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

Martijn Klabbers, Advisian (Worley), Perth, Australia, Martijn.Klabbers@Advisian.com
Jentsje van der Meer, Van der Meer Consulting bv, The Netherlands, IHE Delft, The Netherlands, jm@vandermeerconsulting.nl
Yao Ming Yong, JTC Corporation. Singapore, Yao_Ming@jtc.gov.sg

ABSTRACT

This extended abstract 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 reasonably 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.

INTRODUCTION

Wave overtopping over shore protection structures in Singapore is expected to increase 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. Most coastal defenses 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.

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/friction and the surface looks quite flat. An example of a single layer pitched rock slope is given in Figure 1 and Figure 2. This extended abstract only discusses the single layer pitched rock slope.

Figure 1. A typical pitched rock slope in Singapore

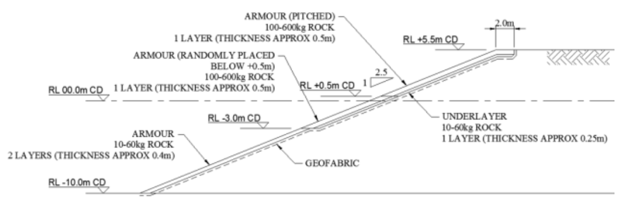

Figure 2. A typical cross-section with a single layer of pitched rock

A first mitigation option was a simple vertical wall at the end of the crest of the rock structure, see Figure 3. 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 3.

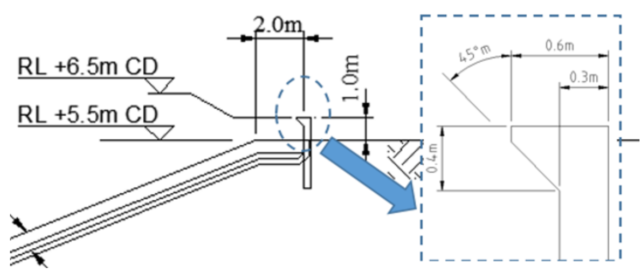

Figure 3. A first mitigation option with a vertical wall, with or without bullnose and 1.0 m or 1.5 m high.

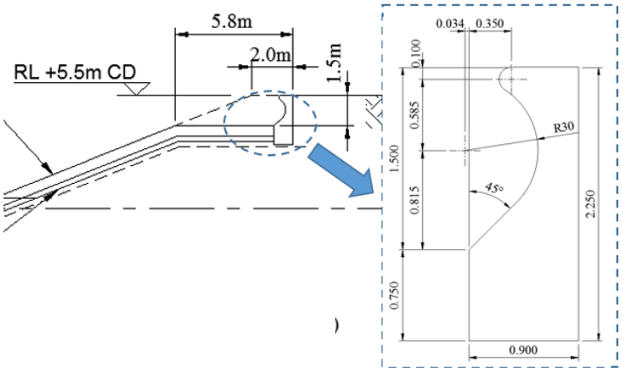

Figure 4. Second mitigation option with a wave return wall, 1.0 m or 1.5 m high.

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 4. The crest of the original structure 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 the original structure.

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.

PHYSICAL MODEL TESTS

Model tests on the pitched rock slopes were executed at Dalian University of Technology, China, using a 1:10 scale. Testing was performed for a wave steepness of $s_{m-1,0}$ = 0.040 and 0.055, considered typical for the Singapore conditions. In total more than 30 tests have been performed on stability and more than 200 tests on wave overtopping.

Figure 5 shows a few pictures of tests with a 1.5 m high vertical wall (see also Figure 3) and with a 1.5 m high wave return wall with the crest at the same level as the original structure, see Figure 4. 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.

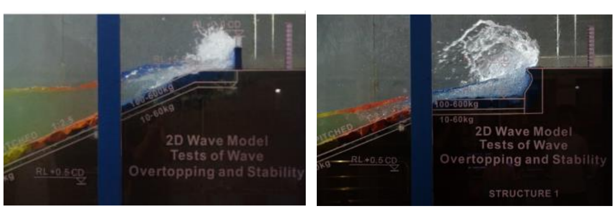

Figure 5. Pictures of testing a 1.5 m vertical wall and a 1.5 m wave return wall.

ANALYSIS OF STABILITY

Stability formulae do not exist for single layer rock or for pitched rock 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.

Figure 6 shows various stages of damages for the single pitched rock layer, together with the damage number S_d, as per the Van der Meer formula.

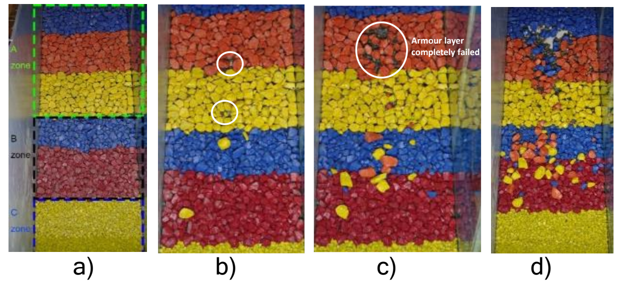

Figure 6. Test results of structure 1, one layer of pitched rock (green box, above swl). a) Before testing; b) start of damage S_d =1.2; c) armour layer failed S_d = 2.3; d) Structure failed S_d = 4.6.

Figure 7 shows these test results plotted in a stability graph, where the damage S_d is given as a function of the wave height.

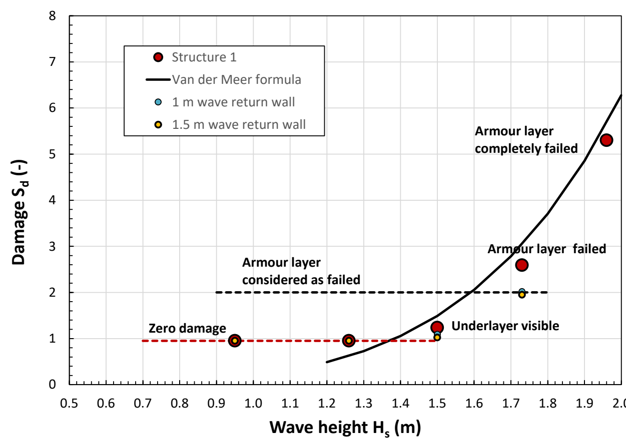

Figure 7. Test results and stability formula for structure with single pitched layer of rock.

Failure of the armour layer for a single layer of pitched rock will be very close to start of damage. 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.

The results indicate that the damage to a single layer of pitched rock can be predicted with the stability formula for a double layer of randomly placed rock. The pitching (more stable) and thinner layer (less stable) are more or less in balance.

Figure 7 shows that there is not much difference between a rock structure and a structure with a wave return wall.

ANALYSIS OF WAVE OVERTOPPING

Figures 8 shows the overtopping results from the physical model tests for the single pitched rock slope. The test results of the various assessed structures are plotted as dots/triangles/diamonds of different colours.

As expected, a large (relative) freeboard results in a low (relative) overtopping discharge and vice-versa. The typical existing structure (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) 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.

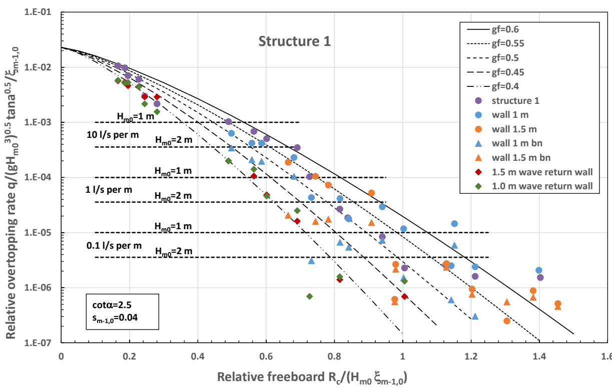

Figure 8. Overtopping results from physical model tests for a single layer pitched rock slope

EurOtop (2018) Equations 5.10 and 5.11 include various influence factors γ. The influence of roughness, γ_f, is 0.55 for the structure with single layer pitched rock.

As expected, the curve of the results with a vertical wall is similar as the curve 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. The decrease in overtopping by increasing the crest freeboard is very significant and the only option if sea level rise in future would be large.

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 might be given by $\gamma_f = 0.47$.

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 $\gamma_f = 0.41$.

As the original rock structure with a plane vertical wall had influence factors of $\gamma_f = 0.55$ and with a bullnose $\gamma_f = 0.47$, the influence factors for the bullnose itself become: $\gamma_{bn} = 0.55/0.47 = 0.85$. In a similar way, the effect of a wave return wall becomes $\gamma_{wrw} = 0.55/0.41 = 0.75$.

CONCLUSIONS

Based on a limited set of stability tests, it can be concluded that that pitched rock 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 the single layer structure seems to be compensated by the thinner armour layer that dissipates less wave energy. However, start of damage is described by $S_d = 1$ and failure of the armour layer by $S_d = 2$, which requires a far stricter design than for double rock layers.

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 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):

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

- Single layer of pitched rock: $\gamma_f = 0.55$
- Double layer of pitched rock (not discussed in this extended abstract): $\gamma_f = 0.51$
- 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 $\gamma_v = \gamma_{wrw} = 0.75$

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