NEW DEVELOPMENTS IN TOE BERM DESIGN FOR BREAKWATERS

by

by H.J. Verhagen[1]

ABSTRACT

In the ROCK MANUAL (2007) some guidance is given for the design of toes for breakwaters. However, for very shallow toes, as well as for very wide toes (or berms) this guidance is only marginally. Recently a number of shallow berms and toes have been constructed, partly with the intention to lower the height of the breakwater. These works showed the need for further research on this topic.

DEFINITION OF DAMAGE

The existing formulas stipulated by GERDING (1993) and VAN DER MEER (1998) describe the stability of the toe as a function of water depth and toe height. The Gerding formula is based on curve fitting techniques to empirical data. Van der Meer re-analysed the same data set with a view that the stability number H/Δd should not go to zero for very shallow water. The formula as presented by Van der Meer is:

$$\frac{H_s}{\Delta D_{n50}} = 2 + 6.2\left(\frac{h_t}{h_m}\right)^{2.7} N_{od}^{0.15} \qquad (1)$$

In this formula h_t is he water depth over the toe and h_m is the water depth in front of the toe. New tests carried out recently at the TU Delft Laboratory of Fluid Mechanics by EBBENS (2009) appear to confirm that the stipulated formula by Van der Meer is in principle correct, the results of the new experimental data is represented by yellow points in Figure 1.

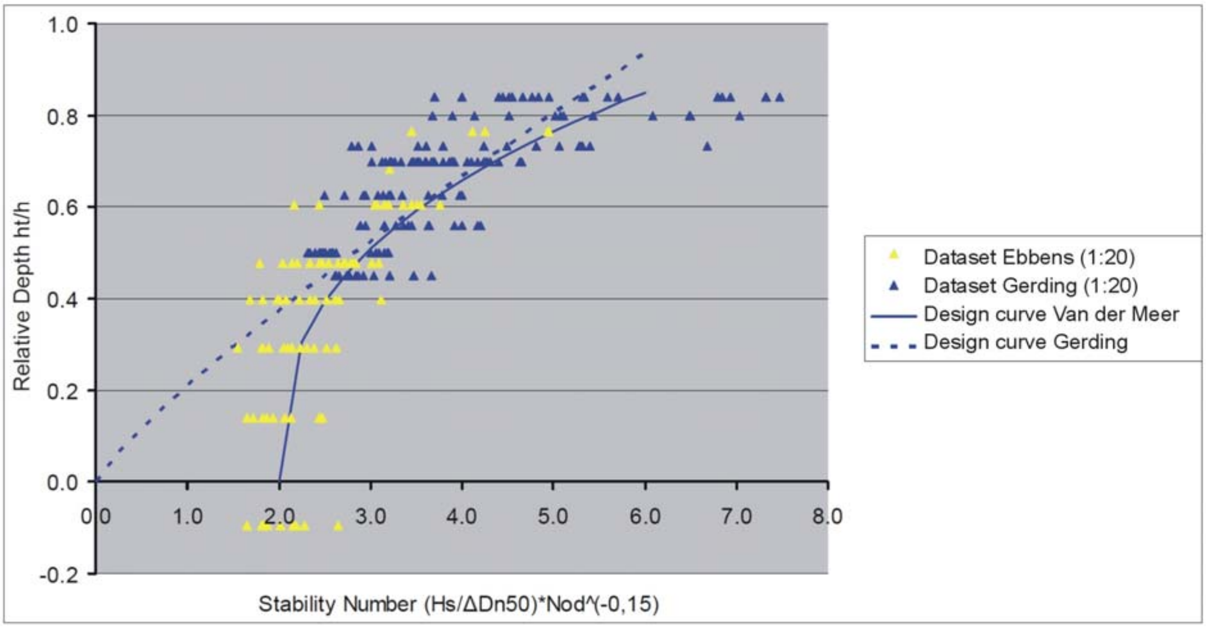

Figure 1: New data for very shallow toes from research by EBBENS (2008)

The spread in data points can be reduced when introducing the foreshore Iribarren number (i.e. $\tan(\beta)/\sqrt{H/L_0}$, in which $\tan(\beta)$ is the foreshore slope). Test results further indicate that the data may be fitted to a power function with an exponent of either 3 or 4. In the region of interest (N_{od} <1) the

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difference between either exponents is small. Figure 2 shows results of toes with different foreshore slopes. A considerable spread can be observed around the Van der Meer design curve.

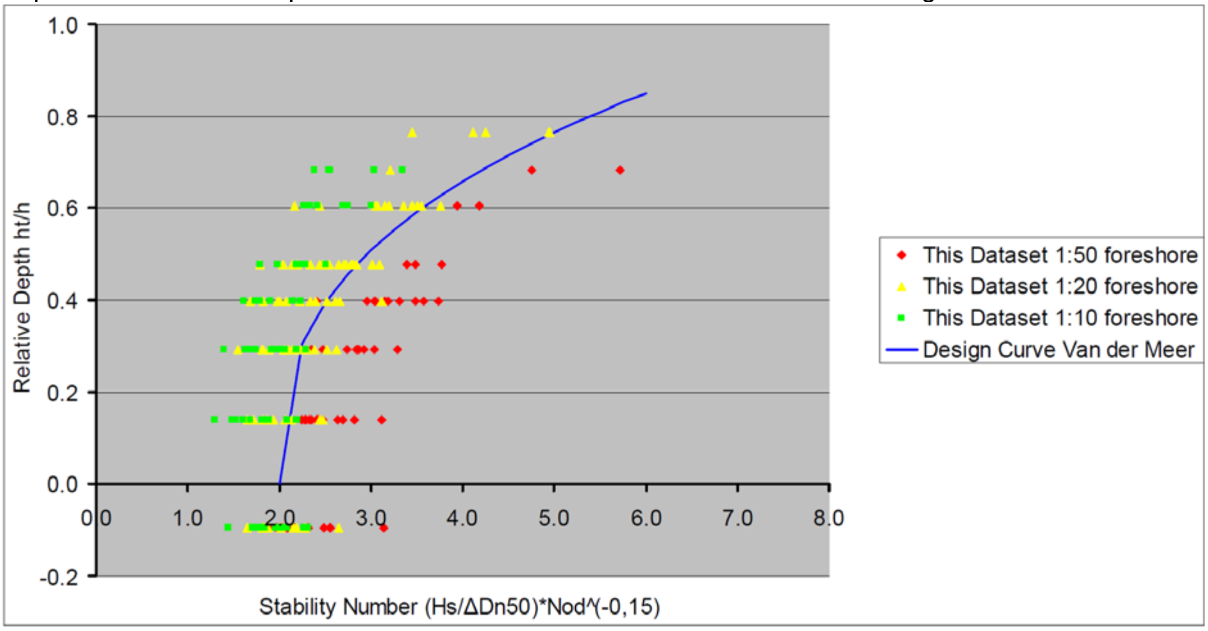

Figure 2: Data with different foreshore slopes (EBBENS, 2008)

For very shallow toes the relative depth (h_t/h_m<0.4) becomes less relevant, because of wave breaking in front of the toe. Therefore this parameter can be excluded from the formula. However, in those cases the amount of damage depends very much on the foreshore slope. In figure 3 the damage is plotted as a function of the foreshore Iribarren number as defined above.

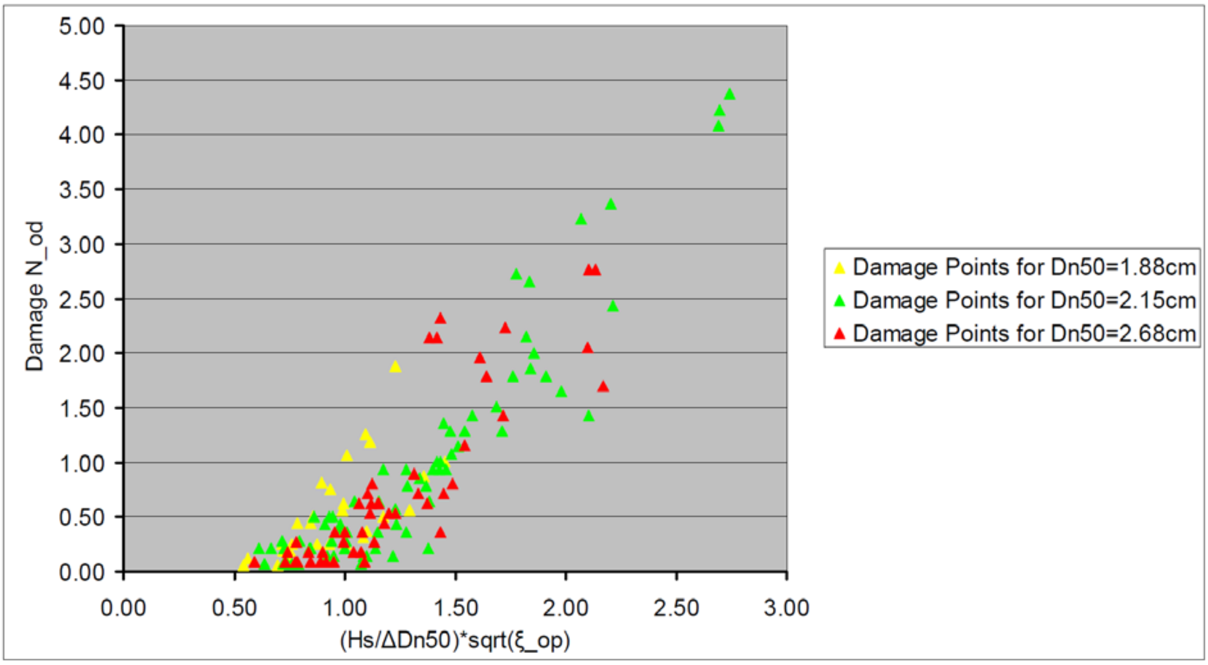

Figure 3: Relation between N_{od} and the foreshore Iribarren number (for h_t/h_m<0.4) (EBBENS, 2008)

Damage is usually defined as a number of moved stones within a strip with a width of D_n. However, for wide berms and toes, this is not very useful. When a toe is wide (and functions also as a berm) damage at the seaward end of the berm does not jeopardize the stability of the upper part of the breakwater. Therefore a better definition of damage is needed; it is suggested to express the damage as a percentage of the surface area of the berm or toe:

$$N_{\%} = 100N \frac{D_{n50}^{3}}{(1-n)V_{tot}} \tag{2}$$

in which N is the number of displaced rocks over a given width of a toe (e.g. the flume width), n is the porosity of the toe and V_{tot} the volume of the toe in the investigated section (e.g. the flume width). This leads to the results as presented in figure 4.

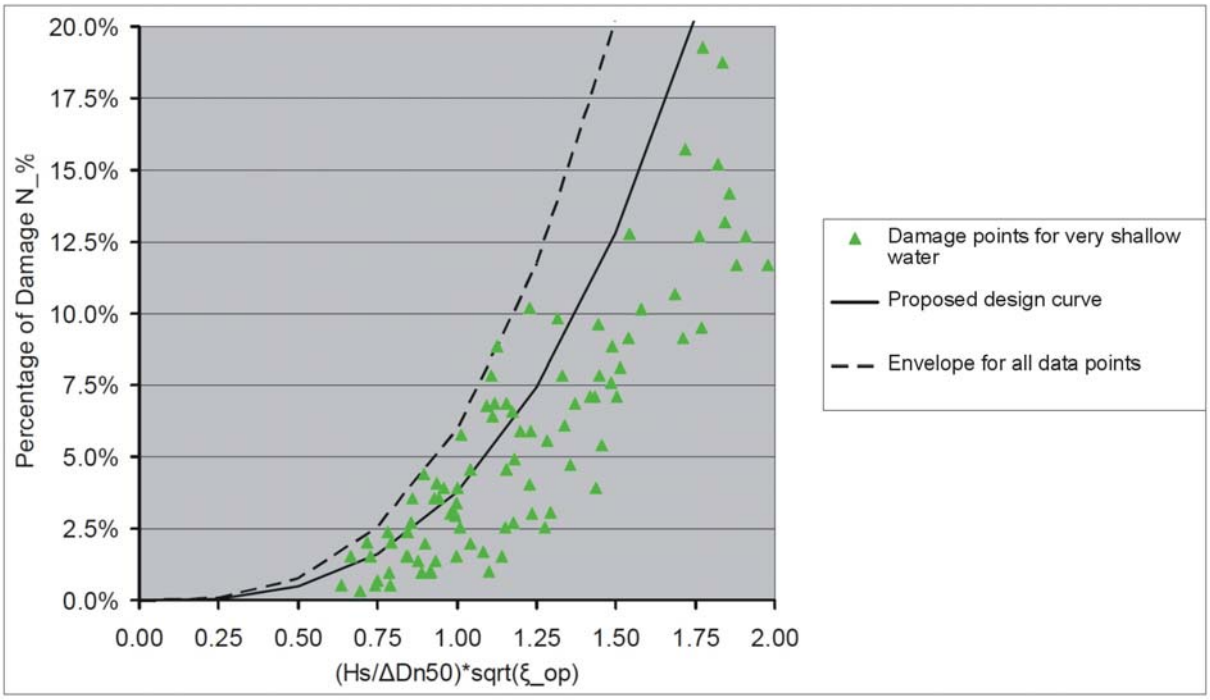

Figure 4: Proposed design equation for toe stability in very shallow water (for h_t/h_m<0.4) (Ebbens, 2008)

The equation of the design curve presented in figure 4 is:

$$N_{\%} = 0.038\left(\frac{H_s}{\Delta D_{n50}}\sqrt{\xi_{op}}\right) \quad \text{or} \quad \frac{H_s}{\Delta D_{n50}} = 3.0\frac{N_{\%}^{1/3}}{\sqrt{\xi_{op}}} \tag{3}$$

THE DOCTERS VAN LEEUWEN DATASET

Comparing de observations of Gerding with other datasets (e.g. USACE 1989 or Sayao 2007) shows that they fit quite well. However, fitting these equations with the dataset of Docters van Leeuwen (1996) shows a discrepancy. When plotting the data of Docters van Leeuwen in a similar graph as Figure 3 or 4, the dataset lies below the design curve. However when on the x-axis the absolute value of the wave height is used, both datasets are nicely in one line. The main difference between the tests of Docters van Leeuwen and the other datasets available is that she tested much smaller (relative) rock diameters that the other investigators. So in fact her berm was much more smooth than usual. Also the values used by Doctors van Leeuwen (e.g. h_t/D_{n50} up to 40 and toe width of 12 times D_{50}) are usually outside the range of normal toe design, the results show that fundamentally something might be wrong with the present approach of plotting the damage as a function of $H_s/\Delta D_{n50}$.

It is therefore suggested to come to a more fundamental approach where the direct hydraulic load on the berm is included, and not the wave height in front of the toe.

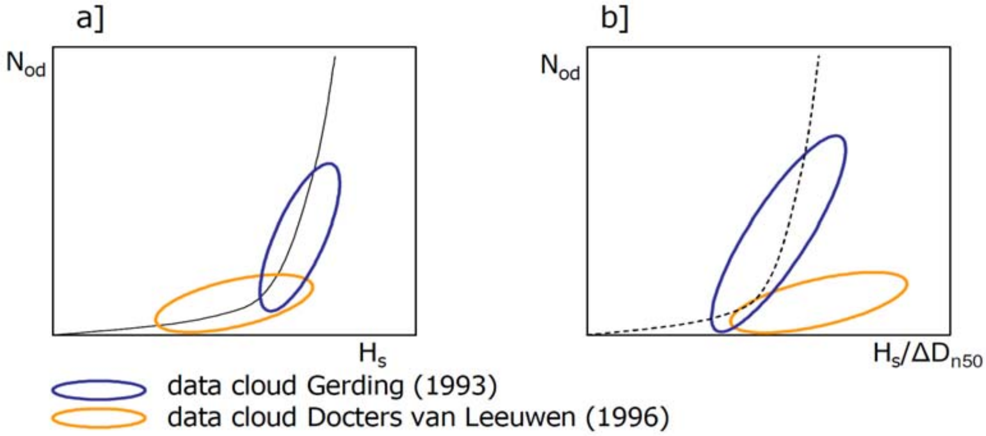

Figure 4: General comparison between the test set-ups fo Gerding and Docters van Leeuwen (Baart, 2008)

A FUNDAMENTAL APPROACH

When comparing the consequences of damage on a narrow and wide toe it is apparent that the loss of a few stones is more relevant for the first than the latter. Therefore with the same damage number N_{od} the risk of failure is likely to be higher for a narrow than a wide toe structure. Hence, it might be useful to adopt a relative damage number which takes into account also the width of the toe. The use of $N_{\%}$ instead of N_{od} makes this easier, but does not completely solve the problem.

An approach based on physical processes causing the damage or movement has been considered as an alternative. The principle driving force for damage was considered to be fluid flow over the toe. Therefore it has been postulated to determine the damage number as a function of the relationship between $\hat{u}_b$ and $\hat{u}_{bc}$, in which $\hat{u}_b$ is amplitude of water velocity at the toe bund, and $\hat{u}_{bc}$ is the critical velocity of the stones. The critical velocity has been calculated with the criterion of RANCE and WARREN (1968). Reanalysis of the datasets by BAART (2008) at TU Delft with this method leads to Figure 5. Γ is a fit parameter (a constant) with a value of 1.05 (for the Gerding dataset). In equation form this reads:

$$\Gamma \frac{\hat{u}_b}{\hat{u}_{bc}} = 1 \quad \text{in which} \quad D_{n50} = \frac{2.15 \hat{u}_{bc}^{2.5}}{T_p^{0.5} (\Delta g)^{1.5}} \tag{4}$$

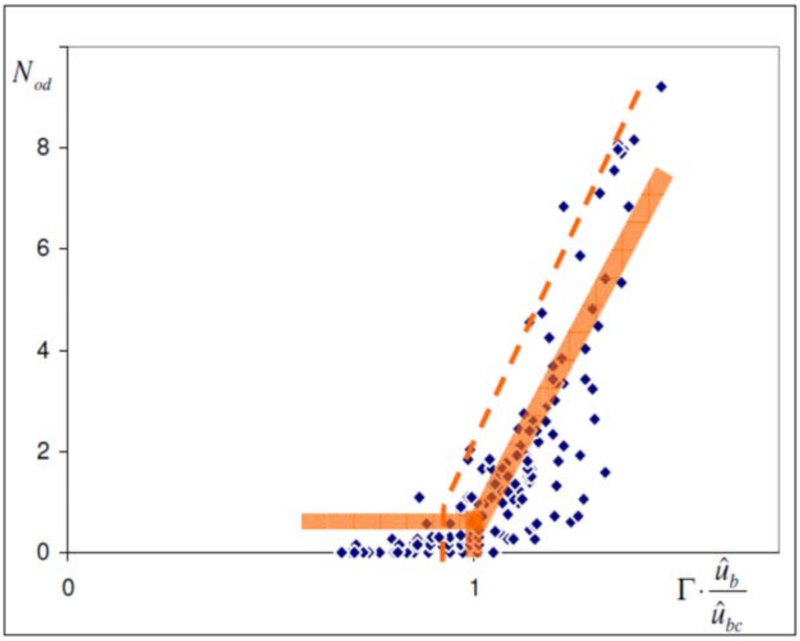

Figure 5: Analysis of toe stability on the basis of the orbital movement on top of the toe (Rance/Warren criterion, by BAART, 2008)

This allows the development of a stability formula on the basis of the local wave conditions and determining the variation of damage over the width of the toe, which is relevant for wide berms. Also it makes it possible to extend these relations to more dynamic stability relations for wide berms.

Because Gerding did measure wave heights just before the toe, but not the orbital velocity on top of the toe, the orbital velocity $\hat{u}_b$ had to be calculated. Linear wave theory was used. Of course it is questionable if linear wave theory is still applicable in this case. Therefore a number of laboratory measurements (with regular waves) have been undertaken by NAMMUNI-KROHN (2009) to establish the effect of this simplification whereby the actual measured orbital velocity on top of a rubble mound toe was compared with calculated velocity values using linear wave theory. In these test the ratio $\hat{u}_{b\text{-}observed}$ /$\hat{u}_{b\text{-}linear}$ theory was determined. This ratio varied during the tests from 0.5 to 1.5, but no clear relation was found as a function of wave steepness and relative toe depth. The measured variation in velocities, even with regular waves, was quite large, probably due to the irregular surface of the toe (Figure 6). This implies that the use of better wave theories will not improve the results. The very irregular surface of the toe causes a high turbulence. This means that an additional coefficient for increased turbulence has to be added. This coefficient can be determined from the standard deviation of the tests. In future the magnitude of the coefficient can be determined as a function of the roughness. This means that for design applications linear wave theory may be acceptable, but that a large standard deviation will have to be taken into account.

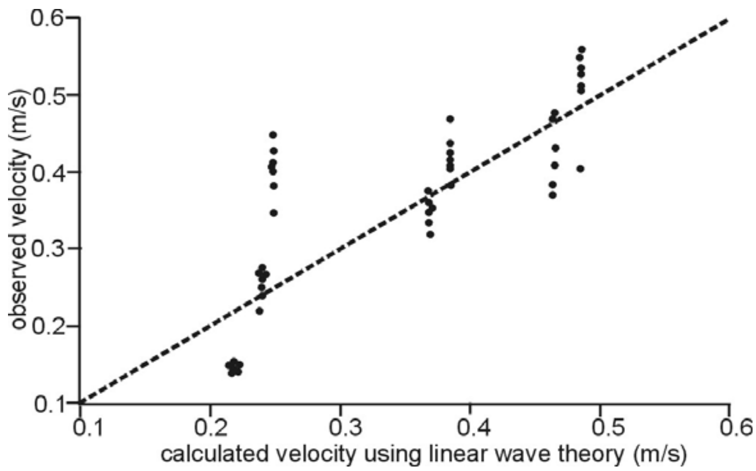

Figure 6: Measured and observed velocity on the toe (NAMMUNI-KROHN, 2009)

A preliminary analysis shows that the 95% exceedance value is in the order of 1.5 times the average value. In the stability equation (4) developed by Baart a fit was made between the calculated orbital velocity and the critical velocity. The research of Nammuni-Krohn shows that in fact a value of 1.5 times the calculated orbital velocity has to be used. This implies that the value of Γ should be adapted and a turbulence coefficient r ≈ 1.5 has to be added. This results then in:

$$\Gamma \frac{r\hat{u}_b}{\hat{u}_{bc}} = 1 \quad \text{in which} \quad D_{n50} = \frac{2.15\hat{u}_{bc}^{2.5}}{T_p^{0.5}(\Delta g)^{1.5}} \tag{5}$$

where $r \approx 1.5$ and $\Gamma \approx 0.7$. The value of r depends probably on the ratio between D_{n50} and the amplitude of the orbital movement on top of the toe. However there are not enough data to determine such a relation.

Because the model setting of Docters van Leeuwen was much smoother than all other tests, one could suggest a value of $r \approx 1.2$ for her tests. Applying this value lead to figure 7.

There is still a difference in the slope of the regression line when $\Gamma\hat{u}_b/\hat{u}_{bc} > 1$, also probably caused by the smoother surface. However for the design criterion (i.e. $N_{od} < 0.4$ for no movement and $0.4 < N_{od} < 0.8$ for small, acceptable movement) the threshold value is the same.

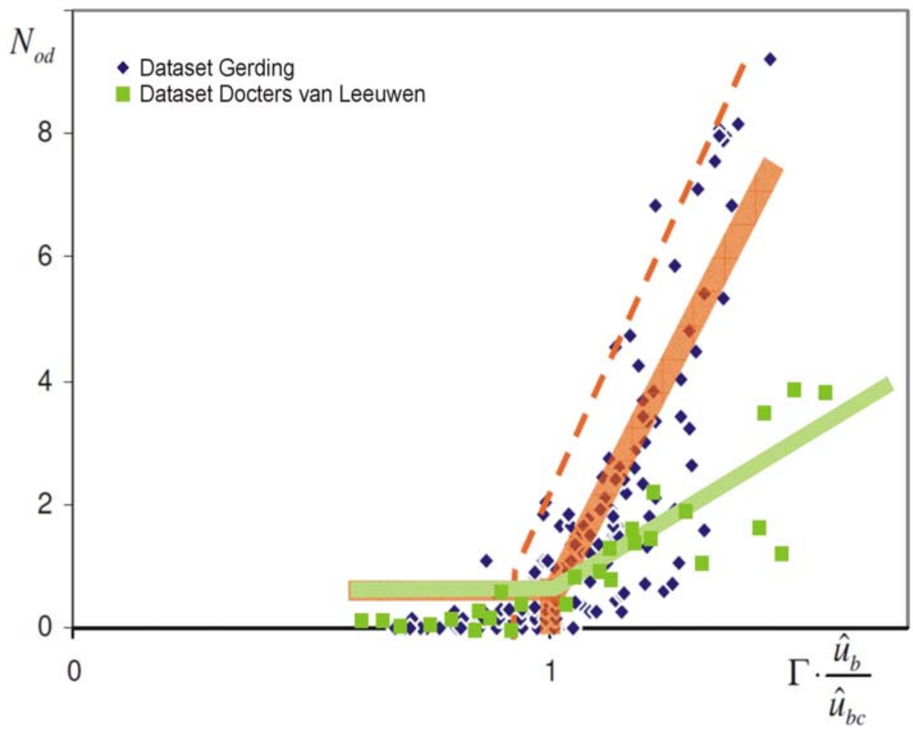

Figure 7: Analysis of toe stability for both the dataset of Gerding and Docters van Leeuwen

UPSLOPE EFFECTS

Wide and shallow berms reduce the load on the upper slope. Because of this, the height can be less, but also the block size can be less. The rules for toe structures as discussed above are not really valid, because such berms are usually much higher than a normal toe. Wide berms around the waterlevel reduce the load on the upper slope. In case for the upper slope a similar stone size is used as for the lower slope, failure will occur at the lower slope. In more sophisticated design one may even decrease the stone size in the upper slope. However, in the research discussed in this paper this optimization was not done.

Tests by DIJKSTRA (2008) at TU Delft showed de magnitude increase factor to be used in cases like this. This factor depends on the level of the berm, but also on the length of the berm. As a basis for the stability calculations the shallow water stability equations as given in the ROCK MANUAL (2007) are used. It was found that basically the damage line for a uniform slope could be used, but that this line shifts towards the right with a factor *rD*. See figure 8.

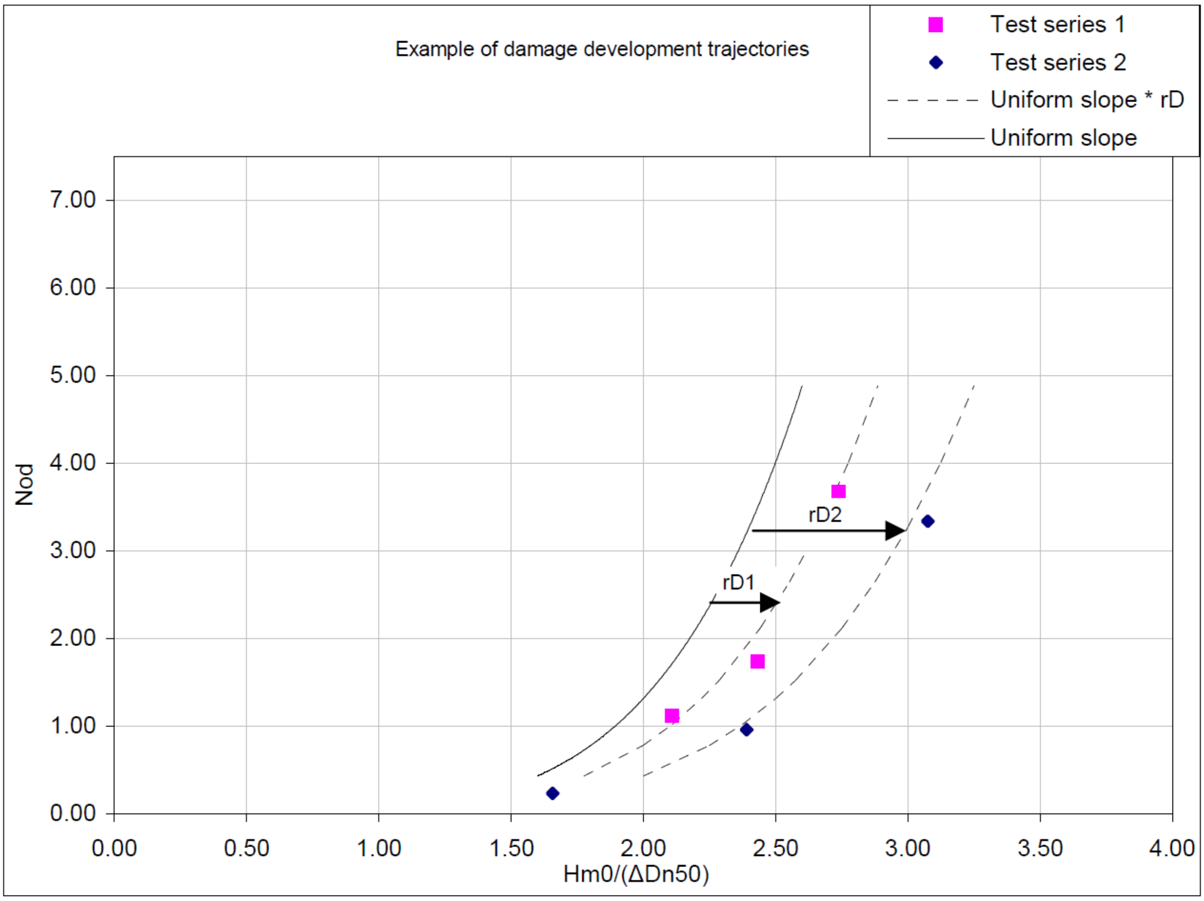

Figure 8: Shift of the damage curve due to the berm (Dijkstra, 2008)

The value of *rD* depends on the configuration of the berm. The most important parameters are the relative crest height (R_c/H_{m0}) and the relative berm width ($B/L_{m-1,0}$). Unfortunately the relation between *rD* and these two parameters is rather erratic. No sound physical relation could be ascertained, as shown in figures 9 and 10.

A general conclusion is that wider berms give more reduction and that higher berms give more reduction. When comparing these results with the design graph in the Rock Manual (figure 596, note the errata-sheet for this figure on http://rockmanual.dicea.nl) the overall picture is similar, but in contradiction to the Rock Manual present results do still have a reduction for berms at design water level. This seems physically also more correct. It is not very likely that a berm with a significant width has zero effect when placed on design water level. For low crested breakwaters with a crest on the waterline the Rock Manual recommends a value of *rD* ≈ 1/0.8 = 1.25 (note that on page 601 the definition of *rD* is different from page 619). The reduction becomes zero at a value of Rc/Hm0 of -0.5 for steep waves (s=0.04) and -1.5 for long waves (s=0.005). One may compare these cases with breakwaters with very wide berms around and just above the waterline. This limiting cases are indicated in figure 10 with blue lines. This also indicates that the design lines from the Rock Manual for berms just below the waterline are too pessimistic.

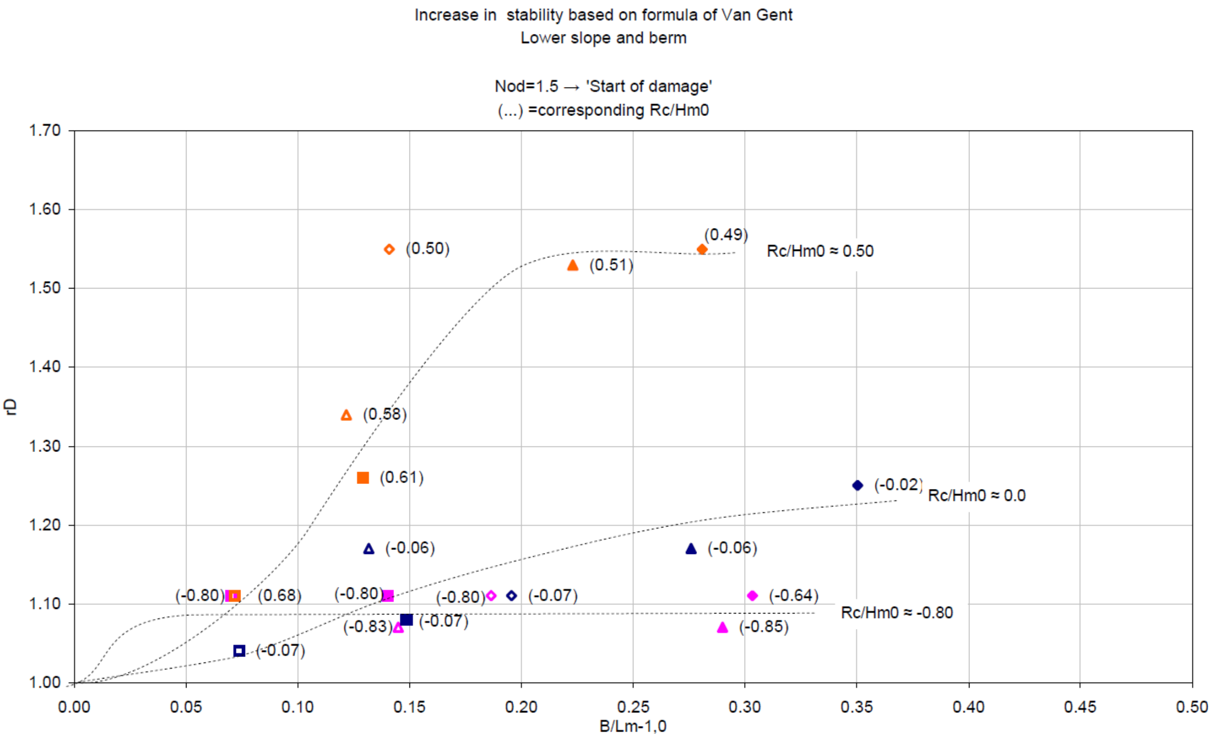

Figure 9: Multiplier coefficient *rD* as function of the relative berm width (Dijkstra, 2008)

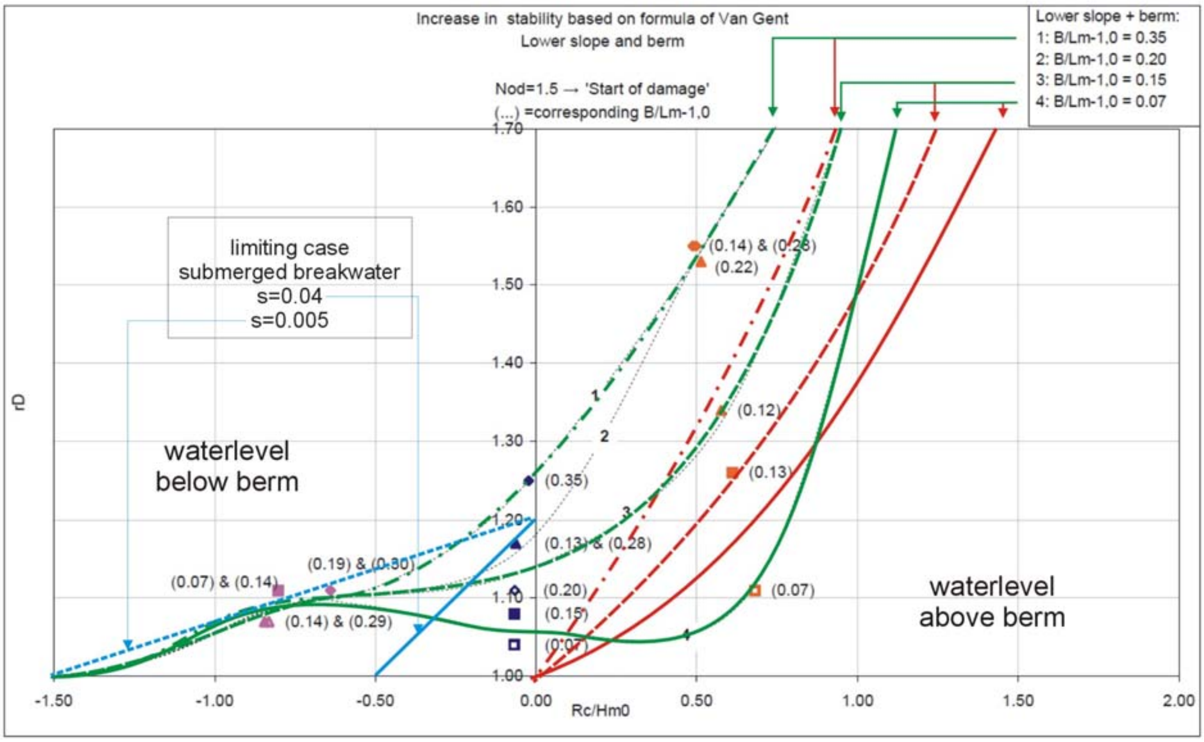

Figure 10: Multiplier coefficient *rD* as function of the relative berm height (Green lines from Dijkstra 2008, red lines from Rock Manual 2007)

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Note: all theses of Delft University of Technology can be downloaded in full text version from: http://repository.tudelft.nl

Errata: In equation 3 a power 3 is missing behind the brackets in the left part and on de bottom of page 7 is referred to figure 596 of the rock manual, this has to be figure 5.69.