OVERTOPPING ON RUBBLE MOUND BREAKWATERS FOR LOW STEEPNESS WAVES IN DEEP AND DEPTH LIMITED CONDITIONS

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In this paper, the investigation of overtopping on rubble mound breakwaters for low steepness waves in both deep and shallow-water conditions are presented. The existing formulae provide quite different results for long waves for both conventional and berm breakwaters. Therefore, new model tests with focus on long waves have been performed for both types of breakwaters. The new model tests showed some deviation from the formulae. Therefore, limitations in the use of the present methods and an update for one of the methods are presented.

Keywords: overtopping; conventional rubble mound breakwater; berm breakwater; long waves

INTRODUCTION

Wave overtopping is an important quantity to investigate when constructing a breakwater as it sets restrictions to the crest level for proper functioning of the breakwater and areas behind.

Wave overtopping on rubble mound breakwaters has been analysed by several authors, and has led to different methods for prediction of the mean overtopping discharge. The EurOtop Manual (2007) provides two formulae depending on the surf similarity; one for breaking waves and one for non-breaking waves. For the non-breaking waves the overtopping reaches an upper limit, and the overtopping becomes independent on the wave steepness. The EurOtop Manual (2007) does not state a validity range for the formulae, which may lead to unreliable results for conditions outside of the validated area. Furthermore, the procedure for calculation of the overtopping discharge described for rubble mound breakwaters is not always clear, since needed information is not given in the same chapter.

For berm breakwaters, Lykke Andersen (2006) proposed an overtopping formula based on several model tests. The formula depends on the sea state, geometric parameters, and a stability parameter, which describe the reshaping of the breakwater. The formula predicts an increase in overtopping with decreasing wave steepness. The formula is based on model tests with wave steepness $s_{0p} > 0.01$.

The CLASH Neural Network (Van Gent et al. (2007)) is a prediction tool based on a database with more than 10,000 model tests from several laboratories. Even though the method includes a variety of geometries and sea state conditions for both conventional and berm breakwaters, there is a lack of data in certain fields of application. The CLASH Neural Network predicts an increase in overtopping with decreasing wave steepness. The method is applicable for wave steepness $s_{0p} > 0.003$.

The existing overtopping formulae provide a significant difference in the predicted overtopping discharges, especially for low steepness waves, which are often referred to as long waves.

The purpose of the present study is to investigate the overtopping for both conventional and berm breakwaters, especially for long waves in both deep and depth-limited conditions. The presented model test results are not corrected for possible scale effects as they are compared solely to formulae that are also based on model tests. The existing formulae and their validity ranges are discussed based on the new model tests.

MODEL TESTS AND OVERTOPPING MEASUREMENT

The overtopping data used in this paper was measured in the tests presented in Røge et al. (2014) for conventional breakwaters, and in Thomsen et al. (2014) for the berm breakwaters. For details about the model set-up, tests programme and wave generation see these papers.

The tested conditions are given in Table 1 for both conventional and berm breakwaters. All the tests were performed on a statically stable structure with only little damage.

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Table 1: Tested parameters.

	Conventional breakwater	Berm breakwater
Deep water peak wave steepness, s_{0p}	0.004 - 0.042	0.004-0.040
Relative depth, H_{m0}/h	0.13 - 0.46	0.15-0.50
Relative freeboard, A_c/H_{m0}	0.95 - 7.11	1.17-3.63
Front slope, cot α	1.5, 2.0, 3.0	1.25, 1.5
Reynold number, Re	$3.03 \cdot 10^4$ - $4.47 \cdot 10^4$	$2.14 \cdot 10^4$ - $3.05 \cdot 10^4$

The overtopping discharge was measured by a 0.30 m wide overtopping tank with a depth gauge. When the water level reached a certain level a pump automatically emptied the tank. The set-up with the overtopping tank is shown in Fig. 1.

Figure 1: Set-up of overtopping tank.

Example of measured overtopping time series is shown in Fig. 2.

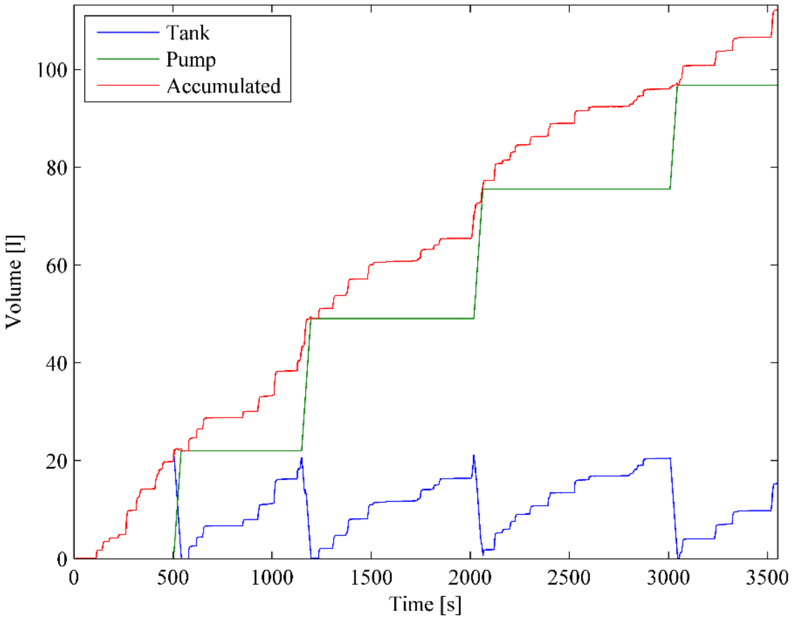

Figure 2: Example of overtopping time series.

SCALE EFFECTS

It has been shown both experimentally and by full scale measurements that significant scale effects occur related to small wave overtopping discharges on rubble mounds, cf. Burcharth (2004), Helgason and Burcharth (2006), Burcharth and Lykke Andersen (2007), EurOtop Manual (2007) and Lykke Andersen et al. (2011).

Model tests are considered unreliable due to scale effects when the dimensionless overtopping volumes are smaller than 10^{-6}. The CLASH Neural Network gives an adjusted estimation if scale effects are present. EurOtop (2007) and Lykke Andersen et al. (2011) provide procedures to scale the overtopping from model scale to prototype. These methods are not used in the present paper since the new model tests are compared with formulae based on model tests.

It is not known if scale effects exist in the present tests with waves with low wave steepness. EurOtop (2007) states that no scale effects are present for a roughness factor > 0.9. For waves with a low wave steepness, it is shown in the present study that the roughness factor increases and thereby no or only small scale effects are expected. Until prototype or large scale tests have been compared with the present model tests it is recommended to use the existing procedure to compensate for scale effects to obtain safe results.

EVALUATION OF EXISTING FORMULAE FOR CONVENTIONAL BREAKWATERS

EurOtop Manual (2007) has presented formulae based on several tests, but no ranges of validity by means of wave conditions and structural conditions are given for the formulae. Eq. (1) and (2) provide the dimensionless average wave overtopping discharge for head on waves and no superstructure.

$$\frac{q}{\sqrt{g\,H_{m0}^3}} = \frac{0.067}{\sqrt{\tan\alpha}}\,\gamma_b\,\xi_{m\text{-}1,0}\,exp\left(\text{-}4.75\,\frac{A_c}{H_{m0}}\,\frac{1}{\xi_{m\text{-}1,0}\,\gamma_b\,\gamma_f}\right) \tag{1}$$

with a maximum discharge given by:

$$\frac{q}{\sqrt{g\,H_{m0}^3}} = 0.2\,exp\left(\text{-}2.6\,\frac{A_c}{H_{m0}}\,\frac{1}{\gamma_f}\right) \tag{2}$$

where q is the average wave overtopping per unit length, H_{m0} the significant wave height in the frequency domain at the toe of the structure, A_c the crest height above still water level, α the front slope angle and $\xi_{m\text{-}1,0}$ the surf similarity parameter given by the spectral wave period $T_{m\text{-}1,0}$ and defined in Eq. (3).

$$\xi_{m\text{-}1,0} = \frac{\tan\alpha}{\sqrt{s_{m\text{-}1,0}}},\quad s_{m\text{-}1,0} = \frac{H_{m0}}{L_{m\text{-}1,0}} \tag{3}$$

The effect of roughness and permeability of the structure is included through the influence factor γ_f. For two-layer armour rocks on a permeable core, the roughness factor is $\gamma_f = 0.4$.

Another method for prediction of the overtopping discharge is the CLASH Neural Network (Van Gent et al. 2007), which is based on a database with a large amount of overtopping tests. To use this model, different geometrical and wave parameters have to be specified including the roughness factor which is $\gamma_f = 0.5$ for two layer armour rocks on a permeable core.

The measured overtopping in the new model tests is plotted in Fig. 3 against the overtopping determined by the EurOtop (2007) formula and the CLASH Neural Network method. The data is separated for different wave steepnesses in deep-water conditions $H_{m0}/h \leq 0.2$ and shallow-water conditions $H_{m0}/h > 0.2$.

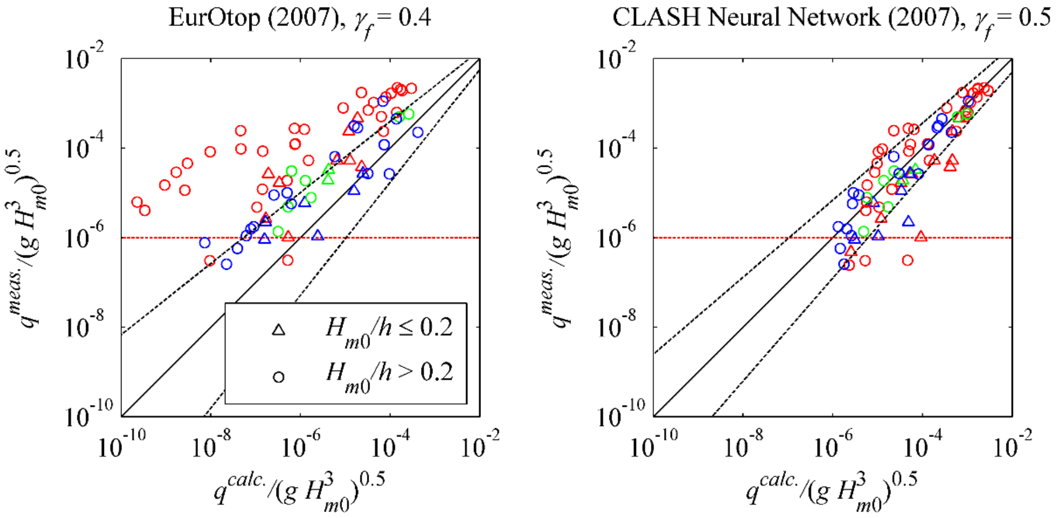

Figure 3: Comparison between calculated and measured dimensionless overtopping for conventional breakwater. Red: $s_{0m} \le 0.015$, green: $0.015 < s_{0m} \le 0.030$, blue: $s_{0m} > 0.030$. The dashed lines are the 90% confidence band. The red dashed line illustrates low overtopping, where large scale effects may exist.

Fig. 3 shows that the formulae by EurOtop (2007) provide a significant underestimation for long waves (red markers) for conventional breakwaters. The figure also indicates that the overtopping increases for long waves, which is not included in the upper limit (Eq. (2)) in the formulae by EurOtop (2007). In general, the CLASH Neural Network method provides a reliable estimate for the present tests, although some scatter for the small overtopping discharges is present. As illustrated in the figure, the CLASH Neural Network does not give any prediction for dimensionless overtopping smaller than 10^{-6}, and it provides less reliable results for measured values below 10^{-5}. In such cases only a few waves overtop and the scatter will be much higher.

For the long waves a large volume of water hits the breakwater which fills the pores with water and causes most of the flow to be in the outer layer of the breakwater. To include this effect in the overtopping formulae by EurOtop (2007), the roughness factor γ_f in Eq. (2) should depend on the wave steepness. When estimating run-up by EurOtop (2007) the upper limit is using a roughness factor, $\gamma_{fsurging}$, that depends on the wave steepness (see Eq. (4)). Therefore it is proposed to introduce in Eq. (2) the roughness factor defined by Eq. (4).

$$\gamma_{fsurging} = \gamma_f + \frac{\left(\xi_{m-1,0} - 1.8\right)\left(1 - \gamma_f\right)}{8.2} \tag{4}$$

When using $\gamma_{fsurging}$ in Eq. (2) much less scatter is obtained as illustrated in Fig. 4. The measured values below $q/\left(g\,H_{m0}^3\right)^{0.5} < 10^{-6}$ provide some scatter which is because a few waves are overtopping.

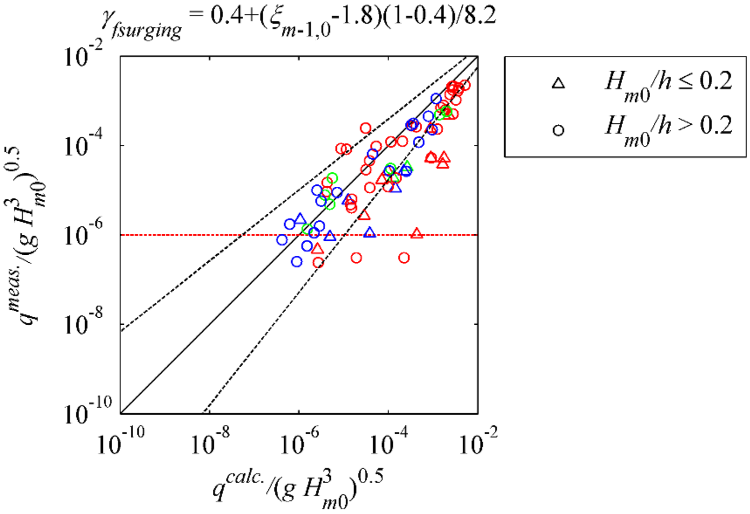

Figure 4: **Comparison between calculated and measured dimensionless overtopping for conventional breakwater by the formulae by EurOtop (2007) with adjusted roughness γ_f. Red: $s_{0m} \le 0.015$, green: $0.015 < s_{0m} \le 0.030$, blue: $s_{0m} > 0.030$. The dashed lines are the 90% confidence band. The red dashed line illustrates low overtopping, where large scale effects may exist.**

EVALUATION OF EXISTING FORMULAE FOR BERM BREAKWATERS

To use the formulae by EurOtop (2007) for berm breakwaters additional factors have to be included. When the upper and lower front slope of the breakwater are different, an average slope has to be calculated by Eq. (5), where L_{slope} is the horizontal length of the breakwater from 1.5 H_{m0} below SWL to $z_{2\%}$ (cf. Eq. (7) and (8)) above SWL.

$$\tan\alpha = \frac{1.5H_{m0} + z_{2\%}}{L_{slope} - B} \qquad (5)$$

The influence of a berm is included by γ_b defined in Eq. (6) consisting of two parts; one that takes the berm width B into account and one that takes the elevation of the middle of the berm in relation to the SWL h_b into account. The influence of a berm is largest when the berm is at SWL and decreases for larger or smaller berm elevations.

$$\gamma_b = 1 - \frac{B}{L_{berm}}\left(0.5 + 0.5\cos\left(\pi\frac{h_b}{x}\right)\right) \text{ with } 0.6 \le \gamma_b \le 1.0$$
$$x = \begin{cases} z_{2\%} & \text{for } z_{2\%} > -h_b > 0 \\ 2H_{m0} & \text{for } 2H_{m0} > h_b \ge 0 \end{cases} \qquad (6)$$

Here h_b is the water depth above the berm, L_{berm} is the horizontal length of the breakwater from H_{m0} below the berm to H_{m0} above the berm and $z_{2\%}$ is the run-up height exceeded by 2% of the incident waves predicted by iteration of Eq. (7) and (8).

$$\frac{z_{2\%}}{H_{m0}} = 1.65\,\gamma_b\,\gamma_f\,\xi_{m-1,0} \qquad (7)$$

with a maximum of:

$$\frac{z_{2\%}}{H_{m0}} = \gamma_{fsurging}\left(4.0 - \frac{1.5}{\sqrt{\xi_{m-1,0}}}\right) \tag{8}$$

For hardly and partly reshaping berm breakwaters Sigurdarson and Van der Meer (2013) proposed another roughness factor $\gamma_f = \gamma_{BB}$ given by Eq. (9) to be used in the upper limit of the overtopping defined in Eq. (2). This makes the overtopping for berm breakwaters (steep slopes) dependent on the wave steepness opposed to formulae for conventional rubble mound breakwaters.

$$\gamma_{BB} = 0.68 - 4.5s_{0p} - 0.05B/H_s \tag{9}$$

Another formula to determine overtopping on berm breakwaters is given by Lykke Andersen (2006):

$$\frac{q}{\sqrt{g\,H_{m0}^3}} = 1.79\cdot 10^{-5}\left(f_{H0}^{1.34} + 9.22\right) s_{0p}^{-2.52}\exp\left(-5.63R_*^{0.92} - 0.61G_*^{1.39} - 0.55h_{b*}^{1.48}B_*^{1.39}\right)$$

$$R_* = \frac{A_c}{H_{m0}};\; h_{b*} = \begin{cases} \dfrac{3H_{m0}-h_b}{3H_{m0}+A_c} & \text{for} \quad h_b < 3H_{m0} \\ 0 & \text{for} \quad h_b \geq 3H_{m0} \end{cases} \tag{10}$$

The amount of overtopping is effected by the stability number of the breakwater which the parameter f_{H_0} accounts for. For the present tests only hardly and partly reshaping berm breakwaters are considered and for such cases $f_{H_0} = 0$. For other cases, see Lykke Andersen (2006).

The tests by Lykke Andersen (2006) were performed on a front slope $\cot\alpha = 1.25$. For other front slopes the berm width B and crest width G_c have to be corrected by Eq. (11), so the volume of the breakwater is unchanged. B is also corrected so that the distance from where the berm meets the upper slope to the back of the crest corresponds to a front slope $\cot\alpha = 1.25$ by Eq. (11).

$$G_* = \frac{G_c + 0.5(A_c + h_b)(\cot\alpha_u - 1.25)}{H_{m0}}$$

$$B_* = \frac{B + 0.5(A_c + h_b)(\cot\alpha_u - 1.25) + 0.5(h - h_b)(\cot\alpha_u - 1.25)}{H_{m0}} \tag{11}$$

When using the CLASH Neural Network method for berm breakwaters the roughness factor for hardly reshaping berm breakwaters (Icelandic berm breakwaters, Van Gent et al. (2007)) $\gamma_f = 0.4$ is applied.

The measured overtopping for the berm breakwaters is in Fig. 5 shown with the formula by Lykke Andersen (2006) and the CLASH Neural Network method together with the formulae by EurOtop (2007) with the roughness coefficient for berms γ_{BB} by Sigurdarson and Van der Meer (2013) in the upper limit.

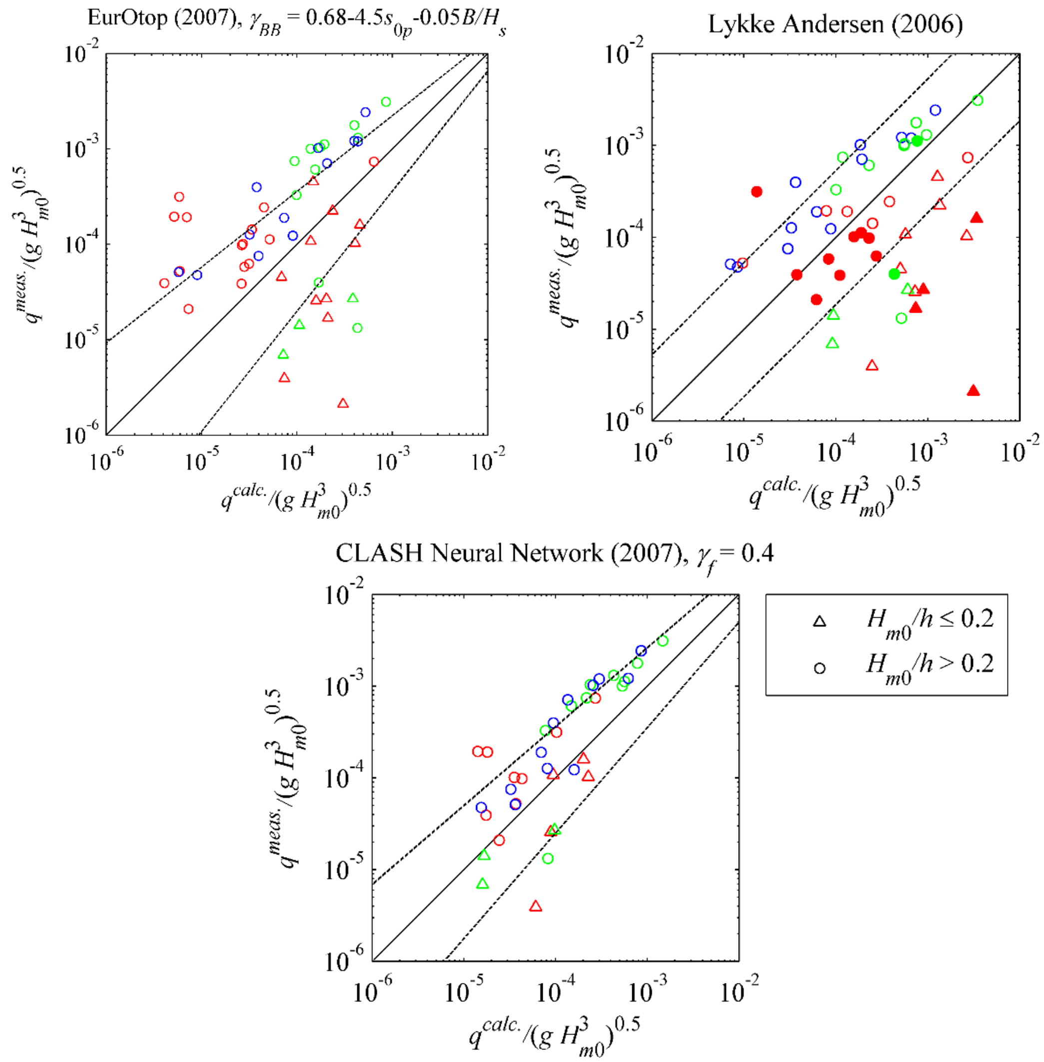

Figure 5: **Comparison between calculated and measured dimensionless overtopping for berm breakwaters. Red: $s_{0m} \leq 0.015$, green: $0.015 < s_{0m} \leq 0.030$, blue: $s_{0m} > 0.030$. The dashed lines are the 90% confidence band. The filled markers are tests with a high berm elevation $H_{m0}/h_b \geq 0.73$ outside the validated area by Lykke Andersen (2006).**

Fig. 5 shows that the formulae by EurOtop (2007) with γ_{BB} provide some scatter and in general also an overestimation for deep-water conditions. The formula by Lykke Andersen (2006) provides the same tendency with an overestimation for all deep-water conditions. Lykke Andersen (2006) did not test high berms (filled markers) and waves with low wave steepness (red markers) as in the present tests.

The CLASH Neural Network provides the most reliable results for the present test conditions, but as seen in Fig. 5, the amount of data is reduced, due to no prediction for certain conditions. For berm elevations higher than H_{m0}, which existed in some of the present tests, no predictions are given. These were also the tests which deviated most from the Lykke Andersen formula (2006).

DISCUSSION OF PRESENT PREDICTION METHODS

For the conventional breakwaters the CLASH Neural Network provides small scatter compared to the other methods. Moreover it provides the best estimations of all the methods based on the standard deviations of the difference between the logarithmic of the measured and calculated dimensionless overtopping, which could be because of no predictions for configurations of the breakwater and wave conditions outside the validation area.

For the conventional breakwater the formula by EurOtop (2007) provides a significant underestimation of the overtopping discharge for the long waves when not including the wave steepness in the upper limit as a strong dependency of the wave steepness was found in the present tests. If the roughness coefficient in the upper limit is changed to include the wave period as in the upper limit in the run-up formula by EurOtop (2007), the formulae provides much less scatter. When using the formula by EurOtop (2007) for long waves on a conventional breakwater, it is recommended to use the varying roughness factor to avoid underestimations. When using the varying roughness factor the standard deviation of the difference between the logarithmic of the measured and calculated dimensionless overtopping decreases from $\sigma = 1.41$ for constant roughness factor to $\sigma = 0.55$.

CLASH Neural Network and EurOtop (2007) with the roughness factor γ_{BB} provide both in general a safe bias for deep-water conditions and an unsafe bias for shallow water conditions for the present overtopping measurements on berm breakwaters.

Lykke Andersen's (2006) formula provides a safe bias for the tests in deep-water conditions, which were outside the validated range of the formula due to low steepness waves and different berm configurations.

Using the formula by EurOtop (2007) significant scatter is obtained and with no validity ranges of the formula it is difficult to determine if the reason is other berm configurations or wave steepnesses.

The methods for conventional rubble mound breakwaters and berm breakwater showed some scatter for dimensionless overtopping < 10^{-5} and significant scatter for < 10^{-6}, which could be caused by scale effects or simply because of statistical uncertainty due to few overtopping waves.

The standard deviations for the different methods are given in Table 2 and Table 3 based on the difference between the logarithmic of the dimensionless measured and calculated overtopping discharge.

Table 2: Standard deviations σ of the difference between the logarithmic of the measured and calculated dimensionless overtopping for conventional breakwater. Data with $q/\left(g\,H_{m0}^{3}\right)^{0.5} > 10^{-6}$ and breakwaters with no failure.

	$H_{m0}/h \leq 0.2$			$H_{m0}/h > 0.2$		
	$s_{0m} \leq 0.015$	$0.015 < s_{0m} < 0.030$	$s_{0m} \geq 0.030$	$s_{0m} \leq 0.015$	$0.015 < s_{0m} < 0.030$	$s_{0m} \geq 0.030$
EurOtop Manual (2007)	1.34	0.34	0.55	2.08	0.45	0.83
EurOtop Manual (2007) with $\gamma_{fsurging}$	0.85	0.37	0.81	0.61	0.19	0.32
CLASH Neural Network (2007)	0.59	0.14	0.69	0.50	0.18	0.31

Table 3: Standard deviations σ of the difference between the logarithmic of the measured and calculated dimensionless overtopping for berm breakwaters. Data with $q/\left(g\,H_{m0}^{3}\right)^{0.5} > 10^{-6}$ and breakwaters with no failure.

	$H_{m0}/h \leq 0.2$			$H_{m0}/h > 0.2$		
	$s_{0m} \leq 0.015$	$0.015 < s_{0m} < 0.030$	$s_{0m} \geq 0.030$	$s_{0m} \leq 0.015$	$0.015 < s_{0m} < 0.030$	$s_{0m} \geq 0.030$
EurOtop Manual (2007) with γ_{BB}	0.94	1.02	-	0.88	0.80	0.64
Lykke Andersen (2006)	1.55	1.12	-	0.52	0.68	0.60
CLASH Neural Network (2007)	0.60	0.38	-	0.60	0.52	0.46

CONCLUSION

The EurOtop (2007), CLASH Neural Network and Lykke Andersen (2006) prediction methods have been analysed against new model tests, also covering low steepness waves in deep and shallow water, with both conventional and berm breakwaters. The analysis showed that overtopping increases with decreasing wave steepness. Using a varying roughness factor $\gamma_{fsurging}$ in the formulae by EurOtop (2007), the effect of the long waves feeling a less rough surface of the breakwater is included, and the formulae provide much more reliable results for long waves.

The formula by Lykke Andersen (2006) and EurOtop (2007) for berm breakwaters provide a lot of scatter for deep-water wave conditions but a safe bias. The reason for the conservative results by Lykke Andersen's (2006) formula is that the present tests are outside the validated ranges. For EurOtop (2007) it is not known whether the new tests are outside the validated ranges since these are not given in the manual.

The analysis showed that the CLASH Neural Network method provides the best estimates for berm breakwaters and for conventional breakwaters for the tested conditions. Furthermore, it is a simple method to use. However, more data covering larger berm elevations should be added.

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