New Design Guidance for Underlayers and Filter Layers for Rock Armour under Wave Attack

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Abstract

Conventional underlayers for rock armoured slopes under wave attack are often designed to have a stone mass M_{50u} that is 1/10th to 1/15th of that of the armour, M_{50a}. But what if a designer or contractor would like to design an underlayer with small and very wide graded material to be placed directly on a geotextile or directly on sand and then acting as a filter layer for the sand? This paper first describes three situations that may exist in reality: conventional underlayers; thin underlayers on a geotextile; and finally thicker underlayers that act directly as a filter for underlying sand.

Small scale physical model tests have been performed on a 1:3 rock armour layer and the size and thickness of the underlayer have been varied. The behaviour of the underlayers as well as the armour layer has been analysed. It appeared that the smallest part of the stones in the underlayers often moved or were displaced, but the overall thickness of the underlayer remained mainly unchanged up to acceptable damage conditions for the armour layer. The smallest and widest graded underlayers resulted in slightly more damage to the armour layer than those with relatively large and narrow graded material. Too small underlayers showed considerable adverse effect on the stability of the armour layer and also showed significant rock movement or displacement from the underlayer. Configurations with a larger thickness of the underlayer gave much better results than configurations with a thin underlayer.

Design criteria have been developed from the model test results, taking into account the practical situations described above and are based on the grading width of the underlayer material and on its size relative to the armour layer rock size.

Introduction

Problem Definition

Rock armour layers on slopes to protect coastal structures such as land reclamations and breakwaters against wave attack are often designed on an underlayer of smaller rock. The main guidance for the stone mass M_{50u} of these underlayers, for rock armour as well as concrete armour units, is to take 1/10th to 1/15th of the mass of the armour, M_{50a}. This gives a secondary layer that still has relatively large stones and is quite permeable, improving the stability of the armour layer.

But what if a designer or contractor would like to design an underlayer with small and (very) wide graded material that should directly be placed on sand and act as a filter layer for the sand? *The Rock Manual* (CIRIA, CUR, CETMEF, 2007) provides guidance on filter rules for the interface stability of geometrically tight filters and on the internal stability. These rules have primarily been developed for horizontal filters, subject to currents. For underlayers of granular material underneath rock armour layers, subject to wave attack, hardly any data exist. To apply the existing design guidance to assess the interface stability of geometrically tight filters as derived for narrow-graded materials and for currents also to underlayers underneath rock armour subject to wave attack, lacks sufficient support and may have to be improved. Another difference with rules based on tests with currents is that damage due to wave attack on to the rock-armoured slope may affect the response of the underlayer. To illustrate the differences with the outcome of the present research this traditional filter rule is also given: $D_{15a}/D_{85u} < 4$ to 5.

The research question is: how small and how wide graded can we make the underlayer, before it has unwanted influence on the stability of the armour layer and/or before the underlayer becomes unstable (loss of material through the armour layer)? The design question then is to establish design criteria, based on the results of physical model testing. This paper describes the physical model testing, the results and the design guidance.

Situations in Practice

A common type of structure, like a breakwater, has an armour layer of rock that has to withstand quite significant wave attack. The underlayer stone size may be designed with the very practical rule that the M_{50u} of the underlayer should be between 1/10th and 1/15th of the M_{50a} of the armour layer. In combination with another underlayer and/or a permeable core the stability of the armour layer can be calculated using $P = 0.4$ as notional permeability factor in the rock stability formulae (Van der Meer, 1988). Any smaller size of underlayer stones or an impermeable core has a direct influence on the permeability and increases the rock armour size required. This type of structure (breakwater with an underlayer and permeable core) has not been the subject of the present investigation.

A land reclamation may also be protected by a rock armour layer. The core may be sand, covered with a geotextile. In such a case an impermeable core is present, leading to a lower permeability (for which a notional permeability factor of $P = 0.1$ can be used), and consequently to a larger rock armour size than for the structure described above. In such a case the main function of the underlayer stones is to prevent that rock armour may damage the geotextile during placement. From an economical point of view such an underlayer may then be thin (about $0.5D_{n50a}$) and small, see Figure 1. The guidance by Thompson and Shuttler (1975) and Van der Meer (1988) gives that an underlayer with $D_{n50a}/D_{n50u} = 4.5$ with a maximum gradation of $D_{85u}/D_{15u} = 2.3$ is still a good underlayer that does not give problems. Such an underlayer is much thinner and smaller than usually applied in a conventional breakwater structure.

Figure 1: Laying small underlayer stones on a geotextile on sand.

A third and innovative option might be a rock armour layer, where the underlayer is designed as small and very wide graded material in a relatively thick layer. The purpose of this layer is that it should directly function as a filter layer for the underlying sand, without a geotextile. No guidance exists for this type of structure, as the filter rules in *The Rock Manual* (CIRIA, CUR, CETMEF, 2007) may not be applicable to the armour layer and underlayer as “filter” and “base material” respectively, under wave attack. Recent research (Van Gent and Wolters, 2015 and Jacobsen et al, 2017), however, is available on granular slopes as open filters under wave loading.

The second and third types of structure, a thin underlayer on a geotextile and a thicker underlayer directly on sand, are subject of the present paper. The sand itself has not been modelled.

Criteria given by Thompson and Shuttler

The old, but still relevant, work of Thompson and Shuttler (1975) gives guidance on thin underlayers on an impermeable core. In their preliminary tests they tested very small and wide graded underlayers, that were not acceptable and they based their main work on a small underlayer that did not show any influence on armour stability and that was stable during testing. Based on those results and a literature study at that time, they came to the following criteria for a small underlayer under a rock slope:

$$\begin{aligned} &D_{15,a}/D_{85,f} < 4 \\ &D_{50,a}/D_{50,f} < 7 \\ &D_{15,a}/D_{15,f} < 7 \end{aligned} \qquad (1)$$

Physical Model Testing

Tests have been performed in a wave flume at Deltares, Delft, NL. The investigation has been reported by Van Gent and Wolters (2016), with a cover note (RWS, 2016) and by two additional notes (Van der Meer, 2016a and 2016b). The maximum capacity of the flume was used, thus minimising the scale effects. Significant wave heights of 0.15 m, 0.20 m and 0.25 m were generated with two wave steepnesses of s_{op} = 0.025 and 0.04. One test consisted of these six subtests of each 1000 waves, starting with the lowest wave height and the largest steepness (smallest wave period). The structure was only rebuilt after a full sequence of six subtests.The water depth was constant at 0.75 m.

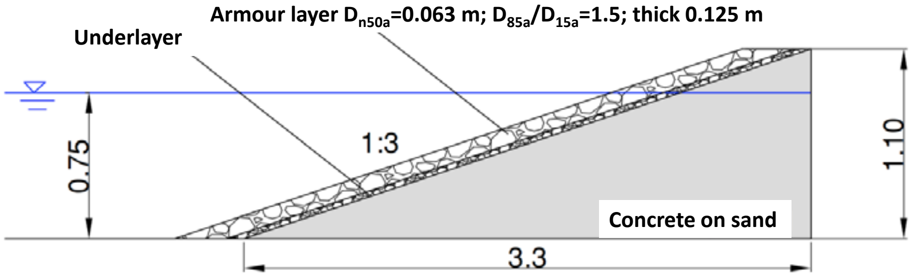

Figure 2: Cross-section tested.

The armour layer consisted of rock with M_{50} = 0.67 kg with gradation D_{85a}/D_{15a} = 1.5, on a 1:3 slope with an impermeable core, see Figure 2. Various underlayer material was tested, all indicated in Figure 3. The underlayer can be described by the D_{n50a}/D_{50u}-ratio, where "a" and "u" refer to armour rock and underlayer rock, respectively and by the gradation D_{85u}/D_{15u}.

Table 1: Underlayer configurations tested, sorted to size of underlayer stones

	Ratio armour/underlayer	Gradation armour	Gradation underlayer	Thickness armour	Thickness underlayer	Remark
Test	D_{n50a}/D_{50u}	D_{n85a}/D_{n15a}	D_{n85u}/D_{n15u}	mm	mm	
1	3.7	1.5	2.3	126	32	
3	3.8	1.5	6.2	126	32	
4	6.0	1.5	2.3	126	32	
5	5.9	1.5	2.3	126	32	Long duration
2	5.9	1.5	6.1	126	32	
6	5.9	1.5	6.1	126	110	
8	5.9	1.5	6.1	126	110	Long duration
7	8.2	1.5	5.2	126	110	

Conventional underlayers have ratios of D_{n50a}/D_{n50u} = 2.2 – 2.5 (1/10th to 1/15th of the armour mass) a gradation $D_{85u}/D_{15u} \leq 2.3$ and a thickness 0.8 to $0.9D_{n50a}$. The reference test series resemble tests performed by Thompson and Shuttler (1975) as well as Van der Meer (1988). This was an underlayer with ratio D_{50a}/D_{50u} = 4.4, gradation D_{85u}/D_{15u} = 2.3 and a thin underlayer, i.e. $0.5D_{n50a}$ thick. In reality armour layer gradings are often selected on mass, whereas underlayer gradings are produced by sieving. For this reason the armour layer has been given by using the *nominal* diameter, based on mass, D_{n50}, whereas the underlayer is given by the *sieve size* D and not the nominal diameter. For the reference test this means that the size ratio of armour and underlayer material is given by D_{n50a}/D_{50u} = 3.7.

Other tests have been performed with gradings as shown in Figure 3 and Table 1, with D_{n50a}/D_{50u}-ratios close to 6 and 8 and with gradations of D_{85u}/D_{15u} = 2.3, 5.2 and 6.2. It is obvious that the stone size of these gradings is much smaller than usual and that the smallest particles (2-4 mm) are very much smaller than the dimensions of an armour stone with D_{n50a} = 0.063 m. Moreover, the gradations are very wide, much wider than for conventional underlayers ($D_{85u}/D_{15u} \leq 2.3$). Figure 3 gives the gradations of the tested underlayers as well as the armour layer (bold black line). For comparison, also the conventional underlayer (1/15th of the armour mass) is given (dashed black line).

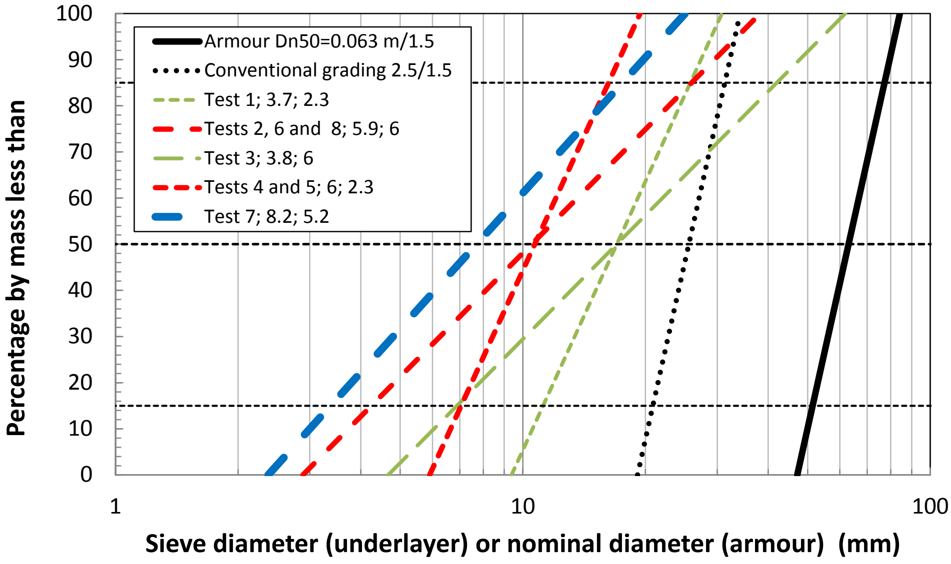

Figure 3: Size of underlayers and armour layer material. First number in the legend is D_{n50a}/D_{50u} and second number D_{85u}/D_{15u}.

Results of Model Testing

Damage development of the armour layer was measured during the tests as well as the behaviour of the underlayer has been described by observations during each step in a test and the reshaping, if present, was measured of the underlayer after the test. The damage was measured by a mechanical profiler that took 9 profiles divided over the width of the flume and these profiles were averaged in order to establish the damage S_d from the erosion area ($S_d = A_e/D_{n50a}^2$, where A_e is the erosion area).

For an armour slope of 1:3 start of damage can be defined as S_d = 2-3 and “under layer visible” as S_d = 12. Figure 4 gives the final stage of test 2 and clearly shows large erosion (not more than one layer of rock left) and large accretion lower down the slope. Actually, with S_d = 17.5 the damage was significantly beyond any design criterion and this final step, where also quite some displacement of underlayer material was observed, should not be taken into account for further analysis.

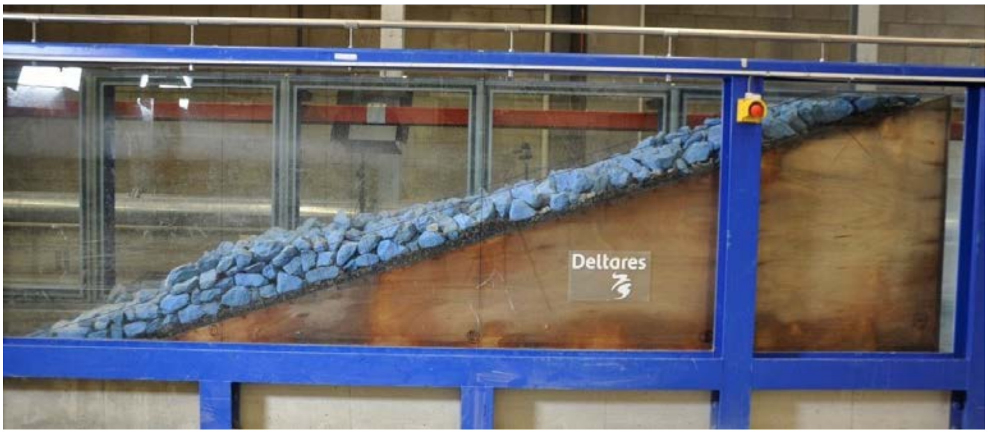

Figure 4: Picture of damage profile in the flume after finalising test 2. Note that S_d = 17.5, well above the criterion of "underlayer visible" – S_d = 12.

Figure 5 gives the final stage of test 6, which is identical to test 2, except that the thickness of the underlayer was increased from $0.5D_{n50a}$ (37 mm) to about $1.75D_{n50a}$ (110 mm). The final damage was only S_d = 8.8, only half of that of test 2 and the only test that gave final damage within acceptable design limits. This indicates that even for small underlayer material, the thickness of the underlayer is important.

Figure 5: Picture of damage profile in the flume after finalising test 6 with the same, but thicker underlayer than in test 2, Figure 4. Note that S_d = 8.8, about half the damage in test 2.

The armour layer showed damage development that was slightly dependent on the size of the underlayer. This will be described more in depth later on. The underlayer showed always some and sometimes significant movement (rocking and displacement) and sometimes, for the larger wave heights, displacement into the armour layer. In various cases underlayer stones came through the armour layer and settled down further down the slope. This often coincided with large damage at the armour layer. It were mainly the smallest part of the stones in the underlayer grading that moved and although the number of underlayer stones that were washing out was sometimes large, the total volume was small compared to the displacements of the armour rock. For most configurations the displacement of armour rock was about 10 times or more in volume than the volume of displacement of the underlayer. Except for the last test step with very large damage, it was not observed that the thickness of the underlayer decreased during testing, which was obviously the case for the armour layer and despite the movements and displacements of small underlayer rock. When removing the armour rock after testing it was often observed that the larger underlayer stones were visible at the surface, where the smaller part of the stones had settled underneath or between the larger part.

Tests 1-4 were performed on the thin underlayer, representing a small underlayer on a geotextile in reality. Tests 1 and 3 had the same average underlayer stone size with D_{n50a}/D_{50u} = 3.7 and also tests 2 and 4 had a similar but smaller average underlayer stone size with D_{n50a}/D_{50u} = 6.2. Tests 3 and 4 had similar size of small material, given by D_{15} = 7 mm, see also Figure 3. Test 2 had the smallest material. Of tests 1-4, test 2 showed the largest movement of underlayer material and the behaviour during the final step (beyond design stage) was concluded to be unacceptable. Overall test 2 gave the worst performance and must be seen as a condition at the edge of what would be acceptable for design, certainly if intermediate damage is taken into account (S_d = 5-8). .

Figure 6 gives the damage S_d of the first four tests as a function of relative wave height-wave period, $H_s/(\Delta D_{n50})\ \xi_m^{0.5}$, being part of the Van der Meer formula (Van der Meer, 1988):

$$H_s/\Delta D_{n50} = 6.2P^{0.18}(S_d/\sqrt{N})^{0.2}\xi_m^{-0.5} \quad \text{for breaking, plunging waves} \qquad (2)$$

This parameter group gives the combined effect of wave height and wave period. Figure 6 does not show the results of the final step that gave damages beyond "underlayer visible". The graph shows that up to start of damage, S_d = 2-3, damage to the armour layer is similar. For damage between S_d = 4-9 differences exist for the four tests on a thin underlayer. Test 1, the reference test with the largest underlayer material and the wide, but not very wide, grading gives the lowest damage. Tests 3 and 4 with similar size of small underlayer material, gave similar damage and a little more than for test 1. Test 2 with the smallest underlayer material applied in tests 1-4 and very wide grading gave the largest damage, in average about 50% more than for test 1.

But how reliable is the damage for one test? Are the differences between tests significant? Repeat tests were not performed during this investigation and the results of tests 1 to 3 show differences, but not very significant. In Van der Meer (1988) repetition tests, however, were performed for almost the same test set-up, an armour layer with an underlayer similar to test 1, but for a slope of 1:4 instead of 1:3. These results are also given in Figure 6 and lead to the conclusion that results of tests 3 and 4 are similar, but that the results of test 1 and those of tests 3 and 4 are quite different; and the same applies to the results of tests 3 and 4 and those of test 2.

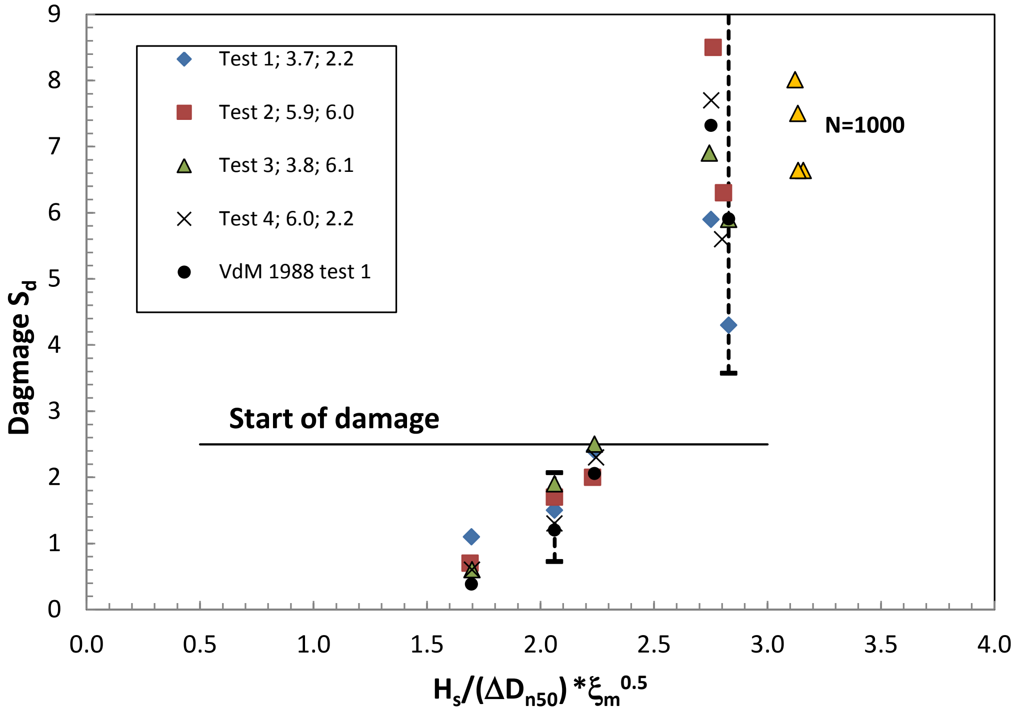

Figure 6: Damage results for tests 1-4 with a thin underlayer. The graph also shows repetition tests of Van der Meer (1988) and the cumulative damage calculated with Equation 2.

Figure 6 also shows the results of the application of Equation 2, in which the damage was, however, calculated as cumulative damage (*The Rock Manual*, 2007 – Box 5.18), as the structure was only rebuilt after a full sequence of six subtests. Calculating cumulative damage means that the damage of the previous test step was taken into account to calculate the damage for the present test step. Start of damage is calculated very well and for larger S_d-values the damage is slightly above test 1 (which is the reference test for Equation 2) and well in the middle of all results. For two steps the reliability of Equation 2 is also given by the 90%-confidence band. All results lie within this band. Overall, the application of the Van der Meer formula gives good or a little conservative results with respect to test 1 and similar results as for tests 3 and 4. Also based on the analysis of the damages to the armour layer here, it must be concluded that test 2 is on the edge of what would be acceptable for design.

Figure 7 shows the results of tests 6 and 7 that were performed on a thicker underlayer of 110 mm, representing an underlayer that might also function as a filter layer for the sand underneath. Test 6 had the same underlayer material as in test 2 with a thin underlayer and that test 2 was considered to be on the edge of acceptable design. This test 6 gave the best results of all tests with respect to damage to the armour layer, even better than the reference test 1. The conclusion is that the thickness of the underlayer affects the stability of the armour layer.

Based on the good results of test 6 the underlayer stone size of test 7 was decreased to D_{n50a}/D_{50u} = 8.2 and with almost the same very wide gradation of D_{85u}/D_{15u} = 5.2. This test gave the worst results of all tests and Figure 7 shows clearly the large difference with test 6, specifically for damage larger than start of damage. Also the observation of the underlayer gave many displacements of small material through and out of this underlayer. It must be concluded that where the underlayer of test 6 leads to an acceptable amount of damage to the armour layer (even lower than for thin underlayers with larger underlayer material), the underlayer of test 7 leads to a significant increase in damage to the armour layer and to an unacceptable amount of washing out of underlayer material.

The armour layer in test 6 was more stable than in test 2, due to the larger thickness of the underlayer. The effect of permeability underneath the armour layer in general terms is described by the notional permeability factor in Equation 2. The reference test 1 has P = 0.1, but a thicker underlayer may lead to a somewhat larger permeability of the structure and therefore a slightly larger P-value. In order to investigate the effect of this P-value, the cumulative damage was calculated by Equation 2, but now for values of P = 0.1; P = 0.15 and P = 0.2. Figure 7 shows the results. Values of P = 0.15 and P = 0.2 describe the results of test 6 best.

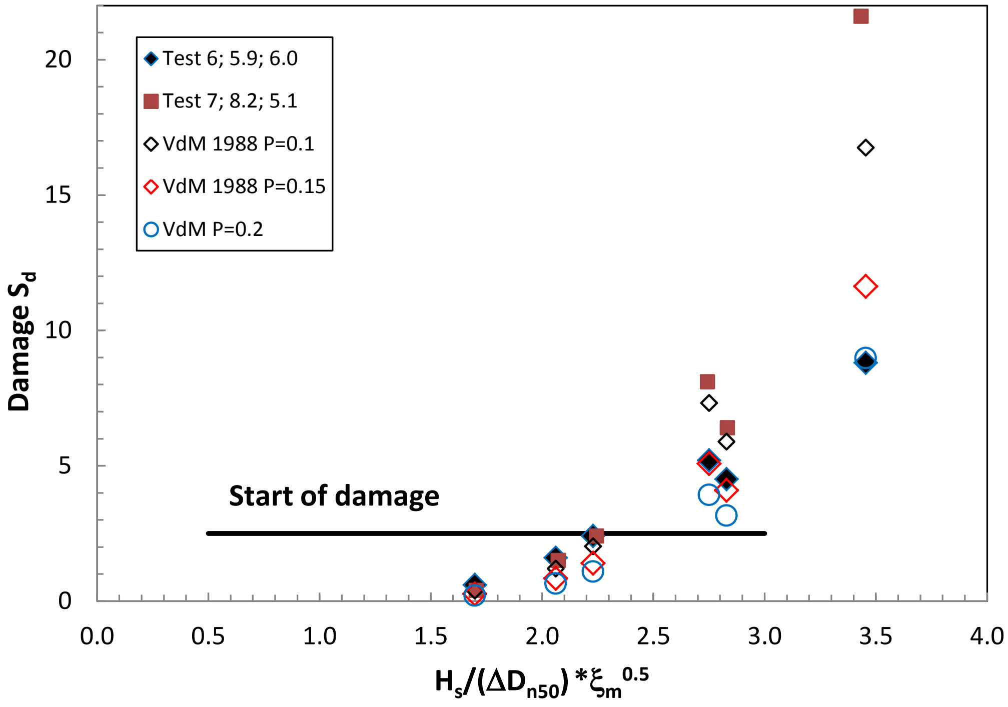

Figure 7: Damage results for tests 6 and 7 with a thick underlayer. The graph also shows the cumulative damage calculated with Equation 2, for various values of the notional permeability factor P.

Design Criteria for Underlayers

Conventional Rock Armour Layers

The investigation was focussed on thin or thicker underlayers with as small stones as possible, not on a conventional structure with an underlayer and permeable core. The advice given in *The Rock Manual* (2007) to take 1/10th to 1/15th of the mass of the armour layer rock to design the underlayer for a conventional rock armour layer is a good advice as, in combination with a permeable core, this leads to a notional permeability factor of P = 0.4. This is much larger than for a thin and/or small underlayer and leads to significantly lower armour sizes.

It does not mean that for conventional rock armoured structures the underlayer cannot be designed with smaller material. But smaller material and consequently thinner underlayers will lead to larger armour sizes required for stability. Often this is an uneconomical way to go. The limit for small underlayers is described in the next sections and leads automatically to application of P = 0.1 in the stability formulae.

Thin Underlayers on a Geotextile

Figure 8 is the decisive graph to establish design criteria for a thin underlayer on a geotextile. The horizontal axis is based on the nominal diameter D_{n50a} of the armour layer material. The underlayer can then be given as a ratio D_{n50a}/D, where D is the sieve diameter of the underlayer stones. This is different from what is shown in Figure 3, where the actual diameters are used. The graph of this Figure 8 has been made dimensionless at the horizontal axis. It gives the gradings of tests 1-4 and also the design criteria of Thompson and Shuttler (1975), described by Equation 1. As now the armour stone size is the nominal diameter and the underlayer stones are given by the sieve diameter, the criteria in Equation 1 have to be adjusted according to these definitions (and also based on $D_{85a}/D_{15a} = 2.25$ and $D_{n50a} = 0.84D_{50a}$):

$$D_{n50a}/D_{85f} < 5.04$$
$$D_{n50a}/D_{50f} < 5.88 \qquad (3)$$
$$D_{n50a}/D_{15f} < 8.82$$

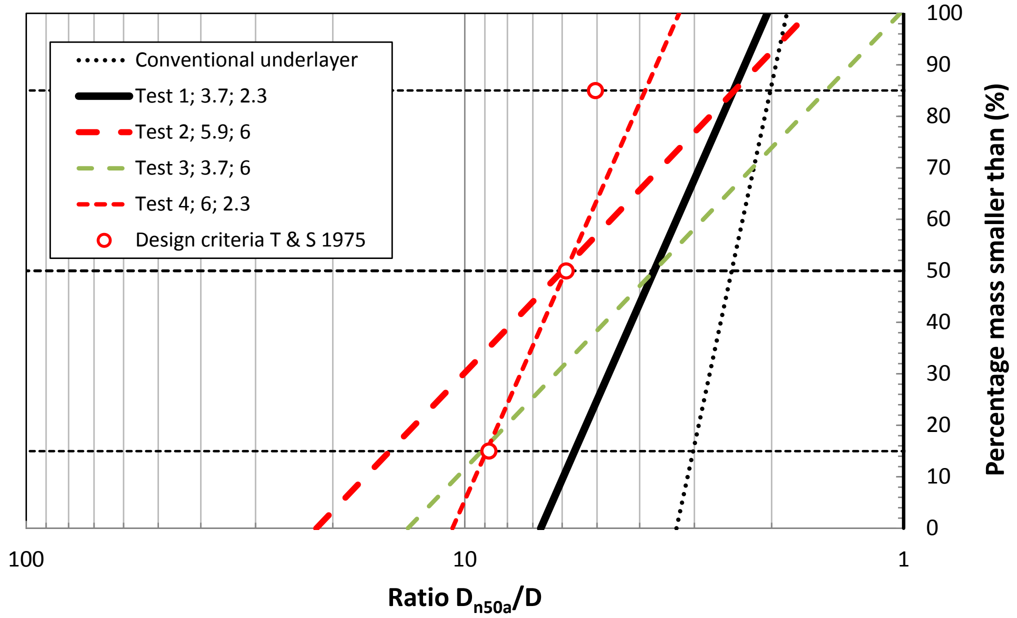

Figure 8: Development of design criteria for a thin underlayer on a geotextile.

Test 2 was on the edge of what could be seen as acceptable, while test 3 was acceptable and a little better than test 4 with respect to the behaviour of the small material in the underlayer. Based on the test results only, the grading of test 3 can certainly be taken as a design criterion and the grading of test 4 only if the damage to the armour layer is limited under design conditions. The design criteria of Thompson and Shuttler (1975) are also given in Figure 8 and come close to the grading of test 4. The actual set of design criteria and ranges of applicability for a thin underlayer on a geotextile is given below and is not only given on test results, but also on practical considerations.

The armour layer

- The armour has to be designed with mass related parameters and for determining stability the nominal diameter D_{n50a} has to be calculated;
- The Van der Meer formulae can be used to calculate the armour layer stone size required for stability, where P = 0.1 has to be used;
- The mass density of the armour rock shall not be larger than 2700 kg/m^3, although the density can be increased if a slightly thicker armour layer would be applied than $2D_{n50}$:

$$d_a = 2D_{n50a}\,(\rho_s - \rho)/(2650-\rho), \text{ where } \rho_s \text{ and } \rho \text{ are mass density of rock and water} \qquad (4)$$

- The gradation of the armour layer stones has to be designed within $1.2 \leq D_{n85a}/D_{n15a} \leq 2.3$;
- The thickness of the armour layer is at least equal to $2D_{n50a}$ (layer thickness coefficient $k_t = 1$).

The thin underlayer on the geotextile

- The underlayer is given by parameters defined by sieve size: D_{15u}, D_{50u} and D_{85u};
- The layer thickness of the underlayer shall at least be $0.5D_{n50a}$;
- The mass density of the underlayer material must at least be 2600 kg/m^3;
- The advice for common application is not to go for ultimate design criteria, but to keep the safe reference test 1, used in the research of Thompson and Shuttler (1975) as well as Van der Meer (1988) as design criterion. This advised grading of the underlayer stones relative to the armour is given by Equation 5 and is given in Figure 8 by the bold black line.

$$D_{n50a}/D_{50u} \leq 3.7 \text{ and } D_{85u}/D_{15u} = 2.3 \qquad (5)$$

- For specific structures somewhat smaller underlayer material may be acceptable. The gradings of tests 3 and 4 (Figure 8) may then give some guidance, but a designer should realize that the underlayer material becomes very small and in a thin layer.

Thick Underlayers acting as Filters

Figure 9 gives the decisive graph for an underlayer that should act as a filter layer for underlying material like sand (or a 2nd underlayer with much smaller stones than the 1st). These underlayers should be fairly thick. Test 6 gave good results, whereas test 7 gave unacceptable results. The results of test 6 are, therefore, used to establish design criteria, The black dots give the design criteria and the full set of criteria and restrictions is given below.

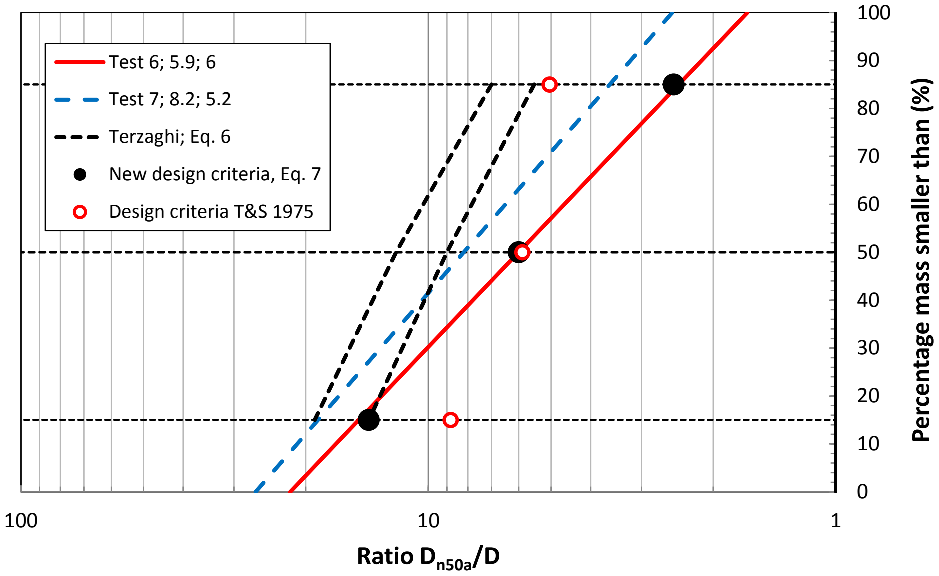

Figure 9: Development of design criteria for a thick underlayer to be used as filter for underlying material.

For the sake of illustration and comparison, the traditional 'Terzaghi' filter rule derived for horizontal filters and flow conditions (D_{15a}/D_{85u} < 4 to 5) is also given. Adjustment of that criterion to the definitions used here and based on the ratio D_{85}/D_{15} = 2.5 to 3 (gradation used in those days) and on $D_{n50} = 0.84D_{50}$, this criterion becomes:

$$\begin{aligned} D_{n50a}/D_{85u} &< 5.5 \text{ to } 7 \\ D_{n50a}/D_{50u} &< 9 \text{ to } 12 \qquad (6) \\ D_{n50a}/D_{15u} &< 14 \text{ to } 19 \end{aligned}$$

It is quite clear from Figure 9 that the 'Terzaghi' filter rule may not be applied for underlayers under wave attack, as it does not fulfil the design criteria given by Equation 7 (black dots in Figure 9).

The armour layer

- The thickness of the armour layer is at least equal to $2D_{n50a}$ (layer thickness coefficient $k_t = 1$);
- The gradation of the armour layer stones has to be designed within $1.3 \leq D_{n85a}/D_{n15a} \leq 2.3$;
- The armour has to be designed with mass related parameters and for determining stability the nominal diameter D_{n50a} has to be calculated;
- The Van der Meer formulae can be used to calculate the armour layer stone size required for stability, where P = 0.1 has to be used;
- Application of design criteria in Equation 7 is restricted to slopes of 1:3 to 1:4;
- The mass density of the armour rock shall not be larger than 2700 kg/m^3, although the density can be increased if a slightly thicker armour layer is used according to Equation 4.

The thick underlayer acting as a filter

- The underlayer is given by parameters defined by sieve size: D_{15u}, D_{50u} and D_{85u};
- The layer thickness of the underlayer should at least be $2D_{n50a}$; During the life time of the structure small material of the underlayer may be displaced at the interface between the armour layer and underlayer. Also armour rock may settle a little in the top part of the underlayer. These phenomena have, however, no effect on the stability of the structure.;
- The mass density of the underlayer material must at least be 2600 kg/m^3;
- The ultimate design criteria are given by Equation 7, and are also given in Figure 9:

$$\begin{aligned} D_{n50a}/D_{85u} &< 2.5 \\ D_{n50a}/D_{50u} &< 6 \\ D_{n50a}/D_{15u} &< 14 \end{aligned} \qquad (7)$$

- It might well be that the criterion of $D_{n50a}/D_{85u} < 2.5$ is too strict, but application of a larger value should be validated by model tests.
- Note that for thicker underlayers smaller material can be applied than for thinner underlayers. However, for this smaller underlayer material the sensitivity to water level variations, the sensitivity to spreading in the damage to the armour layer, and the importance of an accumulation of transport of material after a number of storms increase, and should be taken into account in the design. The guideline includes an additional layer-thickness of the underlayer of $0.25D_{n50a}$ compared to the performed tests to account for some washing out of underlayer material and other potential negative effects. Moreover, a value of P = 0.1 has to be used for design of the armour layer, which gives a little extra safety as the real damage to the armour layer in test 2 was less than calculated with P = 0.1. Both measures probably take into account the concerns about applying very small underlayer material, but only additional model tests may validate this.

Recommendations for further research

The research described in this paper was focussed on fairly gentle rock slopes covering (sand) embankments as a protection against wave attack. The sand has not been modelled in the tests, the topic was the effect of the size of underlayer on the stability of the armour layer and the behaviour of the underlayer itself. Therefore quite some limiting criteria have been set for practical application. Recommendations for further research might be:

- To increase the armour slope angle to slopes of 1:2 and 1:1.5, being more the slope angles applied for breakwaters;
- For steep slopes applying a concrete single /or double armour layer;
- Apply sand underneath the underlayer, with or without an extra filter layer and compare with the work of Van Gent and Wolters (2015).

References

CIRIA, CUR, CETMEF (2007). *The Rock Manual. The use of rock in hydraulic engineering (2nd edition)*. C683, CIRIA, London.

Jacobsen, N.G., M.R.A. van Gent, J. Fredsoe (2017), Numerical modelling of the erosion and deposition of sand inside a filter layer, *Coastal Engineering*, **120**, 47-63.

Thompson, D.M. & Shutter R.M. (1975). *Riprap design for wind wave attack. A laboratory study in random waves*. HR Wallingford report EX 707, Wallingford.

RWS (2016). *Oplegnotitie RWS onderzoek onderlagen.* Nota Rijkswaterstaat 22-11-2016 (in Dutch).

Van der Meer, J.W. (1988). *Rock slopes and gravel beaches under wave attack.* PhD-thesis Delft University of Technology, Delft.

Van der Meer, J.W. (2016a). *Analyse resultaten van de proeven naar onderlagen*. Memo vdm15430.21916.1 (in Dutch).

Van der Meer, J.W. (2016b). Ontwerpregels voor onderlagen als filters onder breuksteen afdeklagen. Memo vdm15430.2710.1 (in Dutch).

Van Gent, M.R.A. and Wolters, G. (2015) *Granular slopes with open filters under wave loading*, *Coastal Engineering*, **104**, 135-150.

Van Gent, M.R.A. and Wolters, G. (2016). Onderzoek naar onderlagen: Fysiek modelonderzoek naar de stabiliteit van onderlagen onder golfaanval en de invloed daarvan op afdeklagen van breuksteen (in Dutch)., *Deltares report 1230029-009-GEO-0003, November 2016*.