THE WAVE OVERTOPPING SIMULATOR IN ACTION

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The wave overtopping simulator is a device which is able to simulate overtopping waves at the crest and at the inner slope of a dike, levee or embankment in situ. The simulator is a high-level water container which is filled with a predetermined supply of water. The supply rate is set according to the desired rate of wave overtopping. The water in the reservoir is released at specific time intervals, creating the proper distribution of overtopping waves. The device has been used for the first time in the European ComCoast project, and was supported by a Dutch research program on water defences (SBW). This paper describes the construction, the trial testing, the actual testing on a sea dike and the analysis of velocity and flow depth measurements during the wave overtopping tests.

INTRODUCTION

The process of wave overtopping on a dike, levee, seawall or embankment has been subject of a huge amount of research, resulting in e.g. equations for maximum velocities and flow depth of overtopping waves at the crest of a dike, see Schüttrumpf and Van Gent, 2003 and the new Overtopping Manual, 2007. The overall conclusion is that the hydraulic part of wave overtopping on a dike is well-defined.

In contrast, the erosive impact of wave overtopping on dikes, embankments or levees is not known well, mainly due to the fact that research on this topic can not be performed on a small scale, as it is practically impossible to scale clay and grass down properly. Hence, in order to establish the resistance or strength of a dike for wave overtopping, field tests are required. For the simulation of overtopping, it is actually sufficient to reproduce the overtopping flow only. Thus, generation of true waves in a large scale facility, such as Delta flume (Netherlands) or GWK (Germany), is not required.

WAVE OVERTOPPING SIMULATOR

Idea behind the simulator

Basically, the following starting-points underlay the idea of the simulator, also described in Van der Meer et al., 2006:

- knowledge on wave breaking on slopes and generating overtopping discharges is sufficient;

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- knowledge on the pattern of overtopping waves, known as volumes, distributions, velocities and flow depth of overtopping water on the crest, is sufficient as well, except for some minor points;
- only the overtopping part of the waves needs to be simulated, see Figure 1.
- tests can be performed in-situ on each specific dike, which is cheaper and more realistic than testing in a large wave flume.

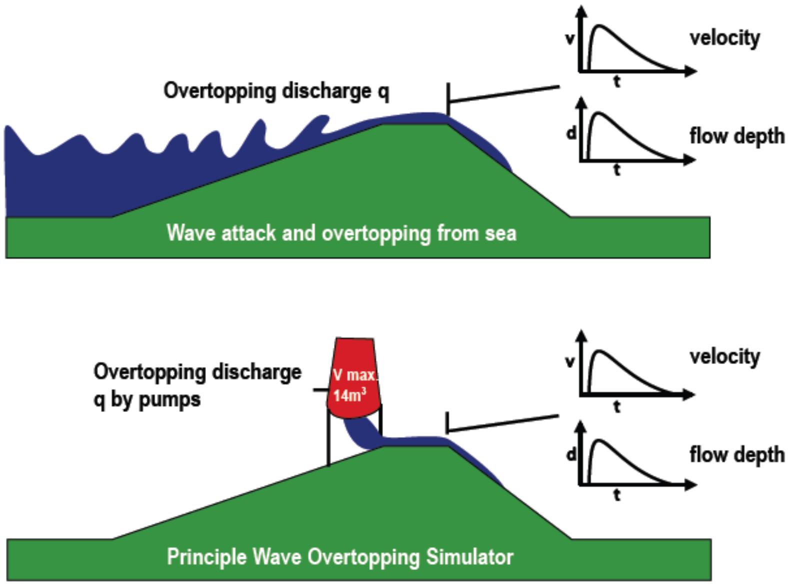

Figure 1. Principle of wave overtopping simulator

Construction and trial testing

The simulator was developed and designed early 2006 within the ComCoast project (a European project between governments along the North Sea, see www.comcoast.org). At first a 1 m wide prototype was constructed and results of the calibration phase have been described by Van der Meer et al., 2006 and the full results on the wave overtopping simulator by Van der Meer, 2007. The design and results of the calibration will not be repeated here.

The final simulator consists of a high-level mobile box (adjustable in height) to store water. The maximum capacity is 3.5 m^3 per m width (14 m^3 for the final, 4 m wide, simulator). This box is continuously filled with a predefined discharge q and emptied at specific times through a butterfly valve in such a way that it simulates the overtopping tongue of a wave at the crest and inner slope of a dike. As soon as the box is filled with a required volume, V, the valve is opened and the water is released on a transition section that leads to the crest of the dike. The discharge of water is released in such a way that flow velocity, turbulence and thickness of the water tongue at the crest corresponds with the characteristics that can be expected. The calibration showed that it is possible to simulate the required velocities and flow depths for a wide variety of overtopping rates, even far beyond present standards. Figure 2 gives an impression of the action of the final simulator at the dike by a series of snapshots.

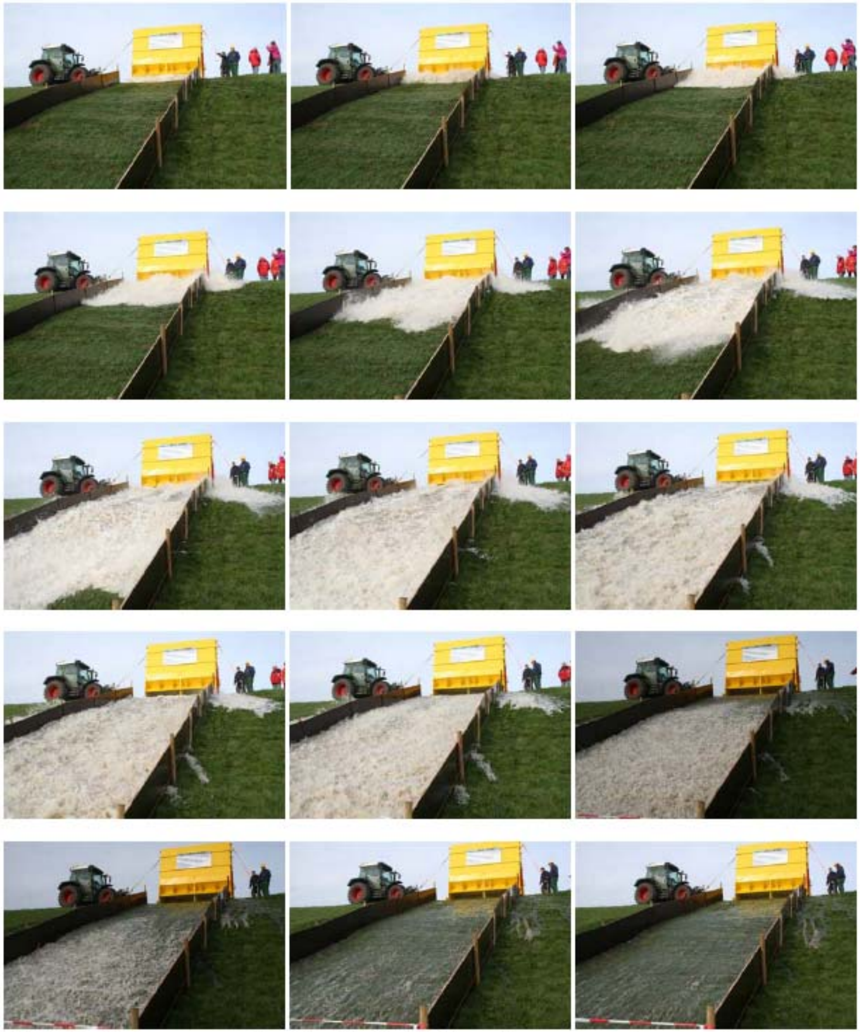

Figure 2. Impression of wave overtopping by the simulator

After calibration, the construction of the final 4 m wide simulator started and final improvements could be introduced directly to the simulator. The final 4 m wide simulator has been constructed by the end of 2006. Trial tests on the dike to be tested, were held in December 2006. They were successful and demonstrated the capabilities of the wave overtopping simulator, including the water circulation system. However, some improvements were necessary for final testing, e.g. the footings of the simulator penetrated too much into the subsoil. For the real tests in February and March 2007, further improvements were implemented to the wave overtopping simulator as well as to the water circulation system. During placement much attention was paid to the footings, that had been reinforced since the trial tests, see Figure 3.

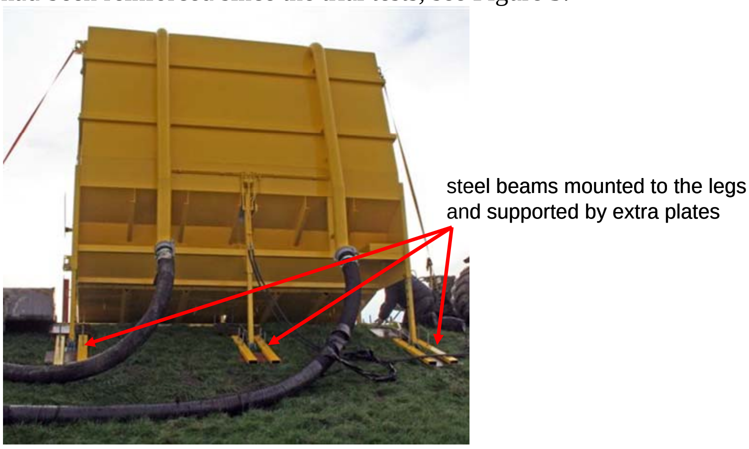

Figure 3. Rear side of simulator. Adjustments to the footings by extra steel girders and plates.

FIELD TESTS ON A DIKE

Test set-up

Field tests on a true dike have been carried out in March 2007. The ComCoast overtopping tests were basically focused on observation of surface erosion behaviour of grass covers and under laying clay under severe overtopping. First results of the performance of the wave overtopping simulator will be described in this paper, where test results of the resistance of the dike have been described by Akkerman et al., 2007-1 and 2007-2.

Three test series were performed at the dike. The first series was focused on the actual clay dike with grass cover. The second series was performed on a strengthened section with a geotextile in the grass sod. This system, called the Smart Grass Reinforcement and developed by Royal Haskoning and Infram under ComCoast (see Akkerman et al., 2007-1 and 2007-2), had been installed in May 2006, just one growing season before testing. The final series was performed on bare clay. Here, 20 cm of the grass cover had been removed, in order to simulate and investigate the erosion behaviour of the clay in case the grass cover in reality would already have been failed and removed by wave overtopping.

For the tests at the sea dike, the boundary conditions have been assessed from average conditions along the Dutch coast: H_s (significant wave height) = 2.0 m, T_p (peak period) = 5.7 s and T_m (mean period) = 4.7 s. In addition, the seaward slope of the dyke has been assumed to be 1:4. The maximum waves in these conditions with an overtopping rate of 30 l/s/m had a volume of 3.5 m^3 per m. Hence, the 4 m wide simulator was designed such as to store 14 m^3.

A 6-hour storm duration has been taken as a representative (conservative) value for producing the design wave overtopping distribution. The initial test program was as follows:

- 6 hours storm with overtopping rate of 0.1 l/s per m width;
- 6 hours storm with overtopping rate of 1 l/s per m width;
- 6 hours storm with overtopping rate of 10 l/s per m width;
- 6 hours storm with overtopping rate of 20 l/s per m width;
- 6 hours storm with overtopping rate of 30 l/s per m width.

For the 0.1 l/s/m, the number of overtopping waves is very limited: hence, this test was speeded up to 36 minutes (by accelerating the intermediate periods 10 times). The other tests were carried out in real-time. After each 2 hours the tests were stopped for a detailed survey of the erosion.

The wave overtopping simulator worked very well throughout the total test program. The erosion strength of the inner slope of the dike was surprisingly large, showing no damage for overtopping discharges up to 30 l/s per m width. It was for this reason that an extra test was included with an upgraded discharge of (approximately) 50 l/s per m width. As this test was beyond its design value, it will be described more in depth.

Description of 50 l/s per m overtopping discharge

The size of the box of the simulator was based on a maximum volume of 3.5 m^3/m, corresponding to a 30 l/s per m discharge. A 50 l/s per m discharge actually requires a larger box. Wave boundary conditions for overtopping calculations have been given above. The 2% run-up level on a slope of 1:4 is 4.0 m with a mean overtopping discharge of 0.74 l/s per m. In order to get a wave overtopping discharge of 50 l/s for these wave conditions, the free crest board should be decreased to only 1.76 m. For a storm duration of 6 hours the following characteristics are found:

H_s = 2 m; T_p = 5.7 s; T_m = 4.7 s

	q = **50** l/s per m
Percentage overtopping	46.98
Number of waves in 6 hours	*4600*
Number of overtopping waves	*2159*
Maximum overtopping volume	*6364 l/m*

It appears that almost half of the waves will reach the crest and will overtop for this condition (47%). The maximum volume in 2159 waves is 6.3 m^3 per m and this is 80% more than the capacity of the box of the simulator (3.5 m^3 per m). The limitation of the simulator is that the maximum volume in one wave can not be more than 3.5 m^3 per m. This will elaborated more in depth below.

Figure 4 gives the complete distribution of overtopping volumes for 50 l/s per m overtopping and a proposal for simulation. With a mean discharge of 50 l/s per m it is not possible to simulate small volumes like 50 or 150 l per m, as this means that the simulator would open every second or 3 seconds, which is not practical. In reality it is possible to have many small volumes, as then the mean overtopping discharge is not constant as for the pump discharge. The only possibility for simulation is that all the small overtopping volumes are simulated by a smaller number of volumes with for instance 400 l per m. The distribution gives 1335 waves with a volume smaller than 400 l per m and 1524 waves with a volume smaller than 550 l per m (the middle between 400 and 700 l per m). All 1524 waves with a volume smaller than 550 l per m were modelled by 648 waves with a volume of 400 l per m. These 648 waves contain the same total volume of water as the 1524 waves in the distribution (274 m^3 per m in total).

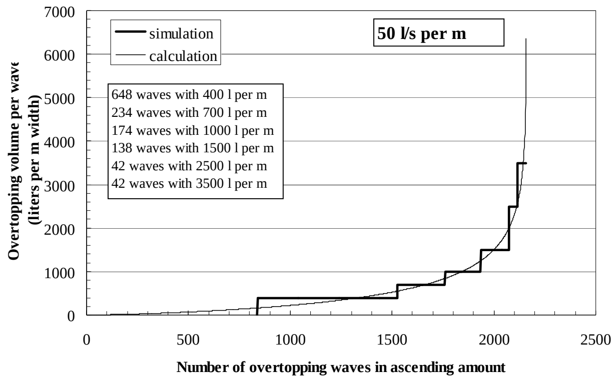

Figure 4. Calculated distribution of overtopping volumes and proposal for simulation. Mean discharge q = 50 l/s per m; full distribution

Another problem in Figure 4 is that the maximum volumes can not be simulated. In order to look more in detail, Figure 5 has been made. In total only 15 overtopping waves have a volume larger than 3.5 m^3 per m and only 5 overtopping waves have a volume larger than 4.5 m^3 per m. These waves can not be simulated by the wave overtopping simulator due to the limited capacity of the box of the simulator. In order to compensate for missing these large volumes, a fairly large number of 3.5 m^3 per m volumes was taken (see Figure 5 for an impression of releasing these volumes). Roughly all volumes between 2.5 m^3 and 3.5 m^3 per m were modelled as 3.5 m^3 per m. In total 27 volumes of 3.5 m^3 per m were taken to simulate volumes between 2.5 m^3 and 3.5 m^3 and 15 volumes of 3.5 m^3 per m were taken to simulate the largest volumes between 3.5 m^3 and 6.3 m^3 per m. Also 42 volumes of 2.5 m^3 per m were taken to simulate volumes between 2 m^3 and 2.5 m^3 per m, see Figure 5. Overall it can be concluded that missing the real large overtopping volumes in the distribution was compensated by simulating in excess a number of 3.5 m^3 and 2.5 m^3 per m volumes. Therefore, the maximum size of the box of 3.5 m^3 per m was not considered as a real restriction to perform a 50 l/s per m test adequately as far as the total overtopping volumes is considered. However, as far as the maximum flow velocities are considered, the simulated waves may not have been fully representative.

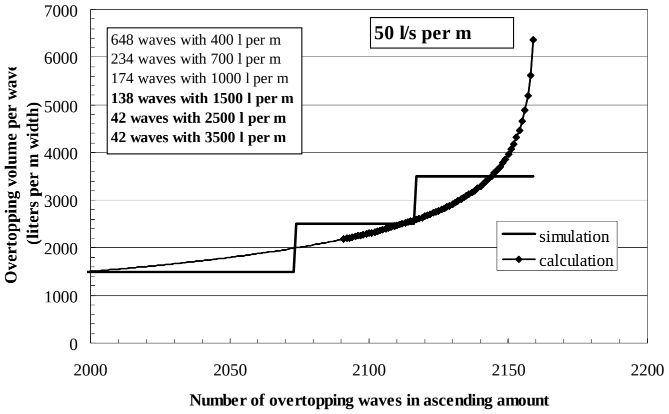

Figure 5. Calculated distribution of overtopping volumes and proposal for simulation. Mean discharge q = 50 l/s per m; full distribution of largest volumes

Figure 6. Wave overtopping simulator at dike, releasing 14 m^3 in a few seconds

WAVE OVERTOPPING MEASUREMENTS AND ANALYSIS

Set-up of measurements

Measurements of flow velocities and depths of the wave overtopping tongues have been carried out at two locations: one location near the crest and one location about halfway the inner slope. The location near the crest changed over time: for the un-reinforced grass section the instruments were placed near the inner crest line and for the reinforced grass section at 2.2 m distance from the crest at the inner slope.

The flow velocity measurements were performed with an electromagnetic type (EMS) meter and the flow depth measurements with a thin wire conductivity meter, as shown in Figure 7. These instruments were hired from Delft Hydraulics, who adapted these instruments especially for this application and also supported the data-acquisition. The flow measurements have been carried out close to the grass cover: about 2 cm above the grass cover for the un-reinforced grass and about 5 cm above the grass cover for the SGR-section.

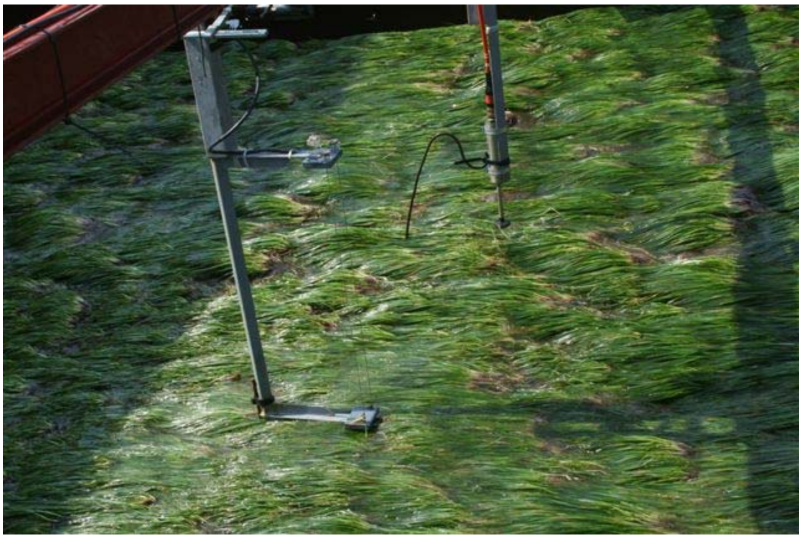

Figure 7. A wire flow depth meter (foreground) with an electromagnetic velocity meter. Flow of water goes from right to left in the picture.

The full measurements have been reported in the separate report on the wave overtopping simulator by Van der Meer, 2007, see www.comcoast.nl. Related to this research, Bosman performed a MSc-thesis on these measurements and analysed literature data (Bosman, 2007). Based on his findings, he arrived at adapted equations for flow velocity, flow depth and overtopping time of overtopping events. His major findings are summarized in Van der Meer, 2007 as well.

Analysis of measurements

The raw flow velocity and flow depth measuring data were processed by Delft Hydraulics and with another, moving average, filtering technique by Bosman, 2007. As mentioned before, overtopping discharge usually is expressed as a constant time-averaged value during the wave overtopping event, but the actual wave overtopping has a real stochastic character. Most of the time there will be no water on crest or inner slope and then during an overtopping event a lot of water comes over in a few seconds. This stochastic character is illustrated in Figure 8, showing measured velocities versus time during the calibration phase of the simulator. The pumped discharge was about 10 l/s per m.

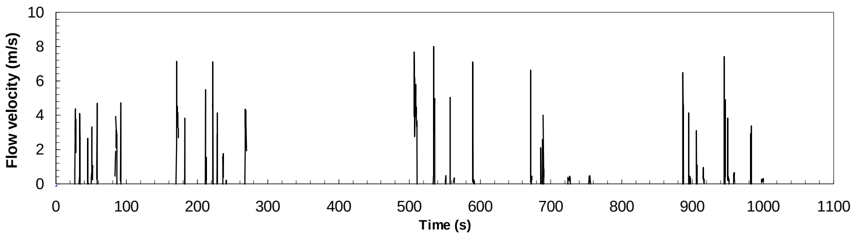

Figure 8. Filtered record of 15 minutes of real time wave overtopping simulation, showing the stochastic character for a constant overtopping discharge of 10 l/s/m.

Theoretical velocities have been described by Schüttrumpf and Van Gent, 2003, and adapted by Bosman, 2007. Based on the geometry of the structure (outer slope), the calculated 2%-run-up value and the actual crest freeboard, a maximum flow velocity or flow depth can be calculated for each individual overtopping volume. During the calibration phase the theoretical velocities were satisfactorily produced by the prototype of the simulator, see Van der Meer et al., 2006.

Pre-defined overtopping volumes were generated by the wave overtopping simulator in random order. Velocities and flow depths were measured at crest and half way the inner slope for each of these overtopping volumes. By filtering techniques the maximum velocity and flow depth were established for each generated overtopping volume.

Figure 9 shows the measured and theoretical maximum flow velocities versus the generated volumes for all test series which were performed at the natural grass section. In this graph, where the actual overtopping volumes are used for the horizontal axis, the data groups for each mean overtopping discharge have been horizontally shifted a little in order to make a clear division between the overtopping discharges. For example, data for 1000 l per m have been given at 920 l/m for 0.1 l/s per m, at 940 l/m for 1 l/s per m, at 970 l/m for 10 l/s per m, at 1000 l/m for 20 l/s per m and at 1030 l/m for 30 l/s per m.

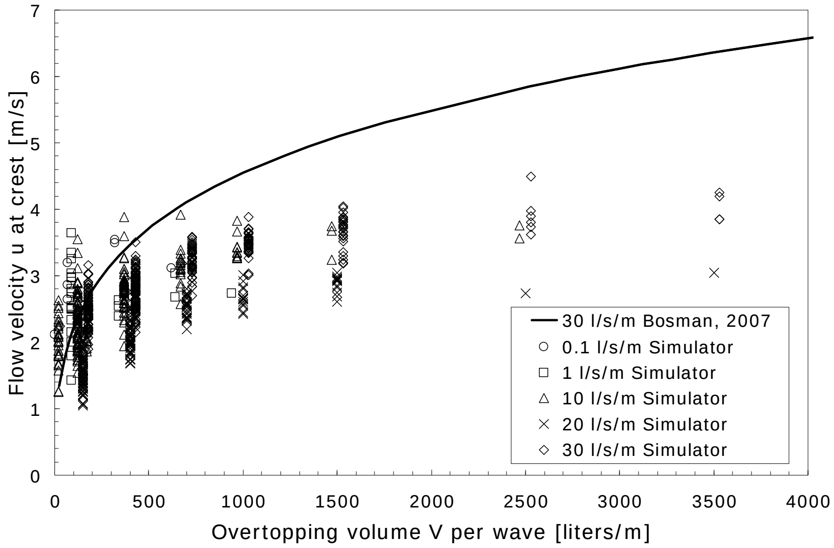

Figure 9. Measured maximum flow velocities at the crest, compared with theory; natural grass section.

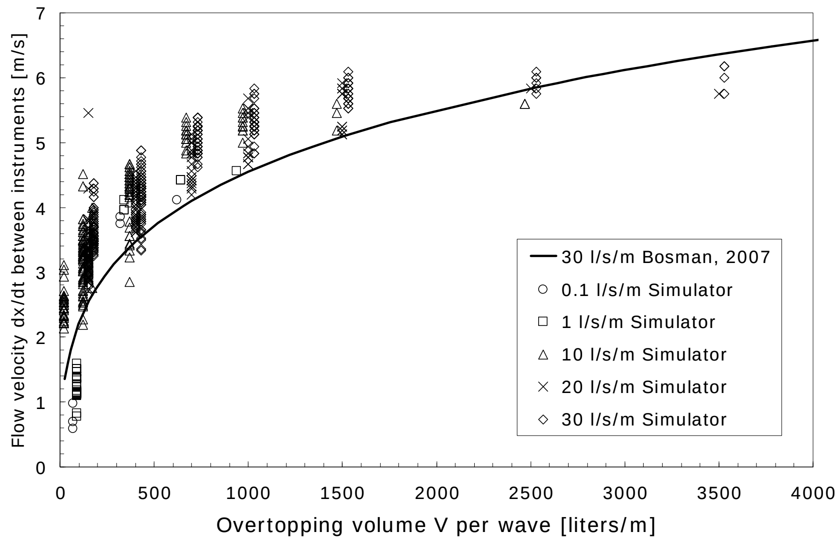

Figure 10. Flow velocity of overtopping front between instruments at crest and at inner slope; natural grass section.

Figure 9 shows that only volumes of 150 l/m gave maximum velocities as expected. For the larger volumes the measured velocities are smaller than expected, up to a factor 2. It can even be concluded that for volumes larger than 1000 l/m the maximum velocity remains the same. This was certainly not the experience during testing, where large volumes seem to give larger velocities.

A way to check the measurements of velocity is to look at the front velocity between the crest and the instruments half way the inner slope. The time between the moments that instruments “get wet”, together with the distance between the instruments (about 8 m), gave this front velocity. Figure 10 gives the front velocities, measured in this way, versus the generated overtopping volumes. Now the front velocities are close to the theoretical ones and in many cases a little higher! The observation that they are a little higher may be explained by the fact that velocities could increase along the inner slope (although not measured), which was not taken into account by the formula used. Based on Figure 10 it can be concluded that the simulator gave more or less correct velocities, but that the instruments were not able to measure correctly.

Measured flow depths were also much less than the depths that could be expected according to Bosman, 2007, see Figure 11. Maximum depths at the crest tend to go up to about 0.17 m at the largest overtopping volumes, where about 0.3 m would be expected and which was also measured during the calibration phase. Hence, also this instrument did not work properly.

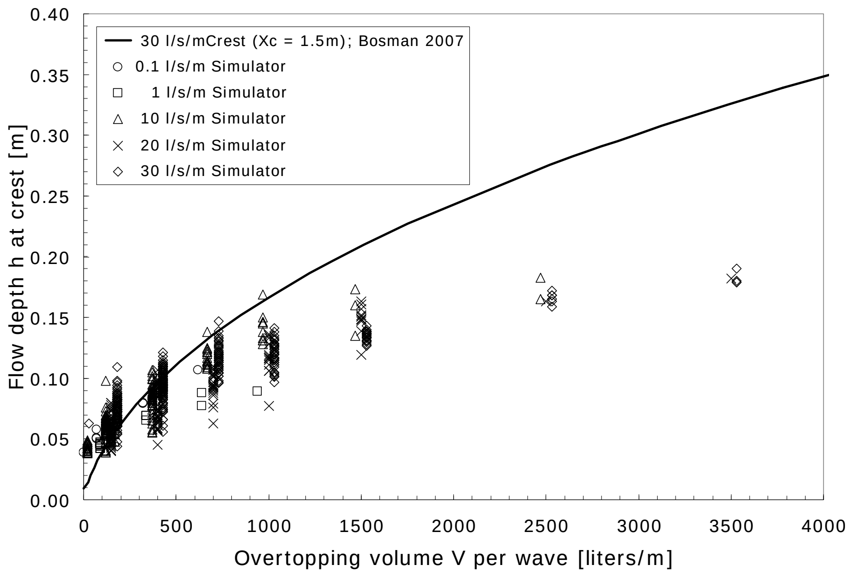

Figure 11. Maximum flow depths at the crest, compared with theory; natural grass section.

CONCLUSIONS AND RECOMMENDATIONS

The simulator was used during 3 weeks, every day and 6 hours for every test condition. It worked well without difficulties throughout the whole test program.

As the dike sections did not show damage for the design value of the simulator of 30 l/s per m, the capacity of the simulator was synthetically upgraded to 50 l/s per m. This upgrading, being the best practice for the field tests, did reproduce the total volumes well, but the maximum volumes were underestimated, maximum overtopping volumes being limited to the size of the box of the simulator of 3.5 m^3 per m, where around 6 m^3 would be required. It is strongly recommended to enlarge the capacity of the simulator for future testing.

The overtopping flow started at the inner slope of the dike section. In future tests it is recommended to install the simulator rather at the seaward slope and take the stability and/or erosion resistance of the crest into account as well.

From the analysis of results it must be concluded that the instruments that recorded velocity and flow depth did not measure properly under the simulated conditions. It appears that measurements are hampered by the highly turbulent and aerated overtopping flow. Hence, the EMS and thin wire gauge need further improvement in future, or alternative instruments should be deployed. The measured front velocities between the two instrument locations were in good agreement with anticipated velocities. This justifies the conclusion that with respect to the velocities of the wave overtopping tongues the simulator performed well and in agreement with the expectations.

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Overtopping discharge
Overtopping simulator
Dikes
Levees
Embankment