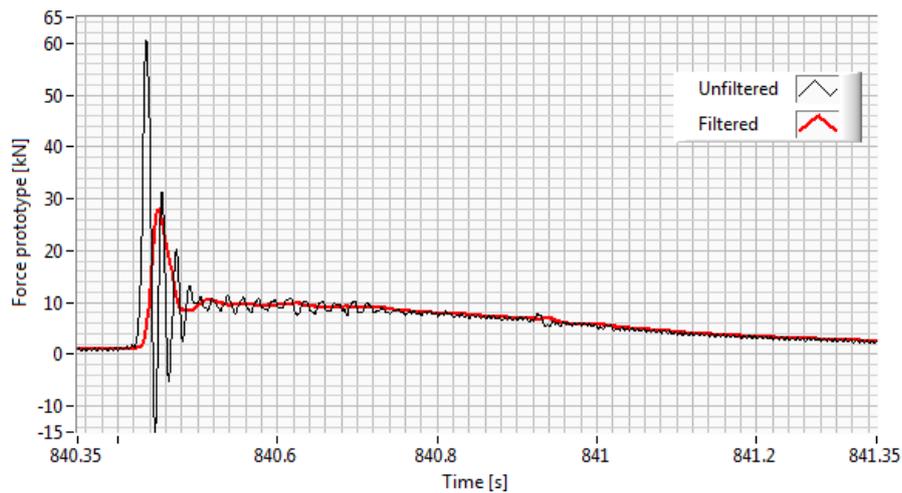


Figure 5. Filtering of the signal leads to correct order of magnitude of the signal.

Due to the uncertainties which occur when working with one maximum (force) value, a common approach (see Coastal Engineering Manual, 2008) is to present the results with the value $F_{1/250}$, which is the average value of the highest 0.4% of the impacts.

The small scale tests give a good insight on the relationship between H_{m0} and $F_{1/250}$ for different geometries, and the overtopping over the storm wall. However, large scale tests for this matter are required for confirmation: flow depth and flow velocity can be measured in large scale more easily, the resonance problem which occurred in the small scale can be verified, possible scale effects can be found, etc.

LARGE SCALE TESTING BY MEANS OF THE WAVE OVERTOPPING SIMULATOR

The Wave Overtopping Simulator was developed by Van der Meer (see Van der Meer et al, 2006) to simulate overtopping waves over the crest of a dike or embankment. The stability of the crest and inner slope of the dike or embankment can be tested by releasing a controlled volume of water out of a container filled with water. The volume of water released by the Wave Overtopping Simulator corresponds with the volume of overtopped water by an individual wave. No real waves have to be generated, and no construction has to be built. The Wave Overtopping Simulator can be installed on the crest of a dike in situ, where the erosion of real grass conditions can be tested. After many test campaigns in The Netherlands (see Steendam et al, 2010), a test campaign was carried out in Tielrode, Belgium, in December 2010 to test the stability of grass dikes, see Steendam et al. (2011). Directly after these tests, the Wave Overtopping Simulator was installed on a flat surface (see Figure 6), where the tests for the storm walls were carried out.

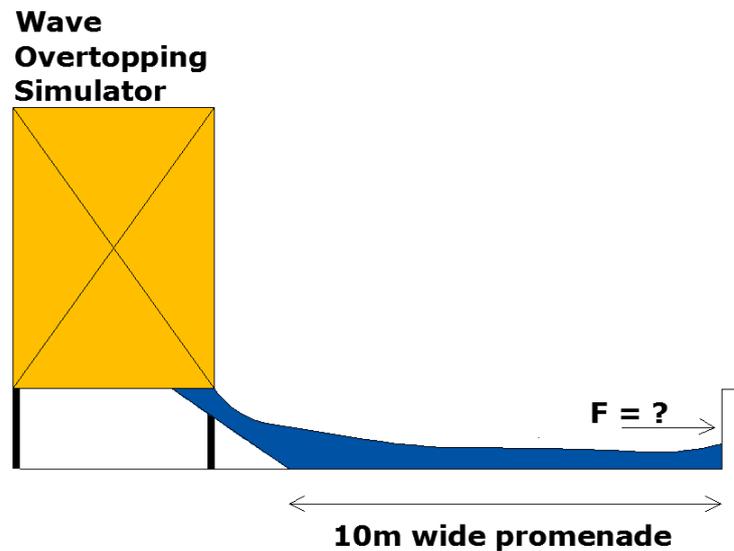


Figure 6. The Wave Overtopping Simulator installed at a flat surface.

A 10m long platform with side walls was built, creating a kind of “flume” (see Figure 7, left picture). At the end of this flume, three aluminum plates (2x vertical, 1.7m high by 0.5m wide, 1x horizontal, 0.5m high by 1.7m wide) were placed which represent a storm wall at 10m behind the overtopped quay wall or dike. They were equipped with load cells to measure the impact force.



Figure 7. The Wave Overtopping Simulator at a 10m horizontal platform guided by side walls (left picture). The released water hits the storm wall and high splash occurs (right picture)

The Wave Overtopping Simulator was filled to a certain volume after which a valve was opened. The water volume released from the Simulator was monitored, the flow depth and flow velocity of the overtopped wave were recorded, and the impact force on the storm wall was measured (Figure 8).

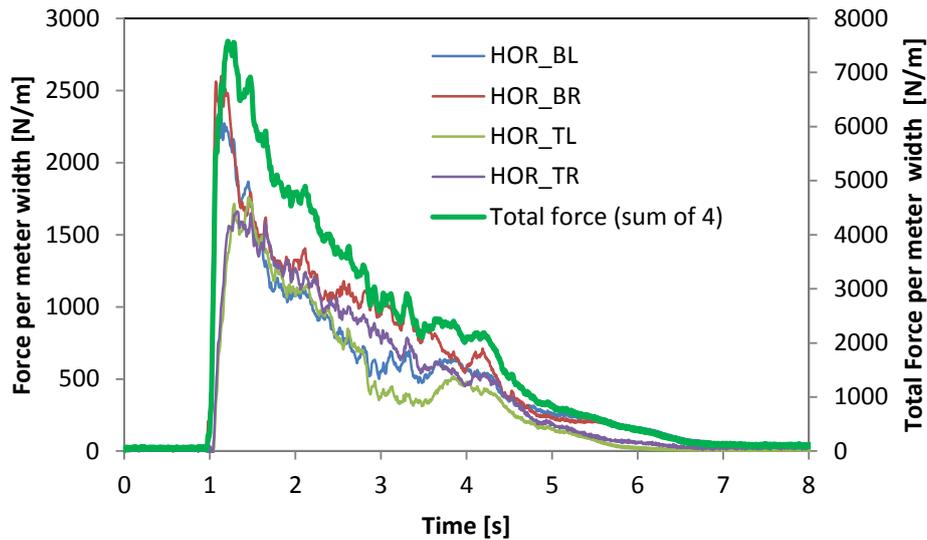


Figure 8. The recording of the impact force over time, for all individual sensors on the plate (left Y-axis, kN/m) and the resultant force as a sum of the individual sensors (right Y-axis)

An overtopping wave of 3500l/m was released from the Wave Overtopping Simulator. The recording of this impact on the horizontal plate is shown in Figure 8. This horizontal plate was attached to 4 force sensors, one in each corner. These 4 recordings (HOR_BL, HOR_BR, HOR_TR, HOR_TL) are on the left Y-axis of Figure 8. The total force (the bold green line) is the sum of the 4 sensors, and is on the right Y-axis of Figure 8. The most important conclusion, related to the small scale experiments, is that no resonance effects were visible in the recordings of all tests. The force signal over time has a (more or less) church roof shape in the full scale tests.

During the analysis, relationships between all recorded parameters were deducted. The impact force as a function of the overtopping wave volume is shown in Figure 9. Equation 2 was developed for the impacts on the horizontally placed plate, and equation 3 for the impacts on the vertically placed plate. Both equations are only valid within the range of tested parameters. The impact force on the horizontal plate (blue diamonds, Figure 9) is a little lower, since a part of the energy disappears by overtopping over the plate (see Figure 7, right picture).

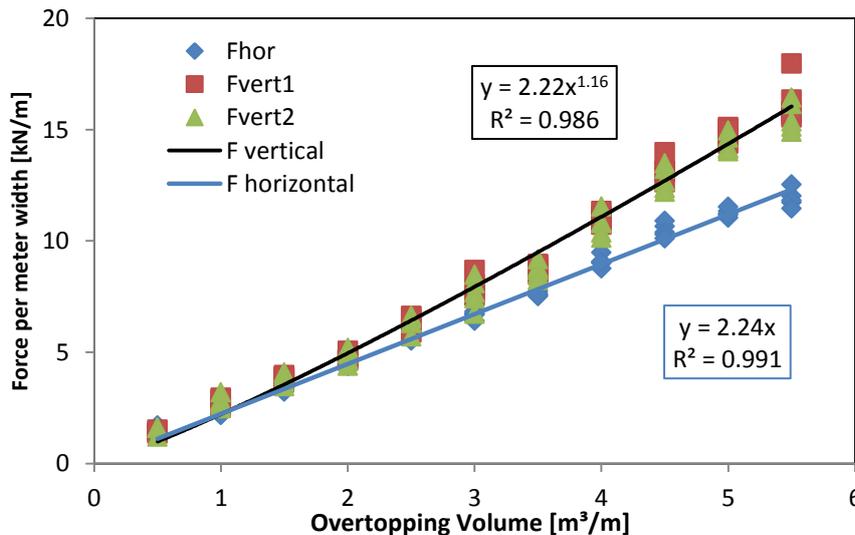


Figure 9. The force on the storm walls (kN/m) as a function of the overtopping volume (m³/m)

Horizontal plate: $F = 2.24 \cdot V$ (2)

Vertical plate: $F = 2.22 \cdot V^{1.16}$ (3) with F in kN/m and V in m³/m.

When assuming that the force recorded on the horizontal plate, is also recorded on the vertical plate, the force distribution over the height is shown in Figure 10. A wave of 3500l/m released from the Wave Overtopping Simulator has a flow depth of 0.23m, and according to formula 2 and 3 a force resultant of 7.84kN/m (horizontal plate) and 9.49kN/m (vertical plate).

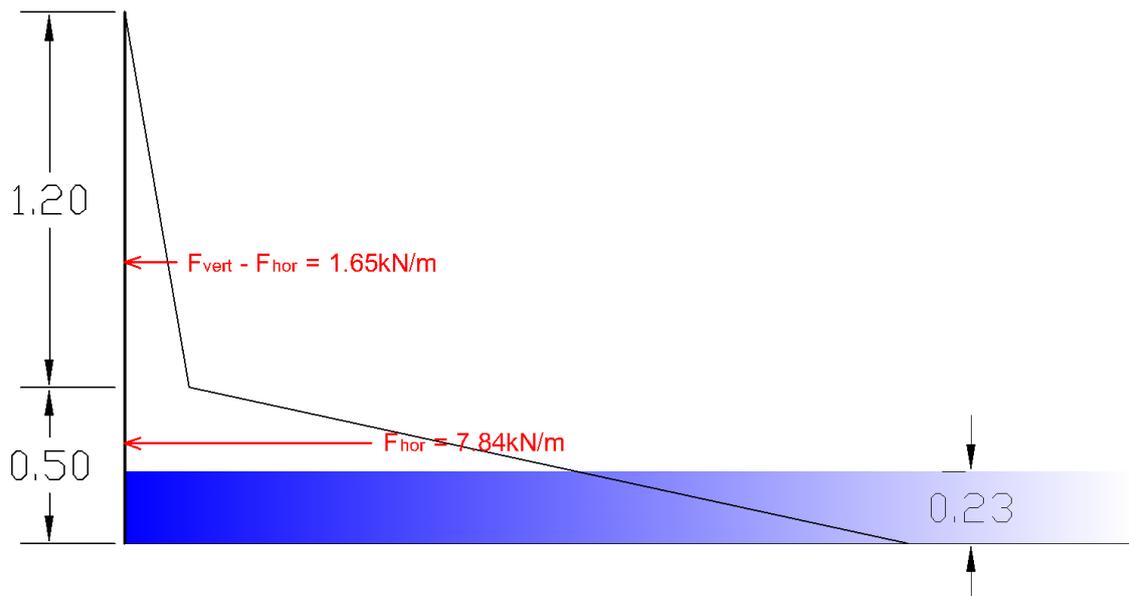


Figure 10. Force distribution over the height of the storm wall for an overtopping wave of 3500l/m

In the tests with the Wave Overtopping Simulator, a volume of water was released from the Simulator, with one flow depth and one flow velocity, giving one impact force on the vertical wall and one on the horizontal wall. Repetition of tests confirmed that there is very little scatter in these values. All relationships between the recorded parameters and the full results will be described in later. A poster presentation will be held at ICCE 2012 (see Van Doorslaer et al., 2012).

LARGE SCALE TESTING IN THE GROSSER WELLENKANAL

Even though the tests with the Wave Overtopping Simulator were very useful, the link with a real wave spectrum and an individual overtopping volume is difficult to make. Also the variable geometry of the overtopped structure (a smooth dike, a rough dike, a quay wall) was not included in these tests. Formulae in the Eurotop manual (see EurOtop Manual, 2007) can be used to predict the individual overtopping volume over smooth dikes, with quite some uncertainty. Consequently, a test campaign was carried out in June 2011 in the Large Wave Flume (Grosser Wellenkanal, GWK) of Forschungszentrum Küste (FZK) in Hannover, Germany, with a dike and waves at real scale. A dike with slope 1:3 was built in the flume with a crest at 6.5m above the flume bottom. A 10m long platform of concrete tiles and a storm wall were built at this crest. The water level was at about 5m above the flume bottom, and waves of 1m to 1.5m high and wave periods from 8 to 12 seconds were created. The overall cross-section is shown in Figure 11.

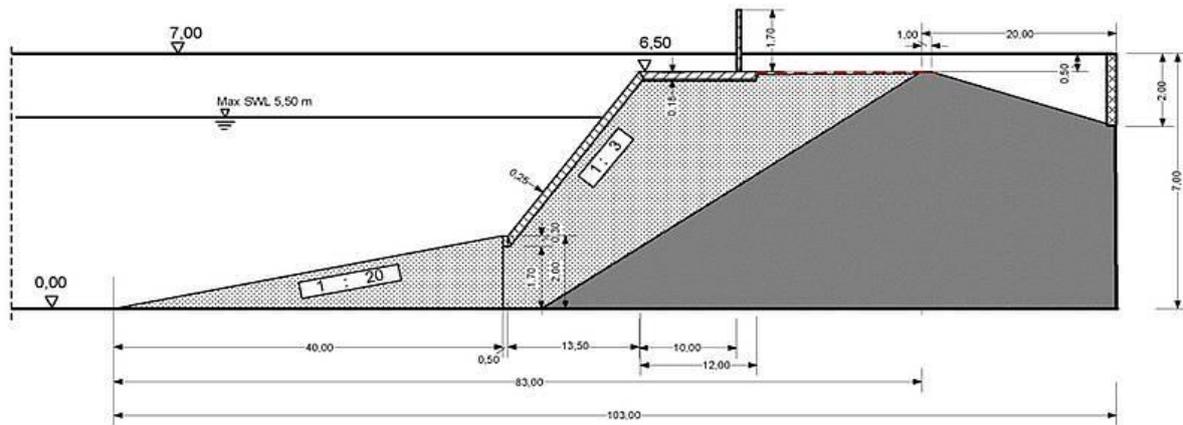


Figure 11. The model setup in the GWK, Hannover: a dike with slope 1:3, a 10m horizontal platform and a storm wall.

Several groups of wave gauges were installed in the flume, to determine H_{m0} at different locations in the flume. On the crest, the flow depth and flow velocity were measured (as was done for the tests with the Wave Overtopping Simulator). Two storm walls were built (similar as for the tests with the Wave Overtopping Simulator), with openings in between to evacuate the water in between two impacts (Figure 12). The left storm wall was equipped with force sensors, while the right wall was made of two plates: one equipped with vertical rows of pressure sensors, the other equipped with force sensors. A comparison between forces and pressures can be made from these tests, and the distribution of the impact force/pressure over the height can be deduced.

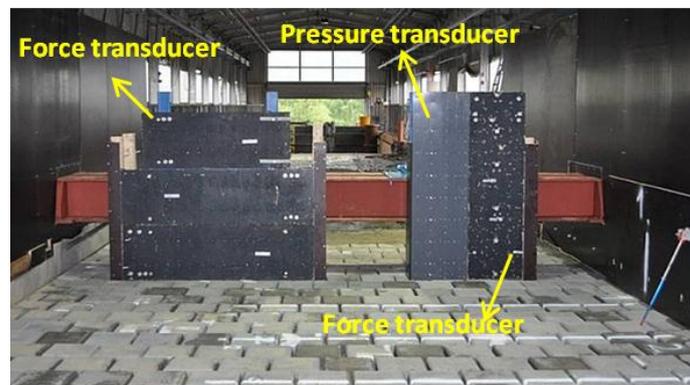


Figure 12. A left storm wall with force sensors, a right storm wall with pressure sensors on the left and force sensors on the right, in the GWK in Hannover.

The results will be described in detail by Ramachandran et al (2012) and De Rouck et al (2012). Some preliminary conclusions of these tests are:

- Other combinations of the flow depth and flow velocity are found compared to the tests with the Wave Overtopping Simulator. Possible reasons are
 - o the geometry of the dike (slope, roughness, etc.)
 - o a continuous wave train in the flume compared to individual waves with the Wave Overtopping Simulator: there was reflection on the storm walls and on the dike which influenced the 2nd and further incoming waves

- the distribution of the force/pressure over the height (see Fig 13) is similar to what was found in the small scale tests.

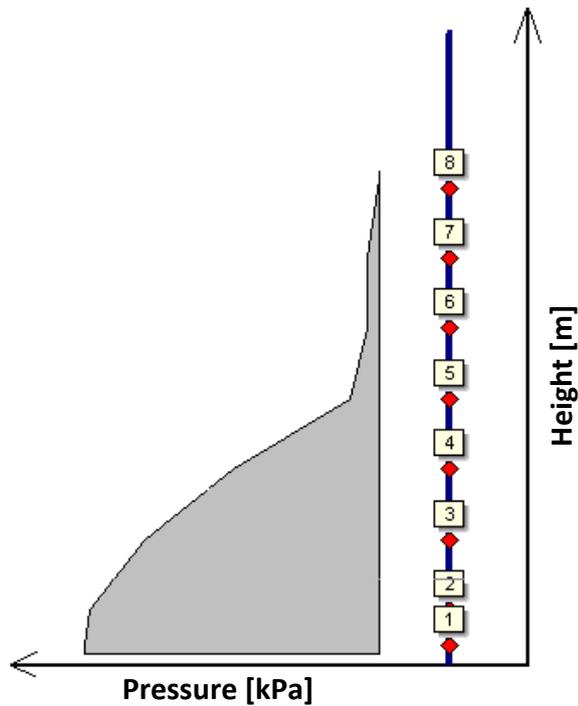


Figure 13. Pressure distribution over the height of the right storm wall

- the force signals look rather similar as in the tests with the Wave Overtopping Simulator. A church roof shape, with a peak value (dynamic) and a constant (quasi-static) part, see Figure 14. No resonance effects were observed in these full scale tests.

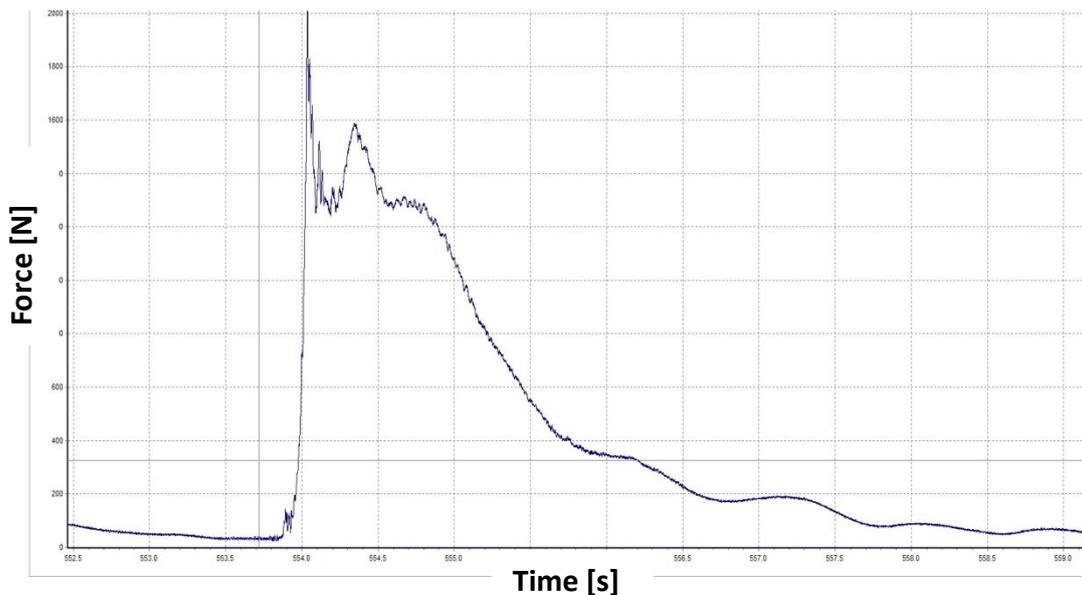


Figure 14. Force record over time of an impact in the GWK-experiments: church-roof record

- When forces are measured, the response of a structure to the impact is measured. The inertia of the structure, and thereby the type of structure or material is included in the measurement. When pressures are measured, the impact itself is measured and is probably independent of the type of structure. However, the location of the pressure sensor is of great importance since the impact spatially distributed. Force sensors on the other hand measure the resultant force, which is less influenced by higher/lower local values. When integrating the pressure sensors over the height, values are comparable to the recordings of the force sensors with a difference of 5-10% higher.

CONCLUSIONS AND FUTURE WORK

The three separate test campaigns individually show interesting results. In the small scale tests, a link between the wave spectrum and the impacting force can be made for many different geometries. However, the absolute maximum impact in small scale tests may be influenced by resonance, and filtering is necessary. This probably leads to a correct order of magnitude of the impact. Some more work can be done to find the influence of the distance of the storm wall to the quay/dike, or the height of the wall, on the impact force.

For the large scale tests with the Wave Overtopping Simulator, all relationships between all measured parameters (overtopping volume, flow depth, flow velocity, impact force) have been deducted, and will be published in a later stadium. The recording of one impact over time looks similar to the (filtered) signal from the small scale tests; no resonance was noticed during the analysis. The force distribution over the height was found to be trapezoidal (bottom) and triangular (top), see Figure 10. The link to a wave spectrum on a dike with a variable geometry however could not be obtained from these tests.

The tests in the Large Wave Flume (GWK) in Hannover were carried out on a dike with slope 1:3. A 10m horizontal berm and a storm wall were built on the crest of this dike, and subjected to spectral waves (H_{m0} from 1 to 1.5m, T_p from 8 to 12s). A similar force record over time was found (church roof) as in the tests with the Overtopping Simulator, and a similar distribution of the impact force/pressure over the height. According to the preliminary analysis, different combinations of flow depths and flow velocities on the crest of the dike were found as in the tests with the Wave Overtopping Simulator. All results need to be analyzed in more detail, together with the links of all measured parameters (wave spectrum, flow depth, flow velocity, impact force, impact pressure). Results are sent for oral presentation at ICCE 2012, Santander (De Rouck et al, 2012; Ramachandran et al, 2012).

A last test campaign has been scheduled in the HYDRALAB IV access, in the CIEM large wave flume at UPC Barcelona. Different geometries (a dike and a quay wall) will be tested in a wider range of varying parameters (water depth, wave height, wave period, etc.). The focus will be on measuring the overtopping volumes, linked to the flow depth/flow velocity and to the impact force/pressure.

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