Full Scale Wave Impact Tests on a Vertical Wall, using the Wave Overtopping Simulator

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Abstract

Storm walls can be built to increase the safety level in coastal towns. To design these storm walls, information about the wave forces they are exposed to is necessary. The Wave Overtopping Simulator has been used to simulate an overtopping wave which hits a storm wall. The flow depth and flow velocity of the overtopping wave were measured, and the impacting wave force was measured.

This paper defines a relationship between the volume of the overtopping wave and the flow depth, flow velocity or impact force. If no information about the overtopping wave is available, the wave force can also be calculated as a function of the flow depth and/or flow velocity.

Keywords: Wave Overtopping, Flow Depth, Flow Velocity, Impact Force, Wave Overtopping Simulator

1. Introduction

Many coastal engineers and researchers worldwide have studied wave overtopping. Those studies have lead to a better understanding of the overtopping process. Formulae to describe both wave run-up and wave overtopping were deducted from their experimental research. Most of this knowledge is gathered in guidelines such as the EurOtop Overtopping Manual [1]. Apart from experimental formulae, some calculation tools (PC-overtopping and Neural Network methods) have been developed as well. Due to all these efforts, wave overtopping is nowadays a well known and well described phenomena. But whatever damage can occur due to overtopping waves, is often still a question remained unsolved, mainly due to existing scale effects or the impossibility to scale down structural strength of the structures to small scale models.

Schüttrumpf and Van Gent [3] made a theoretical and experimental study about the hydraulic conditions of overtopping waves. In order to evaluate erosion and infiltration on the crest and the landward slope of coastal structures, they determined flow velocities and flow depths of the overtopping wave. This research topic was a first step to finally examine the stability of structures subjected to wave overtopping.

In [5], the use of the Wave Overtopping Simulator is explained for the first time. The idea was to simulate an overtopping wave on a dike or embankment, by releasing a volume of water out of a container filled with water. No real waves had to be made, and no construction had to be built. The Wave Overtopping Simulator could be installed on the crest of a dike in situ, where the erosion of real grass conditions could be tested. In the years following to the first tests in 2007, the simulator has been enlarged (a volume of 22m³/m and a maximum discharge of 125l/s/m) and improved at some details (see [6]). Also the instrumentation to measure the flow depth and flow velocity has been improved (see [7]). Up to now, the simulator was especially used to test sliding stability and erosion resistance of the landward slope of a dike or embankment.

This paper will describe the use of the Wave Overtopping Simulator to determine the impact forces from an overtopping wave on a storm wall or building on the crest of a dike or quay. These storm walls are one of the possible measures to protect the hinterland from violent wave overtopping and flooding. Many reductive measures have been investigated in scale model tests (Stilling Wave Basin: [2], Parapet: [8], storm wall: [9], …) mostly regarding reductive capacity against wave overtopping. On behalf of the design of these reductive measures, information about the impact forces they are exposed to is required. No theoretical formulae exist to calculate impact forces created by an overtopped wave. The Wave Overtopping Simulator was used to simulate this overtopping wave hitting a structure Figure 1. Impact forces are measured and linked to the recordings of flow depth and velocity.

Figure 1. Wave Overtopping Simulator to test impacts on a storm wall
2. Model setup
In 2010 the Flemish agencies responsible for flood protection carried out experiments to examine the real strength of the grass cover of the dikes. These experiments have been carried out with the Wave Overtopping Simulator in Tielrode (see [4]). Directly after, the test described in this paper were carried out on the same location. But instead of on the crest of an overtopped grass dike, the Wave Overtopping Simulator was now installed on a 10m long horizontal platform with side walls, creating a kind of “flume” (Figure 1). At the end of this flume three aluminum plates were placed which represent a storm wall at 10m behind an overtopped quay wall or dike.

![Figure 2. Two vertical plates on the left (0.5m wide, 1.7m high), one horizontal plate on the right (1.7m high x 0.5m wide).](image)

Two rectangular aluminum plates were placed vertically on the left frame, next to each other. Each plate was 1.7m high and 0.5m wide. A third aluminum plate, 0.5m high and 1.7m wide, was placed horizontally on the right frame. All plates were equipped with four force sensors, positioned at the corners of each plate. The total impact force can be obtained by summing the force signals of the four sensors. An estimation about the force distribution can be obtained by comparing the magnitude of the sensors on the top and the bottom, and the sensors of the horizontal and vertical plates.

Furthermore, the flow depth and flow velocity of the overtopping wave were measured by means of a surfboard (see [7]). The surfboard was about 2m long, and was positioned in the middle of the 4m wide and 10m long flume. Flow depth and flow velocity do not vary much over this distance. The wave overtopping simulator was filled to a certain volume, after which the valve was opened. Every wave was repeated at least 3 times, from 500l/m to 5500l/m in steps of 500l/m. In total 33 tests (3 x 11) have been carried out per setup. This paper will have a detailed look at the results (flow depth, flow velocity and force) and will also determine a relationship between the volume of the overtopping wave and the flow depth, flow velocity or the force. In case no information about the individual wave overtopping volume is available, the flow impacting force can also be calculated as a function of flow velocity and/or flow depth.

3. Analysis and results
3.1 Recordings
3.1.1 Flow Depth and Duration
Flow depth is measured with a surfboard which is hinged on a beam over the flume. The surfboard is hinged at one end, and floats on top of the overtopping wave. A potentiometer measures the rotation over time at the hinging point, which on its turn can be transferred into a varying flow depth over time. The maximum flow depth, together with overtopping duration can be determined.

![Figure 3. A surfboard floats on the overtopped wave, and measures the layer thickness](image)

The flow depth signals over time are shown in Figure 4: three waves of 1500l/m and three waves of 3500l/m. The flow depth signal over time has a more or less triangular shape, and the repeatability is high.

![Figure 4. Flow depth signal: three times an overtopping wave of 1500l/m, three times 3500l/m](image)

This figure also shows that a larger wave volume leads to a larger maximum flow depth and a longer duration of the overtopping wave. An overtopping volume of 1500l/m has a duration of 4.5s, 3500l/m lasts about 5.5 to 6s.

In [7], a relationship between the volume V and the flow depth h measured on the crest of a dike is stated.

\[
    h = 0.133 \cdot V^{0.5}
\]

(with h in m³/m, V in m³)

Remark that this coefficient 0.133 and the ones in other formulae in this paper are not dimensionless!
Eq. (1) is a very good representation for the flow depth measured in the middle of a 10m horizontal platform. Due to the high reflection at the walls, measuring flow depths above 3500l/m show some scatter and are left out of the analysis.

They also have a triangular shape, but there is more fluctuation in the signal due to the sensitivity of the paddle wheels. However, the shape, the maximum and the flow duration show good repeatability for the various overtopping volumes.

Figure 5. Flow depth as a function of wave volume. The existing relationship (see [7]) is valid for the new data obtained in the middle of a 10m horizontal platform.

3.1.2 Flow Velocity and Duration

Two paddle wheels are built in the surfboard to measure the velocity of the flow passing underneath this surfboard. The first one is located near the end of the surfboard, the second one in the middle. For large flow depths, the end of the curved surfboard can be lifted out of the water. In this case the middle paddle wheel will give the correct speed. For small flow depths, the one in the middle might no longer measure the velocities. In that case the paddle wheel at the end gives the correct velocity. The flow velocity can be found as the maximum of both paddle wheels. The duration of overtopping can also be deducted from these records, and compared to the duration deducted from the flow depth record.

Figure 6. Two paddle wheels installed in the surfboard to measure flow velocity.

For the same volumes as in Figure 4 (three times 1500l/m and three times 3500l/m), the velocity records over time have been plotted in Figure 7.

![Figure 7. Flow velocity record: three times an overtopping wave of 1500l/m, three times 3500l/m](image)

The relationship between flow velocity and overtopping wave volumes found in [7] is deducted from measurements on the landward slope of a dike. Due to gravity, the overtopping wave flows faster on the slope compared to the measurements on a horizontal surface (Figure 8). A new best fitting curve is deducted, valid for the flow velocity on a horizontal platform, such as the crest of a dike.

Figure 8. Flow velocity as a function of wave volume. The existing relationship for inner slopes (black line) is not valid. A new best fitting curve is drawn, valid for maximum velocities on the horizontal crest of the dike.

\[ y = 5x^{0.34} \]

\[ y = 4.2x^{0.3} \quad R^2 = 0.793 \]

They also have a triangular shape, but there is more fluctuation in the signal due to the sensitivity of the paddle wheels. However, the shape, the maximum and the flow duration show good repeatability for the various overtopping volumes.

3.1.3 Impact Force

The force record over time is shown for an overtopping wave of 3500l/m, measured on the horizontal plate (Figure 9) and one of the vertical plates (Figure 10). The 4 individual sensors (Bottom left (BL), bottom right (BR), top left (TL) and top right (TR)) are to be read from the left Y-
axis, and are expressed per meter width (N/m). The sum of the four sensors, divided by the width of the measurement plate is to be read from the right Y-axis (also in N/m).

The force records of the horizontal plate (Figure 9) have a very steep rise over time: the maximum is reached in 0.1 to 0.2s for the bottom sensors (_BL and _BR) and about 0.3s for the top sensors (_TL and _TR). The bottom sensors measure the highest forces. The top sensors are located above the flow depth, and measure less high forces. The measurements of the left and right sensors on both top and bottom are very similar.

![Figure 9. Force record of a horizontal plate, under an overtopping wave volume of 3500l/m](image)

The bottom sensors of a vertical plate (Figure 10) also have a very steep rise over time: the maximum is reached in about 0.2s. This maximum is a multiple of what is measured by the top sensors. For these top sensors, which are located higher than the flow depth, it takes longer to reach the maximum: 0.6s. The green and purple line in Figure 10 show that the top sensors of the vertical plate don’t register the sudden impact, and their maximum value is maintained longer. Water that cannot evacuate through overtopping, keeps on pushing against the storm wall. For the horizontal plate, the maximum of the top sensors reduces faster. Maybe this is due to higher overtopping over the horizontal plates.

![Figure 10. Force record of a vertical plate, under an overtopping wave volume of 3500l/m](image)

A dataplot of forces versus wave volume shows that tests have a very good repeatability: all data within the same color show very little scatter (Figure 11). Also the 2 vertical plates (red and green symbols in Figure 11) confirm each other well.

![Figure 11. Force as a function of volume. Horizontal plate (0.5m high) in blue, Vertical plate (1.7m high) in red and green](image)
A comparison between forces on horizontal and vertical plate is difficult to make, since the horizontal plate is much more overtopped than the vertical plate. This effect becomes more clear for higher overtopping volumes. The trend lines in Figure 11 are thereby dependent on the height of the plate.

Forces can be expressed per meter width, by dividing the measured value by the width of the plate.

Horizontal plate: \[ F = 2.24 \cdot V \] (3)
Vertical plate: \[ F = 2.22 \cdot V^{1.16} \] (4)
with \( F \) in kN/m and \( V \) in m³/m.

The difference in magnitude between the horizontal and vertical plate is rather small, despite the fact the vertical plate is 3 times as high. As mentioned before, the higher the location of the sensors (top sensors vertical plate > top sensors horizontal plate > flow depth > bottom sensors of horizontal and vertical plate), the lower the force-measurements are. This is an indication that the flow depth is a governing parameter in the load distribution on the plates.

In an attempt to reproduce the force distribution over the height, it can be assumed that the load measured by the horizontal plate (divided by the width, in kN/m) will also be measured by the vertical plate (also expressed in kN/m). The part of the vertical plate above 0.5m will then be loaded by the difference between the total force on the vertical plate (eq. (4)) and the force on the bottom part (eq. (3)).

For \( V = 3.5\text{m}^3/\text{m} \), this becomes \( F = 9.50\text{kN/m} \) (on 1.7m high) to be divided in 7.84kN/m (on 0.5m) and 1.65kN/m (on 1.2m). If a trapezoidal and triangular load is assumed, the force distribution over height is shown in Figure 12. The flow depth for an overtopping wave of 3500l/m is 0.25m.

### 3.2 Relationship between parameters

The volume of individual overtopping waves is not always easy to measure. It can be calculated, but still some uncertainties in these formulae exist. For these reasons, it might be easier to measure flow depth (i.e. with a simple wave gauge or pressure transducer) and/or flow velocity (i.e. with a propeller) on the crest of the overtopped dike or quay wall. The measured forces will hence be related to the flow depth and/or flow velocity. Again, formulae for the horizontal plate and vertical plates will be treated separately.

#### 3.2.1 Force vs Flow Depth and Flow Velocity

When information about both flow depth and flow velocity in actual situations is available or can be measured, the force can be calculated with high accuracy. Regression analysis leads to eq. (5) and (6).

Horizontal plate (0.5m high): \[ R^2 = 0.94 \]
\[ F = 1.15 \cdot U + 32.60 \cdot h - 6.90 \] (5)
Vertical plate (1.7m high): \[ R^2 : 0.928 \]
\[ F = 1.09 \cdot U + 52.10 \cdot h - 9.50 \] (6)
with \( F \) in kN/m, \( U \) in m/s and \( h \) in m.

#### 3.2.2 Force vs Flow Depth

In case only the flow depth is known or can be measured, the force can still be estimated. This prediction is less accurate compared to eq. (5) and (6), since only 1 parameter is available.

Horizontal plate (0.5m high): \[ R^2 = 0.869 \]
\[ y = 60x^{1.45} \]
Vertical plate (1.7m high): \[ R^2 = 0.885 \]
\[ y = 100x^{1.69} \]

Note that the difference between both formulae only becomes significant for flow depths of 0.20m and larger. For smaller flow depths, the forces on the vertical and horizontal plate are almost the same.

If information about the overtopping volume \( V \) is available, it’s strongly advised to use eq. (3) and (4), instead of using eq. (7) and (8) in combination with eq. (1).

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**Figure 12.** Force distribution over height, based on a trapezoidal and triangular load distribution

**Figure 13.** Relationship between forces and flow depth of an overtopping wave.
3.2.3 Force vs Flow Velocity
A relationship between the force and the overtopping flow velocity is deducted in Figure 14.

$$F = 0.101 \cdot U^{2.408}$$  \hspace{1cm} (9)

$$F = 0.069 \cdot U^{2.723}$$  \hspace{1cm} (10)

Figure 14. Relationship between the forces and the flow velocity

Horizontal plate:

$$F = 0.101 \cdot U^{2.408} \quad \text{horizontal}$$

$$F = 0.069 \cdot U^{2.723} \quad \text{vertical}$$

The same remark as in the previous paragraph is valid here: if information about the volume is available, it is strongly advised to use formulae (3) and (4) to calculate the impacting force.

4. Conclusions and recommendations
The Wave overtopping Simulator has been used to simulate an overtopping wave which impacts a storm wall. Analysis has shown that there is a very good repeatability between the tests with a same overtopping wave volume. A relationship between the overtopping volume and the flow depth (eq. (1)), flow velocity (eq. (2)) and impact forces (eq. (3) and (4)) is found.

It's not always easy to measure or calculate the overtopping wave volume. Therefore, the impact force can also be calculated from the flow depth and the flow velocity of the overtopping wave (eq. (5) and (6)). If only information of one of those parameters is available, the force can still be calculated: eq. (7) to (10).

The formulae to calculate wave forces have been split up in horizontal plate (0.5m high) and vertical plate (1.7m high). The difference between the formulae is found in the fact that the horizontal plate was much more overtopped than the vertical plate.

During the period of experimental testing, oblique wave impact has also been simulated by rotating the measurement plates over 45°. Those results still have to be analyzed in detail. Another setup has also been tested: jacking up the simulator for 60cm. This created larger flow velocities, smaller flow depths and larger impacts (especially for low overtopping wave volumes). Detailed analysis still has to be done, to verify if eq. (1) to (10) remain valid. Remark that those formulae are, until further notice, only valid for the setup as described in this paper: perpendicular wave impact on a vertical wall at a distance of 10m from the wave overtopping simulator.

Furthermore this paper describes a first assumption of the force distribution over height. In a next test series pressure sensors will be implemented in the measuring plates to have a better view on this matter. Those plates should not be overtoppable, to allow comparison between horizontal and vertical plates.

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6. References