WAVE OVERTOPPING MITIGATION BY A VERTICAL WALL OR A WAVE RETURN WALL AT THE END OF A PITCHED ROCK SLOPE

J.W. van der Meer[1], John Kiong[2], Eunice Chin[2], Yao Ming Yong,[2], M. Klabbers[3], Junsheng Jiang[3], Hongjuan Han[3] and R. Bing[4]

[1]Van der Meer Consulting bv, The Netherlands, IHE Delft, The Netherlands,;
[2]JTC, Singapore;
[3]Advisian (Worley), Singapore and Perth, Australia;
[4]State Key Laboratory of Coastal and Offshore Engineering; Dalian University of Technology, Dalian, China.
[*]corresponding author: jm@vandermeerconsulting.nl

ABSTRACT

This paper contains two topics: stability of a pitched rock slope (in contrast to randomly placed rock) and mitigation of excessive wave overtopping at an existing rock slope. The stability of a single pitched rock layer could reasonable well be predicted by the Van der Meer formula. The criteria for start of damage and failure, however, become much stricter for a single armour layer. The commonly used EurOtop-equations for wave overtopping were used to fit influence factors for a vertical wall, with and without bullnose, and for a wave return wall. A vertical wall will increase the crest level, where the wave return wall, replaces a part of the crest of the rock structure and has the same crest level as the original structure. Test conditions were focused on steep waves (high wave steepness) only, as this is the actual design situation for Singapore structures facing the sea directly.

1. Introduction

Climate change may influence the behaviour of coastal structures in Singapore in the future due to sea level rise and more extreme storms. Singapore wave conditions are relatively mild, mostly between 1 and 2 m significant wave height (H_s) for design conditions. Therefore sea level rise only may already have a significant effect on wave overtopping. Most coastal defences are pitched rock slopes with a 2 m wide crest. Mitigation measures were sought that do not increase the footprint of the coastal structure. Two options have been investigated in small scale modelling: a vertical wave wall on top of the pitched rock slope, with and without bullnose, and a wave return wall at the same level as the existing crest level. This wave return wall replaces part of the crest of the rock structure.

Physical model tests have been performed in the State Key Laboratory of Coastal and Offshore Engineering; Dalian University of Technology, Dalian, China. A limited number of stability tests have been performed and a large number of wave overtopping tests.

2. Pitched rock slopes and mitigation options

Most of the structures in Singapore are situated in deep water, from 10 m to 20 m deep. The lowest part below -3 m CD has often been designed with two layers of 10-60 kg rock. From thereon upwards, the rock size is increased and designed as a single as well as a double layer of rock. In both cases the rock layer above +-0.5 m has been pitched: carefully placed in such a way that individual stones have more interlocking and the surface looks quite flat (also because most stones have at least one flat surface). Smaller stones may be placed in between or underneath larger stones. Such a pitched rock slope is given in Figure 1.

Figure 1. A typical pitched rock slope in Singapore.

From a survey of existing structures around Singapore, two typical structures have been selected for testing, see Figures 2 and 3. Figure 2 shows a single layer of pitched rock with a grading of 100-600 kg (structure 1), where Figure 3 gives the cross-section of a double layer of larger rock with a grading of 500-1500 kg (structure 2). The upper layer of structure 2 has also been pitched. Both structures have a single underlayer of 10-60 kg. The structures have a slope of 1:2.5, although slopes of 1:3 also exist. In both cases the crest level is at +5.5 m CD (Mean Sea Level, MSL, is +1.69 m CD). Note that single armour and underlayers are quite unusual.

Figure 2. A typical cross-section with a single layer of pitched rock (Structure 1).

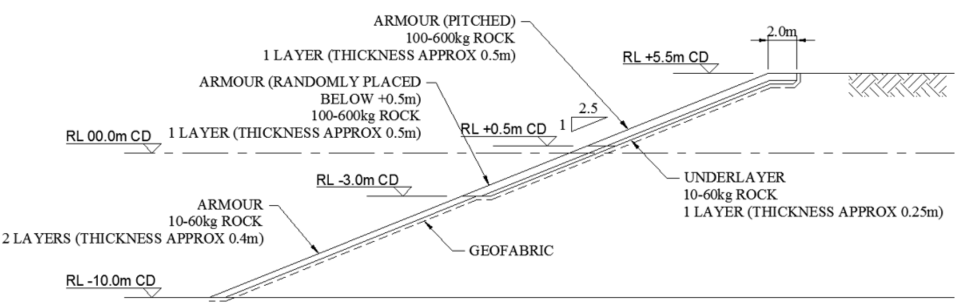
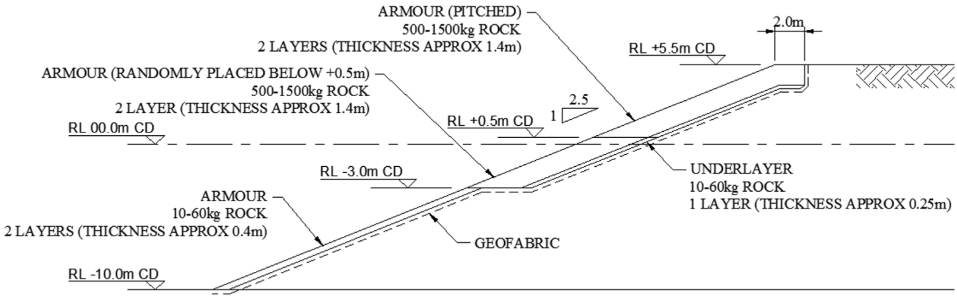


Figure 3. A typical cross-section with a double layer of pitched rock (upper layer only – Structure 2).



A first mitigation option against sea level rise was a simple vertical wall at the end of the crest of the rock structure, see Figure 4. It would not take extra space, as the wall is relatively thin, and is an effective measure to increase the crest freeboard and decrease wave overtopping. A 1 m and a 1.5 m high vertical wall have been considered. The wave overtopping could be further decreased by a bullnose at the top of the vertical wall. Dimensions are also given in Figure 4.

Figure 4. A first mitigation option against sea level rise with a vertical wall, with or without bullnose and 1.0 m or 1.5 m high.

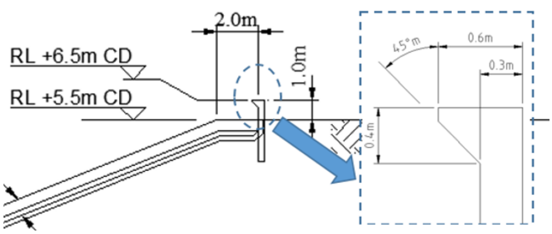
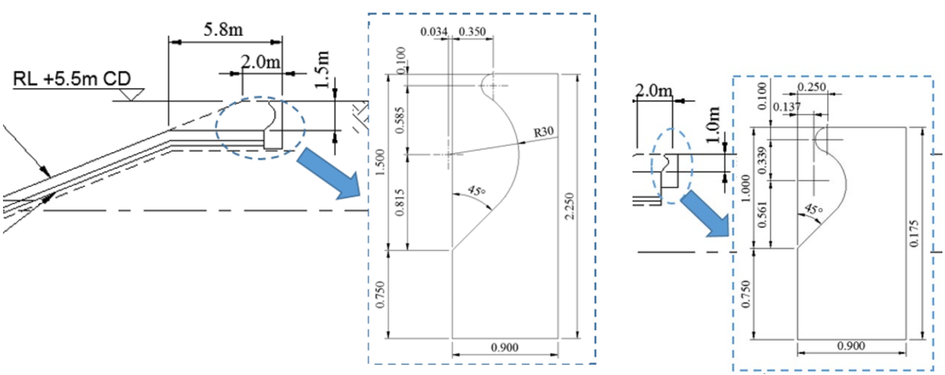


Figure 5. Second mitigation option with a wave return wall, 1.0 m or 1.5 m high.



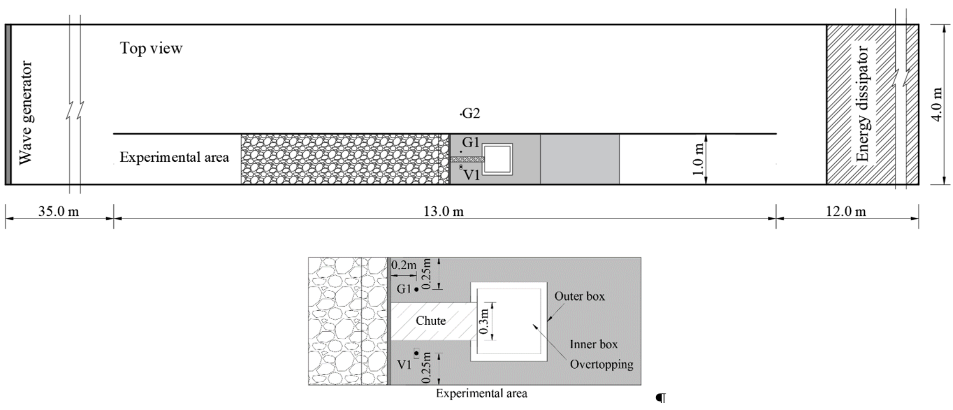
A disadvantage of a vertical wall is that direct access to the sea is blocked, which in some cases may not be allowed. Therefore a second option has been developed: a wave return wall constructed in and at the crest of the rock slope, see Figure 5. The crest of the pitched rock slope is lowered by 1.0 m or 1.5 m and at the end the wave return wall is placed. The crest level is the same as with for the pitched rock slope. It is clear that this option will not be as successful as the vertical wall to reduce wave overtopping, but it is interesting to know to what level the overtopping will be reduced.

3. Physical model tests

Model tests have been performed at Dalian University of Technology, China. First stability tests were performed on two structures: a 1:2.5 rock slope with one layer of pitched rock and a similar structure with slightly larger rock grading and two layers of rock, with the upper layer constructed as a pitched layer. These tests provided the test conditions for wave overtopping (with a stable structure). Wave overtopping tests were performed for the original structures after which vertical walls, with and without bullnose, were added and subsequently the crest part was reconstructed to include a wave return wall. The height of the walls was varied. In total more than 30 tests have been performed on stability and more than 200 tests on wave overtopping.

The wave flume was 60 m long and 4 m wide, where it was divided in a 1 m test section and a 3 m section in order to avoid re-reflection of waves from the wave generator as much as possible, see Figure 6. The scale of the experiments was 1:10. Overtopping waves were caught on a 0.3 m wide chute leading to the inner overtopping box, which was located in another outer box (to remain dry) and the overtopping water was measured by a weigh cell. The total volume of water during a test was measured, leading to the discharge q, as well as to the volumes of individual overtopping waves.

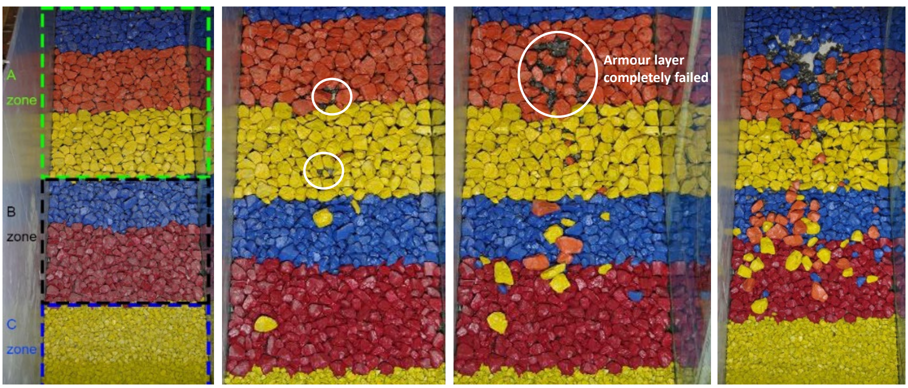
Figure 6. Layout of the wave flume and test set-up.



The test conditions were based on a wave climate study around Singapore and this study showed that test conditions were always caused by strong wind conditions that caused the wave heights directly. As the water depth was always large, depth limited wave breaking did not occur and for these reasons the wave steepness $s_{m-1,0}$ was always larger than 0.040, where the steepness is defined by the spectral wave period $T_{m-1,0}$ ($s_{m-1,0} = 2\pi H_s/(gT_{m-1,0})^2$. Test results, therefore, are applicable only for these fairly large steepness. Testing was performed for a wave steepness of $s_{m-1,0} = 0.040$ and 0.055. The wave heights for testing started with $H_{m0} = 1.0$ m and increased in steps to $H_{m0} = 2.0$ or less, depending on the stability of the structure tested. The tested water level was +2.0 m CD.

The stability testing showed the behaviour of the pitched rock slopes and Figure 7 shows a result of such testing (which will be described more in depth further on). The green box in the left graph a) shows the pitched area above +0.5 m CD (zone A). The box below is under water and was randomly placed. The number of stones displaced out of the coloured band was counted as damage.

Figure 7. Test results of structure 1, one layer of pitched rock (green box, above swl). a) Before testing; b) start of damage S_d =1.2; c) armour layer failed S_d = 2.3; d) Structure failed S_d = 4.6.



a) b) c) d)

Figure 8. Pictures of testing a 1.5 m vertical wall and a 1.5 m wave return wall.

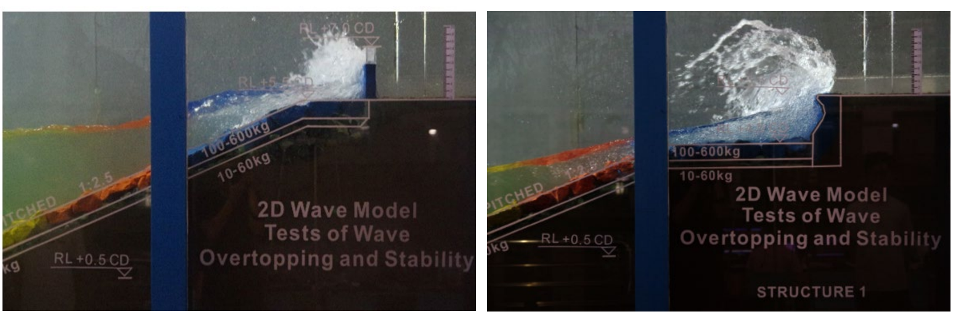


Figure 8 shows a few pictures of testing structure 1 with a 1.5 m high vertical wall (see also Figure 4) and with a 1.5 m high wave return wall with the crest at the same level as the original structure, see Figure 5. A bullnose as well as a wave return wall were quite effective in returning part of the water to the sea instead of overtopping the structure.

4. Analysis of stability

Stability formulae do not exist for single and double layer pitched rock slopes under wave attack. But the results can be compared with the Van der Meer formula, as given in the Rock Manual (2007) and applicable for randomly placed rock armour in two layers or more.

$$\frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \xi_m^{-0.5} \qquad \text{with } \xi_m < \xi_{cr} \qquad \text{(Rock Manual 5.136)}$$

$$\frac{H_s}{\Delta D_{n50}} = c_s P^{-0.13} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \sqrt{cot\alpha}\, \xi_m^{P} \text{ with } \xi_m > \xi_{cr} \qquad \text{(Rock Manual 5.137)}$$

where $\xi_{cr} = \left[\frac{c_{pl}}{c_s} P^{0.31} \sqrt{tan\alpha}\right]^{\frac{1}{P+0.5}}$ and c_{pl} = 6.2 and c_s = 1.0. For symbols see the Rock Manual.

All test conditions qualified as plunging waves and therefore equation 5.136 was deemed appropriate for use in this circumstance (as all waves were plunging, partly due to the high wave steepness). The tested structures deviate from a double layer of randomly placed rock. Structure 1 has only one layer of armour rock and this layer has been pitched, not randomly placed. Randomly placed rock in one layer is not a feasible structure and is not used (to our experience) in reality. The structure will be quite unstable and as soon as rock has been displaced, the underlayer will become visible. And such a situation is not allowed.

A single layer system of rock can only become more stable if the rock has been placed in a specific way to increase interlocking and friction. And that is what pitching should do. Considering stability of one layer of pitched rock leads to two aspects that have controversial effects with regard to a double layer of randomly placed rock. The pitching itself will increase stability. But this might only be up to a certain damage level. If damage occurs, the pitching effect is lost and damage may increase faster than for a randomly placed layer. The second effect is that one layer is thinner than two layers and will absorb less wave energy in the armour layer. This effect may decrease the overall stability compared to a double layer.

This is a little different for structure 2 where the armour layer is a double layer, but the upper layer of rock has been pitched. The pitching might be different and more difficult for such a structure than for a single layer. With structure 1 the armour rock is pitched on a nice flat underlayer of small rock. With structure 2 the upper layer is pitched on the large armour stones of the second layer and may become more difficult. For structure 2 the permeability/porosity of the armour layer will be similar to a double layer of randomly placed rock. The upper pitched layer may be a little more stable.

Another aspect is very important for applying one or two layers of armour rock. And that is the definition of failure of the armour slope, or the damage level that must be considered for failure. In design procedures one should not pass the threshold of failure of the armour layer, even not for overload conditions (such as 1.2 times the 100-years condition, or a 1000-years condition). The failure criterion for a double armour layer of rock is well known: S_d = 8 for a 1:2 slope, 12 for a 1:3 slope and consequently S_d = 10 for a 1:2.5 slope. Start of damage is often seen as S_d = 2. Intermediate damage will be between start of damage and failure of the armour slope.

This all may be different for a single layer of pitched rock. As soon as a few stones in the same area will be displaced, the underlayer will become visible. And that is the criterion for "failure of the armour layer". This means that failure of the armour layer for a single layer of pitched rock will be very close to start of damage. And that is a large difference with a double layer of rock, where large parts of the upper layer have to be displaced before the underlayer becomes visible. A double layer of randomly placed armour is therefore much more resilient for larger wave heights after start of damage than a single layer of pitched rock. Comparison of the test results with the Van der Meer formula must show the difference in behaviour of structures 1 and 2 with respect to a randomly placed double layer of rock.

The damage in the physical model tests was achieved by counting the number of stones that was displaced out of the coloured band. This gives indeed a measure of damage, but is not according to the damage parameter S_d. To establish S_d the average erosion profile of the armour layer is measured and the surface of the erosion area is related to D_{n50}^2, where D_{n50} is the nominal diameter. Van der Meer (1988) measured damage by profiling, but for a substantial number of tests he also counted the number of displaced stones that were displaced out of a coloured band of $4.5D_{n50}$ wide. Structure 1 has coloured bands of about $6D_{n50}$ wide and for structure 2 this was about $4D_{n50}$. All three values are fairly close. The relationship between the number of displaced stones per D_{n50} width, N_{od}, can be compared with the damage from the erosion profile, S_d, by:

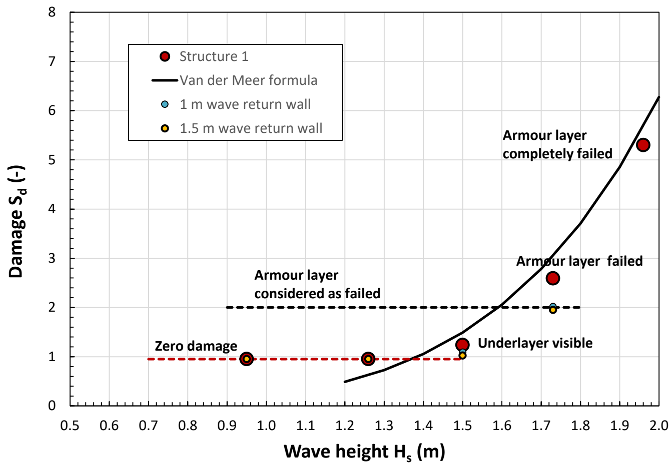
$$S_{d-approx} = 1.32 * N_{od} + 0.95 \qquad (1)$$

S_d does take into account porosity and therefore it will be larger than N_{od} (the factor 1.32 in Eq. 1 gives a 32% difference). Another difference is that S_{od} never becomes zero as it is very difficult to assess a good erosion profile for an armour layer with hardly any damage. Therefore, start of damage is given as S_d = 2 and not 0. It is for this reason that by counting the number of displaced stones, a minimum calculated level will always be S_d = 0.95.

Test results have been plotted in stability graphs, where the damage S_d is given as a function of the wave height. The real wave height has been chosen instead of a stability number, as the options of height of return wall are not dimensionless. Also the Van der Meer formula can be given in such a graph for a direct comparison. Figure 9 shows the results for structure 1, including the results with a wave return wall. The pictures of damage are shown in Figure 7.

The final test showed a complete failure of the structure, including the armour layer, with $S_d = 4.6$, see Figure 7d. Up to a wave height of $H_s = 1.26$ m nothing happened. For a wave height of $H_s = 1.5$ m a damage level of $S_d = 1.2$ was reached, normally described as no damage (Figure 7b). The next step with $H_s = 1.73$ m showed more damage with $S_d = 2.3$, normally described as a little more than start of damage (Figure 7c). Due to the fact that the armour has only one layer, it is clear that the underlayer becomes visible as soon as a few stones have been displaced, already for S_d =1.2.

Figure 9. Test results and stability formula for structure 1 with pitched slope.



The results in Figure 9 show that a single layer of pitched rock may well be comparable with a double layer of randomly placed rock. The pitching (more stable) and thinner layer (less stable) are more or less in balance. Structure 1 has also been tested on stability with a 1 m and 1.5 m wave return wall. The effect is that the crest of the armour is 1 m or 1.5 m lower than the original crest of the structure, but it is still significantly above water as the stability tests were performed with a water level of +2 m CD. Figure 9 shows that there is not much difference between a rock structure and a structure with a wave return wall. The tests with structure 1 and a wave return wall with $S_d = 2$ show a picture where the underlayer is visible, although the picture is just a little better than at Figure 7c with the rock structure only and a little larger damage of S_d =2.3.

Figures 7 and 9 show that the underlayer becomes visible already for $S_d = 1.2$ and that the armour layer should be considered as failed for $S_d = 2.0 - 2.6$. The situation with $S_d = 5.3$

is beyond any acceptable damage. A double layer randomly placed rock on a slope 1:2.5 has start of damage for S_d = 2 and failure for S_d = 10. This is a large contrast and a significant draw back of a single layer system. The results validate that the stability of a single layer pitched rock may be calculated with the Van der Meer formula, but the design values should be changed to start of damage S_d = 1 and failure of the armour layer to S_d = 2.

Figure 10 shows the stability results of structure 2. Start of damage occurs for a wave height of H_s = 1.73 m and the damage is a little larger than expected from the formula, but still close. Obviously, pitching of an upper layer on top of a large underlayer does not give the same increase in stability as for pitching on a smooth underlayer as for structure 1. The difference for the higher wave height of H_s = 2.06 m is a little larger, but still within the scatter of stability testing.

Figure 10. Test results and stability formula for structure 2.

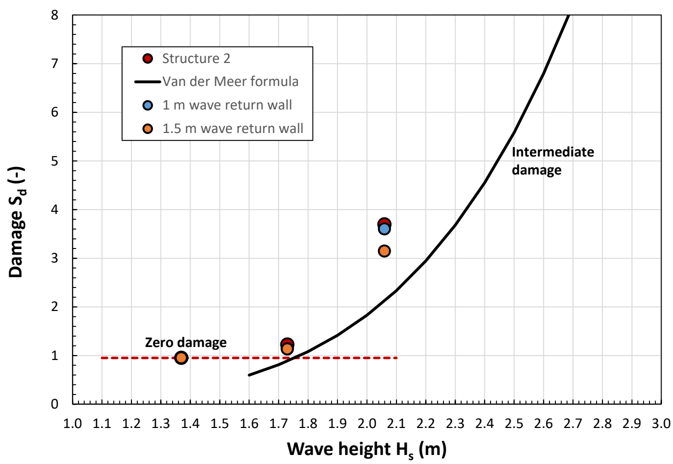


Figure 10 shows that a test with a larger wave height could have been added. The maximum damage is now S_d = 3.7 and that is well below intermediate damage. The damage is indeed similar to structure 1, but as structure 2 has two layers of armour, the underlayer does not become visible for such a damage. The formula predicts start of damage fairly well, but as damage for really larger wave heights are missing, one can only conclude that the formula and damage from testing of structure 2 are in the same order of magnitude.

5. Analysis of wave overtopping

Figures 11 and 12 show all the overtopping results from the physical model tests for structures 1 and 2, respectively. The horizontal axis presents the relative freeboard and the vertical axis the relative overtopping rate, all according to EurOtop (2018). The vertical axis is presented on a logarithmic scale. The test results of the various assessed structures are plotted as dots/triangles/diamonds of different colours. EurOtop (2018) Equations 5.10 and 5.11 include various influence factors γ, which are given by a “g” in the legends of the graphs. The influence of roughness, γ_f (gf in the legends), has been given in the graphs by various lines. The two graphs show a lot of data of which a number of conclusions can be drawn. As expected, a large (relative) freeboard results in a low (relative) overtopping discharge and vice-versa.

Figure 11. Overtopping results from physical model tests for structure 1.

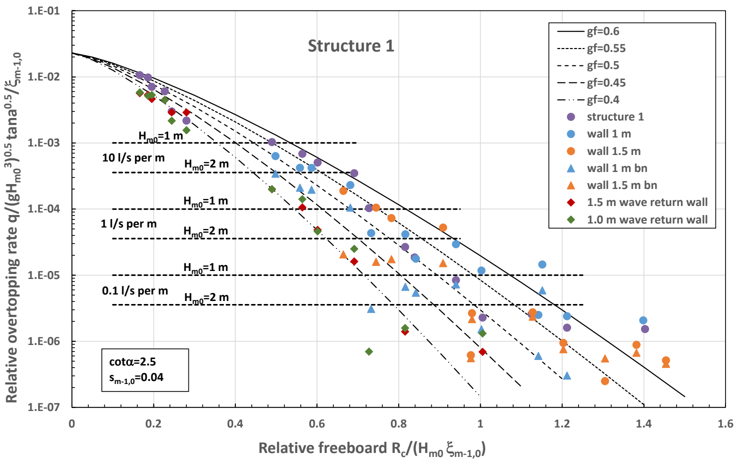
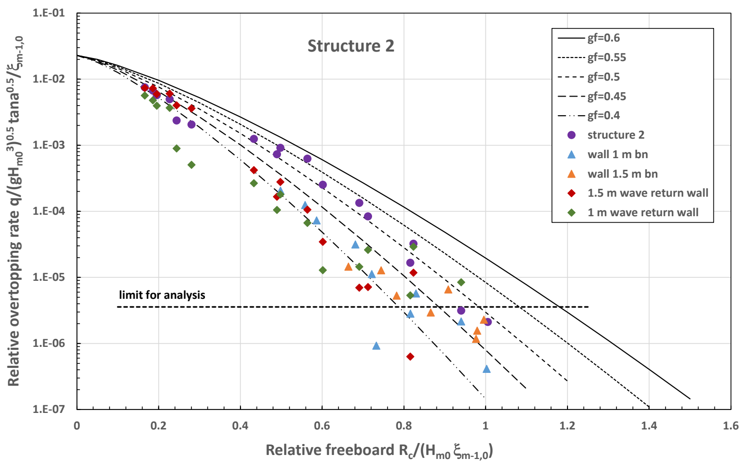


Figure 12. Overtopping results from physical model tests for structure 2.



The typical existing structures 1 and 2 (purple dots) have a larger overtopping than with a wave return wall or a vertical wall with a bullnose. The data for a vertical wall (blue and orange dots in Figure 11) follow a similar trend as the original structure, but have less overtopping due to the much larger freeboard in the tests of the vertical wall compared to the original structure.

Figure 11 also show horizontal lines with overtopping discharges of 0.1 l/s per m (very small, almost no overtopping), 1 l/s per m (often used in design) and 10 l/s per m (quite some overtopping). Such lines depend on the conditions used to calculate them. Here $\cot\alpha = 2.5$ and $s_{m-1,0} = 0.04$ were used with a wave height of $H_{m0} = 1$ m and 2 m, respectively. The lines show that there are quite some test results below the lines for 0.1 l/s per m. From scientific point of view, they may be interesting, but they show often a large scatter in that area and they would not be important for application of results. The analysis of fitting of results has therefore been focussed on data points above the line for 0.1 l/s per m and $H_{m0} = 2$ m. That line is also included in Figures 12 to 19.

The influence of roughness, γ_f, has been determined for both structure 1 (single layer pitched armour rock) and structure 2 (double layer of armour rock with upper layer pitched) as presented in Figure 13. To include the influence of the vertical wall, a factor γ_v has been determined. In a similar matter a factor γ_{bn} has been determined for the influence of a bullnose as well as a factor γ_{wrw} for a wave return wall.

Figure 13. Comparison of overtopping discharges and derived curve of influence factors of roughness for structure 1 and 2 (note gf: γ_f).

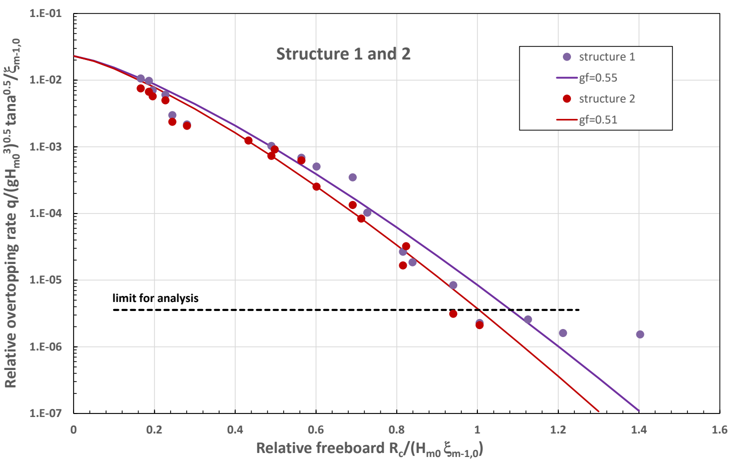


Figure 13 shows a comparison of wave overtopping results and the influence factors of roughness γ_f for the structures 1 and 2. The fit indicates a $\gamma_f = 0.55$ for structure 1 (single layer pitched armour) and $\gamma_f = 0.51$ for structure 2 (double layer armour of which upper layer is pitched). This is more or less according to expectations, as the influence factors of randomly placed rock structures are in this range and the difference between structure 1 and structure 2 is mainly caused by the difference in permeability between one layer and two layers of armour rock. Structure 2 did dissipate a little more wave energy than structure 1, hence the lower γ_f-value.

Figure 14. Derived curve of influence factors for structure 1 with vertical wall.

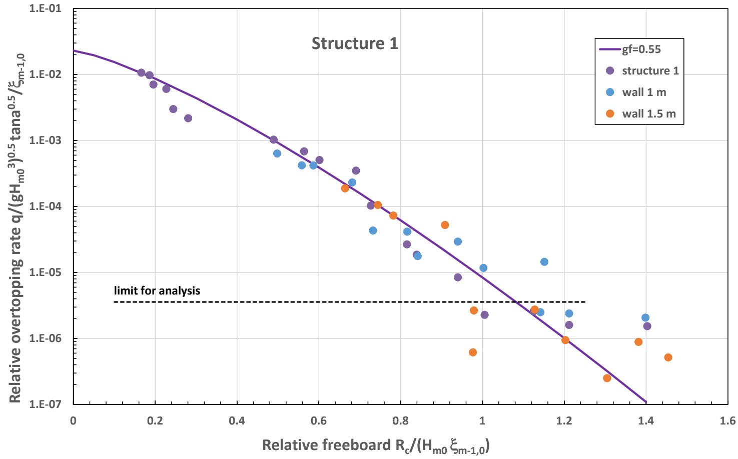


Figure 15: Derived curve of influence factors for structure 1 with wave wall 1 m with and without bullnose

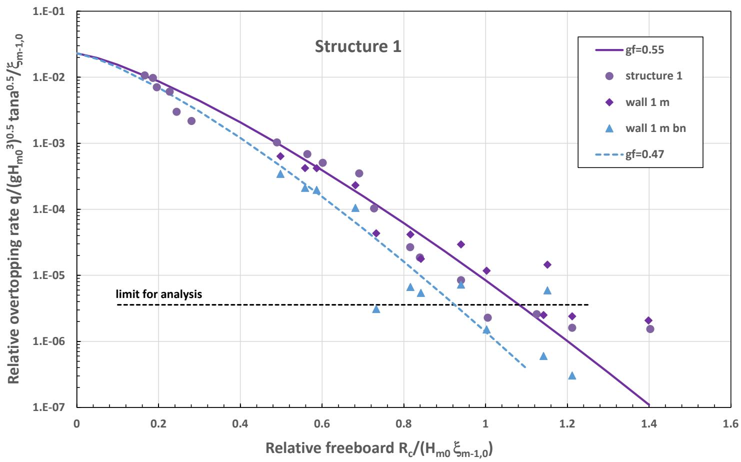


Figure 14 shows the effect of a vertical wall for structure 1. As expected, the curve of the results with a vertical wall is similar as the curve of structure 1 without a vertical wall. This because the inclusion of a vertical wall on the crest has more or less the same effect as increasing the crest level by rock with 1 m or 1.5 m. As the freeboard increases, the data points for a vertical wall shift to the right. This is the reason why there are no data in the upper left corner for the vertical walls. The decrease in overtopping by increasing the crest freeboard is very significant and a good option if sea level rise in future would be large. Figure 14 shows that a vertical wall is in line with the fit for structure 1. It means that an influence factor $\gamma_f = 0.55$ can be used for this structure with $\gamma_v = 1.0$.

Figure 16. Derived curve of influence factors for structure 1 with wave wall 1.5 m with and without bullnose.

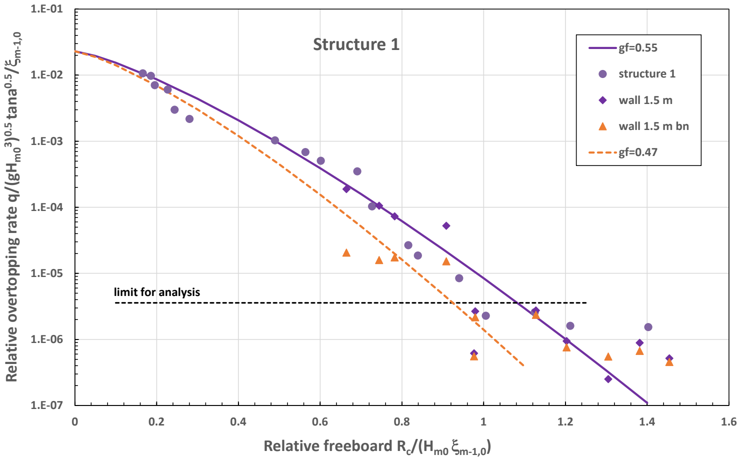


Figure 17. Derived curve of influence factors for structure 1 with wave return wall.

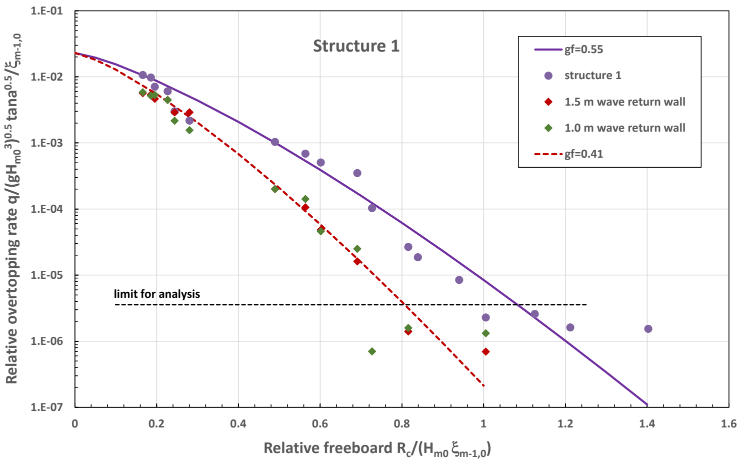


Figure 15 and 16 compare the overtopping results for cases with and without a bullnose on a 1 m and 1.5 m vertical wall respectively. The results clearly show a reduction in overtopping for the wave wall with a bullnose, indicating a clear advantage in having a bullnose. The fit in both figures might be given by $\gamma_f = 0.47$.

Figure 17 shows the overtopping rates for structure 1 with a 1.0 m and 1.5 m return wall. The testing results indicate the effect of inclusion of a wave return wall in structure 1. The structure with the return wall shows less overtopping for the same crest freeboard. There is negligible difference between a 1 m or 1.5 m return wall. Based on the curve derived from the 1.0 m and 1.5 m return wall test results, the γ_f for the wave return walls is taken as $\gamma_f = 0.41$ for structure 1.

Figure 18 shows the influence of a vertical wall with bullnose (1 m and 1.5 m high) for structure 2. Tests on a vertical wall without a bullnose were not performed. The fitted influence factor gives $\gamma_f = 0.43$. Figure 19 shows the influence of a wave return wall for structure 2. The estimated influence factor is similar for the two heights that were tested and amounts to $\gamma_f = 0.38$ for structure 2.

As the original rock structures 1 and 2 with a plane vertical wall had influence factors of $\gamma_f = 0.55$ and 0.51, respectively, and with a bullnose $\gamma_f = 0.47$ and 0.43, the influence factors for the bullnose itself become: $\gamma_{bn} = 0.55/0.47 = 0.85$ and $\gamma_{bn} = 0.51/0.43 = 0.84$. These factors are almost the same, giving a general $\gamma_{bn} = 0.85$. In a similar way, the effect of a wave return wall becomes $\gamma_{wrw} = 0.55/0.41 = 0.75$ and $\gamma_{wrw} = 0.51/0.38 = 0.75$.

Figure 18. Derived curve of influence factors for structure 2 with 1.0 m and 1.5 m vertical walls with bullnose.

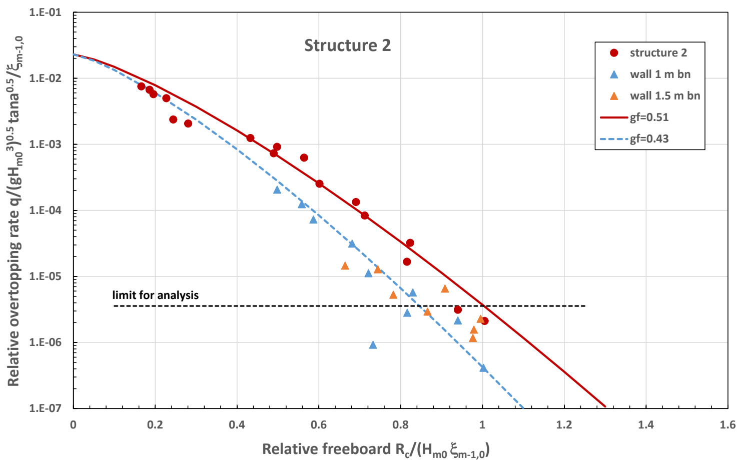
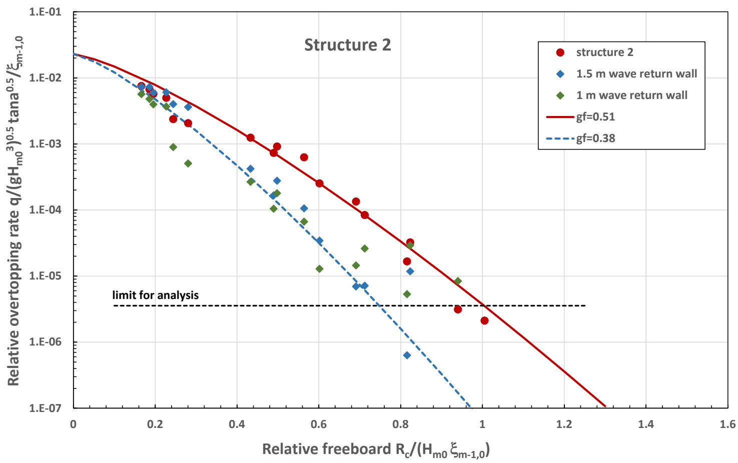


Figure 19. Derived curve of influence factors for structure 2 with 1.0 m and 1.5 m wave return walls.



6. Conclusions

Only a limited set of stability tests have been performed on pitched armour layers with a seaward slope of 1:2.5 and with a fairly steep wave steepness of $_{sm-1,0}$ = 0.040. Structures with only rock and with a 1 m and 1.5 m wave return wall were tested. Structure 1 was a structure with a single layer of pitched rock on a small underlayer. Structure 2 had a double layer of rock, where the upper layer was pitched. The pitched part started from 0.5 m CD upwards, where the tested water level was higher at 2.0 m CD.

The test results show that armour stability for both structures can reasonably well be calculated by the Van der Meer formula, which was developed for a double layer of randomly placed stones. The increased stability by the pitching at structure 1 seems to be compensated by the thinner armour layer that dissipates less wave energy. The pitching at structure 2 may be more difficult than at structure 1, as it had to be constructed on the second armour layer with large stones and not on a flat underlayer with small stones.

But there is a very significant difference between a single and a double layer of pitched rock. A double layer may be designed for start of damage at S_d = 2 and failure of the armour layer at S_d = 10. For the single layer this is much more strict: start of damage is described by S_d = 1 and failure of the armour layer by S_d = 2.

Wave overtopping results were compared with EurOtop (2018) and provided influence factors γ to be used in the given equations. It was found that vertical walls are very effective, especially with a bullnose. Also wave return walls, that replace a part of the crest of the existing structures, without increasing the crest freeboard, appeared to be effective.

A further analysis has been made for the individual influences of a bullnose as well as for a wave return wall. The influence factors for a bullnose γ_{bn} and a wave return γ_{wrw} wall are found by dividing their overall influence factor by the one for the original structure. The conclusion is interesting: similar influence factors are found for both structures. This means that the final outcome of the testing gives general influence factors that can be applied in the wave overtopping for plunging waves, Equation 5.10 in Eurotop (2018):

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.023}{\sqrt{\tan\alpha}} \gamma_b \cdot \xi_{m-1,0} \cdot \exp[-(2.7 \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v})^{1.3}] \qquad \text{EurOtop 5.10}$$

with a maximum of

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot \exp[-(1.5 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma *})^{1.3}] \qquad \text{EurOtop 5.11}$$

With for structures 1 and 2 and a wave steepness $s_{m-1,0} > 0.035$:

Single layer of pitched rock:	$\gamma_f = 0.55$
Double layer of pitched rock:	$\gamma_f = 0.51$
A vertical wall on top:	$\gamma_v = 1.0$
A bullnose on the vertical wall:	$\gamma_v = \gamma_{bn} = 0.85$
A wave return wall	$\gamma_v = \gamma_{wrw} = 0.75$

7. Acknowledgements

JTC is acknowledged for this interesting study that not only led to practical mitigation options for sea level rise in Singapore, but also gave influence factors on wave overtopping of these options for application in EurOtop formulae that can be used generally worldwide.

8. References

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