The maximum influence of wind on wave overtopping at seawalls with crest elements

van Gent, Marcel R.A.; van der Bijl, Ruben J.; Wolters, Guido; Wüthrich, Davide

DOI
10.1680/cmsb.67042.1007

Publication date
2024

Document Version
Final published version

Published in
Coasts, Marine Structures and Breakwaters 2023

THE MAXIMUM INFLUENCE OF WIND ON WAVE OVERTOPPING AT SEAWALLS WITH CREST ELEMENTS

Marcel R.A. van Gent[1,2*], Ruben J. van der Bijl[1,2], Guido Wolters[1] and Davide Wüthrich[2]

[1] *Deltares, Dept. of Coastal Structures & Waves, Delft, NL, marcel.vangent@deltares.nl*
[2] *TU Delft, Dept. of Hydraulic Engineering, Delft, NL*

ABSTRACT The crest level of seawalls is often based on estimates of the amount of wave overtopping. Methods to estimate the mean overtopping discharge have been provided in several guidelines. One of the important parameters affecting wave overtopping is the wind. However, the effects of wind have not been accounted for in detail in present design guidelines although some guidance for coastal structures with crest elements is provided in literature. For onshore wind the expected wave overtopping discharge at coastal structures with a crest element can be up to a factor 5 larger than for situations without wind. In the present study the maximum influence of wind on wave overtopping at impermeable seawalls with crest elements has been studied based on physical model tests. The result of the study is a guideline to estimate the maximum influence of wind on wave overtopping at seawalls with crest elements.

1. Introduction

For the design and adaptation of seawalls, it is important to limit the amount of wave overtopping to meet the functional requirements of these structures. Estimates of wave overtopping generally determine the required crest level of seawalls. Due to climate change and the resulting sea level rise the adaptation of existing seawalls has become more important. For seawalls in relatively shallow water, sea level rise can increase the wave loading since less wave dissipation occurs before the waves reach the structure. Estimates of the speed of sea level rise are uncertain. Therefore, it may be suitable to design seawalls that can be adapted once the sea level rise appears to be more severe than expected. An economically attractive solution to increase the crest level of a seawall can be to add, or to increase the height of, a crest wall (see for instance Van Gent, 2019, and Hogeveen, 2021). For the design and adaptation of seawalls with crest elements accurate predictions of wave overtopping are required. Prediction methods to estimate wave overtopping discharges generally provide little guidance on the potential effects of wind on wave overtopping (see for instance TAW, 2002, or EurOtop, 2018). Especially when a coastal structure is vertical or contains a vertical part such as a crest element (crown wall), the wave motion is changed into a direction with an important vertical component, see Figure 1. A part of the water volumes reaching levels higher than the crest level, can fall back and stay seaward of the crest while the other part can overtop the crest of the structure. Onshore wind can significantly increase the part that overtops (see for instance De Waal *et al*, 1996 and Wolters and Van Gent, 2007). The present study is focussed on the maximum effect of onshore wind on wave overtopping discharges at impermeable seawalls (dikes). For this purpose, physical model tests have been performed in a wave flume and a guideline is developed to account for the maximum effect of wind on wave overtopping discharges.

Figure 1 Wave overtopping event at a breakwater affected by wind.

2. Literature review

Guidelines to estimate wave overtopping discharges at coastal structures generally include influence factors to account for various effects such as wave obliquity (*e.g.* De Waal and Van der Meer, 1992; Napp *et al*, 2004; Van Gent and Van der Werf, 2019; Van Gent, 2020, 2021), roughness (*e.g.* Bruce *et al*, 2009; Capel, 2015; Molines and Medina, 2015; Chen *et al*, 2020a,b), a berm in the seaward slope (*e.g.* De Waal and Van der Meer, 1992; Chen *et al*, 2020a,b, 2022; Van Gent, 2020, 2022), a crest wall (*e.g.* Molines and Medina, 2016; Van Doorslaer, 2018; Van Gent *et al*, 2022), the presence of swell in combination with sea waves (*e.g.* Van der Werf and Van Gent, 2018; Van Gent, 2021). However, to account for the effects of wind on wave overtopping relatively limited guidelines are available despite the fact that wind can significantly increase the amount of wave overtopping (see Ward *et al*, 1994, 1996; De Waal *et al*, 1996; Medina, 1998; Gonzalez-Escriva *et al*, 2004, 2006; Wolters and Van Gent, 2007; Chowdhury *et al*, 2020).

Most of the available guidelines to estimate wave overtopping discharges are based on small-scale physical model tests. Modelling wind in small scale physical model tests is affected by scale effects since the interaction of air and water during an overtopping event cannot be modelled based on a model for which Froude scaling is applied. Therefore, test results obtained by direct modelling of wind on wave overtopping at coastal structures modelled on a small scale, cannot be accurately scaled to prototype situations; the effects of wind on wave overtopping need to be studied on prototype scale or in the field (see for instance Franco *et al*, 2003).

However, instead of modelling the actual effects of wind on wave overtopping, a method to model the *maximum* effect of wind on wave overtopping discharges was developed by Hans de Waal and applied to study the maximum influence of wind on wave overtopping at vertical breakwaters (De Waal *et al*, 1996). This method is based on using a paddle wheel at the top of the structure. The paddle wheel mechanically transports the water that exceeded the crest level of the structure into an overtopping box behind the structure. The paddle wheel thus allowed to assess the maximum amount of overtopped water by measuring all the water that is potentially transported over the crest: The overtopping volumes that would overtop without wind plus all the other water volumes that reach the crest level of the structure but would fall back to the seaward side of the crest in absence of wind. By comparing the overtopping discharges for the same conditions with and without the paddle wheel, the maximum influence of wind can be assessed, thus for situations where the wind blows all the water that reaches the crest level or higher, over the crest.

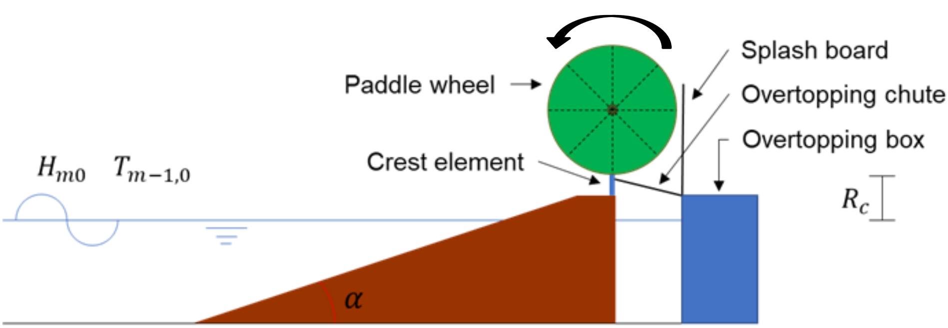
Based on this principle Wolters and Van Gent (2007) constructed a paddle wheel, optimised the rotation speed of the paddle wheel, and studied the maximum influence of wind on wave overtopping for sloped structures with a crest element. The same paddle wheel was applied in the tests described in the next section.

Note that here we focus on the maximum effect of wind on wave overtopping and that effects of the wind on water levels (set-up) and the wave loading itself (*i.e.* the wave conditions at the toe) need to be taken into account in the boundary conditions (water level and wave conditions at the toe) separately.

3. Physical model tests

Physical model tests were performed in a wave flume within the Pacific Basin at Deltares in Delft. The width of the wave flume was 1.0 m (within the basin with a total width of 14 m). A smooth impermeable structure was constructed with a slope of 1:3. On top of the structure a crest wall was positioned. The height and the position of the crest wall was varied. In order to measure the overtopping discharge, a chute was used to guide the discharge to an overtopping box.

Figure 2 Test set-up with a paddle wheel above the crest wall of the seawall.



Experiments were conducted for several combinations of significant wave height H_{m0} and wave period $T_{m-1,0}$, using 1000 waves to represent a JONSWAP wave spectrum. Three wave gauges were positioned in front of the structure to obtain the incident waves from the measured surface elevations. The wave height and wave steepness of the incident waves varied between H_{m0} = 0.10 m and 0.20 m and $s_{m-1,0}$ = 0.020 and 0.042 respectively. Most tests were performed with a water depth of h = 0.7 m, the end of the slope at A_c = 0.3 m above the water level, and crest elements with a height of 0.05 m and 0.08 m. A few checks were made with other water depths but the tests with h = 0.7 m are used to assess the influence of various parameters and to develop a guideline. For each of these crest elements, the position of the crest element was varied between at the end of the slope (G_c = 0 m) and a position 0.15 m landward, forming a kind of promenade seaward of the crest element (G_c = 0.15 m). Thus, in total four configurations with a crest wall were tested.

Table 1 shows the parameter ranges of the test programme. The measured non-dimensional wave overtopping discharges $q^*=q/(gH_{m0}^3)^{0.5}$ were in the range between q^* = 4.8 10^{-7} and 1.8 10^{-3}. The tested conditions include conditions that are referred to as “breaking waves” (mainly those with a steepness of $s_{m-1,0}$ = 0.04) and conditions that can be considered as “non-breaking waves” (generally those with a steepness of $s_{m-1,0}$ = 0.02 and 0.03).

Figure 3 Tested positions and heights of the crest wall (four configurations, each with one wall).

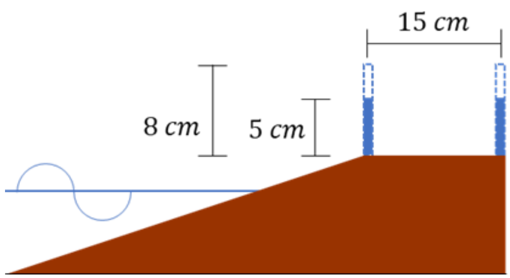


Figure 4 Front view and side view of the paddle wheel above the crest wall.

To study the maximum influence of wind on the wave overtopping discharge each test was performed with and without a paddle wheel. The paddle wheel (with a diameter of 1.4 m and 12 paddles) above the crest wall rotated with such a speed (the speed was optimised by Wolters and Van Gent, 2007, to 22 rotations per minute) such that the water that reaches the level of the crest wall, was transported over the structure into the overtopping box. Based on variations of the rotation speed and visual observations, the effectiveness of paddle wheel to transport all water reaching the crest elevation into the overtopping box was estimated to more than 90%. No correction on the test results was applied for potential water drops reaching levels above the crest elevation but falling back to the seaward side of the structure without being transported by the paddle wheel.

Figures 2 and 3 show the schematised test set-up while Figure 4 shows pictures of the paddle wheel.

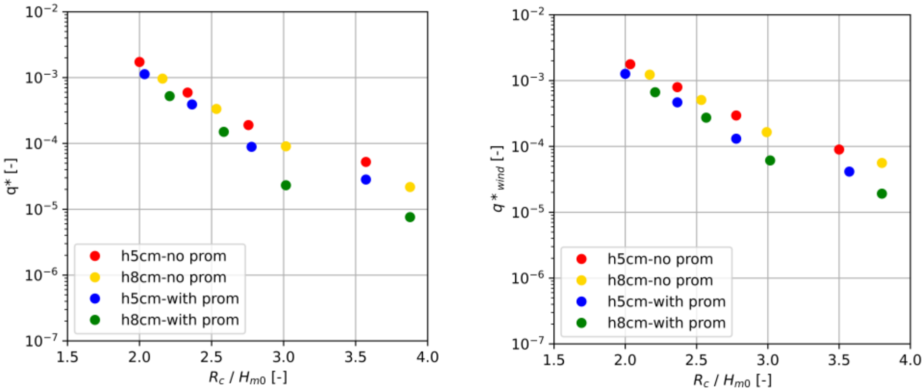
Table 1 Parameter ranges of the test programme:

Parameter	**Symbol**	**Value / Range**
Seaward slope angle (-)	cot α	3
Crest freeboard (m)	R_c	0.20 – 0.48
Promenade width (m)	G_c	0 & 0.15
Promenade level w.r.t. SWL (m)	A_c	0.15 – 0.40
Height of crest wall (m)	h_c	0, 0.05 & 0.08
Water depth (m)	h	0.60 – 0.85
Incident significant wave (m)	H_{m0}	0.098 – 0.202
Mean spectral wave period (s)	$T_{m-1,0}$	1.25 – 2.36
Number of waves (-)	N	1000
Relative crest freeboard (-)	R_c / H_{m0}	1.49 – 3.98
Relative promenade width (-)	G_c / H_{m0}	0 – 1.53
Relative promenade level (-)	A_c / H_{m0}	1.46 – 3.47
Wave steepness ($s_{m-1,0}=2\pi H_{m0} / gT_{m-1,0}^2$) (-)	$s_{m-1,0}$	0.020 – 0.042
Breaker parameter ($\xi_{m-1,0}$ = tan α /$s_{m-1,0}^{0.5}$) (-)	$\xi_{m-1,0}$	1.62 – 3.00
Overtopping discharge (without wind) (-)	q^*	4.8 10^{-7} – 1.7 10^{-3}
Overtopping discharge (with wind) (-)	q_w^*	1.9 10^{-6} – 1.8 10^{-3}
Maximum wind effect (-)	γ_w	1.0 – 4.0

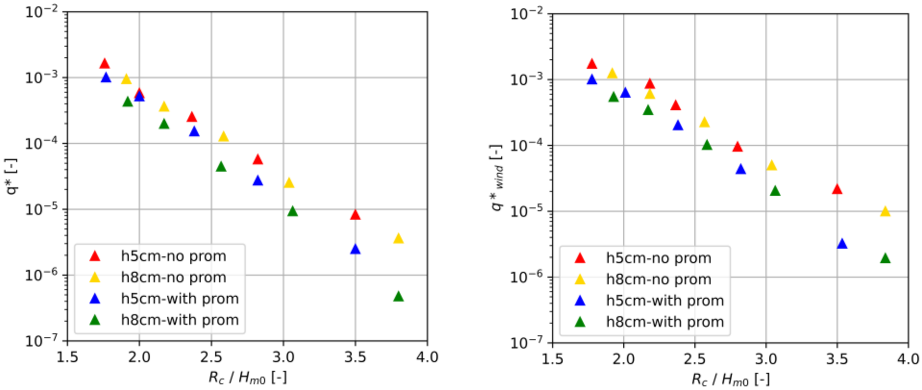
Figure 5 shows test results sorted by wave steepness (upper panels show conditions with $s_{m-1,0}$ = 0.02, mid panels show $s_{m-1,0}$ = 0.03, and lower panels show $s_{m-1,0}$ = 0.04) with the non-dimensional wave overtopping discharges q^* as function of the non-dimensional freeboard R_c / H_{m0}. To demonstrate the influence of various parameters, only conditions with a water depth of h = 0.7 m are shown here. The left panels show results without wind (*i.e.* without paddle wheel) and the right panels show results with wind (*i.e.* with paddle wheel). The colours of the symbols denote the four different crest wall configurations (red and yellow symbols without a promenade and blue and green symbols with a promenade).

Figure 5 Wave overtopping discharges as function of the freeboard for various wave steepness and for conditions without wind (left panels) and with wind (right panels) ('h5cm' refers to a crest wall height of 5 cm and 'with prom' refers to a promenade width of 15 cm seaward of the crest wall).

$s_{m-1,0} = 0.02$



$s_{m-1,0} = 0.03$



$s_{m-1,0} = 0.04$

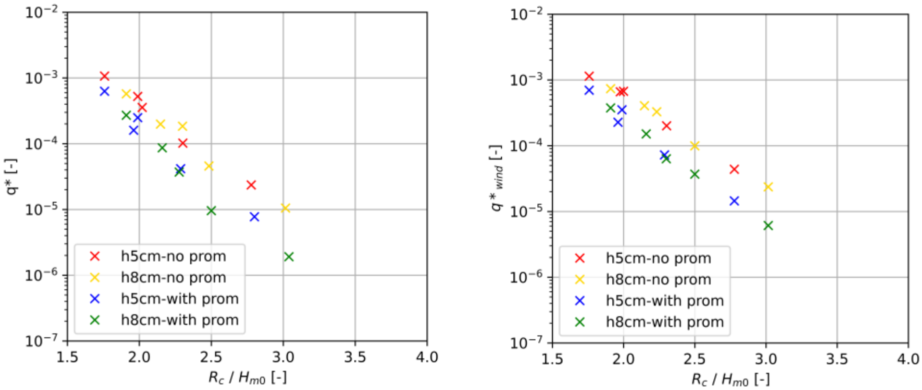


Figure 5 shows that for each wave steepness the results per crest wall configuration (*i.e.* colours of the symbols) are close to straight lines using a logarithmic vertical axis (non-dimensional freeboard) and a linear horizontal axis (non-dimensional freeboard). For all crest wall heights and positions the highest wave steepness generally leads to the lowest discharges, while the lowest wave steepness generally leads to the highest discharges. Since the conditions with a wave steepness of $s_{m-1,0}$ = 0.02 and 0.03 are associated with so-called "non-breaking waves", this indicates that there is an influence of the wave steepness for "non-breaking waves".

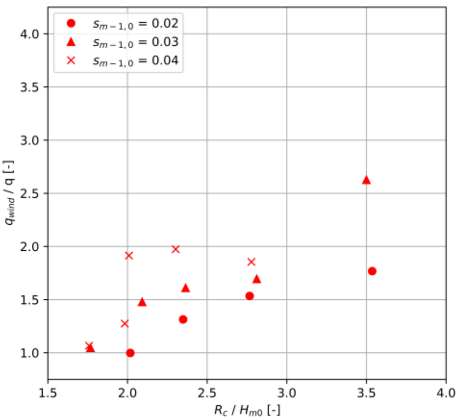
Figure 5 illustrates that the influence of the height of the crest wall is accounted for by using the freeboard (R_c / H_{m0}) since the trends and values for the low and high crest walls are very similar (red and yellow symbols in Figure 5 show the same trends and similar values; and the blue and green symbols also show similar trends and similar values). However, the position of the crest wall is important since the results for the crest wall with a horizontal part in front of the wall (promenade) show consistently lower discharges than those without (red and yellow symbols show consistently higher discharges than the blue and green symbols). This is valid for each wave steepness and for the conditions without wind (left panels) and for the conditions with wind (right panels).

Figure 6 shows that the conditions with wind (right panels) consistently show higher discharges than the same conditions without wind (left panels), except for two tests for which the ratio is 1. This is illustrated per crest wall height and position in the four panels of Figure 6, where the maximum influence of wind is shown on the vertical axis and the non-dimensional freeboard on the horizontal axis. Figure 6 shows again a clear influence of the wave steepness for each crest wall configuration: For all crest wall heights and positions the highest wave steepness generally shows the highest maximum influence of the wind, while the lowest wave steepness generally leads to the lowest influence of the wind. Note that the influence factors for a lower wave steepness go together with larger overtopping discharges while those for a higher wave steepness go together with lower overtopping discharges. Note that for the low wall with a promenade (lower-left panel) the conditions with the lowest waves (R_c / H_{m0} close to 3.5) show two test results that deviate from all other results, namely a higher non-dimensional freeboard (that go together with small discharges) with relatively low factors for the influence of wind. For all other results the trend is that the influence factor increases for higher non-dimensional freeboards (*i.e.* lower discharges). The maximum influence factor of wind reaches a value 4 in these tests.

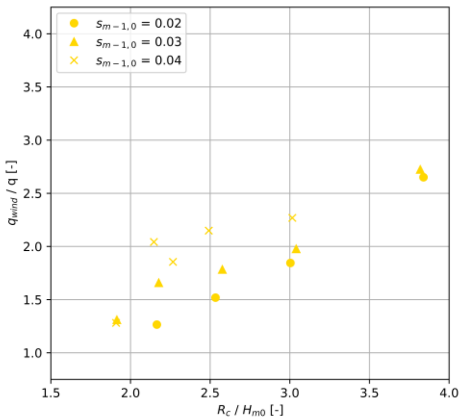
Figure 7 shows the results with respect to the maximum influence of wind on overtopping discharges (h = 0.7 m), where in the right panel the same data is shown as in the left panel, but in the right panel the non-dimensional discharge on the horizontal axis is shown on a logarithmic scale. The symbols match with those applied in the previous figures, where each of the four crest wall configurations is denoted by different colours in Figure 7, and each of the three values for the wave steepness is denoted by different symbols.

Figure 6 Maximum wind influence as function of the freeboard for various heights and positions of the crest wall.

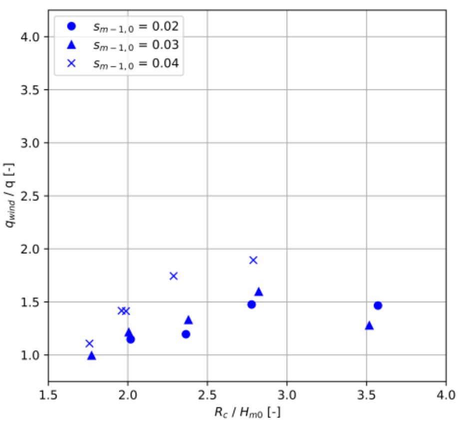
Low wall, no promenade:



High wall, no promenade:



Low wall, with promenade:



High wall, with promenade:

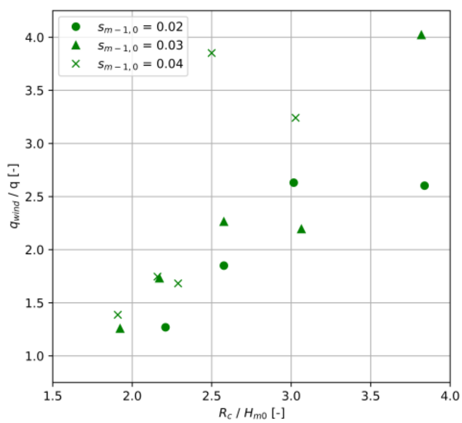
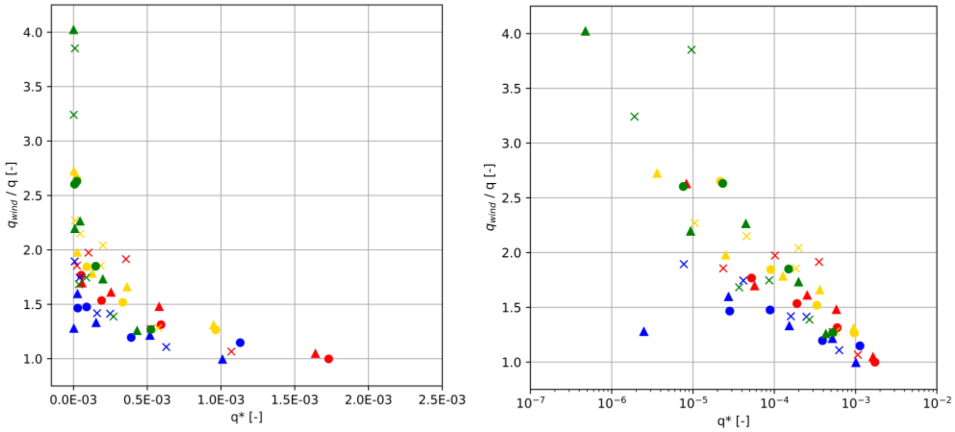


Figure 7 clearly shows that the maximum influence of wind is generally larger for the lower overtopping discharges. The configuration with the lowest crest wall and a horizontal part in front (promenade) shows somewhat lower factors than the other crest wall configurations. The other three configurations show not only similar trends (higher factor for lower discharges) but also the values of the factors are similar. This indicates that, except for the mentioned exception, the influence of all varied parameters (wave height, wave steepness, height and position of the crest wall) is accounted for in the magnitude of the overtopping discharge, and that the influence of wind depends on the overtopping discharge only, and that no additional influence on this influence factor for wind is present for the varied parameters.

Figure 7 Influence factor of wind on wave overtopping discharge as function of the (non-dimensional) overtopping discharge. Left: x-axis on linear scale; Right: x-axis on logarithmic scale.



4. Influence of wind

The maximum influence of wind on the wave overtopping discharge is expressed by a factor that multiplies the wave overtopping discharge without wind:

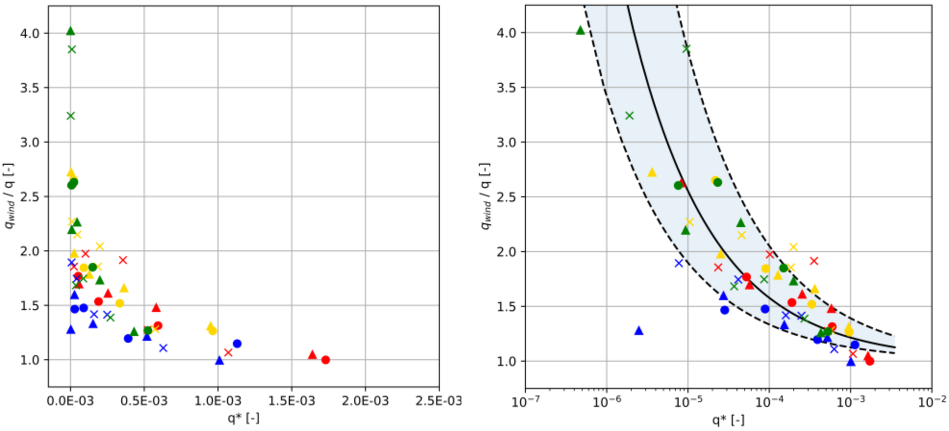
$$\gamma_w = \frac{q_{\text{with wind}}}{q_{\text{without wind}}} \tag{1}$$

Note that if the influence factor γ_w would be based on the ratio of non-dimensional wave overtopping discharges rather than on dimensional discharges, this would lead to the same factor as shown in Equation (1). The test results show that the influence of wind on wave overtopping discharges is larger for low wave overtopping discharges, and smaller for high overtopping discharges. Thus, it is reasonable to estimate the maximum influence of wind on wave overtopping by using estimates of the wave overtopping discharges without wind. The following expression was calibrated based on the present test programme:

$$\gamma_w = 1 + 0.011\left(q^*_{\text{without wind}}\right)^{-0.43} \tag{2}$$

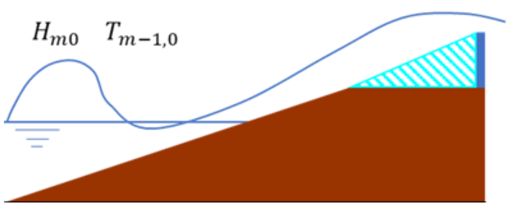
Figure 8 shows the influence factor of wind on wave overtopping discharges as function of the (non-dimensional) overtopping discharge without wind. The black curves show Equation (2) and the dashed curves indicate the 90% confidence interval based on the relative error between the measurements and Equation (2). All symbols denote the performed tests, with each of the four crest wall configurations (denoted by different colours in Figure 8) and with each of the three values for the wave steepness (denoted by different symbols in Figure 8). Figure 8 shows that, except for a few tests, Equation (2) provides a reasonable match with the data.

Figure 8 Influence factor of wind on wave overtopping discharge as function of the (non-dimensional) overtopping discharge. Left: x-axis on linear scale; Right: x- axis on logarithmic scale.



As mentioned, the configuration with a horizontal part in front of a relatively low crest wall (blue symbols in Figure 8) shows a somewhat lower influence of wind than the other three configurations, resulting in a slight overestimate of the influence of wind for this configuration if Equation (2) is used. It is expected that this could be due to the relatively small space in front of the crest wall, that first fills up with water before the rest of the wave tongue overtops (see also Figure 9). This causes that the motion of water at the wall has an important horizontal velocity component, which is expected to lead to a lower effect of the wind than if the motion of water would be mainly in the vertical direction.

Figure 9 Illustration of space (blue triangle) filled with water after which the wave tongue overtops the crest wall.



Note that in the present tests the measured influence factors were in the range between 1 and 4. However, it is likely that the maximum value 4 is limited due to the amount of overtopping in the performed tests. For conditions that lead to an even smaller overtopping discharge, the factor is likely to increase to values higher than 4, as Equation (2) suggests. Nevertheless, wave overtopping discharges smaller than $q^*= 10^{-6}$ are often less relevant and scale effects may be present in small scale physical model tests. Limiting the validity of empirical expressions to estimate wave overtopping discharges without wind, or other methods based on data from physical model tests, to values larger than $q^* = 10^{-6}$ would mean that the influence factor of wind does not reach values larger than 5.2. Note that for other structure types as tested by De Waal *et al* (1996) for vertical breakwaters and by Wolters and Van Gent (2007) for various types of sloped structures with a crest wall, similar maximum values were found for the maximum influence of wind on overtopping discharges. However, they did not provide a quantitative guideline to estimate the influence factor for wind based on the overtopping discharge.

Note that Equation (2) can be applied in combination with any accurate estimate of the wave overtopping discharge. Thus, the expression does not depend on whether the wave overtopping discharge is predicted using a specific empirical expression for overtopping discharges without wind, a numerical model without wind, or a machine learning method not taking wind into account.

5. Conclusions and recommendations

The maximum influence of wind on wave overtopping discharges at seawalls has been studied by performing physical model tests. Four configurations of a crest wall (two heights and two positions) were studied. The maximum influence of wind was obtained by comparing the wave overtopping discharges without wind and the discharges obtained after collecting all the water that reaches the crest level, assuming that onshore wind will blow all the water reaching the crest level over the structure. In the present tests the maximum influence of the wind was between a factor 1 and 4; thus, onshore wind can lead to an overtopping discharge that is a factor 4 larger than without wind. It was found that the influence of wind depends on the wave overtopping discharge itself. The hydraulic boundary conditions (wave height, wave steepness) and structure configurations (freeboard, height and position of crest wall) affect the wave overtopping discharge but once all these effects are accounted for in the overtopping discharge, the maximum influence of wind is dominated by the discharge itself and these parameters hardly show additional effects on the maximum influence of wind.

A guideline was developed (Equation 2) to estimate the maximum influence of wind on wave overtopping discharges. The match between the data and the guideline is rather good, although for lower crest walls that are positioned behind a horizontal part in front of the crest wall, the guideline is conservative. This indicates that the validity of the guideline is limited to crest walls that cause a relatively important vertical motion of the water reaching the crest wall (thus excluding applications for very low crest walls).

In the present study physical model tests were performed with a 1:3 seaward slope. In earlier investigations by Wolters and Van Gent (2007) steeper slopes were studied (1:1.5 and 1:2). The slope angle affects the wave overtopping discharges but it is yet unclear whether the slope angle has an additional effect on the maximum influence of wind on wave overtopping if this influence is accounted for using Equation (2). It is recommended to analyse the influence of the slope angle on the maximum influence of wind and to verify whether Equation (2) is accurate for other slope angles.

Acknowledgements

The assistance by Wesley Stet, Peter Alberts and Danny van Doeveren (Deltares) during the model tests is highly appreciated. Freek van den Bergh is acknowledged for the picture in Figure 1.

References

Bruce T, Van der Meer JW, Franco L, Pearson JM (2009) Overtopping performance of different armour units for rubble mound breakwaters, Coastal Engineering, 56, 166–179; https://doi.org/10.1016/j.coastaleng.2008.03.015

Capel A (2015) Wave run-up and overtopping reduction by block revetments with enhanced roughness, Coastal Engineering, 104, 76–92; https://doi.org/10.1016/j.coastaleng.2015.06.007

Chen W, Van Gent MRA, Warmink JJ and Hulscher SJMH (2020a) The influence of a berm and roughness on the wave overtopping at dikes, Coastal Engineering, 156; https://doi.org/10.1016/j.coastaleng.2019.103613

Chen W, Marconi A, Van Gent MRA, Warmink JJ and Hulscher SJMH (2020b) Experimental study on the influence of berms and roughness on wave overtopping at rock-armoured dikes, MDPI, J. Mar. Sci. Eng. 2020; https://doi.org/10.3390/jmse8060446

Chen W, Warmink JJ, Van Gent MRA, Hulscher SJMH (2022) Numerical investigation of the effects of roughness, a berm and oblique waves on wave overtopping processes at dikes, Elsevier, Applied Ocean Research, 118, https://doi.org/10.1016/j.apor.2021.102971

Chowdhury SD, Zhou JG, Qian L, Causon D, Mingham C, Pullen T, Hu K, Russell M, Manson S, Stewart D, Wood M, Winter H, Joly A (2020) Wind effects on wave overtopping at the vertical sea defence. Proc. ICCE 2020, papers.40; https://doi.org/10.9753/icce.v36v.papers.40.

De Waal JP, Tönjes P and Van der Meer JW (1996) Wave overtopping of vertical structures including wind effect, Proc. ICCE 1996, ASCE, 2216-2229.

EurOtop (2018), Manual on wave overtopping of sea defences and related structures, Van der Meer JW, Allsop NWH, Bruce T, De Rouck J, Kortenhaus A, Pullen T, Schüttrumpf H, Troch P, Zanuttigh B (Eds.), www. overtopping-manual.com

Franco L, Bellotti G, Briganti R, De Rouck J, Geeraerts J (2003) Full scale measurements of wave overtopping at Ostia yacht harbour breakwater, Proc. Coastal Structures 2003, Portland.

Gonzalez-Escriva JA, Garrido JM, Medina JR, Geeraerts J (2004) Laboratory real storm reproduction using wind, World Scientific, Proc. ICCE 2004, 677-689, Lisbon.

Gonzalez-Escriva JA (2006) The role of wind in wave runup and overtopping of coastal structures, Proc. ICCE 2006, 4766-4778, San Diego.

Hogeveen, KPJ (2021) Climate adaption of rubble mound breakwaters; A study to the accuracy of overtopping formulas for combination of solutions, M.Sc. thesis, TU Delft, Delft, http://resolver.tudelft.nl/uuid:3a6ec8ac-0b81-4d32-adf1-6d7b4f842ceb

Medina JR (1998) Wind effects on runup and breakwater crest design, ASCE, Proc. ICCE 1998,1068-1081, Copenhagen.

Molines J and Medina JR (2015) Calibration of overtopping roughness factors for concrete armor units in non-breaking conditions using the CLASH database, Coastal Engineering, 96, 62-70; https://doi.org/10.1016/j.coastaleng.2014.11.008

Molines J and Medina JR (2016) Explicit wave-overtopping formula for mound breakwaters with crown walls using CLASH Neural Network-derived data, J. of Waterway, Port, Coastal, and Ocean Engineering 142, https://doi.org/10.1061/(ASCE)WW.1943-5460.0000322

Napp N, Bruce T, Pearson J and Allsop W (2004) Violent overtopping of vertical seawalls under oblique wave conditions, Proc. ICCE 2004, Lisbon.

TAW (2002), Technical Report Wave Run-up and Wave Overtopping at Dikes, Technical Advisory Committee on Flood Defence (TAW), Delft.

Van der Werf IM and Van Gent MRA (2018) Wave overtopping over coastal structures with oblique wind and swell waves, J. Mar. Sci. Eng. 2018, 6 (4), 149; https://doi.org/10.3390/jmse6040149

Van Doorslaer K (2018) Reduction of wave overtopping by and wave-induced forces on storm walls and promenades at crest level of smooth dikes; an experimental study, Ph.D. Thesis, Universiteit Gent, Belgium.

Van Gent MRA (2019) Climate adaptation of coastal structures, Keynote in Proc. Applied Coastal Research (SCACR 2019), Bari, Italy.

Van Gent MRA and Van der Werf IM (2019) Influence of oblique wave attack on wave overtopping and wave forces on rubble mound breakwater crest walls, Coastal Engineering, 151, 78-96; https://doi.org/10.1016/j.coastaleng.2019.04.001

Van Gent MRA (2020) Influence of oblique wave attack on wave overtopping at smooth and rough dikes with a berm, Coastal Engineering, 160, https://doi.org/10.1016/j.coastaleng.2020.103734

Van Gent MRA (2021) Influence of oblique wave attack on wave overtopping at caisson breakwaters with sea and swell conditions, Elsevier, Coastal Engineering, 164; https://doi.org/10.1016/j.coastaleng.2020.103834

Van Gent MRA, Wolters G and Capel A (2022) Wave overtopping discharges at rubble mound breakwaters including effects of a crest wall and a berm, Elsevier, Coastal Engineering, 176, https://doi.org/10.1016/j.coastaleng.2022.104151

Ward DL, Wibner CG, Zhang J, Edge B (1994) Wind effects on runup and overtopping, ASCE, Proc. ICCE 1994, 1687-1699, Kobe.

Ward DL, Zhang J, Wibner CG, Cinotto CM (1996) Wind effects on runup and overtopping, ASCE, Proc. ICCE 1996, 2206-2215, Orlando.

Wolters G and Van Gent MRA (2007) Maximum wind effect on wave overtopping of sloped coastal structures with crest elements, Proc. Coastal Structures 2007, Venice, 1263–1274, doi:10.1142/9789814282024_0111