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Desk Study Tools for Upgrade of Breakwaters against Increased Loadings Caused by Climate Change

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Abstract: Burcharth et al. (2014) studied different upgrade solutions for a typical shallow water revetment and found that the most economical solution was to add an extra layer of armour rocks to the existing two layers. Because none of the existing design formulae for armour stability and overtopping cover designs with armour consisting of three layer of rocks, the related design parameters had to be estimated. Recently performed physical model tests presented in Eldrup et al. (2019) provide information of the performance of three layer rock armour and formed the basis for determination of the related notional permeability factor in the Van der Meer (1988) rock armour stability formula. The application of this formula and the Eldrup and Lykke Andersen (2018) overtopping formula is discussed in relation to armour consisting of two and three layers of rocks. The study shows that upgrading from two to three rock armour is a method to increase the stability and reduce the wave overtopping of existing structures.

Keywords: Climate changes; Breakwater upgrade; Rock armour stability; Wave overtopping

1 Introduction

Sea level rise and increase in storm intensity necessitates upgrade of many existing coastal structures in the near future. The upgrade consists of modifying the structure profile and adding structure elements such that armour stability is maintained, and acceptable overtopping discharge assured. The problem is most severe in shallow water with depth-limited waves.
Burcharth et al. (2014) performed a desk study of different concepts for upgrade of a typical rock armoured revetment in shallow water. The applicable upgrade concepts depend on whether an increase in crest level is acceptable or not. Fig. 1 shows examples for which an increase in the crest level is acceptable, while Fig. 2 shows examples where crest level increase is unacceptable.

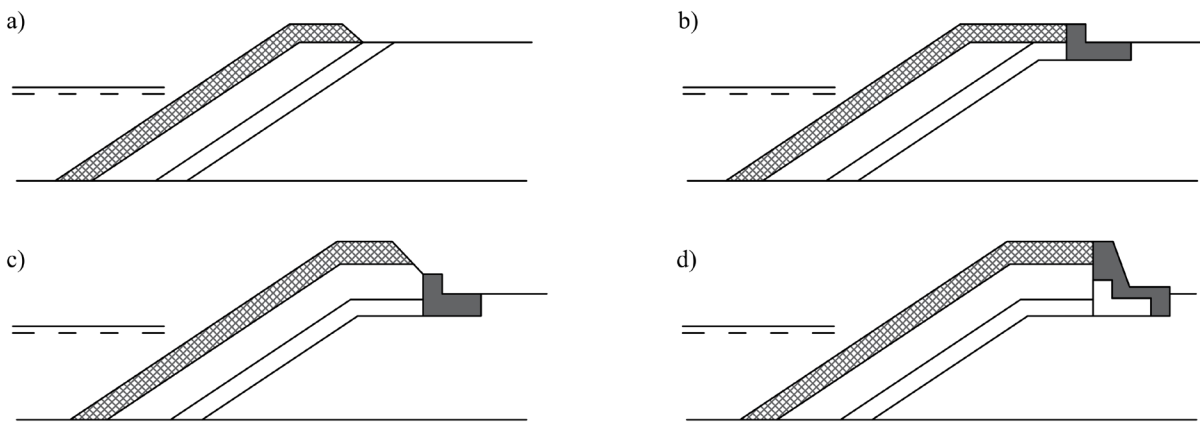

Fig. 1. Cross section of typical revetment with increase of crest elevation. Based on Burcharth et al. (2014).

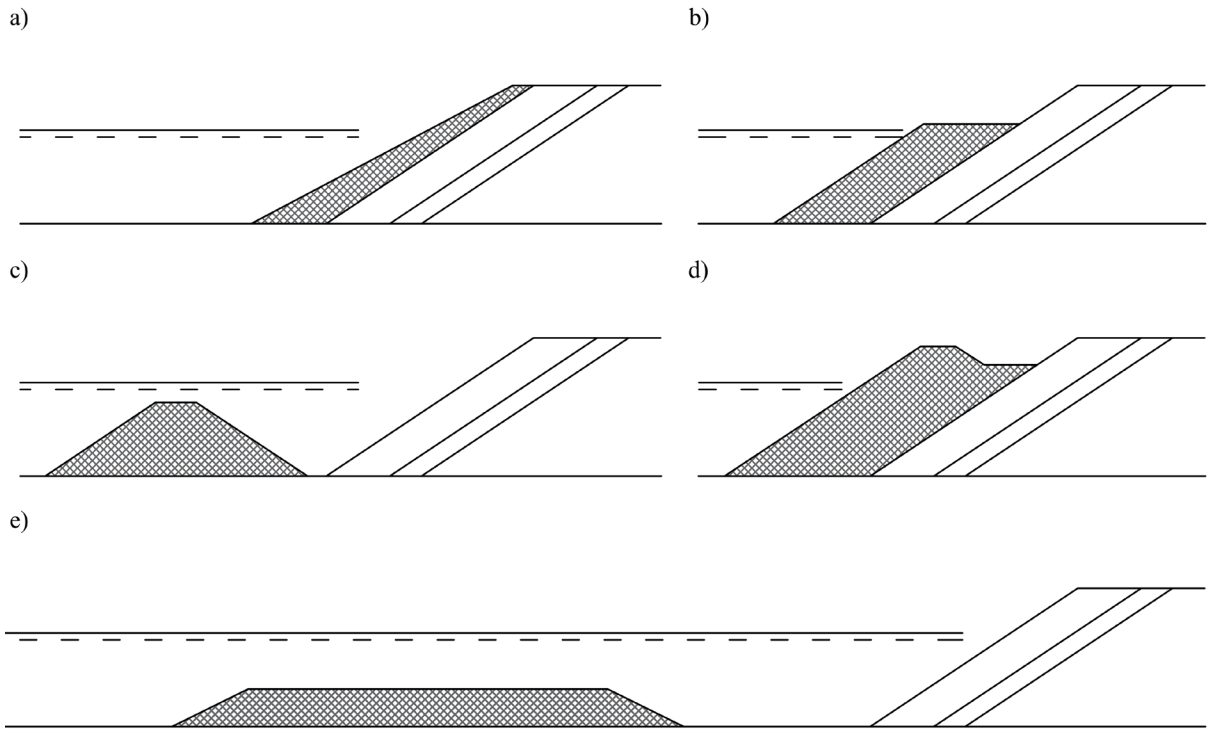

Fig. 2. Concepts of upgrading revetments where no increase in crest level is acceptable. Based on Burcharth et al. (2014).

The analysis by Burcharth et al. (2014) showed that generally the most economical solutions involve adding an extra armour layer or a berm to the structure. The upgrade solutions were assessed by existing desk design tools and involved some engineering judgement of parameter values because the tools had to be applied outside their validity range.

For the assessment of armour stability, Burcharth et al. (2014) used the rock armour stability formulae by Van der Meer (1988). In the formulae the effect of the permeability of the breakwater is included by a notional permeability factor P. The lowest value of $P = 0.1$ corresponds to a layer composition with double layer armour of armour rocks, a thin filter layer and an impermeable core. The maximum value of $P = 0.6$ corresponds to a homogenous structure consisting entirely of armour stones. For a conventional structure with a double layer of armour stones placed on a filter layer on quarry run core material, a value $P = 0.4$ is commonly used. On this basis, Burcharth et al. (2014) estimated a P value of 0.55 for a three layer armour structure but concluded that supplementary tools for the prediction of armour stability and overtopping for the upgraded structure were needed.

Recently, Eldrup et al. (2019) established a formula for the notional permeability factor based on physical model tests with 13 different layer compositions including two and three rock layer armour. The related notional permeability factors were determined. When adding the extra armour layer, it was concluded that the largest increase in P was for compositions with an impermeable core, and the smallest increase was for compositions with a coarse core. Furthermore, the increase in armour thickness implies that more stone displacements can take place before the filter layer is exposed. However, no further analysis of this was performed.

Burcharth et al. (2014) evaluated the wave overtopping discharge using the CLASH NN overtopping tool by Van Gent et al. (2007). The overtopping is dependent on several parameters of which the roughness factor γ_f is supposed to decrease when adding an extra armour layer. Dependent on the upgrade type, the crest width G_c and crest height A_c might also change. Burcharth et al. (2014) assumed that γ_f decreased from 0.55 to an estimated value of 0.4 when adding an extra armour layer. This estimate is in the present paper evaluated based on the results of the model tests by Eldrup et al. (2019) which included wave overtopping measurements.

In the present paper, a short description of the Eldrup et al. (2019) model tests and the formula for prediction of the notional permeability are given. Based on the model test results, design values of the damage parameter in the Van der Meer (1988) rock armour stability formula is discussed for two and three rock layer armour.

Finally, the formula for the prediction of wave overtopping discharges by Eldrup and Lykke Andersen (2018) is evaluated on the basis of the model tests.

2 Tested Cross-Sections in Physical Model Tests

Eldrup et al. (2019) tested different layer compositions of which those dealt with in the present paper are shown in Fig. 3. The armour layer damage was determined by laser measurement of the armour surface profile combined with visual identification of filter layer exposure. Wave overtopping discharge was measured at the rear shoulder of the armour crest.

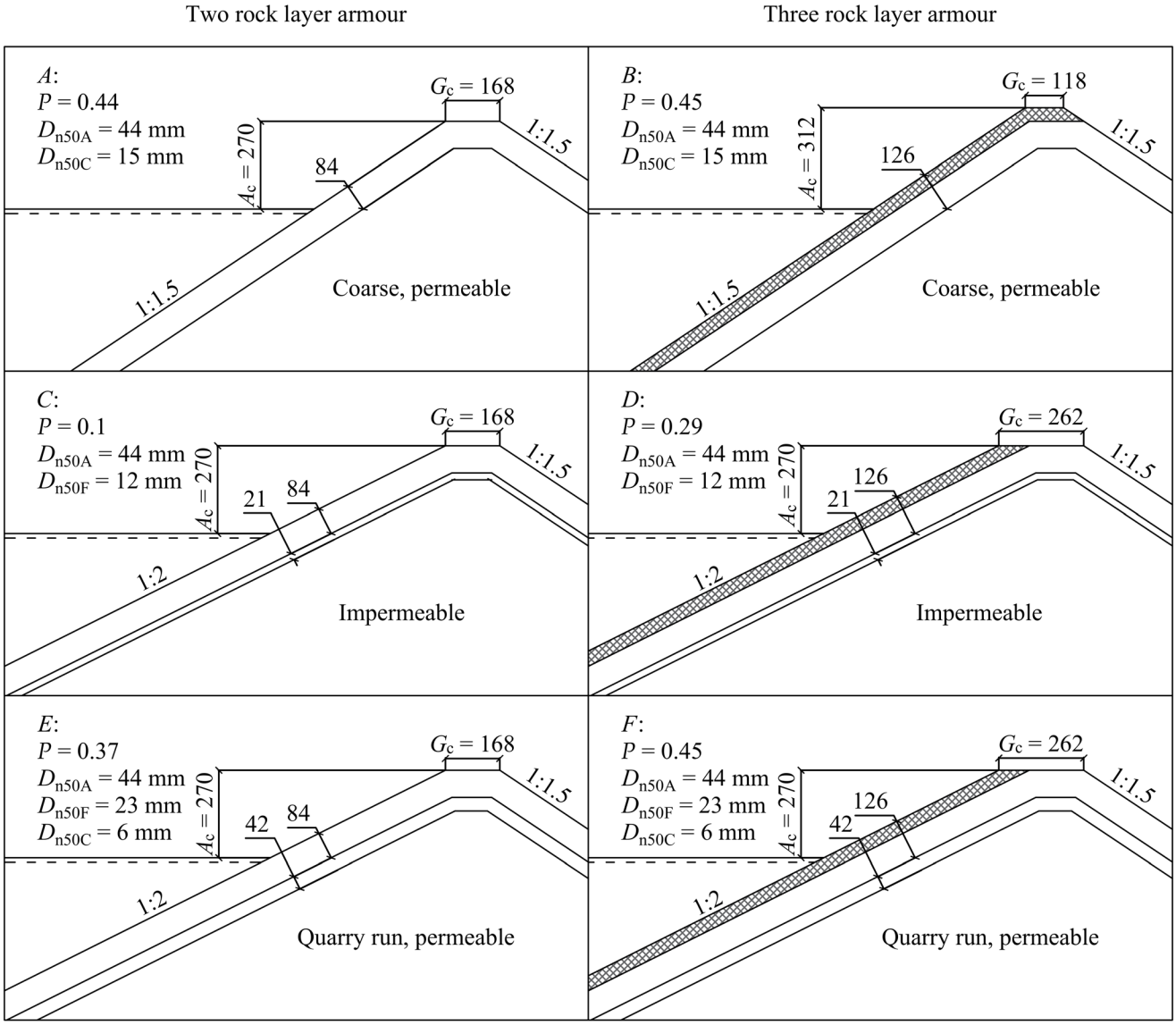

Fig. 3. Layer compositions tested by Eldrup et al. (2019) used in the present study. Measurements are in mm.

Composition *A* consists of a two layers of rocks placed on a coarse permeable core. Composition *B* is an upgrade of composition *A* by placing an extra layer of armour rocks and increasing the crest elevation with one layer of armour units. This reduces the width of the crest. Layer composition *C* has two layers of rocks placed on a thin filter layer and an impermeable core. Composition *D* is an upgrade of composition *C* by placing an extra armour layer without increasing the crest elevation. This increases the crest width. Layer composition *E* has two layers of rock placed on a filter layer on a permeable core of quarry run material. Composition *F* is an upgrade of composition *E* in that an extra rock layer is added without increasing the crest level. Only the crest width is increased.

3 Determination of the Notional Permeability in the Van der Meer Rock Stability Formulae

The rock armour stability formulae by Van der Meer (1988), Eq. (1), reads:

Plunging waves ($\xi_{0m} < \xi_{0m,cr}$ or $\cot(\alpha) \geq 4$):

$$\frac{H_{1/3}}{\Delta D_{n50A}} = 6.2P^{0.18}\left(\frac{S_d}{\sqrt{N_w}}\right)^{0.2}\xi_{0m}^{-0.5}$$

Surging waves ($\xi_{0m} \geq \xi_{0m,cr}$ and $\cot(\alpha) < 4$):

$$\frac{H_{1/3}}{\Delta D_{n50A}} = P^{-0.13}\left(\frac{S_d}{\sqrt{N_w}}\right)^{0.2}\sqrt{\cot(\alpha)}\ \xi_{0m}^{P} \tag{1}$$

The transition between plunging and surging formula is given by:

$$\xi_{0m,cr} = \left(6.2P^{0.31}\sqrt{\tan(\alpha)}\right)^{\frac{1}{P+0.5}}$$

$H_{1/3}$ is the average of the 1/3 highest waves at the toe of the structure, Δ is the reduced density of the armour rocks, and D_{n50A} is the nominal size of the armour rocks. P is the notional permeability factor, $S_d = A_e/D_{n50A}^2$ is the damage parameter where A_e is the eroded area, N_w is the number of waves, ξ_{0m} is the breaker parameter calculated from $H_{1/3}$ and T_m at the toe of the structure, and α is the seaward front slope angle.

The notional permeability factor has mainly been estimated by model tests supplemented by application of numerical models, by Jumelet (2010), Van Broekhoven (2010) and Van der Neut (2015). Recently, Eldrup et al. (2019) made a simple empirical formula to estimate the notional permeability based on the layer thickness and the material size, see Eq. (2).

$$P = \max\begin{cases} 0.1 \\ 1.72k - 1.58 \end{cases} \tag{2}$$

P is thus related to a fictitious permeability (k) of the breakwater which is calculated and summed for each layer (i=1..N) in the breakwater. The fictitious permeability k is estimated by Eq. (3).

$$k = \int_0^{z^*_{max}} f(z^*)g(z^*)dz^* \tag{3}$$

$f(z^*)$ is a function describing the influence of the material size and $g(z^*)$ is a function describing the influence of the distance from the surface of the armour layer. Eq. (3) can be expressed as a closed form solution, see Eq. (4).

$$k = 0.79\sum_{i=1}^{N}\left[\left(1-\exp\left(-4.1\frac{D_{n50,i}}{D_{n50,A}}\right)\right)\left(\frac{\exp\left(-0.62z^*_{1,i}\right)-\exp\left(-0.62z^*_{2,i}\right)}{0.62}\right)\right] \tag{4}$$

$D_{n50,i}$ is the material size of layer i and $D_{n50,A}$ is the material size of the armour layer stones. $z^*_{1,i}$ and $z^*_{2,i}$ are the relative distance from the armour surface to top and bottom rocks of layer i, see Fig. 4. $z^*_{2,i}$ is used with a maximum of 13 as the $g(z^*)$ function is close to zero implying that the influence on k insignificant for larger values of $z^*_{2,i}$.

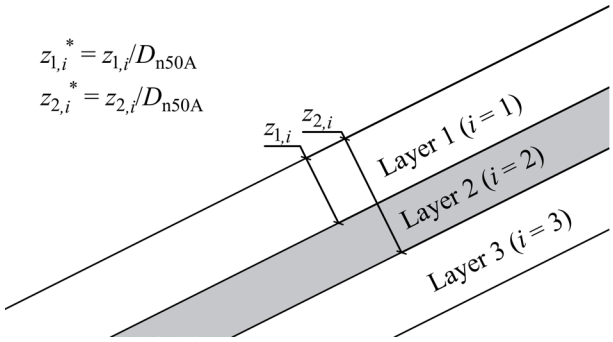

Fig. 4. Definition of relative distance z_1^* and z_2^* for layer $i = 2$.

The model tests and the formula show that the increase in P when placing an extra armour layer is most significant for breakwaters with a small P value. Tab. 1 shows an example of estimated P values for a structure with two and three rock layer armour, filter layer and a permeable core.

Tab. 1. Example of P values estimated by Eq. (2) for a cross-section with two and three rock layer armour.

Structure	Two rock layer armour			Three rock layer armour		
Layer	Armour	Filter	Core	Armour	Filter	Core
Density, ρ [t/m^3]	2.65	2.65	2.65	2.65	2.65	2.65
Median stone mass, W_{50} [t]	7.5	0.5	0.05	7.5	0.5	0.05
Nominal rock size D_{n50} [m]	1.41	0.57	0.27	1.41	0.57	0.27
Layer thickness [m]	2.8	1.2	-	4.2	1.2	-
z_1^*	0	1.98	2.83	0	2.97	3.82
z_2^*	1.98	2.83	13.00	2.97	3.82	13.00
k	0.89	0.12	0.12	1.05	0.07	0.06
P		0.36			0.46	

4 Failure Damage Levels for Upgrades with Extra Armour Layer

It might be reasonable to accept more displacements of armour stones in the three rock layer armour than in the two rock layer armour. Thus, the absolute failure limit is taken as the beginning of extraction of underlayer material. In the tests by Eldrup et al. (2019) photos were taken to observe the visibility of the underlayer material. Fig. 5 shows an example of underlayer exposure in a structure with front slope angle cot(α) = 2 and an armour layer thickness of $2D_{n50}$. For damage parameter S_d = 5.7 the underlayer was just visible. For S_d = 11.5 extraction of stones from the underlayer started.

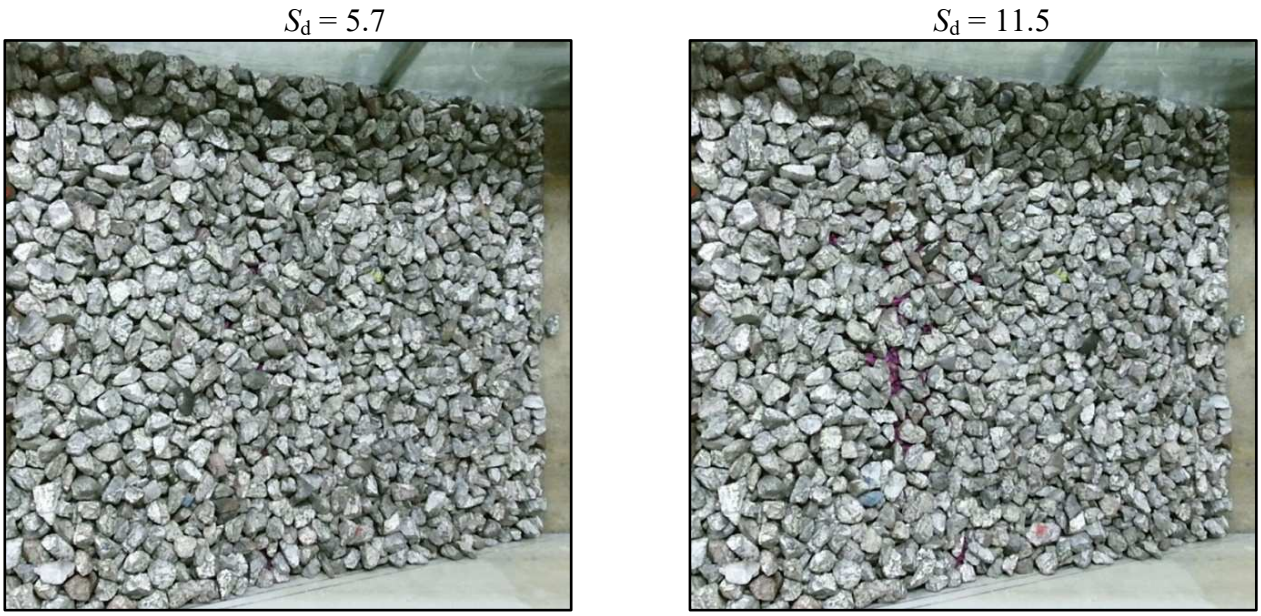

Fig. 5. Armour stone displacements in a breakwater with a front slope angle of cot(α) = 2 and armour layer thickness of $2D_{n50}$. The purple painted filter material in the breakwater becomes more visible as the damage increases.

If geometrically similarity is assumed for the erosion in two and three layer rock armour, then it must be expected that for the three layer armour the S_d damage parameter value is increased by a factor $(3/2)^2 = 2.25$ compared to the two layer parameter value, see Fig. 6.

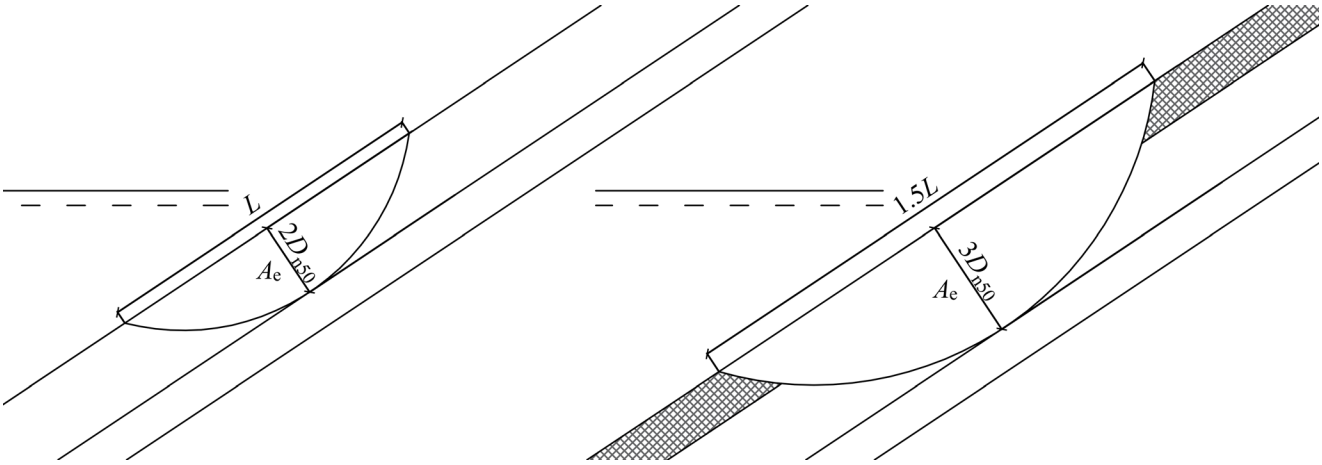

Fig. 6. Illustration of geometrically similarity between erosion in $2D_{n50}$ and $3D_{n50}$ layer thickness armour.

In Tab. 2 the failure damage measured in several test series is given depending on the front slope angle and the armour thickness. The table shows that the failure damage increases with increasing cot(α) and increasing armour layer thickness.

Tab. 2. Measured and recommended S_d damage parameter values for two and three layer rock armour.

Armour thickness	$2D_{n50}$			$3D_{n50}$		
Front slope, cot(α)	1.5	2	3	1.5	2	3
S_d for visible filter layer	9.1	15.0	17.8	23.0	27.7	41.1
	9.4	10.9	17.4	24.7	32.6	-
	10.5	13.7	13.3	19.5	25.2	-
	10.1	14.8	17.1	-	-	-
	12.3	13.7	14.5	-	-	-
	12.2	11.5	-	-	-	-
	-	10.6	-	-	-	-
Design value for visible filter based on present results	8	10	12	18	23	27
Values by Van der Meer (1988) for visible filter	8	8	12	-	-	-

In order to account for the scatter in the test results and in order to introduce some safety, the proposed S_d design values given in Table 2 for armour layer thickness $2D_{n50}$ are smaller than the S_d values obtained in the model tests. The proposed design values for armour layer thickness $3D_{n50}$ correspond to the proposed design values for $2D_{n50}$ armour layer thickness multiplied by the factor 2.25. Still, these design values are all smaller than the S_d values measured in the model tests.

The S_d value by Van der Meer (1988) for cot(α) = 2 and $2D_{n50}$ armour layer thickness is smaller than the values measured in the model tests and significantly smaller than the present recommended value. Moreover, the same values of $S_d = 8$ is given for slopes cot(α) = 1.5 and 2. It seems that this value for slope cot(α) = 2 and $2D_{n50}$ armour thickness is on the safe side.

The proposed design value in Tab. 2 are not recommended as general design values. In shallow water with depth limited waves and consequently frequent occurrence of maximum waves, the acceptable damage level might be chosen lower (corresponding to a smaller S_d value) because of the needed resistance to a very large number of maximum waves. This is not discussed further in the paper because local conditions determine the acceptable damage level.

5 Overtopping

Burcharth et al. (2014) used the CLASH NN by Van Gent et al. (2007) to estimate the wave overtopping discharge for upgraded breakwaters. However, in the present study the formulation by Eldrup and Lykke Andersen (2018) is used to estimate the wave overtopping discharge. This formulation is a slightly modified version of the formulation in the EurOtop Manual by Van der Meer et al. (2016) in that a different varying roughness coefficient is introduced. The coefficient improves the predictions for surging wave conditions. The modified formula is given by Eq. (5).

$$\frac{q}{\sqrt{gH_{m0}^3}}=\frac{0.023}{\sqrt{\tan\alpha}}\gamma_b\xi_{m-1,0}\exp\left(-\left(2.7\frac{R_c}{\xi_{m-1,0}H_{m0}\gamma_b\gamma_{f,surging}\gamma_\beta\gamma_v}\right)^{1.3}\right)C_r$$

With a maximum of

$$\frac{q}{\sqrt{gH_{m0}^3}}=0.09\exp\left(-\left(1.5\frac{R_c}{H_{m0}\gamma_{f,surging}\gamma_\beta\gamma^*}\right)^{1.3}\right)C_r$$

Crest width reduction factor by Besley (1999) (5)

$$C_r=3.06\exp\left(-1.5\frac{G_c}{H_{m0}}\right)\text{ with a maximum of 1}$$

Varying roughness factor

$$\gamma_{f,surging}=\begin{cases}\gamma_f & \xi_{m-1,0}\leq 1.8\\ \gamma_f+\dfrac{\left(\xi_{m-1,0}-1.8\right)\left(1-\gamma_f\right)}{8.2} & \xi_{m-1,0}>1.8\\ 1 & \xi_{m-1,0}>10\end{cases}$$

Here q is the mean wave overtopping discharge, g is gravity and H_{m0} is the spectral wave height at the toe of the structure. α is the seaward slope angle, γ_b is the reduction factor for a berm and $\xi_{m-1,0}$ is the breaker parameter calculated with H_{m0} and $T_{-1,0}$ at the toe of the structure. R_c is the crest freeboard, γ_β is the reduction factor for wave obliquity, $\gamma_{f,surging}$ is the varying roughness factor while γ_f is the constant roughness factor dependent on armour type. γ_v is the reduction factor for a wall at the end of the seaward slope while γ^* is the reduction factor for a storm wall on the seaward slope or on a promenade. $\gamma_b = \gamma_\beta = \gamma_v = \gamma^* = 1$ in the present study. C_r is a reduction factor for wide crested structures.

The wave overtopping measured in the tests by Eldrup et al. (2019) is shown in Figs. 7-9. Fig. 7 shows the wave overtopping results for the layer compositions with an armour layer and a coarse permeable core (composition *A* and *B*). A roughness factor of $\gamma_f = 0.39$ is used for two layer rock armour with a permeable core, see Eldrup and Lykke Andersen (2018). The influence of C_r is not very significant in this case as the crest width is rather small. Anyway the figure shows that the results for the two and three layered rock armour are slightly separated when the crest width reduction factor C_r is neglected. When including C_r, the slight separation disappears. Thus it may be concluded that the influence of the extra layer on the roughness factor is insignificant for this layer composition.

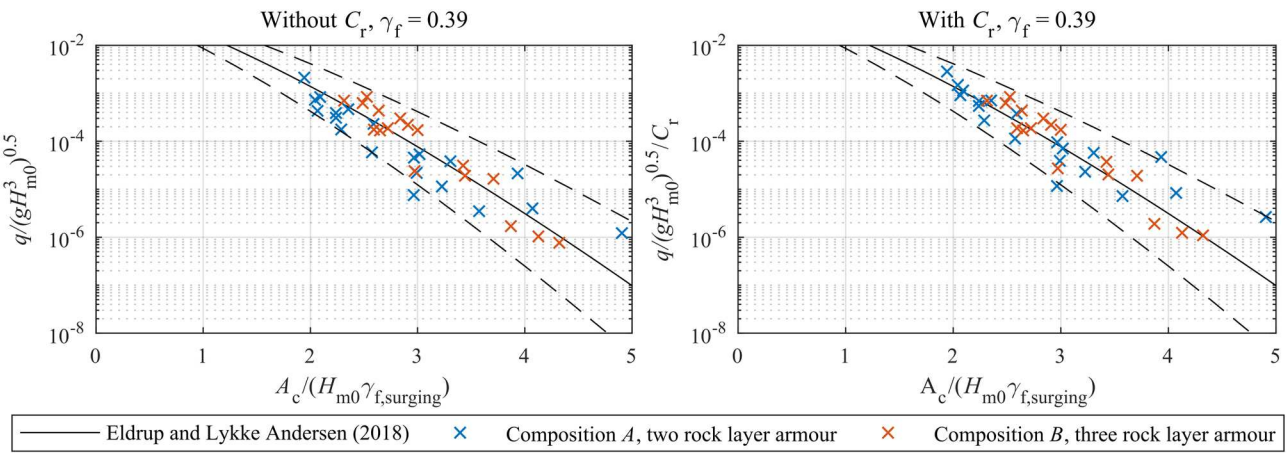

Fig. 7. Overtopping results for composition A and B with and without crest width reduction factor C_r. The dashed lines are the 90% confidence band of the Eldrup and Lykke Andersen (2018) formula.

The wave overtopping results for the layer compositions with an armour layer, a thin filter layer and an impermeable core (composition C and D) are seen in Fig. 8. A roughness factor of $\gamma_f = 0.48$ is used which is valid for two rock layer armour with an impermeable core, see Eldrup and Lykke Andersen (2018). Comparing the results of the two and three rock layered compositions without C_r, the results are not separated, and most of the data are close to the estimated overtopping. However, when including C_r the results of the three rock layer armour is adjusted too much. This might be due to less influence of the crest width due to the impermeable crest, cf. the discussion in Eldrup et al. (2018) of the influence of a permeable crest. Fig. 8 thus indicate that the influence of the crest width is much less for structures with an impermeable core, but this should be verified also for wider crests.

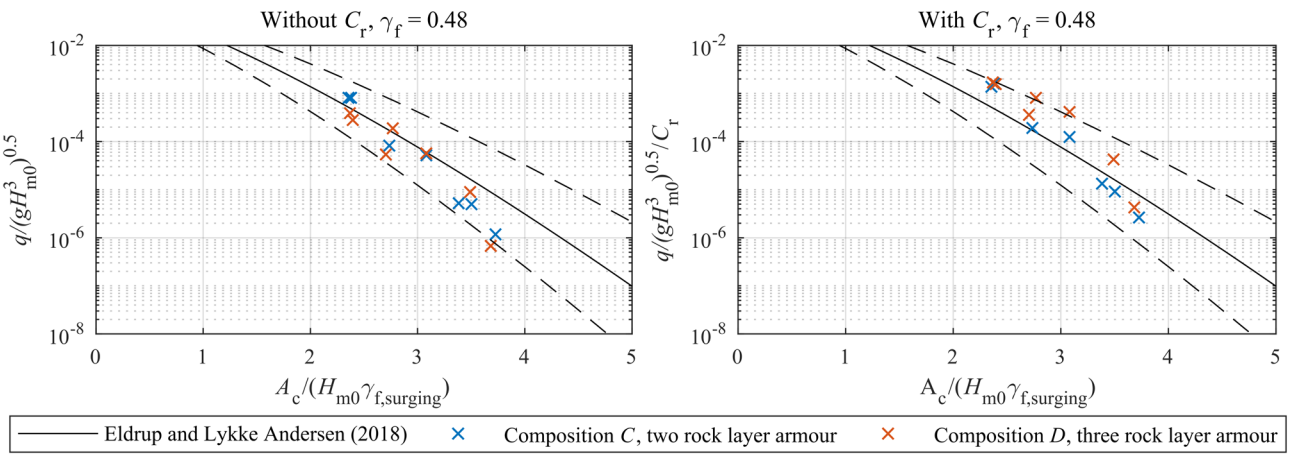

Fig. 8. Overtopping results for composition C and D with and without crest width reduction factor C_r. The dashed lines are the 90% confidence band of the Eldrup and Lykke Andersen (2018) formula.

The wave overtopping results for the layer compositions with an armour layer, a filter layer and a small grained permeable core (composition E and F) are shown in Fig. 9. A roughness factor of $\gamma_f = 0.39$ is used which is valid for two rock layer armour with a permeable core. However, the predictions are significantly underestimating the measured overtopping when C_r is included. The reason for this might be that the core consists of finer rock material and is behaving closer to an impermeable core. Analysis shows that a best fitted roughness factor for composition E and F is 0.52 which is close to value for an impermeable core given as 0.48 by Eldrup and Lykke Andersen (2018). This shows that the roughness factor is more sensitive to the permeability of the core compared to the thickness of the armour layer.

Comparing the results of the two and three rock layer compositions without C_r, a separation of the data is seen. This separation is reduced significantly when including the crest width reduction factor C_r.

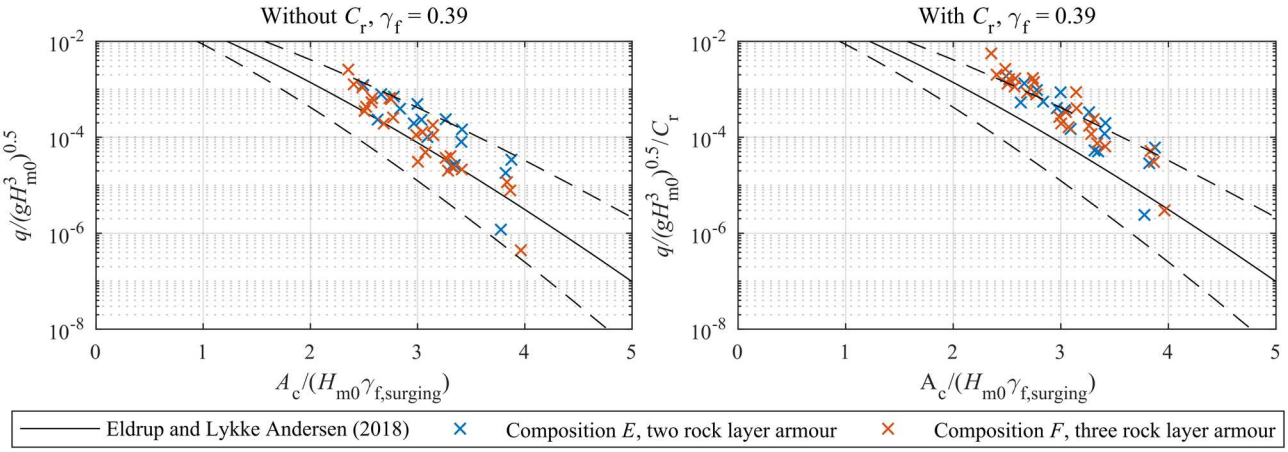

Fig. 9. Overtopping results for composition E and F with and without crest width reduction factor C_r. The dashed lines are the 90% confidence band of the Eldrup and Lykke Andersen (2018) formula.

6 Conclusions

Desk study tools have been evaluated against experimental data with breakwaters upgraded by adding an extra rock layer to the conventionally used two layers. The experimental data by Eldrup et al. (2019) which includes rock armour stability and wave overtopping measurements was used. Three compositions with different permeabilities and with two and three rock layer armour were tested.

For the upgraded compositions, the increased stability can be predicted by increasing the notional permeability factor in the Van der Meer (1988) formula. The notional permeability factor can be estimated by the Eldrup et al. (2019) formula. Furthermore, a 225% increase in the damage parameter S_d was obtained for the upgraded breakwaters before the underlying material was exposed and started to be extracted.

The wave overtopping could be predicted by applying the formula by Eldrup and Lykke Andersen (2018). Their formula includes the crest width reduction factor by Besley (1999) which showed to describe the influence of the crest width on the studied experimental results for structures with a permeable core. However, the present study showed that the permeability of the core is important when a roughness factor is selected.

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