Wave overtopping measurements at a real dike

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Abstract: Wave overtopping is not easy to measure in real situations. In a 12-years program wind, wave and water level conditions will be measured in a complex estuary, together with wave overtopping measurements at dikes. The first winter storm has been measured on 8 January 2019. Wave and water level conditions have been measured directly in front of the dike. Overtopping has been measured with two identical overtopping boxes that were placed in the dike, but at different levels. A measuring pole in front of the dike did measure wave and water level conditions already for 10 years and the design of the overtopping boxes was based on those data. This paper describes the analysis of those 10 years of measurements together with the recently measured storm that included wave overtopping. The overtopping box functioned well, but can be optimised for the next year. It appears that measuring in reality is not easy and one needs more time to fine tune the system. A first outcome was that the distribution of overtopping wave volumes differs from expectations that were solely based on physical small scale tests.

Keywords: Wave overtopping, dikes, wave overtopping boxes, wave measurements, field research;

Introduction

The Eems-Dollard estuary in the north of the Netherlands is a highly complex estuary with several barrier islands, deep tidal channels, shallow tidal flats and wetlands, which is part of the Wadden Sea, see Fig. 1. Multiple extensive studies, some including field measurements, have been performed before in the major area of the Wadden Sea, to gain a more detailed understanding of this complex area. These studies mainly focused on the tidal channels and tidal deltas at the transition from the North Sea to the Wadden Sea. The Eems-Dollard estuary itself is an even more complex area and almost no studies have been performed in this estuary and no measurements are available inside the estuary.

A twelve years long lasting research project has started in 2018. The focus of this study lies on the dike section between the Eemshaven (the main port in the area) and the town of Delfzijl, as indicated by the red line in Fig. 1. This dike protects a large part of the province of Groningen from flooding. A particular aspect for this area is that the design conditions for dikes are characterized by very obliquely incident waves, up to 80° relative to the dike normal. Extreme storms in the area tend to start out in the southwest and then turn to the northwest, but they never cross north to become eastward directed. This means, that at the dike of investigation, the wind is offshore directed during extreme conditions, as indicated by the arrow in Fig. 1.

Wind, water levels, currents, waves and wave run-up and overtopping are being measured in this extensive field measurement project. The storms and wave overtopping will be measured and then numerically hindcasted, giving validation and/or improvements to existing predicting models. The measurements on wave overtopping will be compared to guidance as available in EurOtop (2018). The final objective after 12 years will be improved design methods for dike crest level assessments with reduced uncertainties of design parameters.

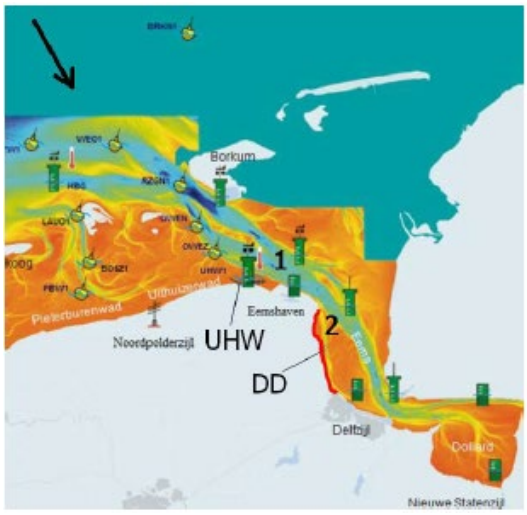

Fig. 1. Eems-Dollard estuary with the deep main channel (indicated by number 1), secondary channel Bocht van Watum (number 2), the dike section of interest (red line), the two locations of interest: Uithuizerwad (UHW) and the Double Dike (DD), and the typical wind direction during extreme conditions (arrow).

Approach on measuring wave overtopping at a real dike

The topic of this paper is on the measurements of wave overtopping at a real dike combined with wave and water level measurements directly in front of the dike. A measuring pole 100 m in front of the dike (location UHW in Fig. 1) exists already for 10 years, giving a good impression of the yearly extreme circumstances with respect to water level and waves. It is for this reason that this dike section has been chosen to measure also wave overtopping. From 2019 also wave overtopping will be measured at a dike section between Eemshaven and Delfzijl (see Double Dike DD number 2 in Fig. 1).

For the specific measurements in the 12 years program extra sensors have been placed like an ADCP and a Wavedroid (a small and cheap wave buoy based on smartphone acceleration techniques). Both are able to measure wave directions and the measurements can be compared with those at the existing pole. The measurements will give the incident wave conditions near the toe of the dike.

The dike is situated with a shallow mud flat in front of it. The waves will always be depth-limited during storms. The dike has a long 1:4 asphalt slope and a grass cover is present near the crest of the dike. The dike itself is so high that only under very extreme conditions, like storms with return periods of 1,000 years or more, some overtopping may be expected. We want to measure overtopping roughly 3 times per year for the extreme yearly storms. To meet this objective, two overtopping tanks have been placed half way the slope into the dike, see Fig. 2. The boxes are about 0.8 m deep and 1.3 m wide and the opening for entering by overtopping waves is 4 m wide. The waves will enter quite oblique with a direction of roughly 50°-65° compared to perpendicular to the dike. The water level in the box is measured by pressure transducers and the water can flow out freely through a calibrated gate in the outflow channel. Two boxes have been installed at different levels in order to be able to measure wave overtopping correctly for storm surges between 2.5 m and 4.0 m above NAP (= Chart Datum).

Fig. 2. The two wave overtopping boxes in the dike. The waves come from the left in the picture and can enter the boxes over a length of 4 m. The structures at the far side in the picture are the outflow channels.

Only one extreme storm occurred in the winter 2018/2019 on 8 January 2019, reaching a maximum water level of 3.19 m. The lowest box has measured many overtopping waves, the highest box only a few. Fig. 3 gives an impression during that storm.

Fig. 3. An overtopping wave entering the lowest box on 8 January 2019.

This paper describes the analysis of wave measurements at the existing pole over the last 10 years, including comparison with the storm of 8 January 2019; the design for the correct placement level of the boxes; and the analysis of the first overtopping measurements, including preliminary comparisons with existing design guidance on wave overtopping.

Wave and water level conditions in front of the dike

Water levels

A measuring pole has been placed in 2008 about 100 m from the dike at Uithuizerwad (UHW), see Fig. 1. At this pole wind and water levels have been measured as well as wave conditions by a step gauge (UHW2) and more recently by a down-looking radar (UHW3). About 10 years of measurements of large storms have been performed. Large storms are defined as conditions where the storm surge at least reaches the level of 2.5 m NAP. Wind velocities are often between 20-25 m/s and wind directions at the peak of the storm around west to northwest (270°-330°). The bottom level at the pole is about 0.65 m NAP, which means that the foreshore becomes dry during low water (without surge). In the period from 2008 17 storms have been selected for further analysis and to predict the kind of water level and wave conditions that might be expected in the 12 coming years of extensive measurements. These expected conditions have also been used to design the size and level of the overtopping boxes.

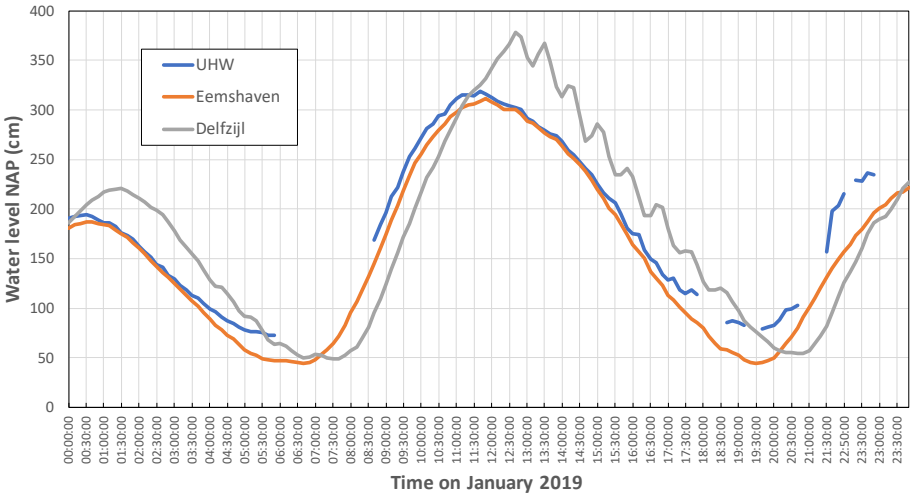

Fig. 4. Water levels measured on 8 January 2019 for the measuring pole (UHW) and two other places, see Fig. 1.

One storm has been measured when the overtopping boxes were present to measure wave overtopping. This storm occurred on 8 January 2019. Fig. 4 gives the water levels for the measuring pole at UHW, at Eemshaven about 4 km further and at Delfzijl, which is more to the south, see Fig. 1. The maximum water level was 3.19 m NAP with an average level around the peak of 3.15 m NAP, which is well above the critical storm surge level of 2.5 m NAP. These measurements can be compared with previous measurements of extreme water levels.

Water levels at the Eemshaven have been measured for a long time and the extreme levels have been given for about the last 30 years in Fig. 5. The 17 selected storms in the period 2009-2017 show only one water level higher than 3.5 m NAP. From the 17 storms in this period only 4 water levels were higher than the water level during the storm of 8 January 2019. This means that this storm had a water level that agrees well with the expected level that may be exceeded in the next 11 years for only a few occasions.

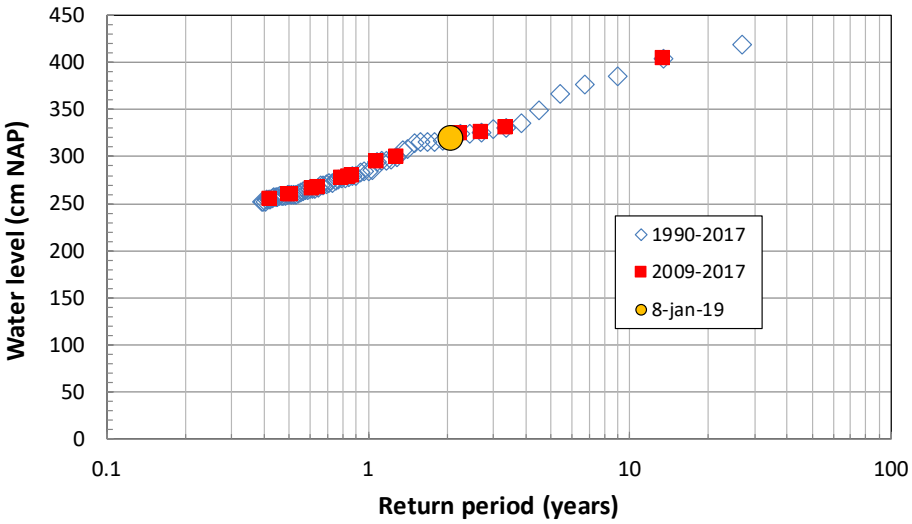

Fig. 5. Extreme water levels over the period 1990-2017, the period 2009-2017 when the measuring pole was present and the water level during the storm of 8 January 2019.

This can also be concluded from Fig. 6, where the water levels of the 17 selected storms are given in ascending order and for 3 locations. The figure also shows that there is quite a good correlation between the water level measurements at the three stations given. The average extreme water level during the peak of a storm at Eemshaven is 0.04 m higher than the average extreme water level at UHW. The difference in averages between Eemshaven and Delfzijl (see Fig. 1) is 0.32 m. As the Double Dike section (DD in Fig. 1) is a little less than half way between Eemshaven and Delfzijl, the expected average extreme water level at DD is then about 0.15 m higher than at the Eemshaven. This can be used to design the overtopping boxes for the DD in 2019.

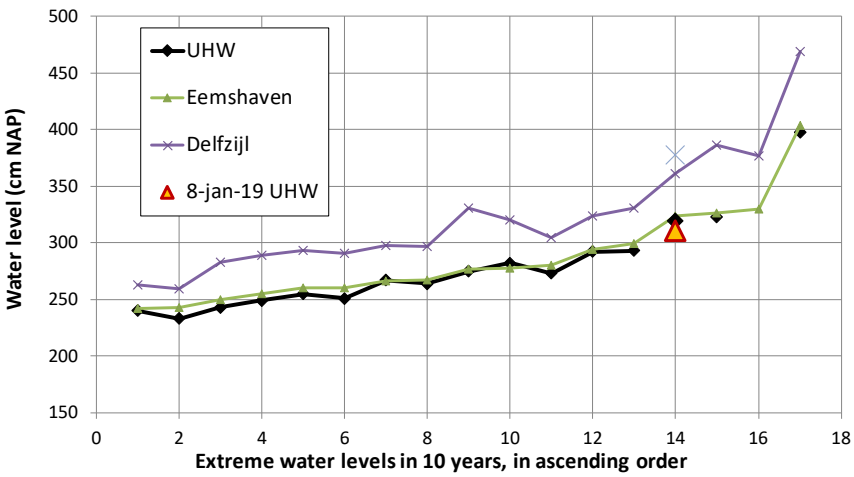

Fig. 6. Extreme water levels for 17 storms in the period 2008-2017 for 3 stations and the measurements on 8 January 2019.

Wave conditions

Wave conditions were measured at the UHW measuring pole by a step gauge (UHW3) and radar (UHW2). Together with the overtopping boxes in the dike also an ADCP and a Wavedroid were installed in 2018, close to the measuring pole. These instruments were expected to give more information than the standard information from the measuring pole, also allowing us to perform more detailed data processing of the peak of the storm. Unfortunately, the ADCP did not measure during the storm of 8 January 2019. It was the first time that a Wavedroid was explored on very limited water depth and it was expected that this small buoy would only measure if 2 m water depth or more would be available. At the peak of the storm of January 2019 the water depth was about 2.5 m, which is sufficient. During data processing it became obvious that sometimes the anchoring of the buoy played a role, giving energy at a large period around 12 s. This had to be filtered out. The results of the Wavedroid will be given here, but are still preliminary.

Fig. 7 gives the wave heights over the full day of 8 January 2019. The spectral wave heights, H_{m0}, are given as well as the significant wave heights from the time domain, $H_{1/3}$. The step gauge UHW3 and radar UHW2 give measurements over a period of 10 minutes. The Wavedroid gives measurements over 30 minutes. The radar missed some periods during the peak of the storm. The radar and Wavedroid give wave heights in the same range, the step gauge heights did not increase during the peak of the storm and it must be concluded that the measurements by the step gauge at that time are not correct. It can also be concluded that the H_{m0} of the radar UHW2 and Wavedroid are quite similar, where the $H_{1/3}$ of the radar is higher than these measurements and the $H_{1/3}$ of the Wavedroid lower. As a preliminary conclusion it seems that the H_{m0} is the most reliable measure.

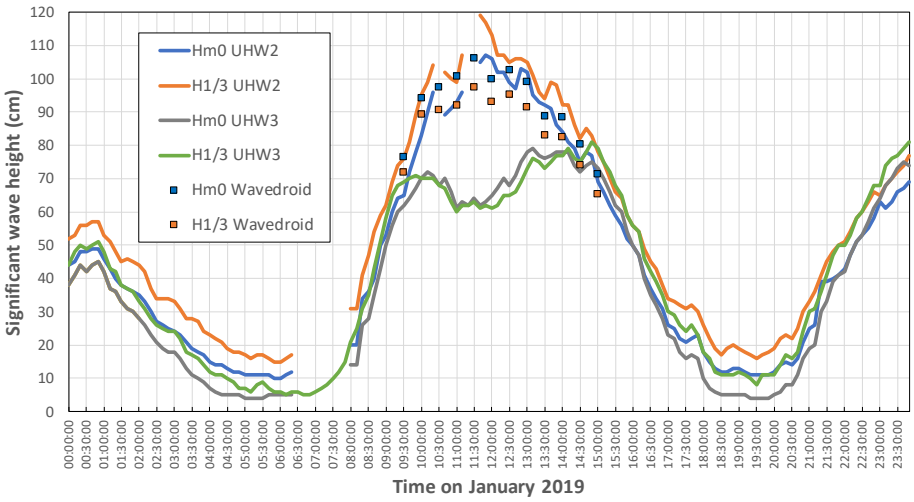

Fig. 7. Wave heights during the storm of 8 January 2019 for three devices at the same location.

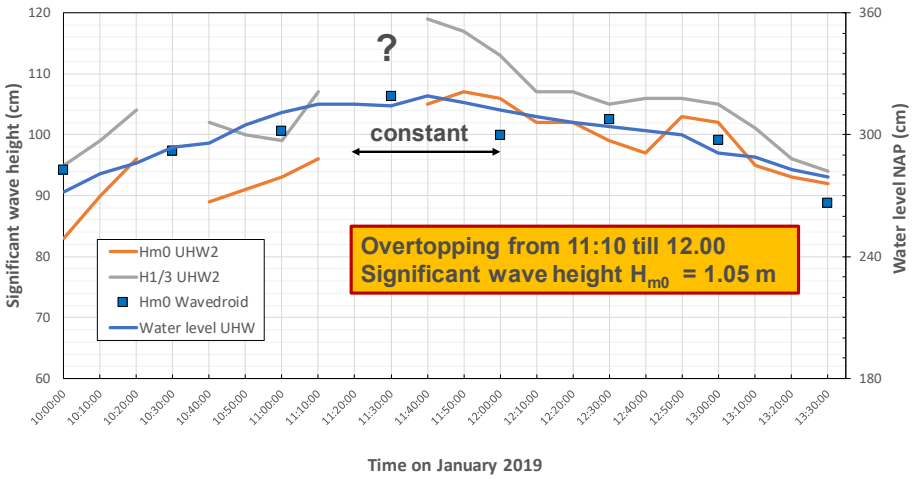

Fig. 8. Wave heights and water levels during the peak of the storm of 8 January 2019.

Fig. 8 gives the details of Fig. 7, during the peak of the storm. Also the water level is given. The water level is more or less constant between 11:00 and 12:00, but the wave height at 11:00 is

significantly lower than between 11:40 and 12:00. The radar UHW2 gives no measurements for two periods (11:20 and 11:30), but the wave droid gives the 30 minute measurement, which is similar to the wave height H_{m0} of the UHW2 for the periods 11:40 to 12:00. Based on these measurements it was assumed that a constant sea state (constant in water level and wave height) was present during the measurements 11:20 till 12:00, with a wave height H_{m0} = 1.05 m. As the measurements took 10 minutes and the data are given after the measurements, the time that the sea state was considered present is from 11:10 to 12:00, which is 50 minutes. This is the time that also wave overtopping circumstances should be considered as constant. Fig. 9 shows the unfiltered water levels of the lowest overtopping box during the storm and indeed the given period to some extent shows a more or less constant behaviour.

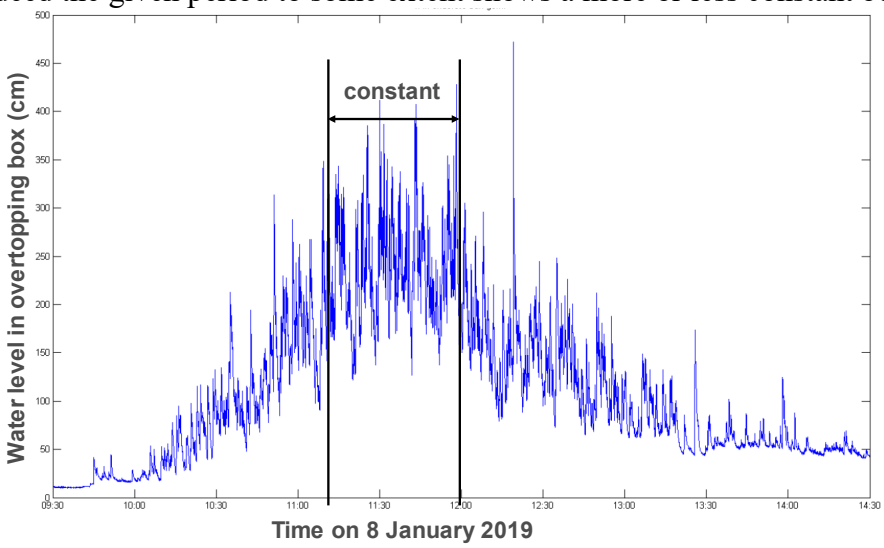

Fig. 9. The water level in the lowest overtopping box, giving a more or less constant picture between 11:10 and 12:00.

Fig. 10 shows the wave height of H_{m0} = 1.05 m and water level 3.15 m NAP of the January storm together with the 10 years of measurements at the pole. It should be noted that the 10 years of measurements are from the step gauge UHW3, which did not measure correctly for the January storm (see Fig. 7) and that the January storm is given by the radar measurements UHW3. The step gauge gave quite some scatter, which is believed to be caused by less reliable measurements.

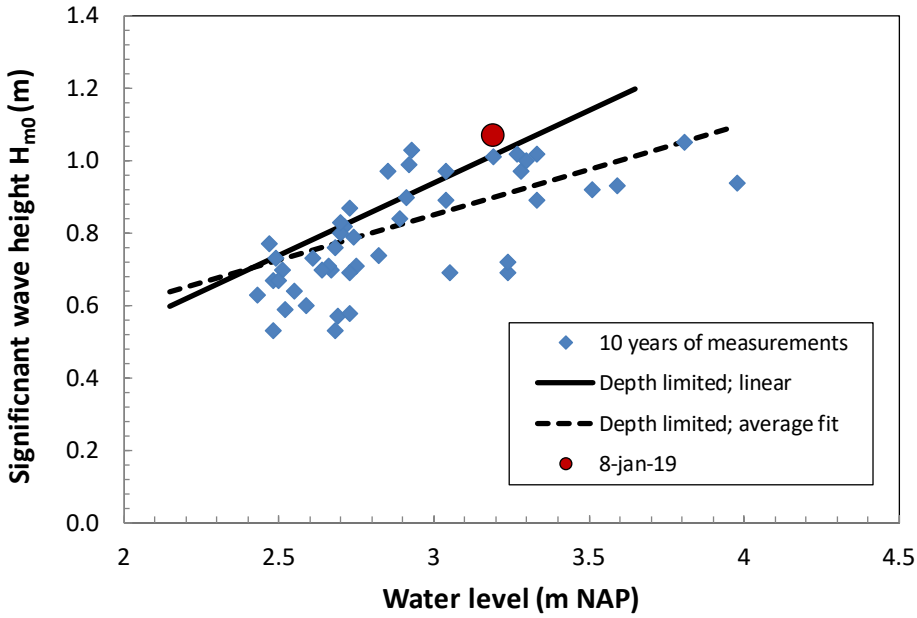

Fig. 10. Wave height – water level trend for 10 years of measurements and for the storm of 8 January 2019.

All wave heights in Fig. 10 are depth limited with the foreshore depth at about 0.65 m NAP. A linear relationship was determined as well as a best fit on the measurements:

$$H_{m0} = 0.4 \bullet (\text{water level} - 0.65) \qquad \text{linear} \qquad (1)$$

$H_{m0} = 0.1 + 0.25 \bullet \text{water}$ best fit, with water level > +3 m NAP (2)

The wave height of 1.05 m during the January storm is close to the line of Eq. 1, but is also the highest wave height measured. This is quite surprising as the water level was not the highest measured in the past 10 years, nor was the wind velocity highest. There might be a bias between measurements with a step gauge and with radar, which should be investigated further.

Fig. 11 gives the measured wave peak periods T_p for the pole, radar and Wavedroid, which give quite a similar trend. The periods increase during raising water level and reach their maximum value at the peak of the storm and then remain more or less constant for some time. The spectral period $T_{m-1,0}$, which was measured by the Wavedroid, shows the same trend. The peak period at the peak of the storm was $T_p = 4.3$ s and the spectral period $T_{m-1,0} = 3.9$ s.

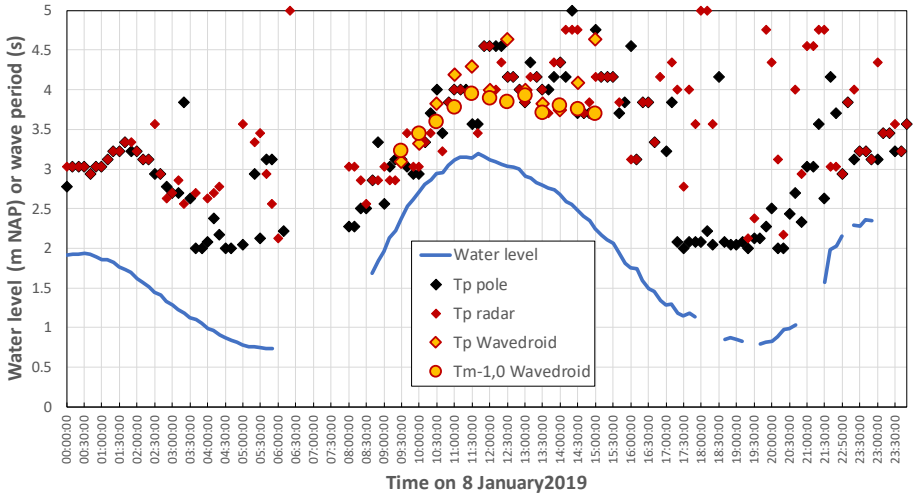

Fig. 11. Wave periods and water levels measured during the storm of 8 January 2019.

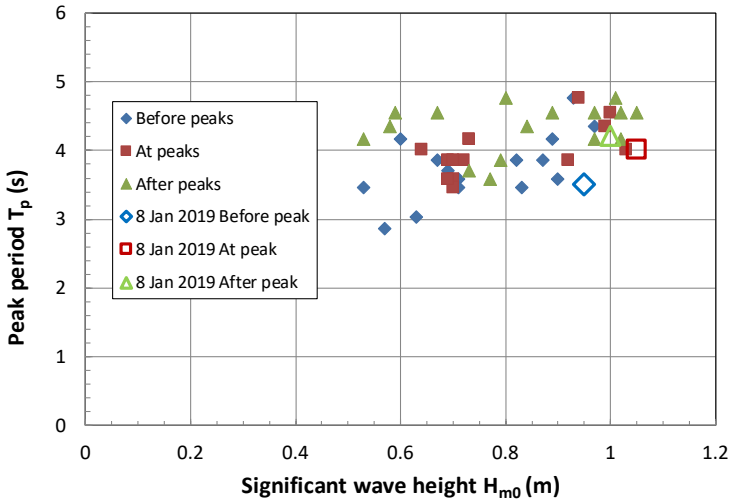

Fig. 12. Peak wave periods T_p before, at and after the peak of the storm, for 10 years of measurements and the storm of 8 January 2019.

Fig. 12 shows the measured peak periods in 10 years with measurements before, at and after the peak of the storm. The picture is similar as in Fig. 11: an increasing period till the peak of the storm and a constant or slightly increasing peak period after the peak of the storm. The data of the January storm coincide well with the earlier measurements, giving more or less a peak period of 4 s regardless of wave height.

Fig. 13 shows a similar graph as in Fig. 12, but now for the spectral period $T_{m-1,0}$. The trend over the peak is similar as for the peak period, but the periods for the January storm are significantly smaller than for the 10 years of measurements. The 10 years of measurements were taken from the step gauge UHW3 and the January storm was taken from the Wavedroid. The average value for the step gauge is about 5 s, which is 25% larger than the peak period of 4 s. For a single peaked spectrum the spectral period is often 10% smaller than the peak period (EurOtop, 2018). The spectral period measured with

the Wavedroid is 3.9 s and this is indeed about 10% smaller than the peak period. Also here further investigation is needed as the expected wave overtopping is highly dependent on the spectral wave period.

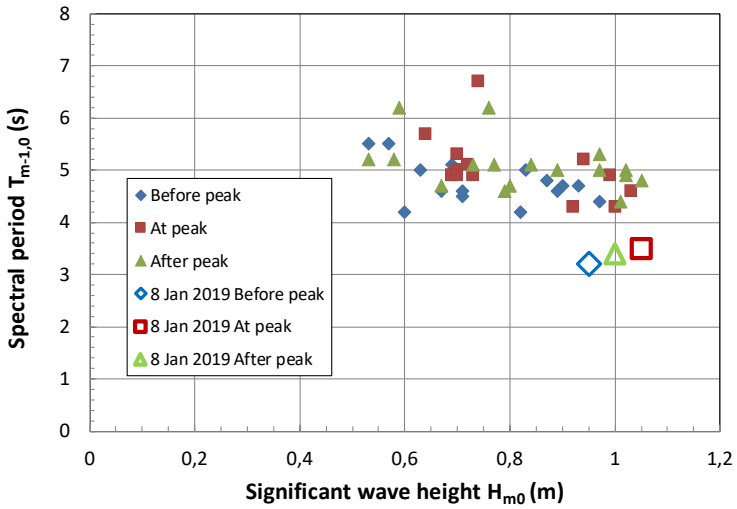

Fig. 13. Spectral wave periods $T_{m-1,0}$ before, at and after the peak of the storm, for 10 years of measurements and the storm of 8 January 2019.

Design of the overtopping boxes

To measure wave overtopping in reality is not an easy task. In a few cases with relatively low structures like breakwaters and seawalls a large overtopping box has been placed behind the crest of the structure, see the CLASH- project, De Rouck et al. (2002). But that system is not possible at a dike that will hardly ever be overtopped. For this reason, it was decided to construct overtopping boxes at two levels in the dike slope, where the level actually represents the "crest" of the dike. For this innovative system the levels should be chosen in such a way that good overtopping measurements would become available for a water level range roughly between 2.5 m NAP and 4 m NAP and maybe a little higher.

Wave overtopping calculations have been made using EurOtop (2018), specifically Equations 5.1 and 5.2 for the 2% run-up level; Eqs. 5.10 and 5.12 for the wave overtopping discharge; Eq. 5.56 for the percentage of overtopping waves; and Eqs. 5.52, 5.53 and 5.57 for the maximum volume in overtopping waves. For the wave height Eq. 1 has been used, which is dependent on the water level. The spectral period was taken as 5 s and the angle of wave attack 50° as well as 65° with respect to the normal of the dike. The actual profile of the seaward slope was taken and the average slope angle was determined for each water level, as the dike slope is a little concave and not straight. Fig. 14 shows the results of many calculations. For crest levels of 3.5 m NAP up to 6 m NAP the overtopping discharge was calculated. The lowest box should measure from a water level of 2.5 m NAP and the highest box should take over when the lowest box would be overrun by waves, which was estimated for overtopping discharges larger than about 10 l/s per m. Based on graphs like in Fig. 14 it was decided to construct the lowest box at a level of 4.4 m NAP and the highest box at 5.3 m NAP. These lines have also been given in Fig. 14. Fig. 2 gives the boxes as constructed and Fig. 3 an impression of the wave overtopping in the lowest box for the January storm.

With a water level of 3.15 m NAP an overtopping discharge was expected of 7.3 l/s per m, where the actual overtopping in the January storm was 3.04 l/s per m. But this was based on a spectral wave period of 5 s. With a period of 4.31 s the wave overtopping would already be equal to the expected one, which validates again the conclusion that more investigation is needed for the wave period. The highest overtopping box got 6 overtopping waves, giving an overtopping discharge of 0.079 l/s per m, where 0.163 l/s per m was expected for a wave period of 5 s.

Based on calculated maximum overtopping volumes and the time required for water to escape from the box, the dimensions of the boxes became 0.8 m deep, 1.3 m wide and 5 m long. The actual length of the opening for waves to enter the box was 4.0 m. At the end of the box an outflow was constructed for release of the overtopping water.

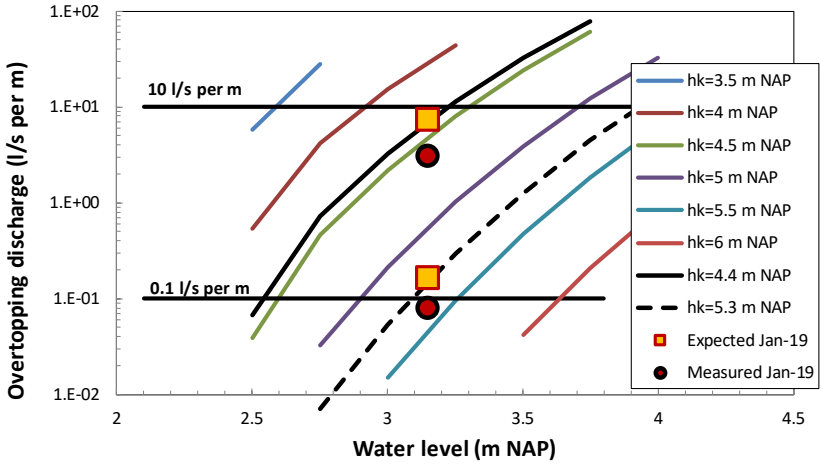

Fig. 14. Overtopping calculations for various crest levels in order to determine the levels for two overtopping boxes. The final levels where 4.4 m NAP and 5.3 m NAP, also given in the graph together with the predictions and measurements for the January storm.

Overtopping measurements and analysis of the 8 January 2019 storm

The volume of each overtopping wave in the lowest box and in the period 11:10 to 12:00 of 8 January 2019 was determined. In total 121 overtopping waves were detected, giving an overtopping discharge of 3.04 l/s per m. EurOtop (2018) gives a prediction of the shape parameter b of the distribution of overtopping wave volumes. The 121 overtopping volumes were first plotted on a Weibull graph as in Fig. 15 in order to determine the b-value. This b-value is the inclination of the line on such a Weibull graph. A b-value of 1.55 was found for fitting on the highest part of the overtopping volumes and a little larger value of 1.70 for the whole distribution. In case of deviation one should always concentrate on the fitting the largest volumes, see Zanuttigh et al. (2013). A value of 1.6 was taken for further analysis.

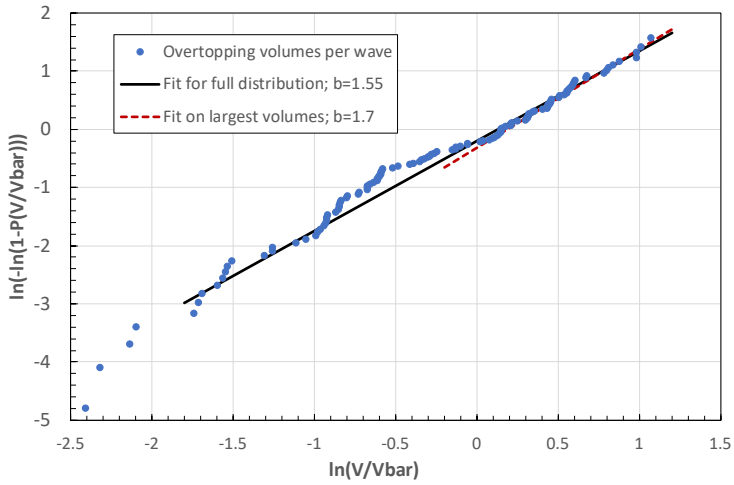

Fig. 15. Distribution of overtopping wave volumes at the January storm on a Weibull graph.

The expected b-value for not too large wave overtopping on a smooth structure is around b = 0.75, which is steeper than an exponential distribution with b = 1 and much steeper than a Rayleigh distribution with b = 2. Distributions with these b-values are given in Fig. 16, together with the measured distribution. The difference between the measured and expected distribution (b=0.75) is very large. The maximum overtopping volumes may differ up to a factor of 2!

The value of 1.6 was also plotted in the EurOtop (2018) graph, together with recent measurements in a wave basin and oblique wave attack on a 1:3 smooth slope (CrossOver project, Leite et al. (2019)). The laboratory measurements fit quite well with earlier measurements; the January storm does not fit at all. One difference between the laboratory measurements and the January storm is that the latter was at depth limited wave conditions, where the lab measurements were performed with relatively deep water. More investigation is required to come to a good explanation for the different b-values.

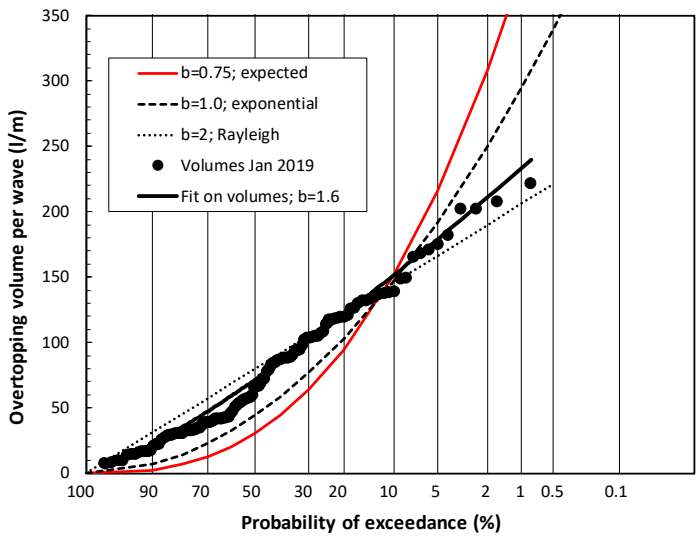

Fig. 16. Distribution of overtopping wave volumes at a Rayleigh scale, including the January storm.

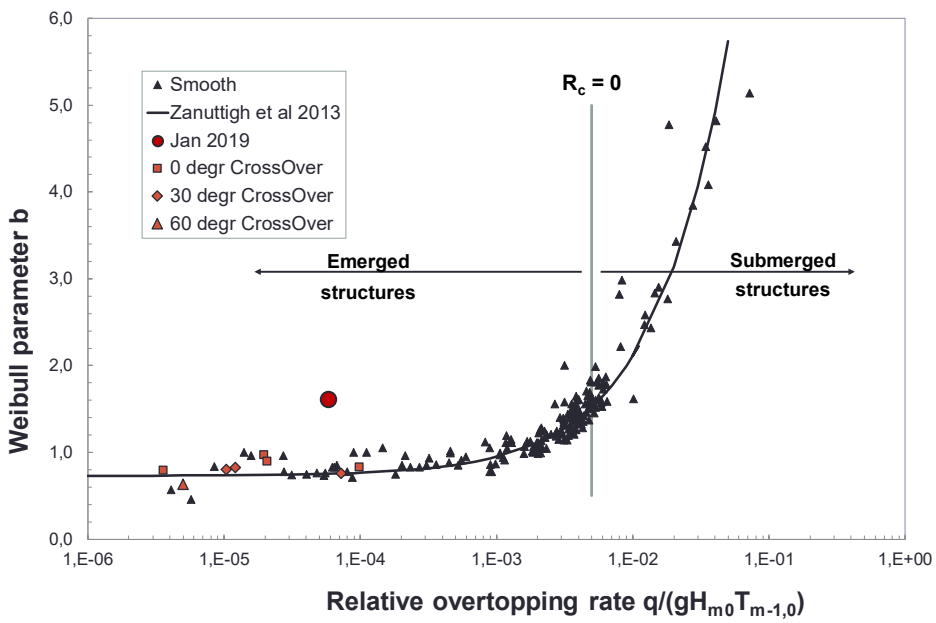

Fig. 17. EurOtop Fig. 5.40 with the b-value for the January 2019 storm and recent measurements in a wave basin.

Conclusions

Wave measurements in reality are not easy to perform and after just one season of dedicated measurements in a 12-year program fine tuning is required to come to more reliable measurements of wave heights and periods. For the January 2019 storm a maximum water level at the peak of the storm of 3.15 m NAP was measured, which was well above the required level of 2.5 m NAP to be able to measure wave overtopping. The significant wave height during the peak of the storm was H_{m0} = 1.05 m, the peak wave period T_p = 4.0 s and the spectral wave period $T_{m-1,0}$ = 3.5 s.

The overtopping boxes worked well and individual overtopping wave volumes could be determined from the measurements. The lowest box got 121 overtopping waves in 50 minutes, giving an overtopping discharge of 3.04 l/s per m. The highest box got only 6 overtopping waves, which only gave an overtopping discharge of 0.079 l/s per m. The shape parameter of the distribution of overtopping wave volumes was determined at b = 1.6 and this deviates significantly from the expected value of 0.75. This is a surprising result as physical scale modelling is quite consistent with respect to this b-value. The effect is that maximum overtopping volumes may be a factor of 2 smaller than expected. The depth limited wave conditions may play a role here and more research will be focussed on this aspect in future.

Acknowledgement

Water board Noorderzijlvest and advisors Rijkswaterstaat, Deltares and KNMI are acknowledged for their support.

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