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Admissible post-wave overtopping flow for persons on a horizontal surface

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Abstract

Admissible wave overtopping is a key parameter in design specifications and also in safety assessments of the crest level of many coastal structures. This paper considers the hazard to people/pedestrians by post-wave overtopping flow over a horizontal surface, like a dike or breakwater crest, or a boulevard. Such flow is given by a flow velocity and a flow thickness. The most recent guideline is given in EurOtop (2018), where a maximum overtopping wave volume of 600 l/m is seen as the admissible or tolerable maximum. But no flow velocities or flow thicknesses are given.

Previous work has been summarised by Sandoval and Bruce (2017) who brought existing fluvial tests on people or human subjects together with data derived from videos of actual overtopping hazard events available from the internet. A graph was developed with stable and unstable combinations of flow velocity and flow depth or thickness.

The paper describes first tests in the Delta Flume of Deltares with a volunteer exposed to wave overtopping hazard on the crest of a dike with wave heights up to 1.8 m. Analysis determines flow velocities and flow thicknesses for stable and unstable situations. Additional tests with the wave overtopping simulator on the crest of a dike are described. In these tests, flow velocities and flow thicknesses were accurately recorded as well as the reaction of a volunteer, guarded by a safety line, on the crest of the dike as well as on the landward slope. These tests gave also stable and unstable situations with known flow velocities and flow thicknesses.

The new data were added to the work of Sandoval and Bruce (2017) and a physically based as well as a simple guideline has been proposed for the transition between stable and unstable situations for people/pedestrians. In general overtopping velocities are allowed of 4 m/s with a flow thickness of 0.2 m, but also a large velocity of 7 m/s with only a flow thickness of 0.1 m. Flow thicknesses are always given without air entrainment.

Keywords

Admissible wave overtopping, overtopping discharge, overtopping volume, flow velocity, flow thickness

1 Introduction

Admissible wave overtopping is a key parameter in design specifications and also in safety assessments of the crest level of many coastal structures. Such a limit may be set to avoid or assess the probability of coastal flooding (breaching of dikes), but also to avoid excessive direct hazard from reaching pedestrians, vehicles and other structures located behind or on the coastal structure. It is a key parameter because the crest level has significant influence on the construction costs of such a structure, or on costs to improve an existing structure. This paper considers the hazard to people/pedestrians by post-wave overtopping flow over a horizontal surface, like a dike or breakwater crest, or a boulevard. Real people are considered and real overtopping flow in full scale. This in contrast to research where small scale physical models or numerical models have been used to measure or calculate volumes and flow velocities and thicknesses and compare or use these with theories on stability of persons (Arrighi *et al.* (2017, 2018), Van Melis (2019), Suzuki *et al.* (2020) and Altomare *et al.* (2020)).

Sandoval and Bruce (2017) give an extensive overall view of what has been investigated in the past on admissible overtopping and the reader is referred to that paper for all relevant references. Only a short summary is given here. The first guidance was related to mean overtopping discharge only (Franco *et al*. 1994, EA / Besley, 1998), although Franco *et al*. (1994) did tests with actual volumes on a human volunteer. The CLASH- project (De Rouck *et al*., 2009) included guidance for pedestrians, vehicles, property behind the structure and structural damage of the rear side, now based on mean discharge in combination with maximum overtopping volumes. It was realised that mean discharge only was certainly not a good measure for admissible overtopping limits. This was adopted by EurOtop (2007). In the second edition, EurOtop (2018), the same combination was made of mean discharge and maximum overtopping volume, but also the wave height came into play. A small wave height will give small overtopping wave volumes, where for the same mean overtopping discharge, a large wave height will give fewer overtopping waves, but with much larger volumes associated with each. So, the overtopping wave volume became the principal parameter instead of the mean overtopping discharge. Table 3.3 of EurOtop (2018) is partly reproduced here in Table 1, only focused on people (pedestrians) and not on vehicles.

Table 1: Part of Table 3.3 from EurOtop (2018) on limits for overtopping for people.

Hazard type and reason	Mean discharge q (l/s per m)	Max volume V_{max} (l/m)
People at structures with possible violent overtopping, mostly vertical structures	No access for any predicted overtopping	No access for any predicted overtopping
People at seawall / dike crest. Clear view of the sea.		
H_{m0} = 3 m	0.3	600
H_{m0} = 2 m	1	600
H_{m0} = 1 m	10-20	600
H_{m0} < 0.5 m	No limit	No limit

Table 1 shows that overtopping water that is coming through the air, mainly from violent overtopping at vertical structures or walls, may hit people and is not allowed at any circumstance. But at a crest of a coastal structure or boulevard, the water flows horizontally (sometimes referred to as “green water overtopping”) over the surface and may hit the feet of people. If the flow velocity and flow thickness is large enough, people may become instable and fall. In Table 1 this is given by a maximum overtopping wave volume of 600 l/m. A very small wave height of 0.5 m will not reach this limit, but a wave height of 3 m or more may easily reach this limiting volume by having just one or two overtopping waves during the storm (and consequently very small overtopping discharges).

The limiting volume of 600 l/m has a physical background but is partly based on expert judgement. During the development of EurOtop (2018) videos had been made of individual overtopping wave volumes, generated by the Wave Overtopping Simulator (Section 4.8 in EurOtop (2018)). Videos were recorded of 100 l/m up to 3000 l/m. Section 3.3.2 of EurOtop (2018) describes these videos, that are available on the EurOtop website: http://www.overtopping-manual.com/eurotop/videos-of-wave-overtopping/. With a small group of people each overtopping volume was watched, starting from 100 l/m, and then an individual assessment was made whether that volume would generate instability of a human person in the flow shown. An overtopping volume of 600 l/m was regarded as the limit that a person could withstand.

It is very well known that similar overtopping wave volumes do not have the same flow velocity and flow thickness. Hughes *et al.* (2012) clearly demonstrate that there is quite a good trend between overtopping volume and velocity, hardly a trend between overtopping volume and flow thickness and no trend at all between flow velocity and flow thickness. They also show that the 2%-values of flow velocity and flow thickness do not occur for the same overtopping volume. Suzuki *et al.* (2020) calculate flow velocities and thicknesses in time and show that they vary tremendously. Maximum combinations did pass the curve of Sandoval and Bruce (2017) into the instable region, but they could of course not prove that this curve was correct as no real persons had been used. Van Melis (2019) calculated overtopping flow over a breakwater under construction and by theoretical instability equations he came to stability limits to persons and damage to equipment. But no experiments were performed with real people or equipment. Altomare *et al.* (2020) measured flow velocities and thicknesses for a specific case and compared them with the Sandoval curve as well as with the curve by Arrighi *et al.* (2017, 2018). As measurements were on small scale, also here real persons were not considered. Arrighi *et al.* (2017, 2018) consider flooding rather than the often faster wave overtopping flow. They consider smaller velocities with larger flow thickness, more according to fluvial flow. They develop a relationship between the Froude number (including the flow velocity) and a mobility number (including flow depth and submergence). Again no real persons were used for validation.

Some guidance on flow velocity and thicknesses and the relationship between wave conditions, overtopping discharge and overtopping volumes can be found by applying EurOtop (2018). Equations 5.10 and 5.11 or equation 5.15 in EurOtop (2018) give predictions of the mean overtopping discharge for a certain crest level of a sloping coastal structure. With Equations 5.1 and 5.2 for the 2%-wave run-up level it is possible to calculate the probability of overtopping waves, assuming a Rayleigh distribution for the wave run-up (Equation 5.56). The distribution of overtopping wave volumes can be calculated by Equations 5.52 to 5.55 and the maximum overtopping wave volume by Equation 5.57. The flow velocity for each probability, including the maximum velocity, can be calculated by Equation 5.58 or alternatively by Equation 5.60. Note that the prediction of these velocities is not very accurate. They only show an average relationship and in reality, there is a significant deviation around the average. The flow thickness at the seaward edge of the crest can be calculated by Equation 5.59 but should be reduced by one third on the crest (Section 5.5.4 of EurOtop, 2018).

But for what combination of velocity and thickness do people become instable and fall? This has partly been discussed in Sandoval and Bruce (2017). They looked at four investigations on fluvial flow, Abt *et al.* (1989), Endoh and Takahashi (1994), RESCDAM (2001) and Jonkman and Penning-Rowsell (2008). In all investigations steady flow was considered with flow velocities between 0.6 m/s and 3 m/s and flow depths between 0.25 m and 1.2 m. The majority of the test data, where people became unstable, was for flow velocities between 1-3 m/s and flow depths larger than 0.5 m.

Then Sandoval and Bruce (2017) analysed videos from the internet where real accidents happened to people. This is of course a different situation than with steady flow. Post-overtopping wave flows hit the people and they withstood the attack, or they fell down. Flow velocities and flow thicknesses were derived from the videos. The final graph of Sandoval and Bruce (2017) is given in Figure 1, but slightly updated. It shows the data for fluvial flow (all unstable situations) and the data for the wave overtopping accidents from videos, where a distinction has been made between stable (black diamonds) and unstable (red diamonds) events. The yellow diamonds were red (unstable) in the original graph of Sandoval and Bruce (2017), but they describe a situation where a cyclist stopped because of the up-rushing wave. The person remained stable, however, and did not fall down. Actually, this is more a stable than an unstable situation for a person and therefore the data have been given a different colour.

The graph also shows theoretical instability curves, based on Endoh and Takahashi (1994), but modified for buoyancy by Sandoval and Bruce (2017). Note that in the original graph an error was introduced for the friction instability, by not using a factor of 2 in the equations. The curves deviate now more than before. There are two failure possibilities: by moment instability, mainly for fluvial situations, and by friction instability (flow on the feet) for wave overtopping. No guideline was given on admissible combinations of flow velocity and depth or thickness, but this should be a curve just below the majority of the unstable data and above the stable data.

This paper will focus on wave overtopping only, not on fluvial flow, although all data in Figure 1 will be used. It means that the interesting area in Figure 1 is for flow velocities larger than about 3 m/s and flow thicknesses from 0.05 m up to about 0.4 m, the lower right part of the graph. The objective of the paper is to establish the stability of a person on a dike crest or boulevard and on the landward slope of a dike, subjected to overtopping wave volumes with known velocity and flow thickness, and finally come with a proposal for admissible wave overtopping in this situation.

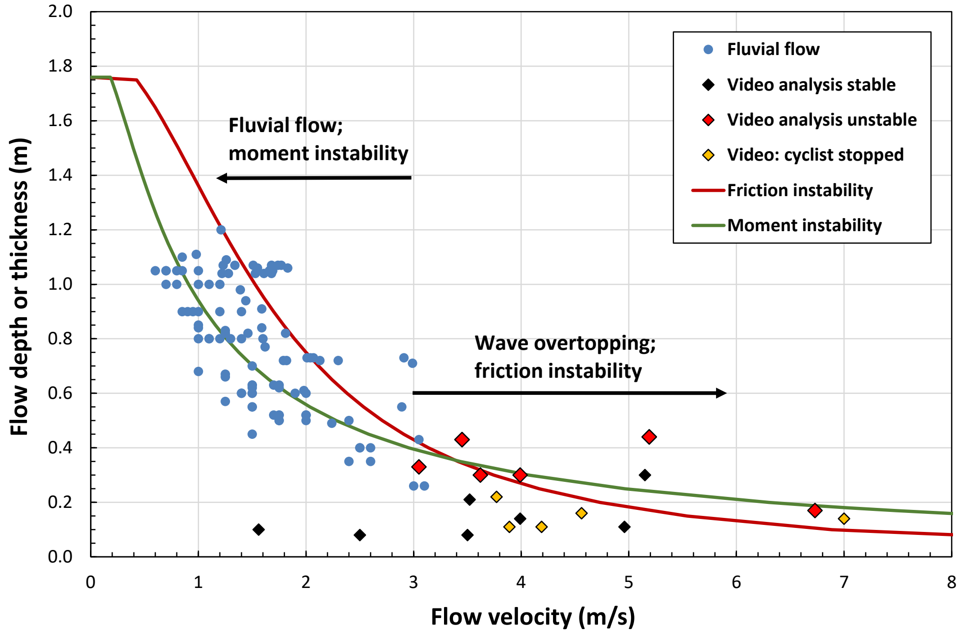

Figure 1: Modified final graph of Sandoval and Bruce (2017), showing video-derived data plotted together with literature studies on controlled fluvial conditions.

Two investigations will be added to the work of Sandoval and Bruce (2017). First, flume tests in the Delta Flume of Deltares (formerly Delft Hydraulics) from 1992 will be analysed, where a grass dike had been constructed on real scale and attacked with significant wave heights up to 1.8 m. In two tests a person was standing on the crest, attached to a safety line, and subjected to wave overtopping discharges of respectively 10 and 25 l/s per m. The second, recent (2020) investigation was a test set-up with the wave overtopping simulator (Van der Meer *et al.*, 2007). This device was placed on an actual dike crest and specific volumes with known flow velocities and flow thicknesses over the crest and landward side of the dike were released. A person with a harness and safety line volunteered to establish when he was stable and when he was washed away. Further details of these tests and the analysis follow in Sections 2 and 3.

2 Delta flume tests in 1992

The stability of a grass dike with a seaward slope of 1:4, a crest width of 2 m and a landward slope of 1:2.5 was tested in 1992 in the large Delta flume of Delft Hydraulics. Large blocks of clay with grass had been transported from a real dike to the flume. The tests have been described and analysed in three Dutch reports: Smith (1994), Klein Breteler and Smith (1996) and Meijer and Verheij (1998).

Part of the tests was concentrated on showing (and videoing) how a certain overtopping discharge looks like in reality for significant wave heights up to 1.8 m. Mean wave overtopping discharges of q = 0.4 – 25 l/s per m were simulated. For two of the largest overtopping discharges of respectively q = 10 l/s per m and about 25 l/s per m a person was standing on the crest during the whole test, attached to a life line (actually two different persons). The person was stable during the whole test with q = 10 l/s per m, with a test duration of just more than one and a half hour. A photograph from that test (Test 114) is shown in Figure 2 and shows very turbulent water coming over the crest with a lot of air entrainment. But velocity and thickness were not enough to make the person instable.

The test with about 25 l/s per m (Test 112a) lasted for only 15 minutes because sometimes the overtopping collection tank overflowed. In this short period the volunteer on the crest was swept away from the crest at least twice. Figure 3-left shows a wave breaking on the seaward slope and the first overtopping water reaching the feet of the volunteer. The right picture shows that the person became unstable. Also here the overtopping water is very turbulent with a lot of air entrainment.

Figure 2: Test 114 in the Delta flume with q = 10 l/s per m. The person was stable during the whole test of 1.5 hours. Picture taken from Smith (1994).

Figure 3: Test 112a in the Delta flume with q = about 25 l/s per m. Left: a wave breaks onto the 1:4 slope and a person is standing on the crest attached to a life line. Right: one of the occasions that the volunteer became unstable and was saved by the life line. Pictures are taken from the video of this test.

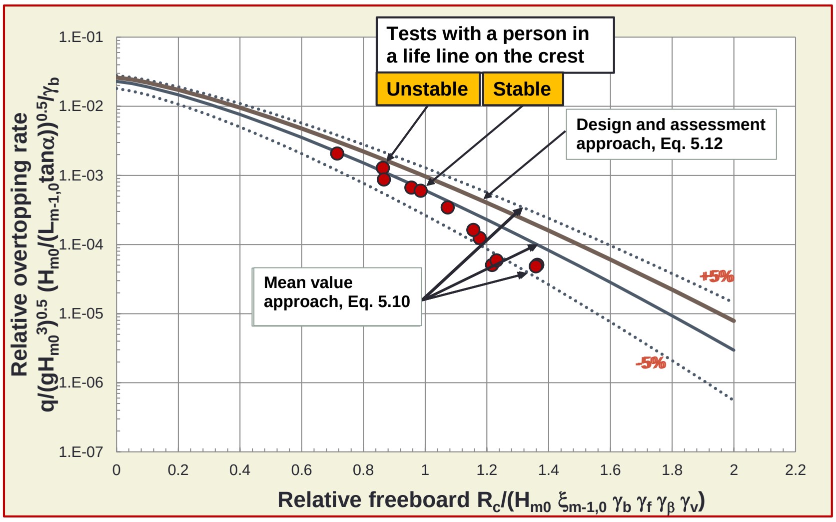

Figure 4: Figure 5.14 in EurOtop (2018) with the overtopping data of the Delta Flume added, using an influence factor for roughness of γ_f = 0.9.

Wave conditions of all wave overtopping tests were measured. Also quite a lot of instruments were placed to measure flow velocities and flow thicknesses on the seaward slope, crest and landward slope. But they nearly all failed to give reliable measurements, due to the turbulence and high velocities. This was also found by Van der Meer *et al.* (2007) when they for the first time made measurements during employment of the wave overtopping simulator. It means that for further analysis the existing (reliable) data should be compared with theory and that existing formulae should give a fair prediction of flow velocities and thicknesses, that are needed to add to Figure 1.

First of all the wave overtopping discharges of all overtopping tests were compared with the formulae in EurOtop (2018), see Figure 4. The measurements and prediction formula for breaking waves, Equation 5.10 in EurOtop (2018), coincide if an influence factor for roughness $\gamma_f = 0.9$ is used. As the grass was in summer condition (growing season – healthy and strong grass), this is a reasonable assumption. Small overtopping discharges deviate from the line, but it was noticed during testing that small overtopping waves often disappeared into the dike and never reached the overtopping collection tank. Figure 4 also shows the two tests with the stable and unstable situation for the volunteer on the crest. Figure 5 shows the predicted and measured overtopping probabilities, or the portion of incident waves that reached the crest and overtopped. The prediction is fair, with quite a significant deviation for the short 15 minute test with q ≈ 25 l/s per m.

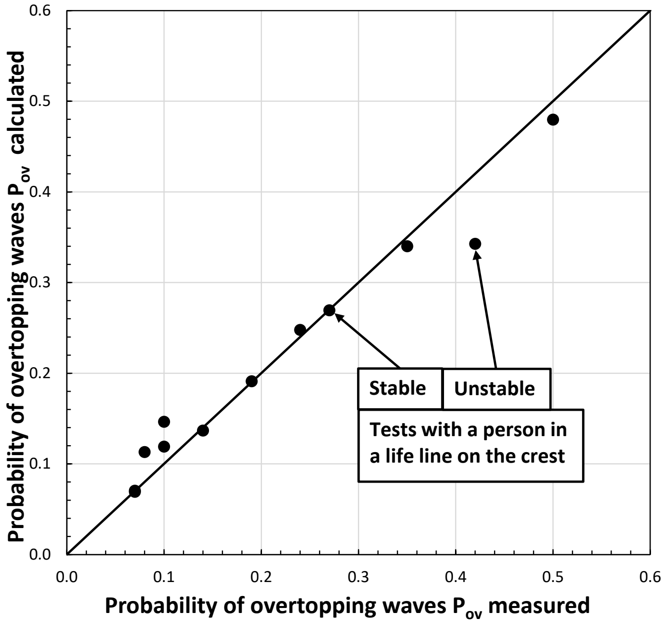

Figure 5: Predicted (EurOtop, 2018) and measured probabilities of overtopping waves for the Delta flume tests.

The test conditions for the two tests with a volunteer on the crest are given in Table 2. Test 112a had a significantly larger wave height than Test 114, with the latter test having a lower wave steepness (and a slightly longer wave period) and a longer test duration. Both aspects do increase the maximum overtopping wave volumes. The overtopping discharges were calculated from the total volumes of water that were collected in the overtopping collection tank. Due to the fact that small overtopping volumes did not always reach the tank, or were slowed down on the landward side and were overtaken by following larger volumes, only large individual wave overtopping volumes could be detected. Overtopping volumes for Test 114 were measured correctly and can be compared with theory, but the given volumes in Smith (1994) for Test 112a include an unknown error and cannot be used. The predicted distributions for overtopping wave volumes for both tests, according to Equations 5.52-5.57 in EurOtop (2018), are given in Figure 6.

Table 2: Test conditions where a volunteer stood on the crest.

Description of parameter	Test 112a	Test 114
Significant wave height (m)	1.80	1.29
Peak period (s)	6.08	6.49
Wave steepness with peak period (-)	0.031	0.020
Crest freeboard (m)	1.80	1.80
Overtopping discharge (l/s per m)	≈25	9.9
Duration of test (s)	881	5500
Number of incident waves (-)	140	1093
Number of waves reaching the crest (-)	59	295
2%-runup level (m)	3.4	3.1
Maximum run-up level (m)	3.5	3.7

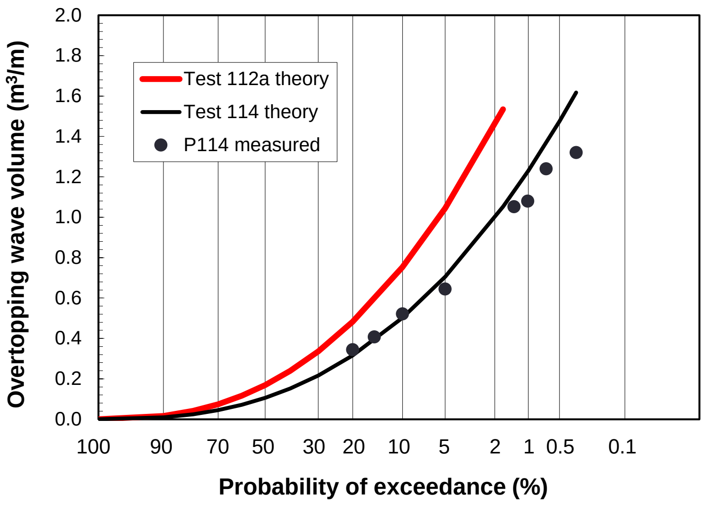

Figure 6: Distributions of overtopping wave volumes for Tests 112a and 114, with also measurements for Test 114.

The prediction for Test 114 in Figure 6 coincides well with the measured overtopping volumes. The maximum predicted overtopping wave volume depends on the number of overtopping waves. Due to the much longer duration of Test 114 the predicted maximum overtopping wave volume is quite similar to Test 112a that had a significantly larger overtopping discharge. The maximum overtopping wave volumes are around 1.5 m^3 per m (or 1500 l/m). But the volunteer withstood the conditions of Test 114 and became unstable for Test 112a. The video also showed more violent wave breaking for Test 112a with more water flying through the air, compare also Figure 2 and Figure 3. Similar overtopping wave volumes may then show a different behaviour in flow velocity and flow thickness, certainly close to the edge of the crest. This demonstrates the importance of relating the extent of the hazard directly to the flow parameters rather than simple to a threshold in overtopping volume.

As previously noted, equations in EurOtop (2018) allow the prediction of (front) velocities of overtopping wave volumes. Equation 5.60 was used to calculate the front velocity for various overtopping volumes and Equation 5.59 gave the flow thickness. Equation 5.1 gave the 2%-run-up levels. These were 3.4 m for Test 112a and 3.1 m for Test 114, respectively, just a little larger for Test 112a with the much larger wave height. The small difference is due to the smaller wave steepness in Test 114. The calculated maximum run-up was 3.5 m (only 140 waves) for Test 112a and 3.7 m (1093 waves) for Test 114. Now the lower wave height gives even a higher calculated maximum run-up, due to the longer duration of the test. As the front velocity of the wave in Equation 5.60 of EurOtop (2018) depends on the maximum wave run-up, the velocities at the crest also appeared to be quite similar for Tests 112a and Test 114.

The theoretically largest velocity and flow thickness on the crest for the largest overtopping wave volume in test 112a is v_{max} = 5.9 m/s and h_{max} = 0.23 m. The third largest volume, where the volunteer was stable, gives theoretically v = 5.4 m/s and h = 0.16 m. The largest conditions in test 114, where the volunteer was always stable, is v_{max} = 6.1 m/s with h_{max} = 0.25 m. The 2%-values (about the 6th largest wave) are $v_{2\%}$ = 5.5 m/s and $h_{2\%}$ = 0.17 m.

It is clear that the similar calculated conditions for Tests 112a and 114 do not make a distinction for being stable (Test 114) or being unstable (Test 112a) for a person on the crest. It must be concluded that the present theory on velocities and flow thicknesses at the crest is not accurate enough. A reason may be that the lower steepness of Test 114 gives a longer flow duration of an overtopping wave volume at the crest and consequently a smaller flow thickness. The videos give this impression, but no formulae are available to describe this. It is the *combination* of flow velocity and flow thickness that makes a person unstable or not, as shown in Figure 1.

Furthermore, the calculated flow thicknesses were established in small scale model tests with minor air entrainment. In reality, and also measured in the Delta flume tests, air entrainment may easily become 30-50%, percentages that are mentioned by Klein Breteler and Smith (1996), with extremes in the tests of 3% and 80%. The effect is that the flow thickness increases with a reduced bulk mass density of the water as a side effect. The calculated flow thicknesses of 0.16-0.25 m may then, with air entrainment, become 0.20-0.50 m. The effect of air entrainment is also present in the videos of real events that were analysed by Sandoval and Bruce (2017) and reported in Figure 1.

3 Tests with the wave overtopping simulator

3.1 Hydraulic measurements

Wave overtopping tests were performed with the wave overtopping simulator early 2020 on a dike along the river IJssel in the Netherlands near Zwolle in order to establish the strength of grass cover directly on a sand dike. Also hydraulic measurements were performed in order to know the flow velocities, flow thicknesses and flow durations of distinct wave overtopping volumes over the crest of the dike and along the landward slope. Finally, half a day was used after these measurements to subject a volunteer in a safety line to overtopping wave volumes. First the hydraulic measurements will be described and then the tests on the volunteer.

Figure 7 shows the general set-up of the testing of the dike. The wave overtopping simulator was placed on the river side slope of the dike with the outflow on top of the crest. Water was pumped with a set discharge from a pond about 100 m away from the test location. The simulator is 4 m wide and guide walls were placed on each side, over the crest and landward slope, forming a kind of wave flume.

Figure 7: General set-up of the wave overtopping tests at the IJssel dike near Zwolle to establish the strength of grass covers on a sand dike. The upper left corner shows the frequency controlled pump and the pond where water was taken from.

The set-up of the hydraulic measurements is given in Figure 8. Paddle wheels (originally placed in small boats to measure their velocity, outdated today by GPS) are able to measure in highly turbulent flows and were placed upside down on the slope, about 3 cm above the surface to avoid boundary layer effects. The numbers 1-7 in Figure 8 show the locations of these paddle wheels. The first one was 1.5 m from the outflow of the wave overtopping simulator and the second one was just behind the crest of the dike. Due to irregularities at the transition from asphalt crest to grass slope this paddle wheel number 2 did not measure correctly and has been deleted from further analysis. Distinct wave overtopping volumes between 200-3500 l/m were released three times and the average measured values were taken for analysis.

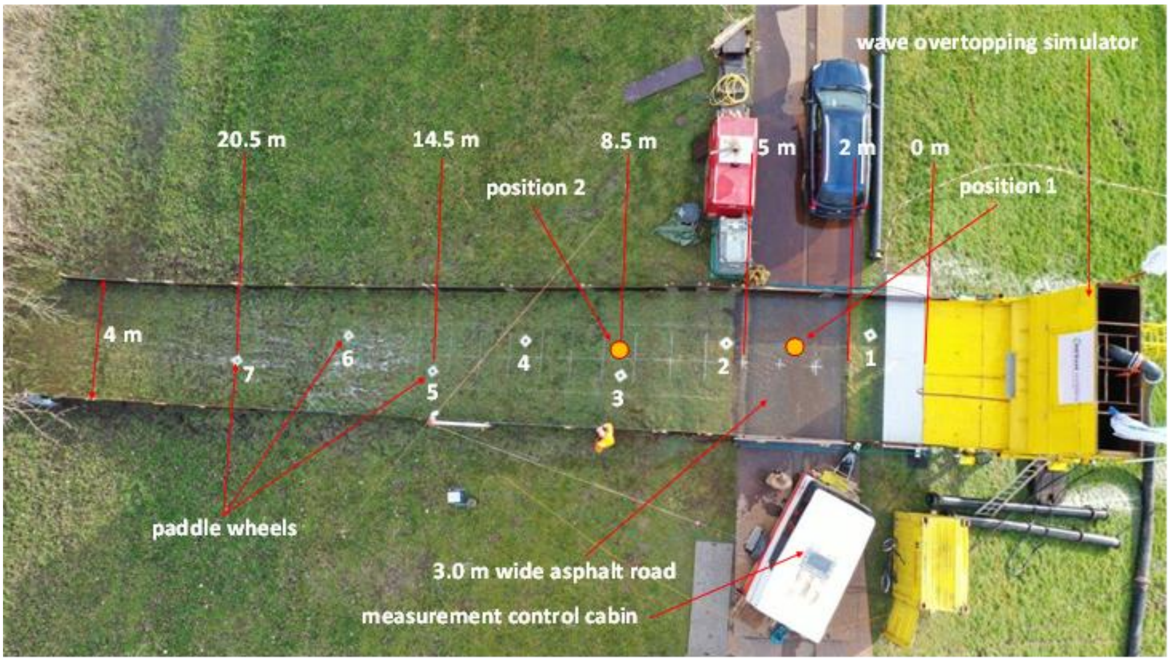

Figure 8: Set-up for the hydraulic measurements with paddle wheels and drone. The matrix painted on the slope is 1 m by 1 m. Positions 1 and 2 were taken by the person that was subjected to overtopping wave volumes.

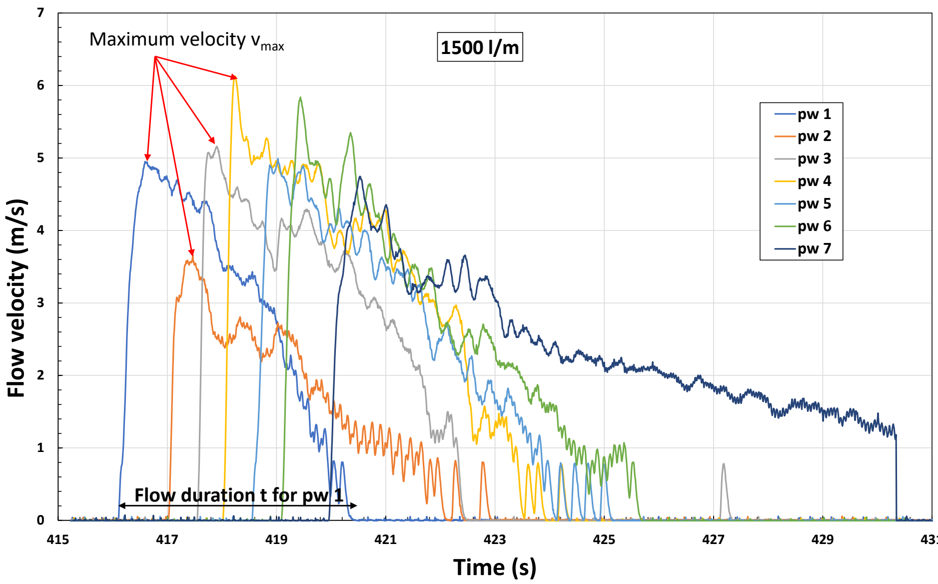

Figure 9: Flow velocity measurements over the crest and along the landward slope. Paddle wheel 2, directly after the crest gave unreliable measurements due to the irregularity at the transition.

Figure 9 shows an example of the measurements with the paddle wheels, for a simulated overtopping wave volume of 1500 l/m. The maximum velocity is often reached within 0.1-0.2 s after arrival of the front of the wave. The graph also shows the unrealistically small velocities measured by paddle wheel 2, due to irregularities described above. Paddle wheels 1 and 3 have almost the same maximum velocity, but then further down the slope the velocity increases due to gravity. At the end of the slope the velocity decreases, now due to friction over the slope. From graphs like Figure 9 one can also detect the flow duration, as indicated for paddle wheel 1 in the graph.

Besides measurements with paddle wheels, videos were also made using a drone directly above the section. Videos were taken with 59.94 frames per s. The front velocity was determined by counting the number of pictures over a certain distance. For this reason a 1 m x 1 m grid was painted on the grass.

The front of the overtopping wave was often irregular over the 4 m width of the test section and changed over distance, see Figure 10. A line was considered reached if about half of the front width had arrived at that line. The determination of the velocity by drone is a little subjective (when does the front really reach a line?), but it gives a fair average of the front velocity over the slope. The deviations over the width are in inherent aspect of wave overtopping in reality. The paddle wheel does not take into account any average over the width as it is based on a specific location in the test section. Front velocities were measured over 3 m.

Figure 10: Irregularity of the overtopping wave front. Above: at the middle of the crest (4 m); middle: at paddle wheel 3 (8.5 m); below: at paddle wheel 6 (17.5 m). Overtopping wave volume of 1500 l/m.

A short summary of the velocity measurements are shown in Figure 11. The graph shows the geometry of the dike: the first metre consists of a steel plate, then 1 m grass and 3 m asphalt. The down slope starts at 5 m, where the upper part until 14 m is about 1:3 and further down the slope it gradually changes to 1:4. The smallest overtopping wave volumes in Figure 11 is 400 l/m and the largest 3500 l/m (almost nine times larger and the maximum capacity of the simulator). In general the front velocity increases over the first 3 m, remains more or less constant on the horizontal crest and then increases on the slope due to gravity. The maximum is generally reached between 8 m and 14 m and then reduces further down the slope. Even a large volume of 3500 l/m reduces after 16 m on the slope. Front velocities up to 8 m are reached.

The paddle wheels record the complete flow of an overtopping wave volume in time, see Figure 9. Thus both the maximum velocity v_{max} in the wave and the flow duration t (the duration that water flows over that particular point) can be determined. Both are shown in Figure 9. The maximum velocities of paddle wheels 1, 3 and 4 were compared with the front velocities as determined from the drone videos in Figure 11.

The graph shows some differences. The maximum velocities at the first paddle wheel at 1.5 m are consequently larger than the front velocity over the first 2 m by drone. They are, however, quite similar to the front velocities over the asphalt road. The reason is probably due to the way the overtopping wave volume was released from the wave overtopping simulator. When the valve of the simulator opens, a part of the water falls vertically down and another part starts to move along the outflow of the simulator and then all the water flows over the first few meters of the horizontal slope. It takes a few moments (0.5-1.5 s) before the valve is fully open and all the water can be released easily. This means that the first water release causes a thin water front and this water may be taken over by the release of water a little later with a larger velocity. This takes place roughly over the first few meters and must be seen as a model effect that is not present in reality. One can distinguish a less steep front for paddle wheel 1 in Figure 9 than for paddle wheel 4, more or less validating that close to the simulator outflow the front velocity will be smaller than the maximum velocity.

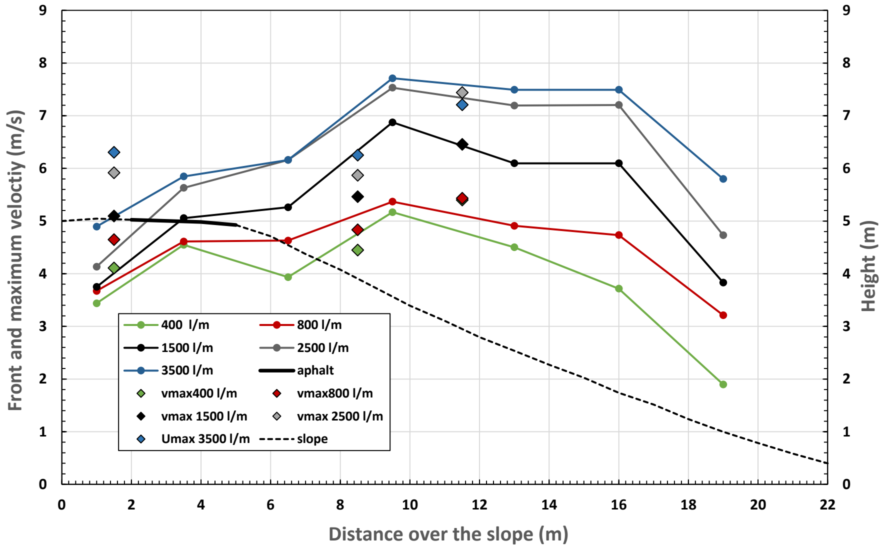

Figure 11: Maximum velocities v_{max} from paddle wheels compared with the front velocities from the drone videos. Overtopping wave volumes range from 400 – 3500 l/m and same colours have the same overtopping wave volume.

The maximum velocities at paddle wheel 3 at 8.5 m are consequently a little smaller than the front velocity. This might be due to the fact that the overtopping wave volume is increasing in speed by the gravity. This increase is not directly followed by giving a larger maximum velocity. Paddle wheel 4 at 11.5 m is in the area where the front velocity is almost maximum and is not accelerating anymore. Here the maximum velocities from the paddle wheel are quite similar to the front velocities.

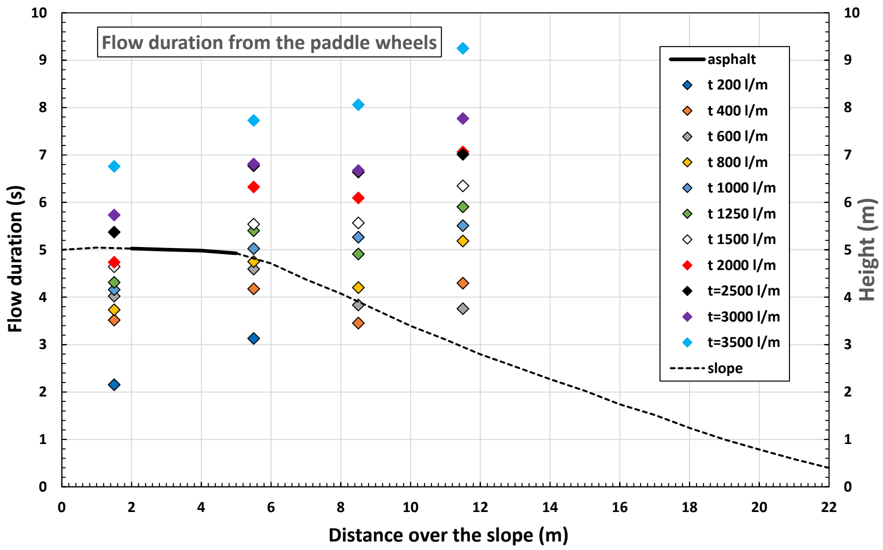

Figure 12: Flow duration of overtopping wave volumes.

Figure 12 shows the flow durations of the overtopping wave volumes over the slope, including paddle wheel 2. The flow duration increases consistently with the distance from the wave overtopping simulator. The further the wave is from the crest, the longer water will flow over that particular point. Larger overtopping wave volumes also give larger flow durations.

The record of flow velocity over time at a specific location has a correlation with the released overtopping wave volume. The flow thickness over time at the same location, multiplied with the flow velocity over time gives the instant discharge over time. The integration of this discharge over time, gives the overtopping wave volume. In our case we have the flow velocity, flow duration and the overtopping wave volume at specific locations. The missing variable is the flow thickness. By *assuming* that the shape of the flow velocity should be similar to the shape of the flow thickness over time at the same location, one can calculate this flow thickness over time. It also gives the maximum flow thickness at the same time as the maximum flow velocity. One should realise that this flow thickness is without any air entrainment, which may be up to 30-50%. All these assumptions apply to the same location. Over the slope the records over time may vary: the duration may increase, acceleration may give larger velocities and consequently smaller flow thicknesses, etc.

Figure 13 shows the calculated maximum flow thicknesses at paddle wheels 1, 3 and 4. The flow thickness at paddle wheel 3 is quite similar to paddle wheel 1, although the maximum velocity increased. This is due to the fact that the flow duration became longer. This is also the case at paddle wheel 4, resulting now in a smaller flow thickness.

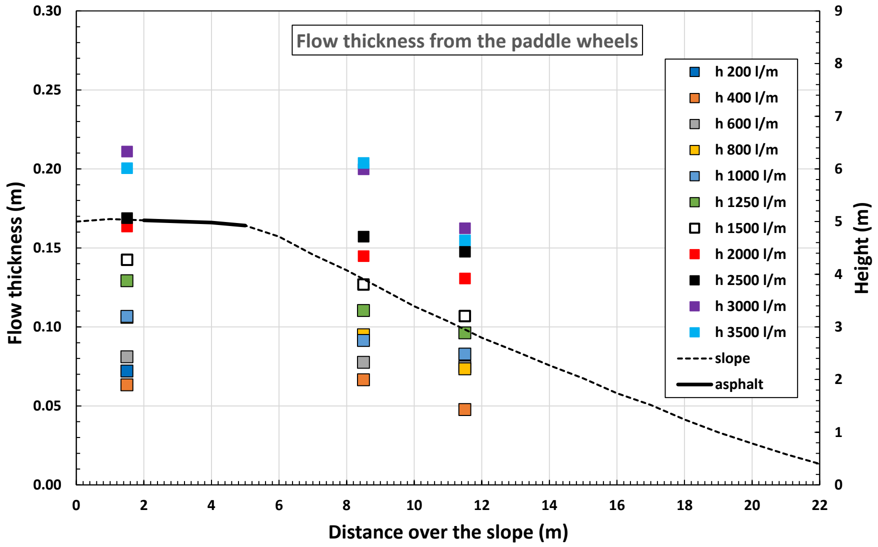

Figure 13: Calculated maximum flow thickness of overtopping wave volumes

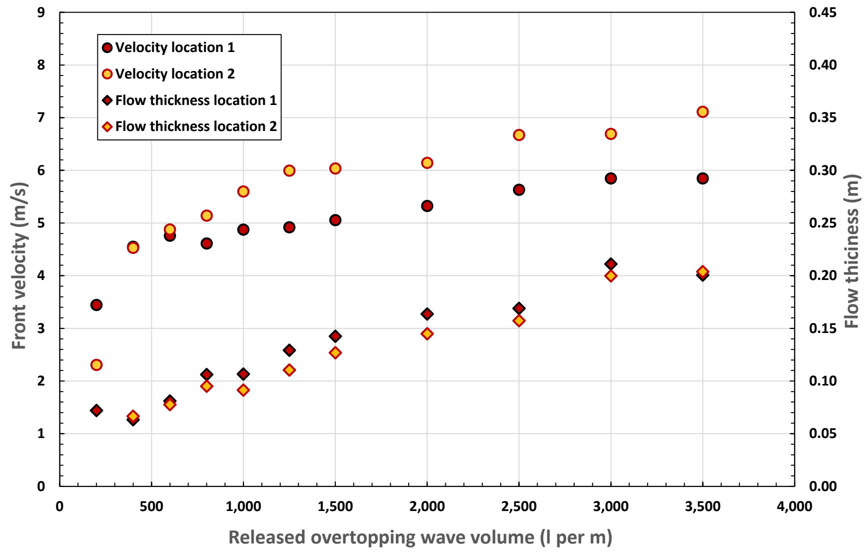

Figure 14: Front velocities and maximum flow thickness (without air entrainment) for position 1 at 3.5 m and position 2 at 8.5 m.

The second part of this chapter deals with the tests on a person that was subjected to overtopping wave volumes. The first position was at the middle of the asphalt road at 3.5 m distance shoreward of the crest and the second position was next to paddle wheel 3 on the slope at a distance of 8.5 m, see Figure 8. For these two locations, the front velocity and maximum flow thickness were determined using above analysis.

For position 1 at 3.5 m the front velocities over the asphalt road from 2 m to 5 m were taken from the drone measurements. The calculated maximum flow thickness was taken from paddle wheel 1 at 1.5 m as the flow velocities at this location were similar to the ones over the asphalt road, see Figure 9, indicating that the calculated flow thickness would also be a good estimate for the location at 3.5 m. For position 2 at 8.5 m the front velocities were taken by the interpolated front velocities from the drone video over 5 m to 8 m and 8 m to 11 m. The calculated flow thickness was taken from paddle wheel 3 at 8.5 m. Velocities and flow thicknesses (without air entrainment) are given in Figure 14 for overtopping wave volumes from 400-3500 l/m and for locations 1 and 2 where the volunteer in a life line was standing during the stability tests.

3.2 Wave overtopping tests on a human volunteer

The wave overtopping simulator was used to release specific overtopping wave volumes when a volunteer was standing on the dike crest or on the landward slope. The first position on the dike crest would be identical to a person on a boulevard, as long as the wave overtopping flows over the surface and does not fly through the air (as could be the case behind a vertical seawall or behind a vertical crown wall).

Figure 15: Volunteer standing at position 1 at the middle of the crest and attached to a safety line.

Figure 15 shows the volunteer at the crest of the dike, 3.5 m away from the outflow of the wave overtopping simulator. The volunteer was 1.85 m tall and weighed 78 kg. He was wearing boots and a dry suit and the total weight of the person including these clothes could have been 85 kg. He was also wearing a harness attached to a safety line that would prevent him from being washed away by an overtopping flow. He could freely step back about 1 m before the safety line would come into function, first by supporting him to stay upright and eventually by saving him from being washed away.

The tests started with releasing small overtopping wave volumes of 200 l/m and gradually these volumes were increased up to a maximum of 3500 l/m. At the second position, 8.5 m from the outflow of the wave overtopping simulator, on the landward slope and next to paddle wheel 3, the overtopping wave volumes started at 600 l/m and finished with a maximum of 2000 l/m.

All tests were taken on video and these videos were analysed in detail. First the observation was made whether the person was completely stable; one foot or both feet slipped away a little; stepped back a certain distance; or became completely unstable and was saved by the lifeline. But also the moment was established, by looking picture by picture, when the front reached the feet and when the first movement of feet and/or body was observed. The time difference would show whether the wave front (impact) would destabilise the person, or maybe a larger actual flow velocity a little later than the wave front. Figure 16 and Figure 17 show four overtopping wave volumes, two at the crest and two at the slope. The pictures show first a situation before the water reached the volunteer, then when the water arrived at the feet and finally the reaction of the volunteer. The left pictures show a situation where the volunteer remained stable, although sometimes with a reaction of stepping back a few decimetres. The pictures on the right side show a situation where the volunteer could not remain stable and was saved by the safety line.

Figure 16: A wave overtopping volume of 1500 l/m passing the crest (left pictures). The feet slipped away about 0.2 m. A wave overtopping volume of 3500 l/m passing the crest (right pictures). The volunteer was washed away.

Figure 17: A wave overtopping volume of 1250 l/m passing the slope (left pictures). The volunteer stepped back about 0.5 m. A wave overtopping volume of 2000 l/m passing the slope (right pictures). The volunteer was washed away.

The results of the analysis of the videos and the data in Figure 14 have been gathered in Table 3 for position 1 on the crest and in Table 4 for position 2 on the landward slope. Volumes of 1000 l/m flowing over a horizontal surface with front velocities up to 4.9 m/s and a flow thickness of 0.12 m were no problem for the volunteer. First signs of instability occurred for an overtopping wave volume of 1250 l/m, when one foot slipped away a little. The volunteer reacted on this by changing his standing position slightly: he bended his knees a little. In fact he became more an experienced person, knowing what was coming to him and trying to stay on his feet as long as possible. He did not move for the third overtopping wave volume of 1250 l/m.

Table 3: Observations and analysis of a volunteer at the crest of the dike subjected to overtopping wave volumes.

Overtopping wave volume (l/m)	Observation	Unstable after front reached (s)	Front velocity (m/s)	Flow thickness (m)
200	Stable		3.5	0.06
200	Stable		3.5	0.06
400	Stable		4.3	0.07
400	Stable		4.3	0.07
600	Stable		4.6	0.08
600	Stable		4.6	0.08
800	Stable		4.8	0.10
800	Stable		4.8	0.10
1000	Stable		4.9	0.12
1000	Stable		4.9	0.12
1250	One foot slipped away about 0.2 m	0.44	5.0	0.13
1250	One foot slipped away a few cm	0.78	5.0	0.13
1250	Knees bend; stable		5.0	0.13
1500	Feet slipped away about 0.2 m	0.42	5.1	0.14
1500	Feet slipped away about 0.2 m	0.22	5.1	0.14
1500	Stable		5.1	0.14
2000	One foot slipped away about 0.3 m	0.26	5.3	0.16
2000	One foot slipped away about 0.3 m	0.36	5.3	0.16
2000	One foot slipped away about 0.3 m	0.26	5.3	0.16
2500	Stepped back about 0.5 m	0.16	5.6	0.17
2500	Stepped back about 0.5-1 m	0.22	5.6	0.17
2500	Stepped back about 0.5-1 m	0.20	5.6	0.17
3000	Stepped back about 1-1.5 m; safety line used	0.10	5.8	0.19
3000	Stepped back about 1-1.5 m; safety line used	0.16	5.8	0.19
3000	Stepped back about 1-1.5 m; safety line used	0.14	5.8	0.19
3500	Completely unstable; saved by safety line	0.12	5.9	0.20
3500	Completely unstable; saved by safety line	0.10	5.9	0.20
3500	Completely unstable; saved by safety line	0.12	5.9	0.20

With 2000 l/m one foot slipped a little, with 2500 l/m he had to step back about 0.5 m to 1 m and with 3000 l/m he had to step back more than 1 m. For this condition the front velocity became 5.6 m and the flow thickness 0.17 m. By stepping back 1 m he got a little support from the lifeline that came under tension. Without a safety line he would probably have fallen. With a little larger overtopping wave volume of 3500 l/m, a front velocity of almost 6 m/s and a flow thickness of 0.20 m he washed away from the crest.

The volunteer was less stable on the landward slope. This was partly due to the slope (not standing on a horizontal surface), but also due to a more slippery and a little uneven surface, and finally due to larger front velocities with the same overtopping wave volumes (acceleration down the slope). When he was standing at the crest, he could build up some experience as the first overtopping wave volumes were quite small (starting with 200 l/m). As nothing happened at the crest up to a volume of 1000 l/m, this series on the slope was started with 600 l/m, a front velocity of 4.9 m and a flow thickness of 0.08 m. The first wave on the slope was a new experience for the volunteer. He stepped down about 0.5 m.

With this experience, he bended his knees again slightly and was better prepared for the next volumes. He was now stable up to an overtopping volume of 1000 l/m, a front velocity of 5.6 m and a flow thickness of 0.10 m. For a volume of 1250 l/m he had to step back about half a metre. For an overtopping wave volume of 1500 l/m, a front velocity of 6.0 m and a flow thickness of 0.12 m he had to step back more than one metre and in the three cases he was caught by the safety line.

For a volume of 2000 l/m he became directly unstable and washed away. For all the tests the volunteer was standing with his feet in the direction of the flow. For the last overtopping wave volume of 2000 l/m he prepared himself by standing sideways with bended knees. Nevertheless, he swept away from the slope immediately when the flow reached him.

Table 4: Observations and analysis of a volunteer at the landward slope of the dike subjected to overtopping wave volumes.

Overtopping wave volume (l/m)	Observation	Unstable after front reached (s)	Front velocity (m/s)	Flow thickness (m)
600	First wave; stepped down 0.5 m	0.26	4.9	0.08
600	Stable; knees bend		4.9	0.08
800	Stable; knees bend		5.1	0.09
800	Stable; knees bend		5.1	0.09
1000	Stable; knees bend		5.6	0.10
1000	Stable; knees bend		5.6	0.10
1000	Stable; knees bend		5.6	0.10
1250	Stepped back with one foot about 0.5 m	0.41	5.8	0.11
1250	Stepped back both feet about 0.5 m	0.34	5.8	0.11
1500	Stepped back 1-1.5 m; safety line used	0.07	6.0	0.12
1500	Unstable; saved by safety line	0.07	6.0	0.12
1500	Completely unstable; saved by safety line	0.07	6.0	0.12
2000	Completely unstable; saved by safety line	0.05	6.2	0.14
2000	Standing sideways; saved by safety line	0.07	6.2	0.14

It is clear that a position on a horizontal surface is more stable than on a slope. The tests also showed that an "inexperienced" person, who had not yet experienced becoming unstable in a certain way, moved earlier by an overtopping wave than on subsequent occasions, after he got this experience. On the crest the volunteer slipped away a little for the first time for an overtopping wave volume of 1250 l/m. When he bent his knees a little, he was better prepared for what was coming and survived the next volume of 1250 l/m. Something similar happened on the slope. The first overtopping wave volume of 600 l/m let him step down half a metre. But then he bent his knees again a little, was better prepared, and maintained stability even up to an overtopping discharge of 1000 l/m. With respect to guidance on admissible wave overtopping from these tests, one should take this into account, although it is well possible that a similar procedure will occur in reality.

On a horizontal surface the volunteer became initially unstable (stepping or sliding back a little) for an overtopping wave volume of 1500 l/m with a front velocity of 5.1 m/s and a flow thickness of 0.14 m (without air entrainment). Note that this overtopping wave volume of 1500 l/m is similar to the maximum overtopping wave volumes during the Delta flume tests, see Figure 6. On the slope this happened for an overtopping wave volume of 1250 l/m, a front velocity of 5.8 m and a flow thickness of 0.11 m. Note that the front velocity on the slope was larger than on the horizontal surface, which was opposite for the flow thickness.

Complete instability occurred on a horizontal surface for 3000 l/m with a front velocity of 5.8 m and a flow thickness of 0.19 m. On the slope this became a much smaller value of 1500 l/m with a front velocity of 6.0 m/s and a flow thickness of 0.12 m. The reason for the larger difference between horizontal surface and slope than for becoming initially unstable, is that on a horizontal surface the volunteer could step back more than 1 m and still remain standing. But stepping back more than one metre on a slope led to slipping away completely. Table 3 and Table 4 show that complete instability occurred often after about 0.1 s of water reaching the person. This is more or less equal to the time of maximum velocity.

4 Admissible wave overtopping

The results of the Delta Flume tests from Chapter 2 and the results from the wave overtopping simulator from Chapter 3 can now be added to Figure 1, the modified graph of Sandoval and Bruce (2017). The velocities and flow thicknesses derived for the Delta Flume tests were based on EurOtop (2018) and have small scale tests as a basis. This means that there was much less air entrainment in the overtopping flow than in reality. This should be taken into account. The velocities during the tests with the wave overtopping simulator were measured, but the flow thickness was determined by calculation, using the overtopping wave volume, the maximum velocity and the flow duration. This calculation also ends up with a flow thickness without air entrainment. The air entrainment is not known and may also vary with flow velocity and thickness. But it may not be ignored as for these high velocities there will always be air entrained.

The air entrainment is clearly visible in Figure 16 and Figure 17. At the second photograph of the series of three the flow reaches the feet of the volunteer. The side boards in the photograph are 0.6 m high. The overtopping wave volume of 1500 l/m (left middle picture in Figure 16) shows an estimated flow thickness of 0.2-0.3 m, where the flow thickness as calculated without air entrainment was 0.14 m. For the larger overtopping wave volume of 3500 l/m (right middle picture in Figure 16) there is a large variation in flow surface, indicating a flow thickness between 0.3-0.6 m, where the calculated flow thickness without air entrainment was only 0.20 m. These estimations give an air entrainment of 30-53% for the overtopping wave volume of 1500 l/m and 33-67% for the volume of 3500 l/m. The figures are well in the range of 30-50% as mentioned by Klein Breteler and Smith (1996).

From the tests in the Delta Flume and the tests with the simulator it has become clear that friction instability, a drag force on the feet by the flow, is the failure mechanism and not moment instability. The drag force needs the product of flow thickness and mass density of the flow. Air entrainment changes both the flow thickness and mass density, but the product remains constant. In order to overcome the discussion or problem with air entrainment it is acceptable to use always a flow thickness without air entrainment and with a mass density of the water without air entrainment. Considering the available data, the fluvial tests have probably low air entrainment and the data are correct. Also the calculated flow thickness in the tests of the Delta Flume and the calculated flow thickness in the simulator tests are given without air entrainment and do not have to be modified. Only the tests from the videos of Sandoval and Bruce (2017) are based on real hazards and the flow thickness was derived from the actual event, including air entrainment. These data should be modified to flow thicknesses without air entrainment in order to make them comparable with the other data. Most of these data have flow velocities between 3-5 m/s, which is on the lower side of the full range of 3-8 m/s for wave overtopping, see Figure 1. Smaller overtopping wave volumes and smaller flow velocities have also less air entrainment than the 30-50% as mentioned in this paper for larger velocities. Therefore it is assumed that the air entrainment in all the observations by Sandoval and Bruce (2017) is 25% and the flow thickness observed has been reduced according to this percentage. In reality this percentage may of course vary with 5-10%.

Figure 18 shows the results of earlier fluvial studies, the video analysis on real hazards by Sandoval and Bruce (2017), now modified for a flow thickness without air entrainment and the new results from the Delta Flume and wave overtopping simulator. The novelty of the graph is for wave overtopping flows, where flow velocities are often larger than 3 m/s and flow thickness smaller than 0.5 m. Part of the fluvial situations (all unstable) have also been given for smaller flow velocities and flow depths, where moment instability may be the failure mechanism. For this reason the curve for friction instability has been terminated at a flow depth or thickness of 0.6 m. All red symbols give unstable situations, all black symbols stable situations and the yellow symbols give a situation in between, where the person reacted, but did not fall.

In general, the stable situations are below the unstable situations and the initially stable situations are in between. Some deviations do exist, for example for test 114 of the Delta Flume, where the volunteer remained always stable. But the unstable situation for test 112a of the Delta Flume with a wave height of 1.8 m and maximum overtopping wave volumes of 1500 l/m coincides well with the test of the wave overtopping simulator.

The friction instability curve by Sandoval and Bruce (2017) fits fairly well for flow velocities larger than 5 m/s, but is too high for flow velocities smaller than 4 m/s. Of course, the curve depends on the size of the person, a smaller person will get a lower curve than a larger and heavier person. The friction instability curve of Sandoval and Bruce (2007) that accounts for buoyancy is given as follows:

$$v = \sqrt{\frac{2 \cdot m \cdot g \cdot \mu}{\rho \cdot C_D \cdot B} \cdot \frac{1}{h} \cdot \left(1 - \frac{h \cdot \rho}{\rho_0 \cdot h_p}\right)} \tag{1}$$

where:

v = flow velocity in overtopping wave volume (m/s)
m = mass of person (kg)
g = gravitational acceleration (m/s^2)
μ = friction coefficient = 0.62 (wet, smooth concrete, based on Endoh and Takahashi 1994) (-)
ρ = mass density of water (kg/m^3)
C_d = 1.1(1 – L_f/h_p) (-)
L_f = width between feet, taken as 0.2h_p (m)
h_p = height of person (m)
B = width of projected area of the body against the flow (diameter of legs) (m)
h = flow thickness in overtopping wave volume (m)
ρ_0 = mass density of human body = 1062 kg/m^3

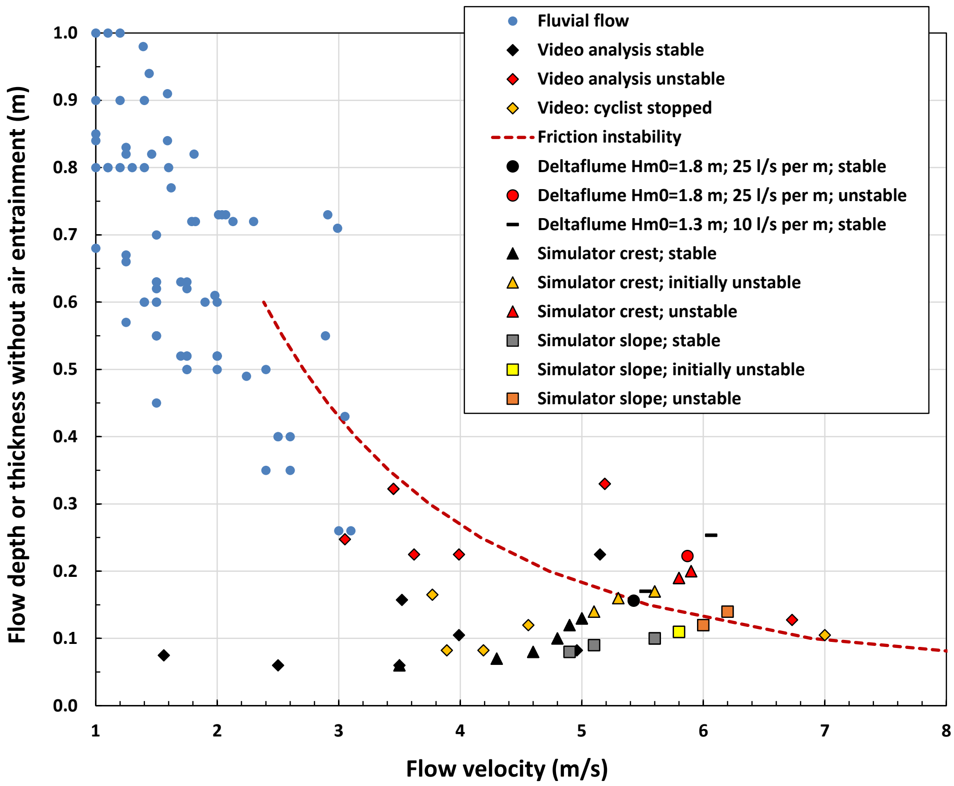

Figure 18: Stable and unstable situations of pedestrians for wave overtopping flow over a more or less horizontal surface as a function of flow velocity and flow depth (fluvial situations – blue symbols) or flow thickness (wave overtopping – all other symbols). The red dashed line proposes the transition between stable (below the line) and unstable situations according to Eq. 1.

The curve in Figure 18 by Sandoval and Bruce (2017) is given by m = 72.54 kg; ρ = 1000 kg/m^3; B = 0.2 m; and h_p = 1.76 m. Figure 19 shows the same data and original curve as in Figure 18, but now the data have been grouped together for the wave overtopping data and three curves are given for three different types of person. The curves are for a child of 40 kg and a length of 1.25 m and two persons with respectively 60 kg and length 1.6 m and 80 kg and length

1.8 m. For the child B = 0.15 m was taken and for the other persons B = 0.20 m. In all cases fresh water was used with ρ = 1000 kg/m^3. The curves give clear deviations between the persons and the curve with the person of 60 kg may be seen as a good transition between the stable and unstable situations. But it still does not represent flow velocities smaller than 4-5 m/s.

Eq. 1 is physically based and can be used for flow velocities v > 4.5 m/s. Based on the observations and not on theory, a simple declining straight line would quite well give the transition between stable and unstable situations, as shown in Figure 19. At least all unstable situations for a more or less horizontal surface are now above the line, as well as a few initially unstable situations.

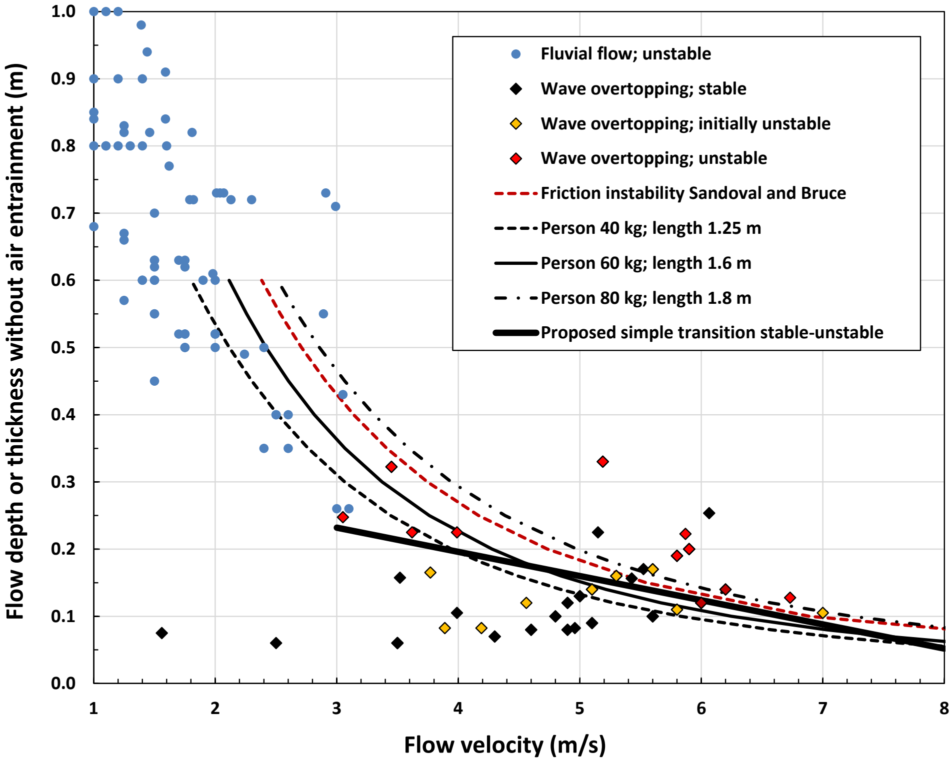

Figure 19: Stable and unstable situations of pedestrians for wave overtopping flow over a more or less horizontal surface as a function of flow velocity and flow thickness. Four curved lines show the difference in person's weight from 40 kg to 80 kg, according to Eq. 1, but they all overestimate stability for velocities smaller than 4.5 m/s. The straight black line gives a simple transition between stable and unstable and can be used for velocities larger than 3 m/s (Eq. 2).

The proposed simple transition line between stable (smaller h) and unstable situations (larger h) for wave overtopping flow over a horizontal surface towards pedestrians can be given by:

$$h = 0.34 - 0.036v \text{ with } 3 \text{ m/s} \leq v \leq 8 \text{ m/s} \tag{2}$$

This gives a combination of 4 m/s flow velocity with a flow thickness of 0.2 m as well as 7 m/s flow velocity with a flow thickness of about 0.1 m. Eq. 2 does not represent a theory and does not deviate in type of person, but it is valid for most persons and from front velocities larger than 3 m/s. Eq. 1 as a theoretically sound equation is not valid, as non-conservative, for front velocities smaller than 4.5 m/s. In all cases the flow thickness is considered as having no air entrainment and a mass density connected to this situation (fresh or salt water).

5 Conclusion

The work of Sandoval and Bruce (2017) on resistance of people/pedestrians to fluvial flow and wave overtopping has been extended with a focus on wave overtopping only. This means in general flow velocities larger than 3 m/s and flow thicknesses smaller than half a metre. Tests in the Delta flume with a volunteer on the crest of the dike resulted in calculated maximum velocities and flow thicknesses that were quite similar in two tests. But one test with an overtopping discharge of 25 l/s per m and a significant wave height of 1.8 m twice showed instability for the volunteer, where the other test showed no instability with a discharge of 10 l/s per m and a significant wave height of 1.3 m. It can be concluded that the equations in EurOtop (2018) for flow velocity and flow thickness are not able to distinguish sufficiently between the two situations. Further research on this topic is encouraged.

The tests with the wave overtopping simulator gave accurate flow velocities and flow thickness for stable, initially unstable and fully unstable situations. The flow thicknesses for the Delta flume tests as well as for the tests with the wave overtopping simulator, were established without air entrainment. This air entrainment in reality is significant and of course enlarges the flow thickness, but reduces mass density. For friction instability, however, the product of flow thickness and mass density is important and this product does not change with air entrainment. Therefore, it is advised to use always the flow thickness without air entrainment and with the normal mass density of water. The data for the videos by Sandoval and Bruce (2017) had to be adjusted for air entrainment. For these test data 25% air entrainment was a priori assumed.

A physically based transition between stable and unstable situations is given by Eq. 1, but this equation is only applicable for flow velocities larger than 4.5 m/s. A simple and easy applicable transition is given by Eq. 2 that may be used for flow velocities between 3 and 8 m/s. In general people may withstand overtopping flows of 4 m/s with a flow thickness of 0.2 m as well as a very fast overtopping flow of 7 m/s, but now with only a flow thickness of 0.1 m.

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Author contributions (CRediT)

JvdM: Conceptualization, Formal Analysis, Writing-original draft, Visualization, Editing. GJS: Logistic performance of testing with the wave overtopping simulator. TB: Originator of the preceding work by Sandoval and Bruce (2017) and manuscript internal review. MKB: Originator of the Delta flume tests by Klein Breteler and Smith (1996) and manuscript internal review.

Notation

Name	Symbol	Unit
Width of projected area of the body against the flow	B	m
Drag coefficient	C_d	-
Gravitational acceleration	g	$\mathrm{m/s^2}$
Flow thickness of overtopping wave	h	m
Maximum flow thickness	h_{max}	m
2%-value of flow thickness	$h_{2\%}$	m
Height of person	h_p	m
Width between feet	L_f	m
Mass of person	m	kg
Probability of overtopping waves	P_{ov}	-
Mean wave overtopping discharge	q	l/s per m
Flow velocity of overtopping wave	v	m/s

Maximum flow velocity	v_{max}	m/s
2%-value of flow velocity	$v_{2\%}$	m/s
Maximum volume	V_{max}	l/m
Influence factor for roughness	γ_f	-
Mass density of water	ρ	kg/m³
Mass density of human body	ρ_0	kg/m³
Friction coefficient	μ	-

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