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THE INFLUENCE OF A CROWN WALL ON WAVE OVERTOPPING OVER BREAKWATERS

Mads Røge Eldrup[1], Thomas Lykke Andersen[1], Koen Van Doorslaer[2] and Jentsje van der Meer[3]

This paper investigates the influence of a crown wall on wave overtopping on rubble mound breakwaters. Existing data is used to modify the EurOtop overtopping formula updated by Eldrup et al. (2022) to cover the influence of the crown wall. The effect of raising the wall above the armour crest (elevated wall) or lowering the wall below the armour crest (lowered wall) is investigated. A crown wall at the armour crest level is considered as the reference case. By increasing the elevation of either the armour crest or the crown wall, overtopping is reduced and by lowering either of them, overtopping increases. The influence of the crown wall height, elevated or lowered compared to the armour crest, is not considered accurately in the present design guidelines and thus corrections are suggested. For an elevated wall, a modified crest width has been defined, to better describe the presence of the armour crest in front of the wall. For the lowered wall the effective freeboard might be taken as the average of the wall and armour freeboards. The improvement compared to existing methods is significant, especially for breakwaters with a large elevated wall. The proposed modifications to the EurOtop Manual increase the range of applicability with respect to the wall configuration.

Keywords: Wave overtopping; Rubble mound breakwater; Crown wall; Crest wall; Superstructure

INTRODUCTION

The EurOtop Manual has, in recent decades, become the most commonly used standard for predicting wave overtopping on coastal structures. Therefore, it is essential that the manual is updated to maintain its status as state-of-the-art within the field. The idea of EurOtop Live has been invented for this (see www.manual-overtopping.com). New studies on wave overtopping should either validate or aim to improve the predictions given in the EurOtop Manual.

It is well known that wave overtopping is highly influenced by the incident wave parameters and structural parameters like the crest freeboard, front slope angle, armour unit type, crest width, and crown wall configuration. However, the influence of these parameters is, in some cases, not fully understood.

The formula given by EurOtop (2018) for non-breaking waves, which is applicable for steep rubble mounds, is given in Eq. (1):

$$\frac{q}{\sqrt{gH_{\mathrm{m0}}^3}} = 0.09\exp\left(-\left(\frac{1.5R_{\mathrm{c*}}}{H_{\mathrm{m0}}\gamma_{\mathrm{f\,mod}}\gamma_{\beta}}\right)^{1.3}\right)C_{\mathrm{r}} \tag{1}$$

Here q is the average overtopping discharge per unit width at the crest rear shoulder (see Figure 1), g is the acceleration of gravity, H_{m0} is the spectral significant wave height. $R_{\mathrm{c*}}$ is the used freeboard height depending on the situation (see Figure 1). In EurOtop (2018) R_{c} is used as the freeboard, but to make it easier to describe the different crest layouts $R_{\mathrm{c*}}$ has been adopted in the present paper. $\gamma_{\mathrm{f\,mod}}$ is the influence factor for the roughness and permeability of the armour layer, including the wave steepness influence (surging waves) from Eq. 3. The effect of wave obliquity is given by γ_{β}; and C_{r} includes the effect of the crest width, see Eq. 2.

The influence of the crest width is in EurOtop (2018) suggested to be calculated with the formula by Besley (1999) with coefficients for rock slopes:

$$C_{\mathrm{r}} = \min\left(3.06\exp\left(-1.5\frac{G_{\mathrm{c}}}{H_{\mathrm{m0}}}\right), 1\right) \tag{2}$$

Here G_{c} is the width of the crest. The equation shows that overtopping will reduce exponentially if the crest width (G_{c}) is larger than $0.75H_{\mathrm{m0}}$.

The influence of the varying roughness factor from EurOtop (2018) is given by Eq 3.

[1] Department of the Built Environment, Aalborg University, Thomas Manns Vej 23, Aalborg, 9220, Denmark
[2] DEME nv, Scheldedijk 30, 2070 Zwijndrecht, Belgium and Ghent University, Technologiepark 60, 9052 Zwijnaarde, Belgium
[3] Van der Meer Consulting B.V., P.O. Box 11, 8490 AA Akkrum, The Netherlands

$$\gamma_{\mathrm{f\,mod}} = \begin{cases} \gamma_{\mathrm{f}}, & \xi_{m-1,0} < 5 \\ \gamma_{\mathrm{f}} + (\xi_{m-1,0} - 5)(1-\gamma_{\mathrm{f}})/5, & 5 < \xi_{m-1,0} < 10 \\ 1, & \xi_{m-1,0} > 10 \end{cases} \tag{3}$$

Eq 3 provide a roughness factor that is constant for $\xi_{m-1,0} < 5$ and then increases linearly from $\gamma_{fmod} = \gamma_f$ at $\xi_{m-1,0} = 5$ to $\gamma_{fmod} = 1$ at $\xi_{m-1,0} = 10$. It should be noted that for permeable structures, Eq. 3 has a maximum of 0.6.

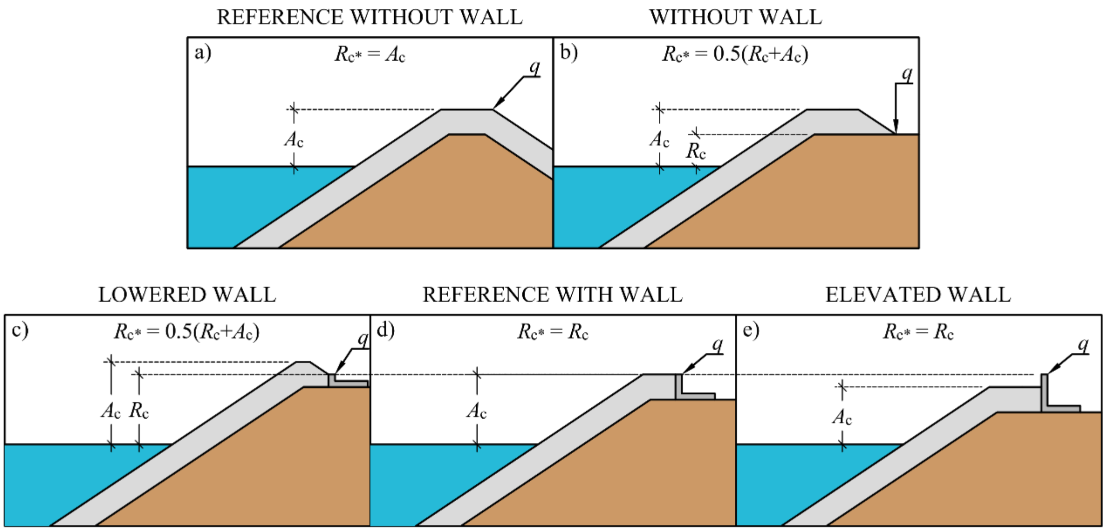

Figure 1. Definition of crest level used by EurOtop (2018). For cases without a wall a) shows the water that gets over the breakwater while b) and c) also includes the water getting through the permeable crest. The cases c), d) and e) shows the different wall configuration and the location for overtopping measurement.

Studies have been carried out recently to improve or validate the EurOtop formula. Christensen et al. (2014) found that the influence of the wave period was underestimated in EurOtop (2007), and they proposed to use a varying roughness factor. Eldrup and Lykke Andersen (2018) used the suggested correction by Christensen et al. (2014) and the crest width influence factor by Besley (1999) to recalibrate the roughness factors γ_f for different armour unit types.

Recently, Eldrup et al. (2022) improved the predictions of the EurOtop method by investigating the influence of the wave period, front slope angle and crest width. Their study was conducted on structures either without a crown wall and with overtopping measured at the rear shoulder (Figure 1-a) or alternatively with a wall at the armour crest level (Figure 1-d). These two structures also use the same crest freeboard, but it can be expected that overtopping is slightly larger in Figure 1-d as the wall blocks the water flow and leads it upwards. The effect of this has not been studied. They found that the roughness influence factor of the structure was always influenced by the wave period and not only for breaker parameters larger than five as given by EurOtop (2018), cf. Eq. 3. The new roughness factor is given in Eq. 4.

$$\gamma_{fS} = \min\left(\gamma_f + 0.05 s_{m-1,0}^{-0.5} - 0.07\min(\cot(\alpha), 3) - 0.09, 1\right) \tag{4}$$

Eldrup et al. (2022) also found that the influence of the crest width increased with the relative freeboard. This is in contrast to the correction factor C_r by Besley (1999) where the influence is independent of the relative freeboard. The discharge correction factor, C_r used by EurOtop (2018) was thus changed to a γ influence factor for the crest width, and thus it modifies the relative freeboard, see Eqs. 5 and 6.

$$\gamma_{cw} = \min\left(1.1\exp\left(-0.18\frac{G_c}{H_{m0}}\right), 1\right) \tag{5}$$

Both influence factors were added to the non-breaking waves formula in Eq. 6.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.09\exp\left(-\left(\frac{1.5R_{c*}}{H_{m0}\gamma_{fS}\gamma_{cw}}\right)^{1.3}\right) \tag{6}$$

The recent study by Eldrup et al. (2022) has only considered the reference cases with $R_c = A_c$. The present paper aims to validate or extend their study to cases with elevated ($R_c > A_c$) and lowered ($R_c < A_c$) walls.

EXISTING METHODS FOR WALL INFLUENCE

Van Doorslaer et al. (2018) used the data by De Meyere and Vantomme (2017) and De Keyzer and De Kimpe (2018) to investigate the influence of crest width, wave period and a crown wall on the wave overtopping discharge. The influence of the crest width and the wave period was in their study described by the parameter $G_c/L_{m-1,0}$, see Eq. 8. They used data with front slope angle cot(α)=1.5 only. Thus, they did not include the influence of the front slope angle, which was found important by Eldrup et al. (2022). Furthermore, when using Eq. 8, the influence of the wave period vanishes for narrow crests. This seems not physically correct, but further data would be needed to verify this.

Van Doorslaer et al. (2018) compared structures with identical wall freeboard R_c and found that by lowering the armour crest A_c so that the wall was elevated (Figure 1-e), higher overtopping discharges than the reference case (Figure 1-d) was measured. The reason is that for the elevated wall, the unprotected part leads to less armour material to dissipate the wave energy. The unprotected part of the wall h_{wall} can be seen in Figure 2 and calculated by Eq. 7.

When comparing the reference case to an elevated wall with both having the same A_c, but for the elevated wall $R_c > A_c$. Then it is logical that the geometry with the elevated wall has lower overtopping discharge over the wall as the measurement point of overtopping also is different.

$$h_{\text{wall}} = R_{\text{c}} - A_{\text{c}} \tag{7}$$

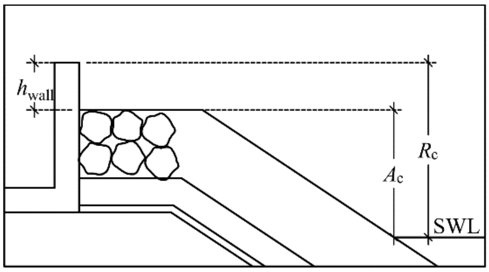

Figure 2. Definition of the unprotected wall height h_{wall}.

Van Doorslaer et al. (2018) also observed that, for identical wall freeboard R_c, the overtopping was reduced when the level of the armour crest A_c was increased so that the wall was lower than the armour crest (Figure 1-c) compared to the reference (Figure 1-d). This reduction in wave overtopping was due to the extra armour material in front of the wall dissipating the incoming wave energy.

When comparing the reference case to a lowered wall, both have the same A_c, but for the lowered wall $R_c < A_c$. Then the structure with the lowered wall has a higher overtopping over the wall which is logical, knowing that the measurement point of overtopping is different.

Overall, it can be concluded that both the wall and armour freeboard are influencing the overtopping. Overtopping may be reduced by an increase in any of the two freeboards A_c or R_c. Based on these observations, they established Eq. 9, which includes the effect of the wall.

$$\gamma_{\text{crest}} = 0.0695 - 0.274 \ln\left(\frac{G_{\text{c}}}{L_{\text{m}-1,0}}\right) \tag{8}$$

$$\gamma_{\text{v}} = \exp\left(0.3131 \frac{h_{wall}}{R_{\text{c}}}\right) \tag{9}$$

Van Doorslaer et al. (2018) included both influence factors in the overtopping formula for non-breaking waves as given in Eq. 10.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.09 \exp\left(-\left(\frac{1.5R_{\text{c}}}{H_{\text{m0}}\gamma_{\text{f}}\gamma_{\text{v}}\gamma_{\text{crest}}}\right)^{1.3}\right) \tag{10}$$

Ozbahceci and Bilyay (2018) conducted tests with rock slopes having a front slope of 1:2, a crest width of approximately $4D_{n50}$ and waves with $s_{m-1,0}$ = 0.026-0.043. Both elevated and lowered walls relative to the armour crest level were studied. Based heron they observed similar wall influence as Van Doorslaer et al. (2018). Ozbahceci and Bilyay (2018) included this influence by a discharge correction factor similar to what Besley (1999) developed for armour crest width correction, see Eq. 11.

$$C_{\mathrm{A_c}} = \begin{cases} \exp\left(-1.205\left(\frac{A_\mathrm{c}-R_\mathrm{c}}{H_\mathrm{m0}}\right)\right) & \text{if } \frac{A_\mathrm{c}}{R_\mathrm{c}} < 1 \\ 1 & \text{if } \frac{A_\mathrm{c}}{R_\mathrm{c}} = 1 \\ \exp\left(-2.733\left(\frac{A_\mathrm{c}-R_\mathrm{c}}{H_\mathrm{m0}}\right)\right) & \text{if } \frac{A_\mathrm{c}}{R_\mathrm{c}} > 1 \end{cases}$$

$$\frac{q}{\sqrt{gH_\mathrm{m0}^3}} = 0.09\exp\left(-\left(\frac{1.5R_\mathrm{c}}{H_\mathrm{m0}\gamma_\mathrm{f}\gamma_\beta}\right)^{1.3}\right)C_\mathrm{r}C_{\mathrm{A_c}} \quad (11)$$

The overtopping formula in Eq. 11 used by Ozbahceci and Bilyay (2018) does not include the influence of the wave period even though it could be expected to have an influence on their results, but unfortunately their data was not available to verify this. In the overtopping formula they used the crest width factor by Besley (1999). These choices might have an influence on their developed crest wall factor C_{Ac}. Since the data used later has a large variation in crest width and wave steepness, it is decided to apply the C_{Ac} factor developed by Ozbahceci and Bilyay (2018) on the wave overtopping prediction formula proposed by Eldrup et al. (2022). Instead of using R_{c*} in the overtopping formula, the crest level R_c is used as the influence of the wall is included in C_{Ac}. The modified Ozbahceci and Bilyay (2018) overtopping formula, including the influence factor γ_{fS} and γ_{cw} can be seen in Eq. 12.

$$\frac{q}{\sqrt{gH_\mathrm{m0}^3}} = 0.09\exp\left(-\left(\frac{1.5R_\mathrm{c}}{H_\mathrm{m0}\gamma_\mathrm{fS}\gamma_\mathrm{cw}}\right)^{1.3}\right)C_{\mathrm{A_c}} \quad (12)$$

DATA FOR PRESENT ANALYSIS

A database with existing overtopping data for lowered and elevated walls is established and used to evaluate existing methods and improve them where needed. A criteria for the data sets included has been that the reference case ($R_\mathrm{c} = A_\mathrm{c}$) has also been tested. Otherwise, it is not possible to investigate the direct influence of the wall. The used data includes both deep water conditions $h/H_{\mathrm{m0}} > 4$ and shallow water conditions $h/H_{\mathrm{m0}} > 1$. The parameter ranges of the used data are shown in Tables 1 and 2.

Pedersen (1996) tested different front slope angles, a large variety of wall heights above the armour level, and different crest widths. For most of his tests, the breakwater was armoured with rocks, but tests with cubes and dolos were also performed. Based on the tests Pedersen (1996) developed an overtopping formula, but the fitting was done on a linear overtopping scale instead of the usual logarithmic. For this reason, this formula is not considered in the present study. Only for the front slope angle cot(α) = 1.5 the reference case has been tested by Pedersen (1996). Thus, structures with cot(α) = 1:2.5 and 1:3.5 are not included in the development of the present wall influence factor, but they are instead only used for evaluation of the final formulae.

De Meyere and Vantomme (2017) performed tests with rock slopes having a front slope angle cot(α) = 1.5. Various configurations for the crest width combined with elevated and lowered walls relative to the armour crest level were studied. De Keyzer and De Kimpe (2018) performed similar tests as De Meyere and Vantomme (2017), but tested HARO and XblocPlus units instead of rocks. For the present study, only tests with the HARO units were considered.

Table 1. Range of parameters for used datasets with elevated walls ($R_c > A_c$). Wave conditions refer to those at the toe of the structure. For the Pedersen (1996) data, $T_{m-1,0}$ was not provided but estimated by $T_{m-1,0} = T_P/1.1$.

Database	Relative crest width, G_c/H_{m0}	Relative crest height, R_c/H_{m0}	Relative wall height, R_c/A_c	Relative water depth at the toe, h/H_{m0}	Front slope angle, cotα	Breaker parameter, $\xi_{m-1,0}$	Wave steepness, $s_{m-1,0}$	No. tests
Pedersen (1996)	0.98 – 3.50	0.93 – 2.78	1.45 – 19.00	2.88 – 6.24	1.5, 2.5, 3.5	1.88 – 5.23	0.016 – 0.068	110
De Meyere and Vantomme (2017)	0.40 – 3.03	1.18 – 2.07	1.53 – 2.75	2.93 – 7.46	1.5	3.35 – 6.20	0.012 – 0.040	62
De Keyzer and De Kimpe (2018)	0.52 – 3.43	0.71 – 1.86	1.76 – 3.12	3.28 – 6.29	1.5	3.51 – 7.13	0.009 – 0.036	40

Table 2. Range of parameters for used datasets with lowered walls ($R_c < A_c$). Wave conditions refer to those at the toe of the structure. For the Pedersen (1996) data, $T_{m-1,0}$ was not provided but estimated by $T_{m-1,0} = T_P/1.1$.

Database	Relative crest width, G_c/H_{m0}	Relative crest height, R_c/H_{m0}	Relative wall height, R_c/A_c	Relative water depth at the toe, h/H_{m0}	Front slope angle, cotα	Breaker parameter, $\xi_{m-1,0}$	Wave steepness, $s_{m-1,0}$	No. tests
De Meyere and Vantomme (2017)	0.46 – 3.96	0.30 – 0.91	0.24 – 0.62	2.60 – 5.39	1.5	3.48 – 6.45	0.011 – 0.037	60
De Keyzer and De Kimpe (2018)	0.57 – 4.82	0.35 – 1.09	0.28 – 0.64	3.36 – 8.41	1.5	3.67 – 9.56	0.005 – 0.033	39

EVALUATION OF EXISTING METHODS

Figure 3 shows the presented existing data compared to predictions by Eq. 6, 10 and 12 using γ_f = 0.40 for rock and γ_f = 0.47 for HARO as given by EurOtop (2018) for permeable structures. The figure shows that for a lowered wall ($R_c < A_c$) the formula by Van Doorslaer et al. (2018) and Eldrup et al. (2022) give most data inside the confidence band, while the formula by Ozbahceci and Bilyay (2018) give data below and above the confidence band.

For the reference case ($R_c = A_c$), Eldrup et al. (2022) predictions are closest to the prediction line. It should be noted that for this case, C_{Ac} = 1 and thus, the modified Ozbahceci and Bilyay (2018) formula and the Eldrup et al. (2022) formula give identical results for the reference case. The predictions by Van Doorslaer et al. (2018) are also close to the prediction line but with slightly larger deviations for the Pedersen (1996) data compared to Eldrup et al. (2022).

For the elevated wall ($R_c > A_c$), the predictions by Ozbahceci and Bilyay (2018) have the smallest deviations, while the predictions by Van Doorslaer et al. (2018) and Eldrup et al. (2022) are deviating more. The prediction by Van Doorslaer et al. (2018) only is deviating for the Pedersen (1996) data, the Eldrup et al. (2022) are deviating also for the other data. However, neither of the predictions provide accurate estimates for the elevated wall and thus improvements are needed.

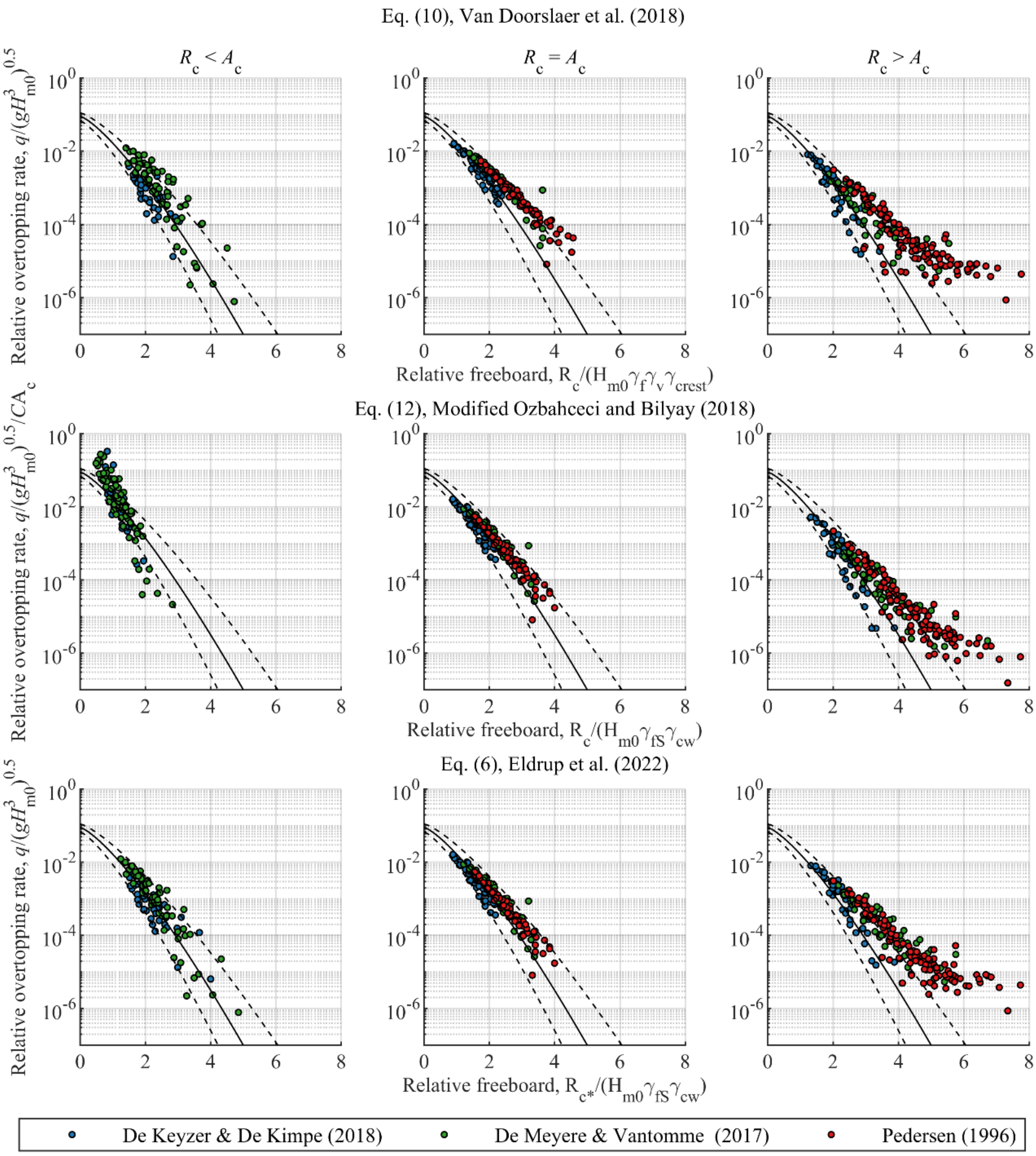

Figure 3. Comparison of the three used data sets to overtopping predictions by Eq 6, 10 and 12 for the three different wall configurations. Roughness factors given by EurOtop (2018) for permeable core is used corresponding to $\gamma_f = 0.40$ for rock armour and $\gamma_f = 0.47$ for HARO armour. The dashed lines show the 90% confidence band given by EurOtop (2018).

DATA ANALYSIS METHODOLOGY

The existing data is affected by different crest widths, roughness factors (wave steepness and armour types) and front slopes. In order to study the influence of the crown wall separately from these effects, it is necessary to compare it to a reference case not influenced by the crown wall. The influence of the crest width can be included by Eq. 5. The influence of the wave steepness and front slope can be described with Eq. 4, but as noted by Eldrup et al. (2022) the permeability of the breakwater, this is the combination of armour layer, underlayer(s) and core, may have a significant influence on the effect of the wave steepness. Therefore, Eq. 4 is used to fit a γ_f for each reference structure. Based on the EurOtop formula, a total γ can be calculated for each test for the reference structure based on Eq 13. From γ the influence factor including the wave steepness is calculated by $\gamma_{fS} = \gamma/\gamma_{cw}$, with γ_{cw} given by Eq. 5.

$$\gamma = \frac{1.5R_c}{H_{m0}} \left(-\ln\left(\frac{q}{0.09\sqrt{gH_{m0}^3}} \right) \right)^{-1/1.3} \quad , \text{for } \frac{q}{\sqrt{gH_{m0}^3}} > 10^{-6} \tag{13}$$

Figure 4 shows an example of the calculated γ_{fS} for the data by De Meyere and Vantomme (2017) and the predicted curve by Eq. 4 using a fitted γ_f of 0.44. Table 3 shows the fitted values of γ_f for each dataset.

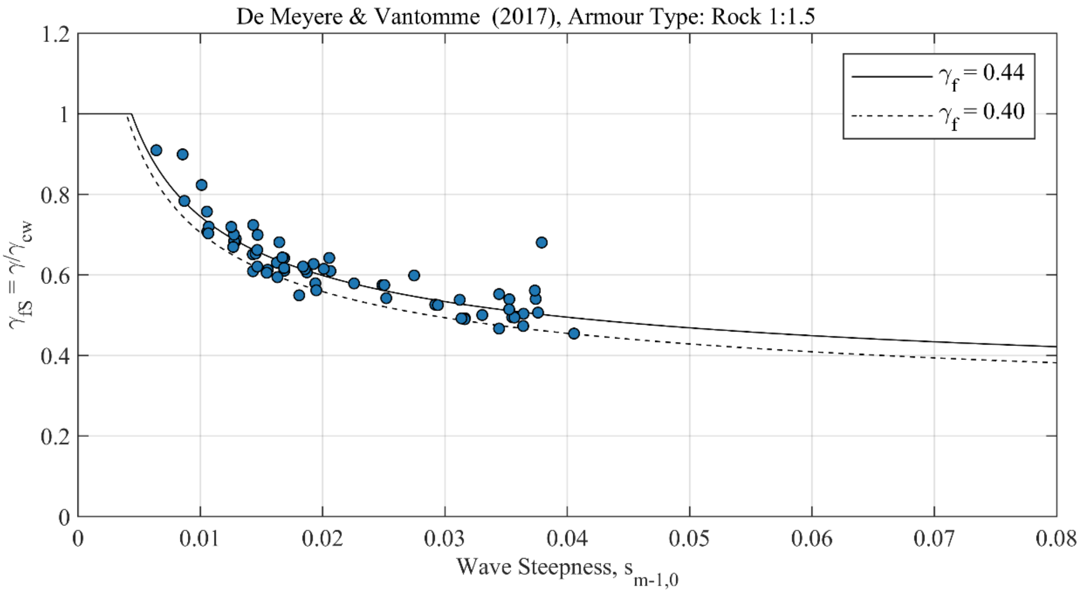

Figure 4. Example of fitted γ_f. Solid line shows Eq. 4 using γ_f = 0.44 while dashed line shows Eq. 4 using recommended roughness factor in EurOtop, γ_f = 0.40.

Table 3. Fitted γ_f values for each dataset based on Eq. 4.

Database	EurOtop (2018) recommendation	Fitted roughness factor
Pedersen (1996)	0.40 for permeable core	0.44
De Meyere and Vantomme (2017)	0.40 for permeable core	0.44
De Keyzer and De Kimpe (2018)	0.47 for permeable core	0.42

Figure 5 shows the dimensionless overtopping for each dataset for the reference case. The relative freeboard used in the figure includes γ_{fS} and γ_{cw}. The figure shows that only a few data points are outside the 90% confidence band. Thus, a quite accurate description of the reference model is obtained. Thereby, it is possible to investigate the influence of the wall for lowered and elevated walls. This will be based on the fitted roughness factors from the reference structure.

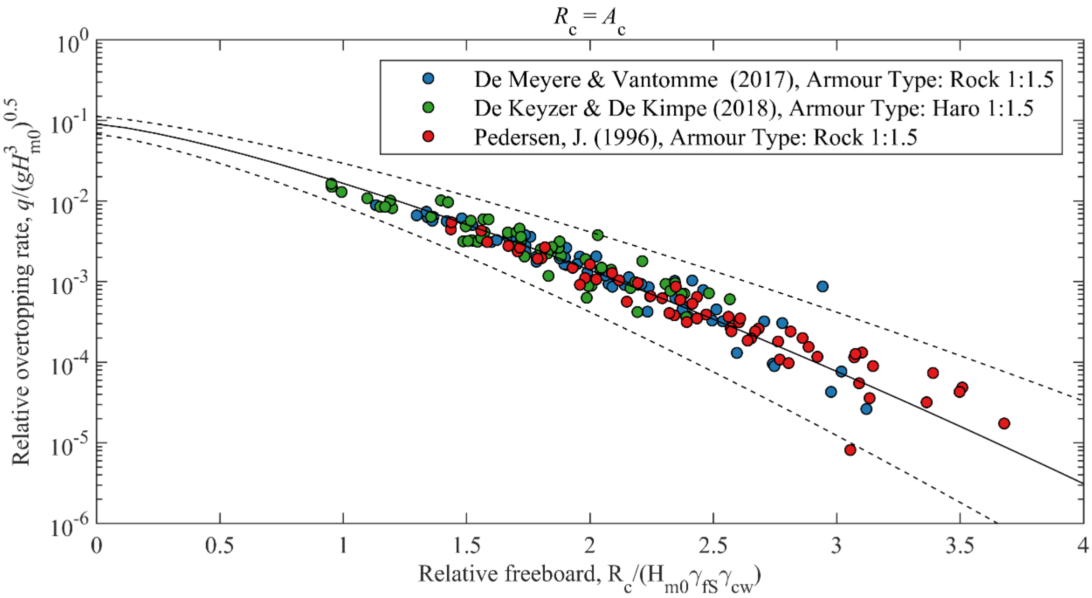

Figure 5. Evaluation of Eq. 6 for the reference case based on the fitted γ_f values for each data set. The dashed lines show the 90% confidence band given by EurOtop (2018).

ELEVATED WALL

EurOtop (2018) suggests for elevated walls to use the wall crest freeboard R_c, but Figure 6 shows that this leads to overtopping being underestimated significantly. Thus, the obtained overtopping reduction by elevating the crest wall is not as large as if both the wall and armour crest freeboard is increased.

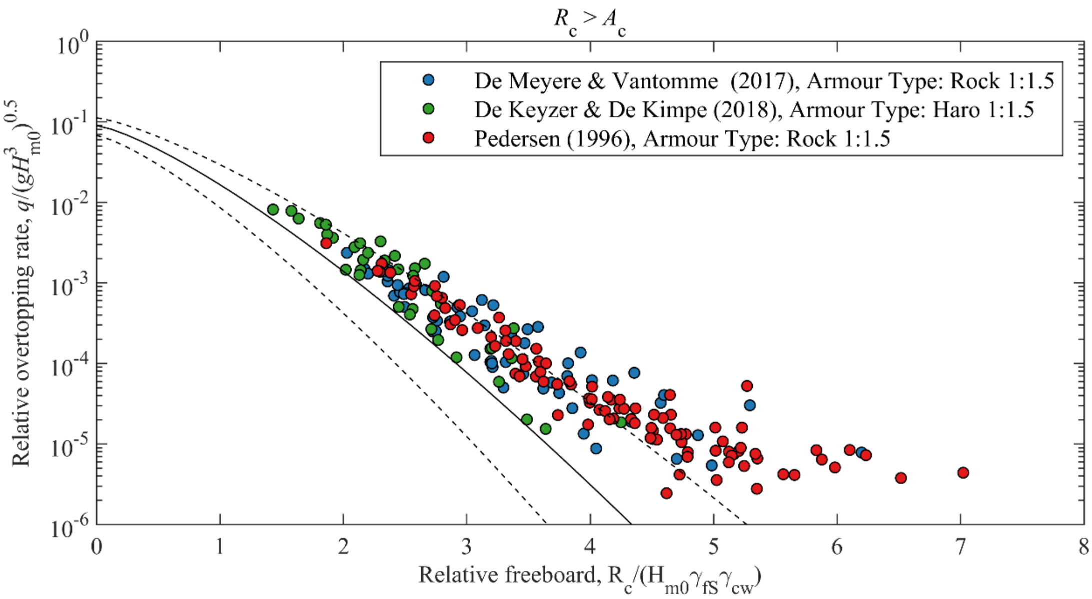

Figure 6. Evaluation Eq. 6 for the elevated wall case. The dashed lines shows the 90% confidence band given by EurOtop (2018).

Further analysis showed that the crest width influence is different for an elevated wall compared to the reference case. Figure 7 shows the data by De Meyere and Vantomme (2017), separated into different crest widths. The figure shows that the different crest widths are clustered and that the widest crest deviates the most. Thus, the crest width influence is overestimated for elevated walls.

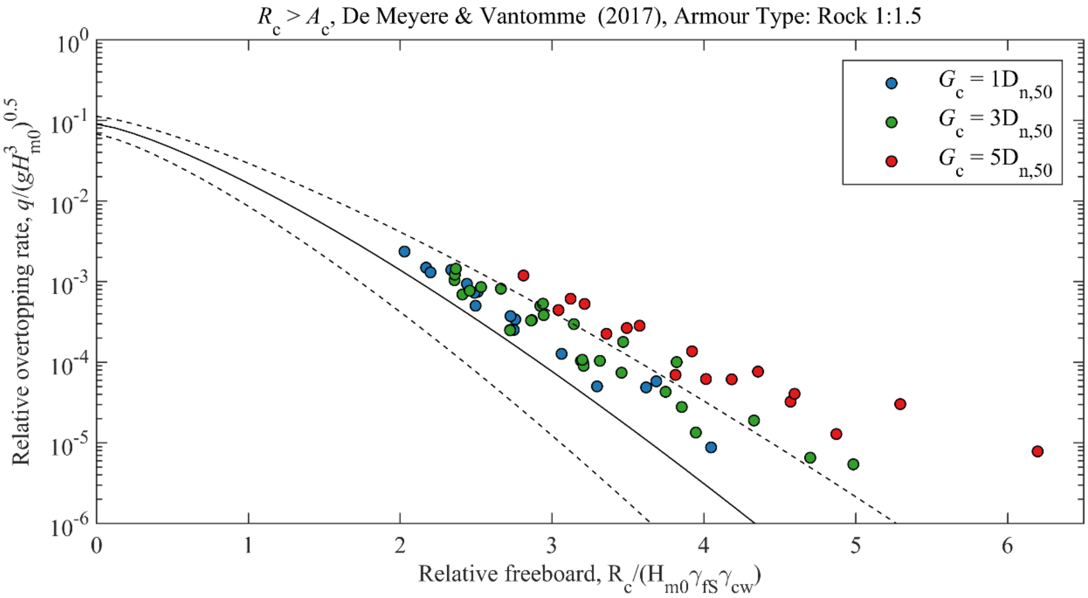

Figure 7. Overtopping predictions for the elevated wall case for data by De Meyere and Vantomme (2017). Data is coloured based on the crest width. The dashed lines show the 90% confidence band given by EurOtop (2018).

The crest width for the reference case is given as the horizontal width at the level where the overtopping is measured, shown as G_c in Figure 8. To compare that to the elevated wall case, the crest width is in the present paper suggested to be taken as the fictitious horizontal width of the crest at the wall freeboard level. The modified crest width G_c^* is shown in Figure 8, and can be calculated by Eq. 14.

$$G_c^* = \begin{cases} G_c & \text{for } R_c \leq A_c \\ \max(0; G_c - h_{wall}\cot(\alpha)) & \text{for } R_c > A_c \end{cases} \tag{14}$$

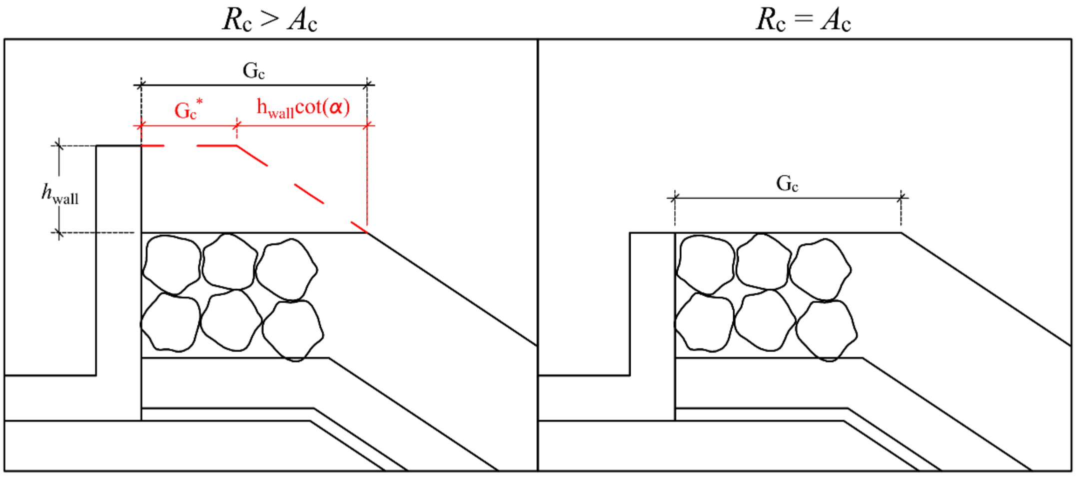

Figure 8. Definition of crest width G_c and modified crest width G_c^* for elevated walls shown in red.

The modified crest width should be used in the crest width influence factor by Eldrup et al. (2022). To complete the crest width factor for the different wall configurations, an extended version is given as γ_{cw^*} in Eq. 15.

$$\gamma_{cw^*} = \min\left(1.1\exp\left(-0.18\frac{G_c^*}{H_{m0}}\right), 1\right) \tag{15}$$

Figure 9 shows the predicted overtopping using the modified crest width influence factor from Eq. 15. With this factor included the separation into crest width is no longer visible and the data are inside the confidence band.

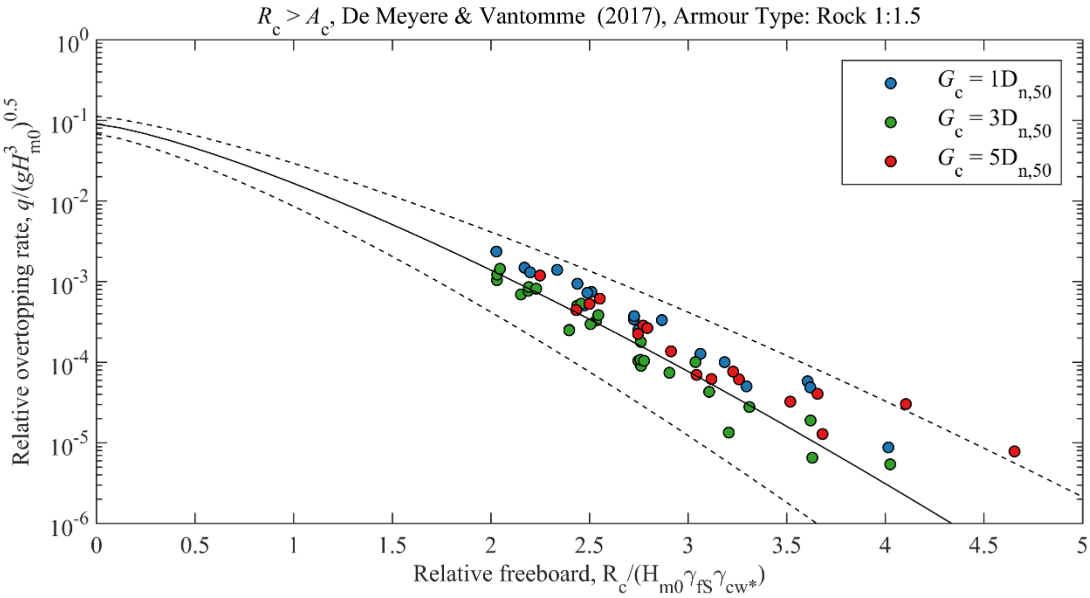

Figure 9. Overtopping predictions for elevated wall case for data by De Meyere and Vantomme (2017) using the modified crest width influence factor γ_{cw*}. Data is colored based on the crest width as in Fig. 7. The dashed lines show the 90% confidence band given by EurOtop (2018).

Figure 10 shows that even when using the modified crest width a slight underprediction is still present for the Pedersen (1996) data at large relative freeboards. The data above the confidence band is characterized by having h_{wall}/H_{m0} > 1.2 which is an unusual design as the wave loads on the wall may be very high. More data and further studies are needed to investigate the underprediction of the overtopping under such conditions before additional influence factors are established.

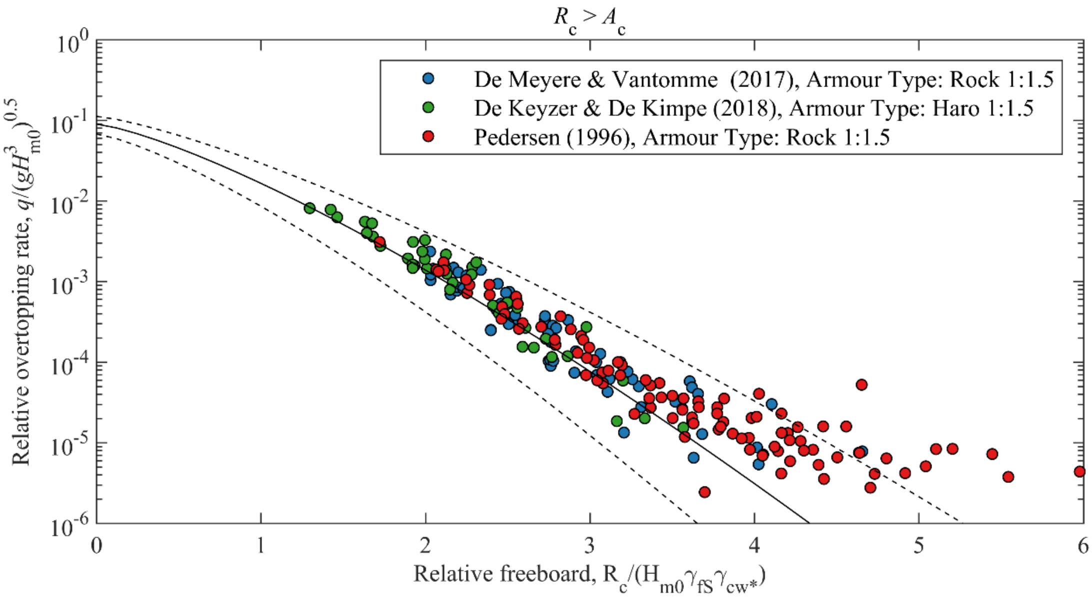

Figure 10. Overtopping predictions for elevated wall case for all datasets including the new crest width influence factor. The dashed lines show the 90% confidence band given by EurOtop (2018).

LOWERED WALL

Figure 11 shows the predicted overtopping for lowered walls using the fitted γ_f from Table 3. Most of the data are within the confidence band when using the recommendation $R_{c*} = 0.5R_c+0.5A_c$ (see definition in Figure 3) given by EurOtop (2018). Thus, the adjustments made to the crest width are not needed for the lowered wall.

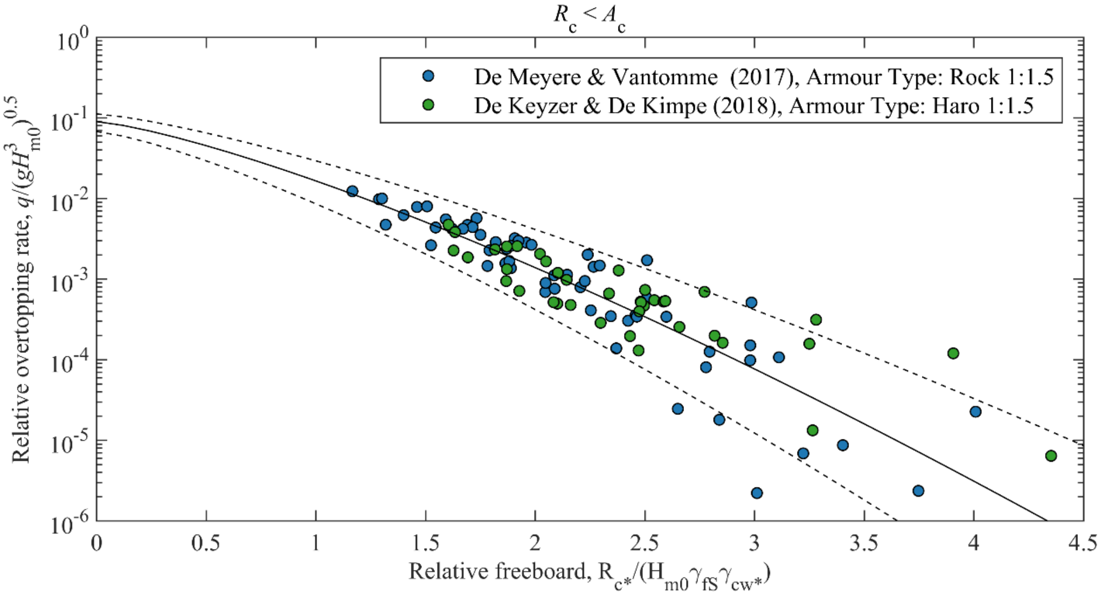

Figure 11. Evaluation Eq. 6 for the case with $R_c < A_c$. The dashed lines show the 90% confidence band given by EurOtop (2018).

OVERALL EVALUATION OF PRESENT AND EXISTING FORMULAE

The modified influence of the crest width for elevated walls is given in Eqs. 14 and 15.Including the new and the modified influence factors, the final overtopping formula for non-breaking waves becomes:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.09\exp\left(-\left(\frac{1.5R_{c*}}{H_{m0}\gamma_{fS}\gamma_{cw*}}\right)^{1.3}\right) \quad (16)$$

Where R_{c*} is the freeboard for structures with and without a crown wall as defined in Figure 1. For structures without a crown wall the overtopping is either measured at the rear shoulder of the armour crest (Figure 1-a) or at the underlayer (Figure 1-b). Figure 12 shows the evaluation of Eq. 16 using the γ_f values recommended by EurOtop (2018). The figure shows that most of the data is inside the confidence band and the data sets are biased which is caused by the difference in the best fitted γ_f value and the one given by EurOtop (2018). The improvement to the Eldrup et al. (2022) formula can be seen by comparing Figure 12 with the lower part of Figure 3. The figures shows that data with an elevated wall is improved significantly as only little data is outside the confidence band.

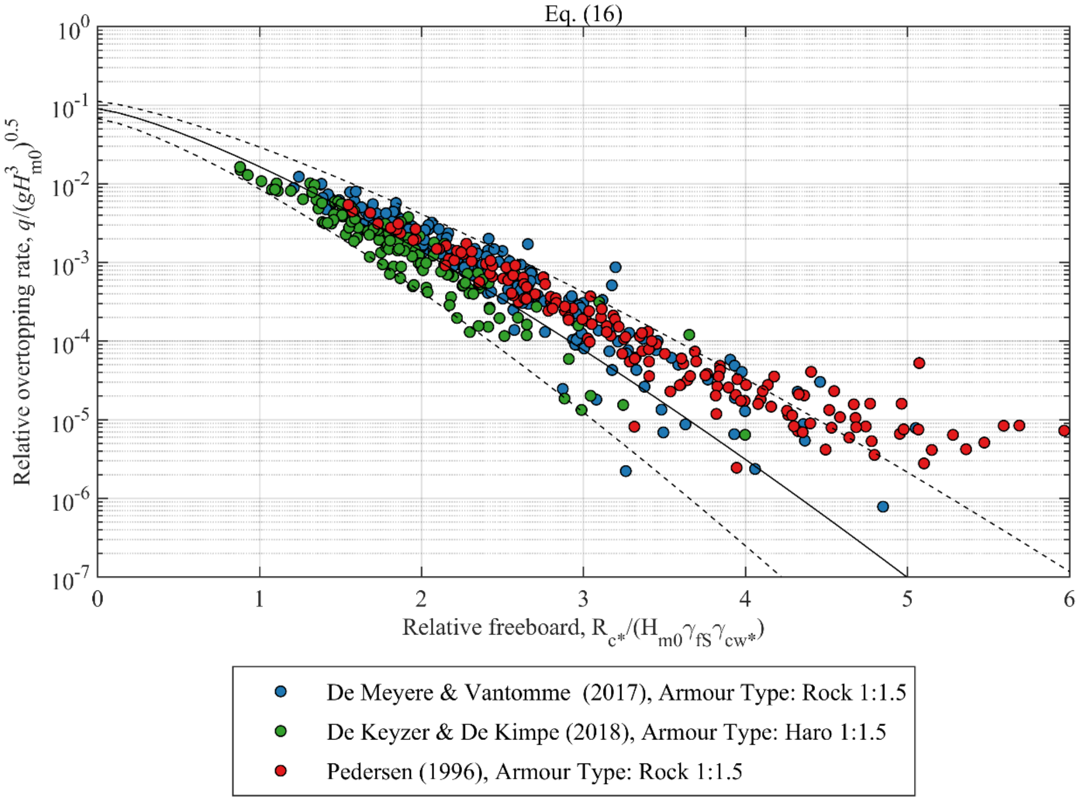

Figure 12. Evaluation of predicted overtopping using Eq. 16 for the different wall configurations by using the γ_f given by EurOtop (2018). The dashed lines show the 90% confidence band given by EurOtop (2018).

CONCLUSIONS

The influence of a crest wall on overtopping at rubble mound breakwaters was investigated. A breakwater with the wall at the level of the armour crest was the reference structure. Additionally, elevated and lowered walls compared to the armour crest level were considered.

For cases where the wall is lower than the armour crest, the recommendation given by EurOtop (2018) provided good results and no modification of the method was needed.

For the case with an elevated wall, the overtopping was underpredicted by the EurOtop method. This is because that also the armour crest width presence in front of the wave wall has its influence on overtopping discharges. A modified crest width was developed that describes the reduction in rubble material compared to the case where the wall and armour crest are at the same level. For high unprotected walls more overtopping is still measured compared to the refence case even with the modified crest width factor. More data with such conditions is needed to verify the present observations before a new influence factor is developed. Anyway, the outliers were conditions that are not typical in real designs. The overall conclusion is that the present method significantly improves the EurOtop Manual predictions for structures with an elevated crown wall.

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