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THE VAN DER MEER FORMULA FOR ROCK SLOPE STABILITY AT SHALLOW WATER

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OBJECTIVE

In Van der Meer (2021) the stability formula for rock slopes under wave attack has been rewritten to remove the mean period T_m and to include the spectral period $T_{m-1,0}$. This formula is now identical to the Modified Van der Meer formula in the Rock Manual (2007 – Eqs 5.139 and 5.140), except for its coefficients and the use of $H_{2\%}$ in the Rock Manual and $H_{1/3}$ in Van der Meer (2021). A method has been given in Van der Meer (2021) by coefficients c_{pl} and c_{su} in the rewritten formula, to include (new) data on rock slope stability where results differ from the original formula and data. The re-fit of the shallow water data by Van Gent (2004) leading to the Modified Van der Meer formula for shallow water comes now to c_{pl}=0.92 and c_{su}=0.96, showing that rock slopes are less stable in shallow water than in deep water (coefficients smaller than 1 show less stability).

The Rock Manual gives as transition from the original formula for deep water to the Modified formula for shallow water h/H_s = 3. This value has not been validated. In practice, it means that often the Modified formula will be used, where it is still possible that the original formula has a much larger application area into shallower water. Moreover, waves at shallow water and very shallow water (h/H_{m0d}<1), where H_{m0d} = the significant wave height at deep(er) water, may give a quite different type of wave attack on the structure. Due to the wave breaking the wave height may reduce significantly and due to infragravity waves the wave period may increase drastically. This all may lead to large and extremely large breaker parameters $\xi_{m-1,0}$, much larger than in the application area of the stability formula. It is expected that at some point of h/H_{m0d} the stability formula will not any longer be correct, not for the original formula, nor for the Modified formula for shallow water.

The main objective is then: when and where do shallow water stability results deviate from the known stability formulae and how can we describe the deviating results. The original dataset by Van Gent (2004) and additional tests by Eldrup (2019) as well as other data have been analysed in depth to come to an improved understanding of rock slope stability in shallow water.

CONSIDERATIONS FOR SHALLOW WATER

Small measured damages have high variability and large damages may include an effect of the underlayer and is well beyond the design level. For this reason tests with small damage S < 1 were not considered, as well as too large damage, defined by 1.5 x underlayer visible. Underlayer visible depends on the slope angle and is S = 8 for slopes 1:1.5 and 1:2; S = 12 for 1:3 and S = 17 for 1:4. The maximum damages for the slopes mentioned were therefore respectively 12, 18 and 25.5. Tests with S-values out of range were neglected. They were also not used for a final comparison, as the only result will be more scatter.

Another aspect with shallow foreshores is that the mean period T_m from the time domain may change over the foreshore and this has directly effect on the number of waves N. There are no really good methods to calculate the change in number of waves. Even measurements in the flume (with and without structure) give significant differences, as shown in the database of Van Gent (2004). As we are not able to predict the number of waves N in shallow water, we take N from the deep water part, also because it is a simple description of the storm duration.

The Modified Van der Meer formula uses $H_{2\%}$. This is not a wave height that can easily be predicted, although we have the method of Battjes and Groenendijk (2000). Goda (2010), however, showed already on the data of Van Gent (2004) that the ratio $H_{2\%}/H_{1/3}$ may decrease from the original 1.4 for deep water to 1.2 at shallow water, *but it increases again for very shallow water up to 1.4.* This is shown in Figure 1 for the 1:100 data of Van Gent (2004). Battjes and Groenendijk give in the graph a limit at $H_{2\%}/H_{1/3}$=1.21, but it should increase again. For this reason the analysis has started with using $H_{1/3}$ for the wave height, where later $H_{2\%}$ and H_{m0} have been used too. H_{m0} has been used in this abstract. Moreover, in application of the Modified Van der Meer formula at h/H_{m0d}<2 and using the Battjes and Groenendijk method to come to prediction of $H_{2\%}$, it is easily possible to underpredict the wave height by 10-20% and to under design the structure.

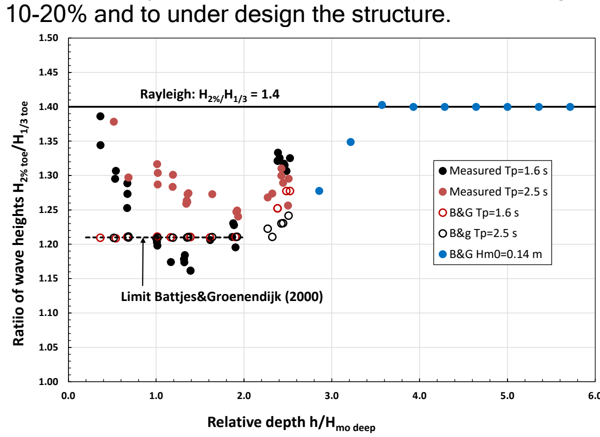

Figure 1 – Change of the ratio $H_{2\%}/H_{1/3}$ over relative water depth and comparison with Battjes and Groenendijk (2000).

Waves are always caused by wind and as such the steepness in design situations is always quite high, often close to the physical limit. We also have swell that travelled long distance over the ocean and the wave steepness may become quite small. There are quite a lot of coasts in the world where actual storms do not occur and the *design* *condition* comes from swell. But it will be quite rare if such design conditions have a wave steepness smaller than $s_{m-1,0}$ = 0.01. Tests for lower wave steepness's are possible, but should not be considered as design conditions.

Deep water in EurOtop (2018) is considered as $h/H_{m0d}>4$. And indeed waves do feel the influence of the bottom for shallower foreshores and may become nonlinear. But the wave height does not change much between $2<h/H_{m0d}<4$ and there is first breaking for smaller values. It is assumed that if the deep water wave height on a gentle slope breaks to 70% of its original height, the VdM formula should still be valid. The wave height is lower, but the wave period does not change significantly and infragravity waves are still small. In such a case the local significant wave height would become about half of the water depth. If we take that value $H_{m0,toe}/h$ = 0.5, then h/H_{m0d} comes close to 1.5. Analysis will first focus on data points with $h/H_{m0d} \geq 1.5$ to validate the assumption and will then continue with shallow water data ($1<h/H_{m0d}<1.5$) and very shallow water data ($h/H_{m0d}\leq 1$).

ANALYSIS

The data set of Van Gent (2004) contains data on rock slopes with a permeable core, foreshore slopes of 1:30 and 1:100 and slope angles of 1:2 and 1:4. Tests on an impermeable core have been performed too for slope angles of 1:2 and 1:4, but only for a foreshore slope of 1:30. As an example of analysis the impermeable core tests will be analysed here for a slope angle of 1:4 (and 1:3 for data from Eldrup (2019)).

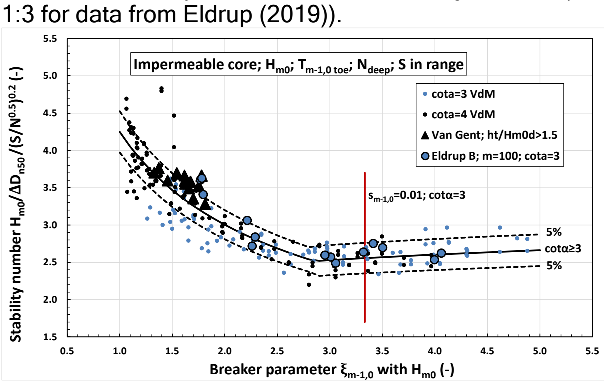

Figure 2 – Results of Van Gent (2004) for a foreshore slope of 1:30 and Eldrup (2019) for a foreshore slope of 1:100, an impermeable core and slope angles of 1:3 and 1:4 and for $h/H_{m0d} \geq 1.5$.

Fig. 2 shows the results. The data from both authors are mainly within the confidence band of the VdM formula, validating the above given assumption. It is also clear that there are quite some original data points as well as data from Eldrup (2019) that have smaller wave steepness's than 0.01 (right from the red line). They are scientifically interesting, but not with respect to design.

The main question is then: what will happen to stability if the water depth reduces, the waves break and the wave energy period will increase due to infragravity waves. The effect in a graph like Fig. 2 will be that data points will shift to the right as the breaker parameter will increase. And the shift is largest for larger breaking and increasing wave periods. But will these data for shallow and very shallow water follow the original formula?

Figures 3 and 4 give possible results, depending on whether the design conditions in deeper water are steep wind waves or gentle swell waves. The data may follow the original formula, maybe to some extent, or may deviate upwards or downwards. The database of Van Gent (2004) has only steep waves in deeper water, which means that it is possible to say something on Fig. 3. But there are no tests available on conditions as in Fig. 4, so at present it is not possible to say anything on the stability of rock slopes at shallow water where swell waves are the design conditions at deeper water.

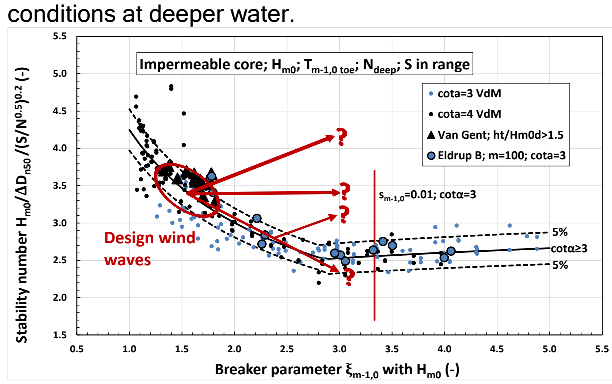

Figure 3 – Possible outcomes for stability at shallow and very shallow water, starting with steep wind waves in deeper water.

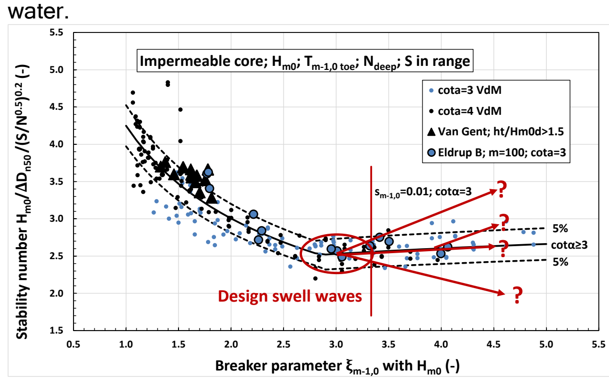

Figure 4 – Possible outcomes for stability at shallow and very shallow water, starting with swell waves in deeper water.

The results for the impermeable core and slope angle 1:4 are given in Fig. 5. The deeper water conditions are similar as in Fig. 2, but due to a lower water level waves were breaking (much) more at the toe of the structure. Fig. 5 shows that data with $1<h/H_{m0d}<1.5$ still follow the original formula, but for very shallow water with $h/H_{m0d}<1$ the stability increases and data are above the curve for the formula. Similar results were found for other structures with an impermeable core and slope angle of 1:2 and also for a permeable core and slope angles of 1:2 and 1:4. The data with $1<h/H_{m0d}<1.5$ did follow the prediction quite well for the plunging wave curve (left in the graphs), up to about $\xi_{m-1,0}$=3 for a slope of 1:4 and even up to $\xi_{m-1,0}$=6 for the 1:2 slope (well into the surging waves).

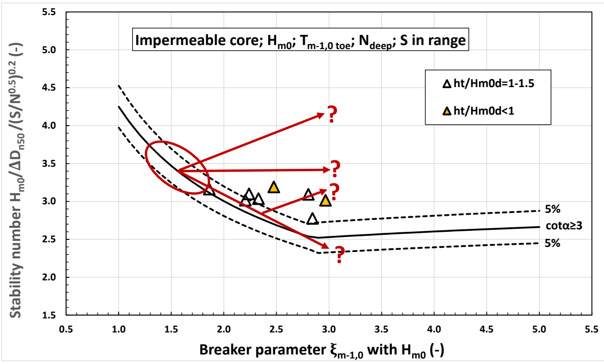

Figure 5 - Results of Van Gent (2004) for an impermeable core and slope angle of 1:4 for shallow and very shallow water.

The results for $h/H_{m0d}<1$ deviated often from the prediction. For $H_{1/3}$ the results were mainly with a horizontal trend and often below prediction, where the use of H_{m0} gave a similar horizontal trend and data above prediction. It is clear that for very shallow water with $h/H_{m0d} < 1$, results deviate from the original AND Modified VdM formula. It means that we actually do not have a good prediction method for very shallow water with $h/H_{m0d}<1$ and a less reliable but first prediction for shallow water with $1<h/H_{m0d}<1.5$.

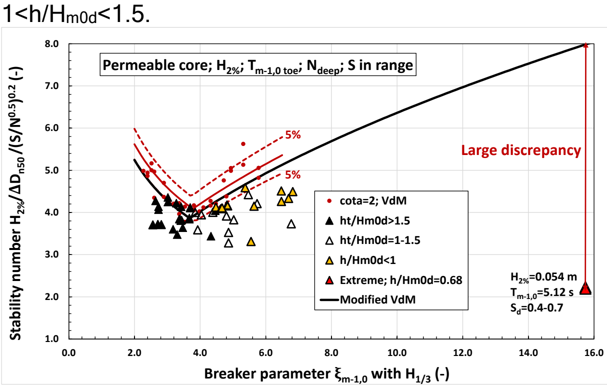

Figure 6 - Results of Van Gent (2004) for a permeable core and slope angle of 1:2 for deeper, shallow and very shallow water, showing one test result far from prediction. Note that $H_{2\%}$ was used to describe stability.

That the part of the formula for surging waves cannot be correct for very shallow foreshores with influence of large breaking and infragravity waves, is shown in Fig. 6. Van Gent (2004) performed one test condition where the wave height reduced from $H_{2\%}$ = 0.194 m to only $H_{2\%}$ = 0.054 m. Due to infragravity waves the spectral period Increased from $T_{m-1,0}$ = 2.18 s to $T_{m-1,0}$ = 5.12 s. The damage was actually out of range (smaller than S = 1) with S = 0.4 (1000 waves) and 0.7 (3000 waves). Due to the very large breaker parameter of $\xi_{m-1,0}$ = 15.9 the data point is far right from all the other data. As the prediction curve for surging waves increases, the discrepancy between prediction and measurements is very large. This example shows that the VdM formula (modified or not) can simply not be extrapolated to really very shallow water conditions. Another approach has to be found.

MAIN CONCLUSIONS

- The analysis was performed with damage data that were in range. Too small and too large damages were not considered. The number of waves N was taken from the deeper water condition. The analysis could only be performed with "wind waves" as condition in deeper water. No data exist with "swell waves" as condition.
- The original (rewritten) Van der Meer formula is valid for h/H_{m0d} > 1.5, regardless of using $H_{1/3}$ or H_{m0}. This is well into the area of breaking waves on the foreshore, but the wave height should not become smaller than about 70% of H_{m0d}.
- For shallow water with $1<h/H_{m0d}<1.5$ the formula gives a little less reliable prediction as long as the breaker parameter is not too large ($\xi_{m-1,0}<3$ for a slope of 1:4 and $\xi_{m-1,0}<6$ for a slope of 1:2). This means actually that the wave steepness at the structure toe should be $s_{m-1,0}$ > 0.007.
- For h/H_{m0d} < 1 results may differ substantially from the formula and show less stability (mainly by using $H_{1/3}$) as well as more stability (mainly by using H_{m0}) and often show a more horizontal trend.
- Double peaked spectra show similar behaviour as singled peaked spectra by using $T_{m-1,0}$. A conclusion already reached by Van Gent (2004).
- The use of $H_{2\%}$ gives by far the worst results, also using the Modified VdM formula. A reason may be that at first wave breaking the ratio $H_{2\%}/H_{1/3}$ may decrease from the original 1.4 for deep water to 1.2 at shallow water, *but it increases again for very shallow water up to 1.4.*
- There is a slight preference to use H_{m0} instead of $H_{1/3}$, not for the database of Van Gent (2004), but in case of nonlinear long waves on fairly steep foreshores as also found by Eldrup (2019).
- At present there is no reliable method to describe stability of rock slopes under wave attack for very shallow water with h/H_{m0d} < 1. The database of Van Gent (2004) can be used to develop another method, but it is proposed to perform first tests with lower wave steepness's (swell design conditions) at deeper water as it is useful to cover the entire range of design conditions before developing an extended method.

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