WAVE IMPACTS AT SMALL AND REAL SCALE FOR THE STEPPED SLOPED SEAWALL DESIGN AT DEN OEVER

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The dike in Den Oever has to be improved. To keep the dike as low as possible and to make it suitable for other uses, the choice was made to install a stepped revetment on the sea side. In order to determine the design wave loading, scale model tests and tests at full scale were performed. The comparison shows that loads, as a result of model and scale effects and by averaging the sensor signals, could be decreased by a factor 4 relative to the scale model tests.

Key words: stepped revetment, scale model test, full scale test, wave run-up simulator, pressure measurements, model and scale effects

DIKE IMPROVEMENT DEN OEVER

Den Oever is a harbour location at the Wadden Sea with a connection to the Lake IJssel by means of a ship lock, see Figure 1. Between the village and the harbour a dike is present which must ensure the village and the hinterland are protected against flooding, also with extremely high water levels and wave loads.

Figure 1: section "Havendijk A" Den Oever with as red line the dike to be improved

The periodic safety assessment of the dike in Den Oever led to the conclusion that the dike no longer meets the legal standards for water safety. It became apparent that the height of the flood defence is insufficient to adequately withstand wave overtopping under extreme conditions. Extreme conditions means in this case a water level with associated waves which has an exceeding frequency of 1/4000 per year. A first study for the necessary improvement of the flood defence indicated that the dike along the village would have to be raised by approximately 3 meters.

The Den Oever harbour is very much connected to the village, but the dike forms a physical barrier. Raising the dike by three meters means that the barrier effect of the dike will increase significantly not only in height but also in footprint. This was not acceptable for the fishermen who use the area for drying their nets. Therefore, it was investigated to limit the heightening (and footprint) as much as possible. Part of the solution is the upgrading of a number of present fore-lying dams, see Figure 1, as part of the dike reinforcement project. Hereby, the hydraulic loading on the dike is reduced.

The required height of the dike is determined by the hydraulic loads in combination with the geometry and roughness the waves encounter on moving up the dike. If the criterion is maintained that

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no or only very little water may come over the dike during extreme conditions, then a smooth dike requires a higher crest than a dike with roughness.

For this reason, a rough seaward slope of the dike was sought, taking into account that the dike is part of the village and part of the harbour. The ambition of the municipality and the village was to make the village and the harbour more attractive. Therefore it was studied whether the rough slope, besides the function for the water safety, could also fulfil a broader social function. This has led to the idea of a stepped revetment on the seaward slope that can also function as a grandstand to view the harbour activities and for possible festivities which could be organised on the harbour terrain.

The effectiveness of a stepped revetment was tested a generic way in a scale model tests on a geometric scale of 1:10 (Deltares, 2012 and Van Steeg et al, 2018). In these experiments systematic variations of wave conditions and dike geometries were made. From the standpoint that the stepped revetment, besides a water safety function, also has a grandstand function, the ideal seating height was studied. Literature study revealed that this is 0.46 m for Dutch people. Therefore, this height was assumed in the determination of the effectiveness of the stepped revetment. Furthermore, the effect was studied of reducing the height of the step to 0.23 m. The results of the model tests showed that with the hydraulic loading associated with the norm conditions, a stepped slope with a step height of 0.46 m has a roughness coefficient γ_f of 0.6 to 0.7. These values have been corrected for model and scale effects. For a step height of 0.23 m, γ_f was found to be 0.8 to 0.9. A larger step height is in the case in Den Oever therefore more effective in reducing the wave run-up.

After the effectiveness on wave overtopping was determined, a first design of the dike in Den Oever with this effective stepped slope was made (see Figure 2). This pre-design of the dike then was tested in a scale model (Deltares, 2013). By means of these tests, the required height of the dike at the various cross-sections was determined.

For making a detailed design of the stepped revetment, a design methodology (HHNK, 2014) was developed during the project. In this methodology the various possible fail mechanisms were studied and attributed to a calculation methodology to determine the strength properties of the stepped revetment. In the design process it is essential to know the wave loading in terms of pressures, forces and impulses on the elements. For this analytical methods were considered and furthermore, pressure sensors were placed in the in the laboratory tests (Deltares, 2013).

It is generally known that in scale laboratory tests for hydraulic loads on structures, model and scale effects may be present. In order to determine the wave loading on the stepped revetment for Den Oever tests were performed at full scale using the wave run-up simulator (Van der Meer, 2012). In this paper, both tests at small and full scale are considered and compared with each other. The result was adopted by the contractor as the starting point in the final design of the stepped revetment.

SCALE MODEL WAVE LOADING

The scale model research was carried out in the Deltares Eastern Scheldt Flume with a geometric scale of 1:10. The Eastern Scheldt Flume is 55 m long, 1.00 m wide and 1.25 m high. The flume has a wave generator where both regular and irregular waves can be created. The wave generator has a wave reflection compensation system and can generate second-order waves All values mentioned in this paper are corresponding to the prototype (this is the 1:1 reality) unless otherwise indicated. The Froude scaling was used to determine the dimensions of the structure and the hydraulic pre-requisites to be used in the model.

The structure was installed in the flume, see Figures 2 and 3. It concerns the pre-design of the seaward side of one of the cross-sections of the future dike (the most north westerly part).
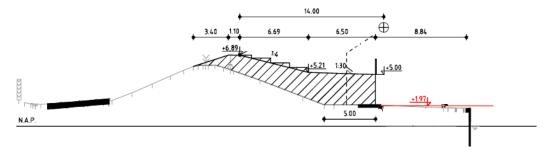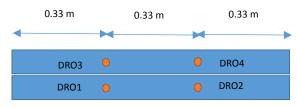

Figure 2: Cross-section pre-design (all measures in m)

Figure 3: Test stepped structure installed in the Eastern Scheldt Flume

In this cross-section, two pressure sensors were installed in the vertical part of the lower step, see Figure 4, (DRO1 and DRO 2: NAP + 5.44 m) and in the second lower step (DRO 3 and DRO 4: NAP + 5.90 m), where NAP is reference level. The pressure sensors were placed at a distance of 0.33 m from the channel sides and 0.33 m apart (model values). During the test, the pressures were recorded with a sampling frequency of 1000 Hz in order to measure very short but high peak pressures and also quasi static pressures after the peak.

Middle step 0.046 m high (pressure sensor at 0.023 m from the bottom: 5.90 m NAP in prototype (5.21 m NAP + 0.46 m + 0.23 m])

Bottom step 0.046 m high (pressure sensor at 0.023 m from the bottom: 5.44 m NAP in prototype [5.21 m NAP + 0.23 m])

Figure 4: front view pressure sensors (sizes in model)

The measured hydraulic conditions just in front of the structure at the test were: Water level h = 5.05 m NAP, Wave height H_{m0} = 1.41 m and Wave period $T_{m-1.0}$ = 5.2 s.

For each pressure sensor the maximum measured pressure was determined and these are shown in Table 1.

Table 1. Maximum measured pressures (prototype values)	
Pressure sensor	Maximum pressure (kN/m^2)
DRO01	99
DRO02	119
DRO03	110
DRO04	66

For all measurements, the distribution of the peak pressures was generated, see Figure 5.
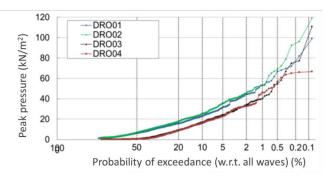

Figure 5: Exceedance curves of the measured peak pressures in the Eastern Scheldt Flume (prototype values).

It can clearly be seen that the pressures on the bottom step (DRO01 and DRO02) are higher than on the step above (DRO03 and DRO04).

For the design of the stepped revetment it is important to know the forces the structure must be able to withstand without being displaced. The pressures were converted to forces on the steps. Hereby it was assumed that the measured pressures apply over the entire height of the step. Further it was assumed that the average of two pressure records could be used as given in equations 1 and 2.

$$P_{bottom\ step}(t) = \frac{P_{DRO01}(t) + P_{DRO02}(t)}{2} \qquad (1)$$

$$P_{second\ step}(t) = \frac{P_{DRO03}(t) + P_{DRO04}(t)}{2} \qquad (2)$$

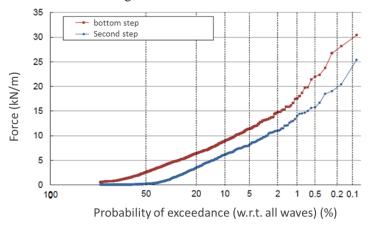This results in the force distribution in Figure 6.

Figure 6: Exceedance curves of the force per m width on the steps (prototype values).

When the peak pressures of Figure 5 would occur in both pressure sensors at exactly the same time, the force per unit of width is approximately 50 kN/m [(119 kN/m^2+99 kN/m^2)/2 * step height 0.46 m]. This is considerably more than can be seen in Figure 6. In Figure 6 the maximum force is equal to 31 kN/m. This difference can be explained by the fact that the maximum peak pressures at the left and right pressure sensors do not occur at exactly the same moment.

FULL SCALE STUDY WAVE LOADING

The maximum measured pressure in the Eastern Scheldt Flume was 119 kN/m^2. Due to scale and model effects (among others, fresh vs. salt water) the actual pressures could be lower by a factor up to 2. To measure the actual pressures a full scale test (scale 1:1) with the wave run-up simulator (Van der Meer et al. 2012, Steendam et al. 2016) was performed, see Figure 7.

Figure 7. Wave impulse with the wave run-up simulator

For model verification for wave run-up on grassed dike slopes in 2014 wave run-up tests were performed with the wave run-up simulator at the dike between Kats and Colijnsplaat at Noord Beveland (Steendam et al. 2017). This test configuration was used to determine the wave loading for Den Oever.

First it was verified whether the loading from the scale model tests in the Eastern Scheldt Flume could be compared with the tests with the wave run-up simulator, see the next section.

Verification of the applicability of the wave run-up simulator as an instrument for carrying out the full scale test

The loading on the stepped revetment is caused by the water flow. Therefore a comparison has been made between the laboratory test and the full scale test concerning the front velocities of individual waves on the quay in front of the structure. The waves overtopping the quay from the laboratory test were analysed using video analysis. The results of the video analysis were then compared with the velocity measurements performed for the wave run-up simulator.

Based on a limited number of large waves in the laboratory test (6 waves which caused wave run-up over the structure or ran high up the slope), it was determined that the wave front velocity on the berm was between 4.5 and 7 m/s. Because the analysis was done with a limited number of waves, it is probable that the highest waves in the test were not analysed. By applying a Rayleigh distribution an extrapolation was carried out to the highest waves in the test. Based on a test with 1000 waves, this means an exceeding frequency of 0.1%. This leads to a front velocity of the highest waves of approximately 8 - 9 m/s.

Earlier measurements with the wave run-up simulator indicated that these velocities could be reproduced with this device. This provided sufficient confidence that the tests with the wave run-up simulator could be applied as full scale test as a means to determine the wave loading to be taken into account in the design of the stepped revetment at Den Oever.

Layer thickness

It was found that the maximum layer thickness's in the laboratory test were substantially larger than those measured with the wave run-up simulator. With the wave run-up simulator, layer thickness's were generated up to 0.7 m while in the laboratory tests the thickness's varied from 0.6 to 1.2 m (prototype). The full scale tests were intended to determine the wave forces on individual steps. Because the layer thickness which needed to be reproduced is larger than the height of the step (0.46 m), the whole step is loaded. In practice, also the second step will be loaded but it is assumed that the bottom step will have the largest loads. All steps in the design for Den Oever are designed as bottom step. The higher steps are thus over-dimensioned.

FULL SCALE TEST

For the full scale test the wave run-up simulator was moved after the WBI2017 tests to the test strip were hydraulic measurements were performed earlier. With these measurements at various locations on the slope layer thickness's and (front) velocities at various run-ups were measured. The hydraulic measurements were carried out with increasing filling heights of the wave run-up simulator whereby each filling height was repeated three times. These measurements provide insight into the velocities and layer thickness's at various locations on the slope. By comparing the velocity records at various locations the front velocity of the run-up can be determined.

At 5 m from the outflow of the wave run-up simulator the schematic model of the step was installed (see Figure 8).

Figure 8. Overview wave run-up simulator and the first step with 8 pressure transducers.

The tested step corresponds to the schematic cross-section of the design for Den Oever. In the schematic cross section (see Figure 2) there is a 6.5 m wide berm at a slope of 1:30 followed by steps 0.46 m high. The steps lie on a slope of 1:4. The profile at the wave run-up tests at Noord Beveland corresponds to this. The flood defence there has a seaward berm with a slope of approximately 1:30 and is paved with concrete blocks. The test was carried out with salt water (Oosterschelde).

The tested step model has a width of 2 m wide and a height of 0,46 m. The pressure sensors were regularly placed in the cover plate at the front (Figure 9).

Figure 9. Pressure sensors in the step.

The top and bottom sensor are placed 0.095 m from the top and bottom. The distance between the sensors is 0.09 m. The construction of the step was such that there was no movement due to the impact of the waves.

Test program

Figure 10. Impression of wave impact on step.

A series of 3x8 impacts was carried out. For the reproducibility each impact was repeated three times. The wave run-up simulator was filled in stages (1, 2, 3, 4, 5, 6, 7 and 7.3 m). In total, 24 impacts were simulated. At the end of the test program, the impacts with a filling height of 4 and 5 m were repeated twice. Figure 10 shows the development of a wave impact.

Front velocity full scale test

In Figure 11 the locations of sensors during the WBI2017 test are indicated. The location of the sensors in the WBI2017 test at 5m corresponds with the location of the front of the step of Den Oever. These measurements are thus important input for the tests of the stepped revetment.
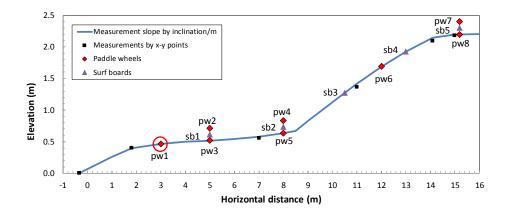
Figure 11. Locations of sensors during WBI2017 test (circled location is also measured during the full scale test).

The measured velocity during the WBI2017 test are presented as a function of the filling height of the simulator in Figure 12.
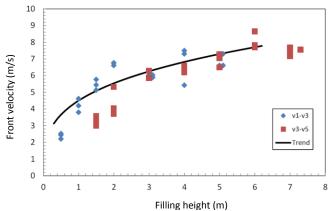

Figure 12. Relation front velocity wave run-up on the berm and filling height of the simulator (v1-v3 means calculated front velocity between paddle wheels 1 and 3. Same for v3-v5).

The trend line which fits up to a filling height of 6 m can be represented by:

$$u_f = 4.5\ h^{0.3}\ (h \leq 6\ m) \tag{3}$$

in which u_f = front velocity in m/s and h = the filling height of the simulator in m. Eq. (3) can also be used to determine the front velocity of the wave which imparts a force against the step of the structure of Den Oever. During the test with the stepped revetment, only the velocity at the location at 3 m (2 m in front of the step) could be measured. This measurement is used as a validation of the hydraulic measurements.

Figure 13 shows an overview of the measured maximum velocities at the point 2 m in front of the step, with and without this step. The measurements with the step (measurement Den Oever) are equal to or slightly higher than without the step (hydraulic measurement). There is no clear reason for this but the differences are small. A trend line is also given for the measured maximum velocity closer to the opening of the run-up simulator, at 1.6 m measured in an earlier test with the wave run-up simulator on another dike with a different cross-section. Especially with large filling heights a higher velocity was found there. For comparison, the trend line (formula 3) for the front velocity found in the hydraulic measurements at the full scale test is also shown. In the figure, the front velocity corresponds reasonably with the maximum velocity which was measured with the test with the step (the blue points).
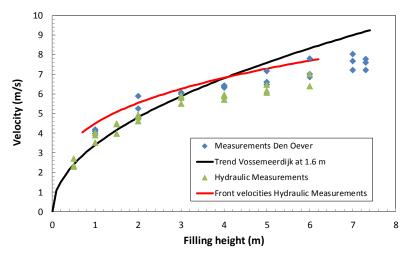
Figure 13. Measured maximum velocity full scale test.

As indicated earlier, to be able to convert the measured pressures to an exceedance curve, a relationship must be determined between the tests in the Eastern Scheldt Flume and the test on site. The starting point is that with the same velocities in the small scale model and full scale test lead to similar pressures or forces whereby in the full scale tests there are no more model and scale effects.

For this, besides the earlier analysis of six large waves, a more extensive analysis of the occurring front velocities was made for the Eastern Scheldt Flume. This analysis concerned all waves in a 10 minute video. Figure 14 shows the exceedance curve of the front velocities. On this line a Rayleigh distribution is fitted and the black continuous line is represented by:
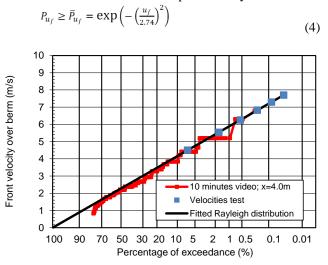
$$P_{u_f} \geq \bar{P}_{u_f} = \exp\left(-\left(\frac{u_f}{2.74}\right)^2\right)$$

(4)

Figure 14. Simulated front velocities coupled with the Rayleigh distribution.

The front velocity from the full scale test can be calculated with Eq. (3). The exceedance probability of this front velocity can be calculated with Eq. (4). This exceedance probability is then also the exceedance probability which must be maintained for the pressures found and wave impacts. This is the basis to link the small and full scale tests. The front velocities from the full scale test are marked with a blue square on the fitted Rayleigh distribution in Figure 14.

Table 2 shows the relation between filling height, front velocity and exceeding frequency in values. Herewith, the relation between the tests with the wave run-up simulator and the test in the Eastern Scheldt Flume is determined. A maximum filling height of 6 m is listed because the front velocity does not increase with greater filling heights.

Table 2. Relation between filling height, front velocity and exceeding frequency		
Fill level (m)	Front velocity (m/s)	Exceedance prob. (%)
1	4.50	6.739
2	5.54	1.677
3	6.26	0.544
4	6.82	0.204
5	7.29	0.084
6	7.70	0.037
7	-	-
7.3	-	-

Pressure measurements

The pressure measurements in the full scale test were sampled with 2000 Hz.
An impression of a measurement (impact 18, pressure sensor 1) is given in Figure 15.
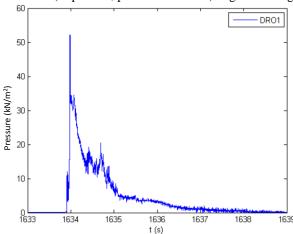

Figure 15. Registration of pressure trajectory during impact 18 (filling height = 6 m) in pressure sensor 1

From Figure 15 (test with a fill height of 6 m) it follows that the maximum measured pressure at this location is equal to approximately 52 kN/m^2. This maximum is reached almost immediately when the water reaches the pressure sensor.

In Figure 16 the trajectory of all pressure sensors during this impact is shown. Here, the upper four figures show the individual pressure measurements. Both pressure sensors at the same elevation are shown in the same figure. The lower figure shows the average pressure across all pressure sensors (also differentiated over the four pressure sensors on the left and the four pressure sensors on the right).

From Figure 16 it can be deduced that each pressure sensor during the recording of impact 18 has a maximum value of between approximately 31 kN/m^2 and 59 kN/m^2. At some pressure sensors a high frequency vibration can be seen. This is possibly a vibration in the construction of the pressure sensor holders. Further, this vibration shall not influence the analysis and results. On the left, the pressure seems to increase after 0.5 s. The reason for this was not investigated.
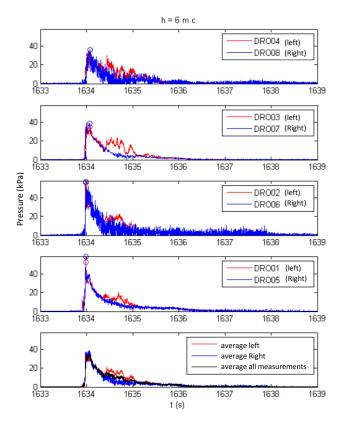
Figure 16. Records of pressure trajectories during impact 18 (filling height = 6 m) in all pressure sensors

The peak pressures have been determined for all impacts per pressure sensor and are shown in Figure 17.
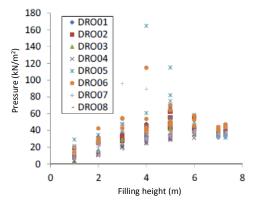

Figure 17. Maximum pressures for all pressure sensors and all tests as a function of filling height (h_{fill}).

In Figure 17 it can be seen that at filling height h_{fill} = 4 m, pressure sensors DRO05, DRO06 and DRO07 recorded a maximum pressure which is clearly higher than the other maximum pressures measured. This is also the case with some other measurements. The scatter however is small. From experience with physical model tests it is known that even with regular waves there may be a significant scatter. This is possibly caused by the variation of the amount of air included the water. Possibly the variation of the shape of the loading (the impact is more like a flow than a breaking wave) is less in this case.

Figure 17 also shows that the pressures on the lower pressure sensors (DRO01 and DRO05) are higher in general than the pressures on the higher placed pressure sensors (DRO04 and DRO08). Further, it appears that the pressure does not seem to increase with a filling height more than 6 m. This can be explained by the design of the simulator. At a certain moment, the water cannot flow out of the simulator any faster.

Forces

Analysis has been performed on the forces on the step as a function of time, F(t). The force is the pressure integrated over the height of the step. With the integration, the (very short) extremes are filtered "naturally". Such an analysis was carried out for all impacts. For all these impacts, the maximum force per unit of width was determined. In Figure 18, this is plotted graphically against the filling height of the run-up simulator.
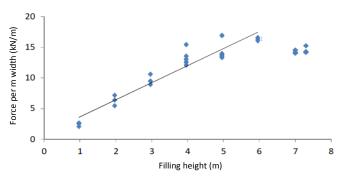

Figure 18. Maximum determined force on the step as a function of the filling height.

In Figure 18 there is a clear link between the filling height and the maximum force on the step. Based on the analysis of both the maximum pressures and the maximum force, it seems there are no more severe impacts above a filling height of 6 m. Based on the data up to a filling height of 6 m, there seems to be a linear relation between the force and the filling height.

The trend line in figure 18 can be described as:

$$F = 2.8\, h_{fill} + 0.7 \qquad \text{for } 1\text{ m} \leq h_{fill} \leq 6\text{ m} \qquad (5)$$

Eq. (5) is not valid for a filling height higher than 6 m (for example, 7 m and 7.3 m) as there is a different trend seen there. With this, the relation between the maximum force on the step and the filling height of the wave run-up simulator is determined.

The corresponding exceeding frequencies are shown in Table 2 and this table together with Eq. (5) lead to six points for the exceedance curve for the forces on the lower step. These points are shown with squares in Figure 19. From the figure it follows that the forces do not follow a Rayleigh distribution but a much steeper distribution (just as individual volumes of breaking waves with wave overtopping).
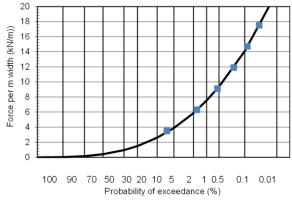

Figure 19. Exceedance curve for the forces on the lower step per m width.

The points in Figure 19 can be fit with a Weibull distribution. Eq. (6) shows the trend line through the points. The number of waves N results in, with $P_F = 1/N$, the probability of the greatest force. With this the necessary safety factors must of course be respected.

$$P_F \geq \bar{P}_F = \exp\left(-\left(\frac{F}{0.72}\right)^{0.65}\right) \qquad (6)$$

The maximum force for N waves can be calculated directly with:

$$F = 0.72 \cdot [-\ln(1/N)]^{1/0.65} \qquad (7)$$

Figure 19 is based on measurements at full scale and with salt water. Prior to the test it was expected that, because of both scale and model effects, the forces in full scale would be smaller than in

the tests in the Eastern Scheldt Flume. The pressures in the Eastern Scheldt Flume were also analysed further. It was seen that the individual pressures of around 120 kN/m^2 can occur but that pressure peaks do not occur simultaneously on a horizontal line, thus not simultaneously on DRO01 and DRO02.

The exceedance curve for the forces determined from the averaging of the peak pressures on the lower step is shown in Figure 20 together with the forces found in the full scale test. With this, the tests in the Eastern Scheldt Flume and the simulator test have become directly comparable. It has to be noted that in small scale tests only two pressure sensors were installed in the lower step whereas in the full scale test eight. This may have been of influence on the difference found.
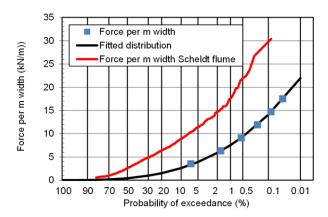

Figure 20. Comparison forces per unit of width for the Eastern Scheldt Flume tests (based on two DRO's) and the simulator tests at full scale (based on eight DRO's).

The forces found in the Eastern Scheldt Flume test are clearly larger than those in the simulator test. On the basis of 1000 waves (0.1%), the force from the Schelde tests is approximately 30 kN/m and for the simulator tests approximately 15 kN/m. This is a factor 2 difference in the maximum force.

It can be concluded that between approaches (a small scale flume test with freshwater and a limited number of pressure sensors and a full scale test with salt water and multiple pressure sensors), there is a factor 2 difference in the (peak) forces on the lower step. Depending on the number of waves or storm duration, in the design approximately 15 kN/m on this step has to be taken into account (without safety factors and unknowns). This is almost four times smaller than was assumed earlier for the first design based on maximum individual pressure peaks in a small scale flume. It should be noted that for final design calculating forces based on individual peak pressures is not an appropriate approach. Eq. (7) can be used to calculate the force on the lower step at a given storm duration.

IMPULSE

The maximum peak forces last only a very short time during a wave impact. It is questionable whether this parameter is the correct one for the design. Impulse (or a parameter derived from this) can possibly be a better determining parameter. The forces (F_{limit}) whereby no movements, deformations, rotations or damage to the block occur may not be included in the determination of the impulse. These forces are already "absorbed" by the friction force and are thus not available to bring the block into motion. The limit value F_{limit} depends on the design of the step. Friction, for example, is one of the resisting forces of a step. Depending on the design, the resisting force due to underlying ground mass and/or resisting force due to higher placed steps may can be considered. Figure 21 shows for one force record (one wave) different threshold values for F_{limit}.
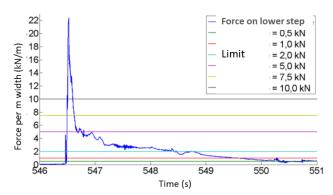
Figure 21. Threshold values for a recorded force signal (one wave)

The integrated area under the threshold value determines the impulse value.

The occurring impulse for each wave in the full scale test is analysed by integrating the force over time. In Figure 22 the result is plotted against the filling height of the run-up simulator.
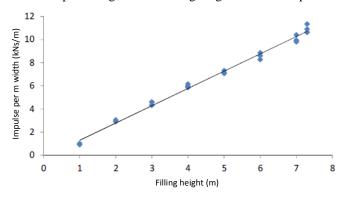

Figure 22. Momentum (or impulse) on the step as a function of the filling height.

In Figure 22, a clear linear relation is seen. The spread is very small. Other than with the forces, measurements with a filling height over 6 m also lie on the trend line. Apparently a filling height even above 6 m leads to a longer lasting loading and not necessarily to a larger maximum force. The formula for the trend line in Figure 22 is:

$$I = 1.5 \, h_{fill} - 0.2 \qquad (8)$$

Whereby I = Impulse per unit of width (kNs/m) and h_{fill} is the filling height of the run-up simulator (m).

In Table the relation between filling height and maximum force and impulse on the step per unit of width is shown. The numerical values for both units are derived from Eq. (3) and Eq. (4). Considering that equation (3) is not valid for a filling height greater than 6 m, for 7 and 7.3 m no forces are shown.

Table 3: Relation between filling height and maximum force and momentum on step		
filling height h_{fill} [m]	maximum force per unit of width F [kN/m]	momentum per unit of width I [kNs/m]
1	3.5	1.3
2	6.3	2.8
3	9.1	4.3
4	11.9	5.8
5	14.7	7.3
6	17.5	8.8
7	-	10.3
7.3	-	10.8

For each identified wave impact on the steps, the impulse was determined.

Also for each of the identified wave impacts on the steps in the tests in the Eastern Scheldt Flume, the impulse was determined. The exceedance curve of the calculated impulse (thus the surface under

Impulse on lower step

the graph but above the limit value) is represented in Figure 23. With this various values of F_{limit} are maintained.
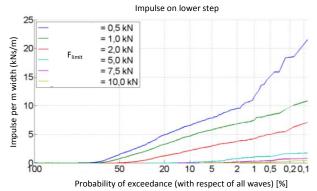

Figure 23. Exceedance percentage of the impulse per unit of width of the steps.

The above was also done for the upper step as measured in the small scale testing. This showed that the impulse on the upper step was clearly smaller than on the lower one. Thus it has been concluded that the lower step is decisive in the design.

From the exceedance curves the exceedance values can be read, for example the impulse at the 2%, 1% and 0.1% exceeding frequency. The exceedance curves were determined for a whole range of limit values F_{limit}. This was done for both the full scale tests and the Eastern Scheldt Flume tests. In Figure 24 both are shown.
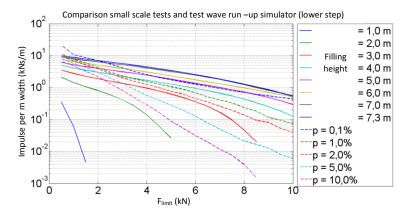

Figure 24. Comparison between the Eastern Scheldt Flume and the wave run-up simulator

As an example, the 0.1% largest wave impacts of the Eastern Scheldt Flume test are considered. These most resemble the test with the run-up simulator with a filling height of 5.0 m. The trajectory of the impulse as a function of the limit value F_{limit} for both cases is shown in Figure 25.
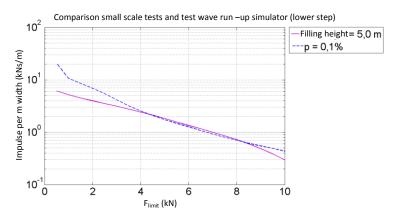

Figure 25. Comparison between the Eastern Scheldt Flume and the wave run-up simulator. Dotted lines indicate the results obtained in the small scale tests, continuous lines indicate full scale tests.

Figure 25 shows that there is much similarity between the 0.1% strongest wave impacts in the Eastern Scheldt Flume and the test with the run-up simulator with a filling height of 5.0 m. This similarity is less evident with a limit value $F_{limit} < 4$ kN. This could possibly be explained because at these lower limit values also the quasi stationary part ("church roof") of the force is included in the determination of the impulse. It is to be expected that the quasi stationary part is less well simulated by the run-up simulator (the run-up simulator is also not designed to simulate this part of the force trajectory). It is expected that this part of the force trajectory is less important because this is probably a smaller force than the limit value F_{limit}.

Concerning possible model effects in the Eastern Scheldt Flume, it is assumed that the impulse is less sensitive than the peak pressure (or the derived peak force). The sharp high peak (church tower) has, because of the very short duration, a relatively small effect on the impulse. This can possibly be explained by the inclusion of air (in freshwater differently than in salt water) whereby the peak in the model can be relatively larger than the peak in reality. By considering the impulse instead of the maximum peak pressure (or the derived maximum force), this possible model effect is negligible. The impulse is thus a more reliable parameter than the maximum pressure or the maximum occurring force.

The impulse in the Eastern Scheldt Flume corresponding to a 0.1% exceedance value was compared with the impulse with the wave run-up simulator corresponding to a filling height of 5.0 m. This shows that the impulses correspond closely (at limit values of $F_{limit} > 4$ kN, which is expected to be the case in practice). This corresponds closely to the study carried out earlier by Van der Meer (2014) in which is stated that a filling height of 5.0 m corresponds to an exceeding frequency of 0.084% (based on analysis of the front velocities).

Both the analysis based on the front velocities and the analysis based on the impulse show a close correspondence between the tests in the Eastern Scheldt Flume and the tests with the wave run-up simulator. Based on this, it is assumed that the maximum forces such as determined with the wave run-up simulator can be used for determining the maximum force on the steps.

CONCLUSIONS

In scale model tests pressures were measured using two pressure sensors. The peak pressure averaged over two pressure sensors at a certain moment appear to be a factor of 2 lower than the maximum peak pressure of an individual pressure sensor.

Analysis of the front velocities of six high waves on the quay in front of the stepped revetment in the scale model showed that the velocities were about 5 to 8 m/s. Measurements with the wave run-up simulator in earlier tests showed that these velocities could be reached with this device.

It is generally known that in small scale model tests there are scale and model effects. A comparison between small scale model tests in a wave flume (with two pressure sensors on one step) and full scale tests with the wave run-up simulator (with eight pressure sensors on one step) on a fabricated corresponding step has indicated that there is a factor of approximately 2 between the measured average peak pressures and therefore also in the derived wave forces to be taken into account in the design of the structure.

Analysis of the "impulse" shows that there is a close correspondence between the small scale model (wave flume) experiments and the full scale (wave run-up simulator) experiments. That corresponds with the fact that in general it is assumed that the "impulse" is less sensitive for scale and possibly also for model effects.

With the above-mentioned conclusions on being able to produce comparable wave front velocities between scale model study and study with the wave run-up simulator in combination with the similarities in the "impulse" between both studies, it became confident that the loading found in the tests with the wave run-up simulator can be used as starting point for the design of the stepped revetment.

Design loadings in the contractor's design could be lowered by a factor of four, using the averaging between multiple pressure sensors and the avoidance of scale and model effects, relative to the earlier estimated values from scale model tests on the basis of the maximum of an individual sensor (not an appropriate method for final design). In the final design calculations a safety factor on the determined values has been taken into account.

ACKNOWLEDGEMENTS

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