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Design guideline for underlayers beneath rock armoured slopes under wave loading

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Content

Preface

This new guideline is presented for the design of an underlayer beneath a rock armour layer and on top of an impermeable/sandy core for structures under wave loading based on physical model tests performed by Deltares in 2016 commissioned by Rijkswaterstaat. In these tests the sandy subsoil was, modelled as fixed and impermeable. Initial publications based on these tests were already published by Van Gent and Wolters (2016) and Van der Meer et.al (2017).

This new guideline is developed in a joint effort project of SBRCURnet. First the members of the SBRCURnet committee criticized the results of the physical model tests performed by Deltares in 2016. Thereafter the members of the committee contributed to the discussion about the new guideline. Based on their input the present knowledge paper was written by Deltares. The overall management has been performed by SBRCURnet.

The members of the SBRCURnet committee are:

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- ir. C.E.J. Jacobs, Rijkswaterstaat (secretary)
- dr. ir. M.R.A. van Gent, Deltares
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The members of the committee are acknowledged for the creation of this guideline.

Rijkswaterstaat is acknowledged for financing the physical model tests on which the presented guideline has been based and for financing the writing of this knowledge paper.

Abstract

Permeable hydraulic structures that consist of rock typically contain a granular underlayer beneath the armour layer. The interface between two rock layers is normally geometrically tight to prevent material washout. However, applying an interface with only minimal loss of material through the layer above could result in a more economical structure. Physical model tests have been performed for the interface between the armour layer and the underlayer. The underlayer consisted of rather small material and various grading widths. Based on these tests guidelines have been derived to design non-standard underlayers beneath rock armoured slopes, under wave loading.

Introduction

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The majority of permeable hydraulic structures contain granular filters, often with more than one rock layer, where the larger rock grading is positioned on top of the smaller grading. The interface between two layers is normally geometrically tight (or closed), to prevent material washout, with a specified ratio of the size of the material in the upper layer and the size of the material in the layer underneath. Underneath the filter layers quarry run material or sand is present, or a combination of a geotextile and sand as core material. For the interface between the armour layer and the rock underlayer (i.e. the first layer beneath the armour layer), besides the filter function also the stability of the armour layer is important. Locally, the thickness of the armour layer can be reduced significantly due to direct wave attack, resulting in a relatively open interface between the armour layer and the underlayer. Therefore, the interface between the armour layer and the underlayer cannot be treated in the same way as interfaces between deeper-lying layers of rock that are not much affected by damage to the armour layer. The Rock Manual (2007) provides a guideline for the design of the underlayer beneath the armour layer (Eqs.5.192 and 5.193): $M_{50,a}$ / $M_{50,f}$ = 10 to 15 which corresponds to $D_{n50,a}$ / $D_{50,f}$ = 1.85 to 2.1 (where $D_{n50,a}$ is the nominal diameter of rock in the armour layer and $D_{50,f}$ the sieve diameter of the underlayer). This guideline for the ratio of the armour layer and the underlayer is stricter than guidelines for other interfaces of granular layers within structures; see for instance Eqs. 5.265-5.273 in the Rock Manual (2007) or Eqs. 2-3 and 23-24 in CUR report 161 (1993). A more economical alternative for the guideline for underlayers beneath armour layers (Rock Manual, Eq. 5.193) is an interface with a larger ratio between the size of the material in the armour layer and the size of the material in the underlayer. Unfortunately little research is available on this topic. Also limited research is available on the influence of a wide grading in the underlayer. Thompson and Shuttler (1975) have investigated this type of interfaces, also with a varying grading width of the underlayer. Based on new research the present guideline focusses on these aspects.

The use of large underlayer material can increase the friction between the armour layer and the underlayer, resulting in a lower risk of slip-failure at this interface and less force on the toe structure. Besides that, during construction a part of the underlayer is directly exposed to wave attack before the armour layer is placed. The stability of the structure during construction benefits from larger material in the underlayer. The latter two aspects have not be taken into account in the present guideline which means that potential effects due to the risk of slip-failure and the performance of the toe structure should be taken into account in the design separately.

Interfaces underneath the underlayer (e.g. the interface from the underlayer to the layer underneath) can be geometrically tight or geometrically open. When applying an open interface the layer thickness of the upper layer may have to be increased compared to the layer thickness for a geometrically tight filter. For open filters, the required layer thickness and rock sizes are designed in such a way that the hydraulic loading at the interface is too low to initiate erosion of base material (and settlement of the material above this erosion) outside an acceptable range. If a limited amount of erosion and settlement is accepted then the range of application of the open filter concept could be widened. Potential applications of open filters include bed protections, toe and slope configurations of revetments or breakwaters. Van Gent and Wolters (2015) and Van Gent et al. (2016) performed physical model tests to estimate the amount of erosion and accretion of sand underneath one or two layers of rock under wave loading. In Jacobsen et al. (2017) and Van Gent et al. (2017) a numerical model is presented to simulate the transport of sand underneath a layer of rock under wave loading. Although the mentioned guidance on geometrically closed (tight) or open granular filters (other than the interface between the armour layer and the underlayer) are relevant for the design of hydraulic structures, the present guideline only focusses on the interface between armour layers and underlayers.

Here, new guidelines are presented for the design of an underlayer beneath a rock armour layer and on top of an impermeable/sandy core. These new guidelines for structures under wave loading are based on physical model tests performed by Van Gent and Wolters (2016). In these tests the sandy subsoil was modelled as fixed and impermeable. Initial guidelines based on these tests were published by Van Gent and Wolters (2016) and Van der Meer et al. (2017).

Physical model tests

The tests on which the guidelines are based are summarized here. For more information on these tests reference is made to Van Gent and Wolters (2016). The tests were carried out in the Scheldt Flume of Deltares (110 m long, 1.2 m high and 1 m wide). The structure consisted of an armour layer of rock, an underlayer of rock, and an impermeable core (representing sand). The foreshore was horizontal. The slope of the structure was 1:3.

The armour layer (in nominal diameters) and the core have not been varied:

Rock size	$D_{n50,a}$	= 63 mm
Armour layer thickness	d_a= 2 $D_{n50,a}$	= 126 mm
Width of the grading	$D_{n85,a}$ / $D_{n15,a}$	= 1.5

The underlayer (in sieving diameters) has been varied:

Rock size	$D_{50,f}$	= 8, 11, 17 mm
Armour layer thickness	d_f = 0.5 to 1.75 $D_{n50,a}$	= 32 mm and 110 mm
Width of the grading	$D_{85,f}$ / $D_{15,f}$	= 2.3 - 6.1

With these underlayers the ratio between the material in the armour and in the underlayer varied between $3.7 \leq D_{n50,a} / D_{50,f} \leq 8.2$. This is a larger ratio than normally used for the underlayer ($1.85 \leq D_{n50,a} / D_{50,f} \leq 2.1$). In Table 1 the tested configurations are summarized (not in the order of execution but in order of the size of the underlayer material, from large to small). Note that for the armour layer nominal diameters ($D_{n50,a}$) have been used and for the underlayer sieve diameters ($D_{50,f}$).

Each series of tests consisted of 6 wave conditions, all with a still-water level of SWL=0.75 m. The structure was not repaired between each individual test condition such that the end result after a full test series is an accumulation of the 6 tested conditions. Each series of tests consisted of individual test conditions with 3 waves heights (H_{m0}=0.15m, H_{m0}=0.20m and H_{m0}=0.25m) and 2 wave steepnesses ($s_{op} = 2\pi H_{m0}/(gT_p^2) = 0.015$ and 0.04, corresponding to $s_{m-1,0} = 2\pi H_{m0}/(gTm_{-1,0}^2)$ = 0.017 and 0.047. Each wave condition was tested with 1000 waves. The sequence of the 6 wave conditions was such that first the lower wave heights were tested with both wave steepnesses (T01 and T02), then the mid-wave height with both wave steepnesses (T03 and T04), and then the highest wave height with both wave steepnesses (T05 and T06).

First the lowest wave with the highest wave steepness was tested (T01; assumed to lead to less mobility than the lowest wave steepness), thereafter the lowest wave with the lowest wave steepness (T02), thereafter the mid-wave height with the highest wave steepness (T03), and so on. Although this sequence does not provide direct information on the influences of the wave height and of the wave steepness, the results from the various test series can be compared with each other.

Table 1 Tested configurations with various underlayers (from Van Gent and Wolters, 2016).

	Ratio armour-underlayer	Grading armour	Grading underlayer	Thickness s armour	Thickness underlayer	Remark
Series	$D_{n50,a}$ / $D_{50,f}$	$D_{n85,a}$ / $D_{n15,f}$	$D_{85,f}$ / $D_{15,f}$	(mm)	(mm)	
S01	3.7	1.5	2.3	126	32	
S03	3.8	1.5	6.2	126	32	
S04	6.0	1.5	2.3	126	32	
S05	6.0	1.5	2.3	126	32	Long duration
S02	5.9	1.5	6.1	126	32	
S06	5.9	1.5	6.1	126	110	
S08	5.9	1.5	6.1	126	110	Long duration
S07	8.2	1.5	5.2	126	110	

Figure 1 Structure after a series of tests.

Measurements were performed of the incident waves, the damage to the armour layer, and the damage to the underlayer. The damage to the armour layer and underlayer was measured using a mechanical profiler. Nine individual profiles were measured over the flume width of 1 m; the distance between the individual profiles was 0.1 m. The profiles of the armour layer were measured at the beginning and end of each test condition. The damage values were obtained from the area of erosion (Ae), being the difference between the initial and end profile. To measure the profile of the underlayer, the armour layer was carefully removed. The profile of the underlayer was measured at the beginning and the end of each series of tests. Transport and washing out of underlayer material was analysed visually. In each test series the armour layer had the same overall porosity. Figure 1 shows a picture of the armour layer after completion of a test series.

Table 2 shows the measured damage to the armour and the underlayer (not in the order of execution but in order of the size of the underlayer material, from large to small).

The parameter S is defined as the eroded area of the armour made non-dimensional using the rock size of the armour layer ($D_{n50,a}$). The parameter S_a is defined as the eroded area of the underlayer made non-dimensional using the rock size of the armour layer ($D_{n50,a}$) while the parameter S_f is defined as the eroded area of the underlayer made non-dimensional using the rock size of the underlayer ($D_{50,f}$). With the exception of the underlayers applied in Series 3 and 7, the eroded area of the underlayer was about a factor 10 smaller than the eroded area of the armour layer.

Table 2 Damage after completion of test series.

	Ratio armour-underlayer	**Grading underlayer**	**Damage armour**	**Damage underlayer**		**Remark**
Series	$D_{n50,a}$ / $D_{50,f}$	$D_{85,f}$ / $D_{15,f}$	S	S_a	S_f	
S01	3.7	2.3	10.8	-	-	
S03	3.8	6.2	16.0	0.4	6	
S04	6.0	2.3	13.2	0.9	31	
S05	6.0	2.3	3.1	0.3	11	Long duration
S02	5.9	6.1	15.1	1.6	55	
S06	5.9	6.1	8.2	1.0	33	
S08	5.9	6.1	3.9	0.4	13	Long duration
S07	8.2	5.2	21.6	4.1	277	

Table 3 Characteristics of damage to armour and underlayers for various underlayers.

Ratio armour-underlayer	Armour		Underlayer	
$D_{n50,a} / D_{50,f}$	Damage S<2.5	Damage S>2.5	Displacements	Washing out
2.0	reference case	reference case	none	none
3.7	no increase	no increase	yes	only for S > 2.5 (limited)
6.0	no increase	increase	many	only for S > 2.5 (many)
8.2	no increase	increase	extreme	many

Figure 2 shows the damage to the armour layer. Besides these measured quantities, the visual observations of transport and washing out of underlayer material have been summarized in Table 3 (S-values refer to measured values), where also observations for standard underlayer material ($D_{n50,a} / D_{50,f} = 2$) has been included based on other tests.

The tests (see also Figure 2 and Table 3 by Van Gent and Wolters, 2016) have shown the following:

- Smaller material in the underlayer can lead to more damage to the armour layer (for S > 2.5); for the configurations with a thick underlayer the additional damage to the armour layer is clearly evident (see the two red-dashed damage curves for $D_{n50,a} / D_{50,f} = 5.9$ and 8.2 in Figure 2).
- A wider grading (with a larger amount of relatively small material) of the material in the underlayer can lead to more damage to the armour layer (for S > 2.5); for the largest damage levels this effect is clearly evident (see green lines with green symbols above the blue lines with blue symbols in Figure 2).
- A thicker underlayer (leading to a higher overall permeability of the structure) leads to less damage to the armour (for S > 2.5); negative effects of the size and width of the grading of the underlayer material on the armour can be compensated by applying a thicker underlayer.
- Smaller material in the underlayer than normally applied ($D_{n50,a} / D_{50,f} > 2$) leads to displacements of underlayer material and can lead to transport and wash-out of underlayer material (depending on for instance the wave conditions, the size of the material in the underlayer, and the amount of damage to the armour layer).
- For material in the underlayer within the range of $3.7 \leq D_{n50,a} / D_{50,f} \leq 6.0$ transport and some wash-out of underlayer material occurred. For smaller material in the underlayer ($D_{n50,a} / D_{50,f} = 8.2$) the transport and wash-out of underlayer material was much more severe.
- Transport of underlayer material still occurred after 10000 waves of mild wave conditions.

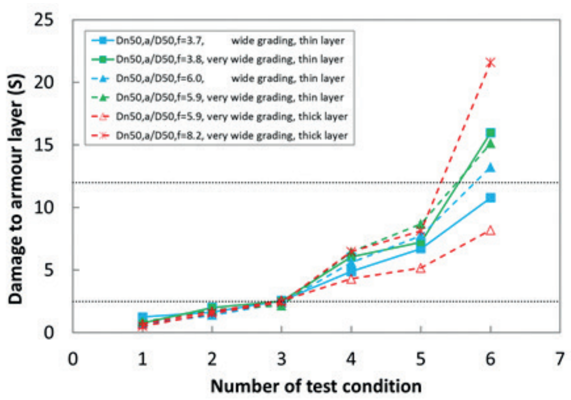

Figure 2 Damage to armour layer after 6 conditions per test series (T01 and T02: lowest wave heights; T03 and T04: mid-wave heights; T05 and T06: highest wave heights).

The model tests have shown effects of applying relatively small underlayer material on the interface of the armour layer and the underlayer. Another effect is that smaller underlayer material could lead to less transport of sand, if the layer beneath the underlayer consists of sand without a geotextile to prevent sand transport. No physical model tests with mobile sand were performed in the described tests. However, guidance to determine the required thickness of the underlayer to limit the amount of transport of sand can be found in Van Gent and Wolters (2015) and Van Gent et al. (2016, 2017).

In the most widely applied guidelines for granulair structures under wave loading no transport or wash-out of underlayer material is allowed. However, depending on the importance, function and maintenance plan of a structure a degree of transport and/or wash-out of underlayer material could be allowable. Therefore, there is a need for a new guideline for underlayers. In Table 4 a new guideline is presented, defining six classes of underlayers where Class I results in the lowest mobility and Class VI in the highest mobility of the underlayer.

Note that the requirements for Class II and Class III are almost the same, except the damage level of the armour layer. The same holds for Class IV and Class V. The larger damage level of the armour layer for Class III and Class V (compared with Class II and Class IV respectively) results in more displacements and more wash-out of underlayer material.

Table 4 Design guideline for underlayers beneath rock armoured slopes under wave loading.

Class	Processes in underlayer	Requirements for armour and underlayer
I	No displacements in underlayer No wash-out of underlayer material	Underlayer: $D_{n50,a} / D_{50,f} \leq 2.1$ and $d_f \geq 0.5\ D_{n50,a}$
		Armour: Not more than intermediate damage (following Rock Manual Table 5.23).
II	Some displacements in underlayer No wash-out of underlayer material	Underlayer: $D_{n50,a} / D_{50,f} \leq 3.7$ and $D_{85,f} / D_{15,f} \leq 6.0$ and $d_f \geq 0.5\ D_{n50,a}$.
		Armour: $S \leq 2.0$ and $1.3 \leq D_{n85,a} / D_{n15,a} \leq 2.2$
III	Displacements in underlayer Some wash-out of underlayer material	Underlayer: $D_{n50,a} / D_{50,f} \leq 3.7$ and $D_{85,f} / D_{15,f} \leq 6.0$ and $d_f \geq 0.5\ D_{n50,a}$.
		Armour: $S \leq 6.0$ and $1.3 \leq D_{n85,a} / D_{n15,a} \leq 2.2$ and Take extra damage to armour layer ($S = \gamma_G S'$) into account for $2.3 \leq D_{85,f} / D_{15,f} \leq 6.0$ using: $\gamma_G = 1 + 0.04 \left(\frac{D_{85,f}}{D_{15,f}} - 2.3 \right)$
IV	Many displacements in underlayer No wash-out of underlayer material	Underlayer: $D_{n50,a} / D_{50,f} \leq 6.0$ and $D_{n50,a} / D_{85,f} \leq 35\ (D_{n50,a} / D_{15,f})^{-1}$ and $D_{n50,a} / D_{15,f} \leq 14.0$ and $D_{85,f} / D_{15,f} \leq 6.0$ and $d_f \geq 2.0\ D_{n50,a}$
		Armour: $S \leq 2.0$ and $1.3 \leq D_{n85,a} / D_{n15,a} \leq 2.2$
V	Many displacements in underlayer Some wash-out of underlayer material Some reduction of underlayer thickness	Underlayer: $D_{n50,a} / D_{50,f} \leq 6.0$ and $D_{n50,a} / D_{85,f} \leq 35\ (D_{n50,a} / D_{15,f})^{-1}$ and $D_{n50,a} / D_{15,f} \leq 14.0$ and $D_{85,f} / D_{15,f} \leq 6.0$ and $d_f \geq 2.0\ D_{n50,a}$.
		Armour: $S \leq 6.0$ and $1.3 \leq D_{n85,a} / D_{n15,a} \leq 2.2$
VI	Loss of the (entire) underlayer Additional damage to the armour layer	Additional requirements to the strength of the geotextile underneath the underlayer.
		Account for additional damage to the armour layer in absence of the underlayer.
		Extra attention to prevent potential slip-failure of the armour layer along the geotextile, with and without the presence of the underlayer.

In addition to Table 4 the following is part of the guideline:

- For underlayers with a minimal layer thickness of df < 2 $D_{n50,a}$ (with layer thickness coefficient 1) only underlayer Classes I, II, III or VI can be selected. Class VI can only be selected for structures with a geotextile underneath the underlayer.
- For underlayers of Class II to V, the damage to the armour should be determined as if the permeability of the structure can be taken into account by using a thickness of the underlayer of df = 0.5 $D_{n50,a}$ (for the Van der Meer, 1988, formula this corresponds to P=0.1) to compensate for potential extra damage as a result of the use of small underlayer material.
- If an underlayer of Class III would be selected, the calculated damage to the armour layer S' (without taking the width of the grading into account) should be increased by an enlargement factor γ_G (see Table 4) with $S = \gamma_G S'$ to take the influence of the width of the grading of the underlayer into account. This increase was not observed for low damage levels $S \leq 2$, so this additional damage needs to be taken into account for Class III but not for Class II.
- The guideline is valid for slopes between 1:3 and 1:4. For other slopes physical model tests to demonstrate the validity (or not) of the guideline should be carried out.
- If the mass density of the material in the armour layer would be larger than 2650 kg/m^3, then the required layer thickness of the armour layer should be increased using $d_a = 2D_{n50,a} (\rho_{s,a} - \rho) / (2650 - \rho)$ and the stone diameters of the underlayer should be determined using $Dn50,a$- for determining size of underlayer = $D_{n50,a} (\rho_{s,a} - \rho)/(2650 - \rho)$.
- The mass density of the material in the underlayer should be larger than 2600 kg/m^3. If the mass density of the material in the underlayer would be larger than 2650 kg/m^3, then the required stone sizes of the underlayer should be increased by a factor $(\rho_{s,a} - \rho) / (\rho_{s,f} - \rho)$ if $\rho_{s,f} \leq \rho_{s,a}$.
- Potential slip-failure of (parts of) the layers of rock along the impermeable core (e.g. sand) should be taken into account in the design. Note that local slip-failure has been observed in performed tests (but not analysed).
- For structures with a traditional underlayer (Class I) no wash-out of underlayer material is expected even if small holes would occur in the armour layer. Note that the guideline $D_{n50,a} / D_{50,f} \leq 2.1$ corresponds to the lower limit of the traditional guideline in the Rock Manual (Eqs.5.193): $D_{n50,a} / D_{n50,f} \leq 2.5$, which corresponds to $D_{n50,a} / D_{50,f} \leq 2.1$. If smaller material would be applied in the underlayer such that wash-out of material can occur (Class III and V), variations around the expectation value of the armour damage have a larger impact on the stability. The variations around the expectation value of the damage to the armour layer should be taken into account in the design of the underlayer, especially for small underlayer material ($D_{n50,a} / D_{50,f} > 2.1$). For such a structure the underlayer should be designed for an amount of damage to the armour layer with a low probability of exceedance (and not based on the expectation value). For instance if the damage to the armour layer should be lower than S=6, then at each position along the structure where small underlayer material is being applied ($D_{n50,a} / D_{50,f} > 2.1$), the probability of exceedance of S=6 should be smaller than x% (with x being a value to be determined and justified between 0 and 50). If a value larger than x=0% is accepted, the structure needs to be inspected after each storm and other conditions that may cause damage to determine the need for repair or other maintenance.
- In the research on which the guideline is based, use is made of linear gradings of the armour and underlayer material (here 'linear gradings' refer to straight lines of the grading curve when shown on a logarithmic scale like in Figure 3). If use would be made of a non-linear grading, the influence of this deviation should be determined before it can be applied in structures with small material in the underlayer ($D_{n50,a} / D_{50,f} > 2.1$). Deviations are especially relevant if diameters of the smaller fractions of the grading ($D_{x,f}$ with x smaller than 15) are smaller than applied in the mentioned research with linear gradings. The mentioned criteria in Table 4 for the minimal required stone diameters are for the lower side of the envelope in which the gradings must be (i.e. minimal values, not mean values).
- For structures that consist of rock use is made of empirical design formulae in the conceptual design phase. As described in the Rock Manual (2007, §5.3.2) the response of hydraulic structures needs to be verified based on physical model tests. This is also valid for the response of underlayers of structures other than those types of structures that have been tested and described here. Deviations from the tested structure configurations can be related to the gradings (e.g. non-linear gradings), layer thicknesses, slopes, permeability of the core, oblique waves, wave steepnesses (outside test range of s_{op}=0.015 to 0.040) and water level variations.

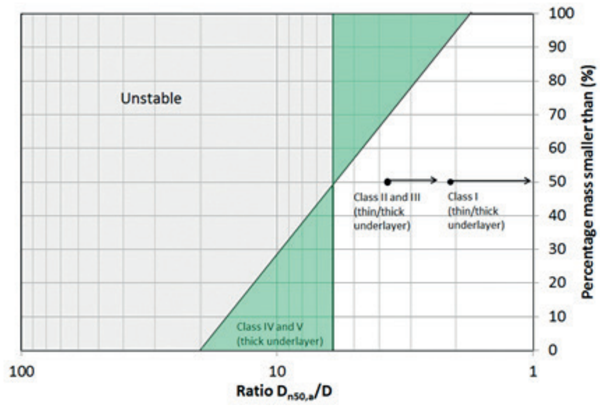

Figure 3 Illustration of the design guideline for underlayers beneath rock armoured slopes under wave loading for various classes of underlayers.

Figure 3 provides an illustration of the design guideline described in Table 4. The ratio of the diameter of the armour layer and the underlayer ($D_{n50,a}$ / $D_{50,f}$) is shown on the horizontal axis. For Class I this ratio should be $D_{n50,a}$ / $D_{50,f} \leq 2.1$. For Class II and III the ratio should be $D_{n50,a}$ / $D_{50,f} \leq 3.7$ (with additional requirements shown in Table 4). For Class IV and V the ratio should be $D_{n50,a}$ / $D_{50,f} \leq 6.0$ with additional requirements shown in Table 4. Furthermore, the green area in Figure 3 illustrates that the linear grading of the underlayer material should fall within this green area in case $D_{n50,a}$ / $D_{50,f} = 6.0$).

Conclusions

Table 4 provides the design guideline for underlayers beneath rock armoured slopes under wave attack. Various classes of underlayers beneath rock armour slopes have been defined where Class I corresponds to the most stable underlayer ($D_{n50,a}$ / $D_{50,f}$ = 2.1). For Class II and III smaller underlayer material ($D_{n50,a}$ / $D_{50,f}$ ≤ 3.7) can be allowed if displacements of underlayer material are considered acceptable. For Class IV and V even smaller underlayer material ($D_{n50,a}$ / $D_{50,f}$ ≤ 6) can be allowed if the thickness of the underlayer is much larger (d_f ≥ 2.0 $D_{n50,a}$.) and many displacements of underlayer material are acceptable. For damage to the armour layer which is larger than start-of-damage (some) wash-out of underlayer material is expected.

An underlayer of Class VI is allowed to disappear after construction, provided that the additional damage to the armour layer is taken into account as well as other aspects of the structure (e.g. strength of the geotextile and potential slip-failure). Depending on the importance, function and maintenance plan (including inspection, possibly resulting in local repair of the amour layer and/ or repair of unforeseen damage to the underlayer) the class of the underlayer needs to be defined, before the structure is to be designed in more detail. Note that during construction the placement of the armour stones should be performed such that no notable damage to the underlayer should occur.

Aspects that have not been analysed in detail but are deemed important need to be addressed if small underlayer material ($D_{n50,a}$ / $D_{50,f}$ > 2.1) is considered. These include deviations from the tested structure configurations on which the guidelines are based, such as non-linear gradings, different layer thicknesses, slopes outside the range from 1:3 to 1:4, ship-generated waves, oblique waves, wave steepnesses outside test range of s_{op} = 0.015 to 0.040 and water level variations.

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List of symbols

$A_{e,a}$	=	Eroded area around *SWL* of the armour layer (m^2)
$A_{e,f}$	=	Eroded area of the underlayer (m^2)
d_a	=	Thickness of armour layer (m)
d_f	=	Thickness of underlayer (m)
D_{nX}	=	Nominal stone diameter (or equivalent cube size: $(M_X/\rho_s)^{1/3}$) (m), with M_x = mass of stone for which x% of the total mass is lighter on the cumulative mass distribution curve (kg)
$D_{X,a}$	=	Stone sieve size of the armour layer that exceeds the X% value of the sieve curve, based on mass (m)
$D_{X,f}$	=	Stone sieve size of the underlayer that exceeds the X% value of the sieve curve, based on mass (m)
H_{m0}	=	Spectral significant wave height = 4 $\sqrt{m_0}$, with m_0 = 0^{th} moment of the wave energy spectrum (m)
$s_{m-1,0}$	=	$2\pi H_{m0}/(gT_{m-1,0}^2)$ = fictitious wave steepness on basis of the spectral wave period (-)
s_{op}	=	$2\pi H_s/(gT_p^2)$ = fictitious wave steepness on basis of the peak wave period (-)
S	=	Damage level of the armour layer, $S = A_{e,a} / D_{n50,a}{}^2$ (-)
S_a	=	Damage level of the underlayer, $S_a = A_{e,f} / D_{n50,a}{}^2$ (-)
S_f	=	Damage level of the underlayer, $S_f = A_{e,f} / D_{50,f}{}^2$ (-)
SWL	=	Still Water Level (m)
$T_{m-1,0}$	=	Spectral wave period (s)
T_p	=	Peak wave period (s)
Δ	=	$(\rho_s - \rho)/\rho$ = relative underwater density of rock (-)
γ_G	=	Factor for the grading width of the underlayer (describes the increase in damage level of the armour layer relative to the damage level using a conventional underlayer)
ρ_s	=	Mass density of rock (kg/m^3)
ρ	=	Mass density of water (kg/m^3)

SBRCURnet

SBRCURnet is een onafhankelijk kennisnetwerk voor de gehele bouwsector. Wij zorgen er voor dat professionals in de Burgerlijke en Utiliteitsbouw en in de Grond-Weg- en Waterbouw hun werk beter kunnen doen.

Wij brengen partijen uit de bouwsector met elkaar in contact voor het ontwikkelen van nieuwe vakkennis over actuele vraagstukken. Wij voorzien de sector van betrouwbare, bruikbare vakkennis. Dat doen we door kennis uit te geven in een breed scala aan producten en diensten. Bovendien helpen we bij het implementeren van kennis.