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DAMAGE CHARACTERISATION OF ROCK ARMOURED SLOPES

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ABSTRACT

In order to design reliable coastal structures, for present and future scenarios, universal and precise damage assessment methods are required. This study addresses this need, and presents improved damage characterization methods for coastal structures with rock armoured slopes. The data used in this study was obtained from a test campaign carried out at Deltares within the EU Hydralab+ framework. During these tests, advanced measuring techniques (Digital Stereo Photography) were used, which are able to survey the full extension of the structure and identify local variations of damage. The here proposed damage characterisation method is based on three fundamental aspects: clear damage concepts, precise damage parameters and high resolution measuring techniques. Regarding damage concepts, first the importance of the characterization width is studied. For damage parameters obtained from the maximum erosion depth observed in a given width ($E_{3D,m}$), the measured damage increases continuously with increased characterization width. But for damage parameters obtained from width-averaged profiles (S and E_{2D}), the measured damage reduces with increased characterization width. Second, a new definition of damage limits (damage initiation, intermediate damage and failure) is presented and calibrated. Regarding the damage parameters, the parameter $E_{3D,5}$, which describes the maximum erosion depth within the characterization width, is recommended as a robust damage parameter for conventional and non-conventional configurations based on three main characteristics: its low bias, its low random error, the ability to distinguish damage levels and is its validity and suitability for all types of structures (conventional and non-conventional). In addition, the results from this study show that the damage measured with the damage parameter $E_{3D,5}$ presents an extreme value distribution.

KEYWORDS: Rock armoured slopes, damage characterization, physical model tests.

1 INTRODUCTION

This study addresses the required research on the assessment and characterization of damage to coastal structures with rock armoured slopes produced by the impact of environmental loads. The development of consistent and accurate damage characterization methods aims to fully describe the response, as well as the remaining strength of the coastal structures after facing a given loading condition. This paper will elaborate on how with high resolution measurements from Digital Stereo Photography (DSP), more advanced damage parameters can be used. Combined with clear damage definitions (such as characterization width and damage limits), this can offer a precise damage characterization of conventional (e.g. straight slope) and non-conventional (e.g. slopes with a berm and roundheads) structures.

Climate change should also be considered, since this phenomenon is increasing the environmental loads acting on coastal structures. In such scenarios, the damage characterization methods presented in this paper have the aim to improve the assessment of conventional and non-conventional structures used as upgrading and adaptation alternatives.

1.1 Background

In the assessment of coastal structures, damage can be defined as “the movement of armour units as consequence of the impact of environmental loads” (Van der Meer, 1988). Hudson (1959) used the percentage of displaced units to characterize damage. Later on Thompson and Shuttler (1975) and Broderick (1984) introduced parameters to describe damage as the number of removed units from the slope. The parameter S (Broderick, 1984) is widely used and is based on the eroded area (difference between the initial and final width-averaged profiles) divided by the nominal diameter of the armour units.

More recently, Melby and Kobayashi (1998) introduced 3 additional damage parameters such as the normalized erosion depth (E), the normalized erosion length (L) and the normalized cover depth (C) obtained for averaged profiles over the width. Hofland *et al*. (2011; 2014) recently incorporated innovative and more accurate measuring techniques such as DSP for the survey of damage in physical modelling tests and presents a three dimensional erosion depth parameter ($E_{3D,m}$) to be used in the damage characterization of conventional and non-conventional coastal structures.

1.2 Current limitations

First, the concepts of “damage initiation”, “intermediate damage” and “failure” are not accurately and uniformly described. Different authors established the current limits based on unconsolidated arguments, also influenced by less detailed measurement techniques (such as obtained from a limited number of profiles). Broderick (1984) defines the condition of no-damage as $S = 2$ “which is the lowest level of damage that can be consistently detected in the survey data” while failure is described “when enough rip-rap is shifted to expose the filter material” again without a filter exposure extension. Van der Meer (1988) defines these limits in a similar manner: start of damage is described as $S = 2$ for a 1:2 slope and failure is reached when the filter layer becomes visible, without describing an extension threshold.

Second, the suitability of innovative damage parameters to accurately characterize the response and remaining strength of rubble mound structures is further investigated. The damage parameter S used by Van der Meer (1988) provides limited information about the structure conditions and is only considered for trunk sections. The damage parameters presented by Melby and Kobayashi (1998) and Hofland *et al.* (2011; 2014) could present a more accurate description of damage for conventional and non-conventional slopes, providing a significant improvement in the characterization of the structure conditions.

Third, damage characterization methods for rubble mound structures can increase their accuracy and reliability due to the continuous development of testing and measuring techniques. New measuring techniques such as DSP (Hofland *et al*., 2011; 2014) are able to provide model surveys with millimetre resolution and describe in detail the damage.

Following the three previously described limitations of current methods, this study focuses on the following aspects of damage characterization: concepts (demand for unified damage characterization concepts) in Section 3.1, parameters (demand for universal and more accurate damage characterization parameters) in Section3.2 and measuring techniques (demand for validating the suitability of innovative survey methods) in Section 3.3.

2 PHYSICAL MODEL TESTS

One physical modelling campaign was carried out at Deltares within the European Hydralab+ framework. These tests were planned with the aim of obtaining the better validation data for addressing the research aims. During those tests, the measurement of damage to the armour layer was done using the Digital Stereo Photography (DSP) technique (Hofland *et al*., 2011, 2014, and Raaijmakers *et al*., 2012).

The Deltares tests were carried out in the Scheldt Flume at Deltares, Delft, The Netherlands (see Figure 1). The set-up was based on shallow coastal areas with wave conditions which are depth-limited. Thus, conditions where the increase in the water level due to climate change would be directly linked to a change in the incident wave height at the toe of the structure were studied.

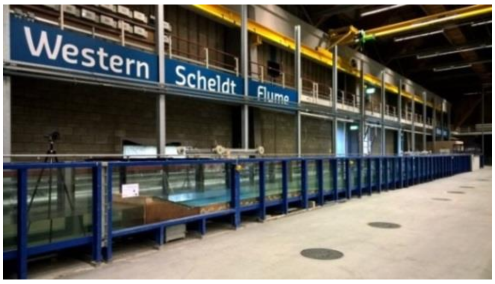


Figure 1. Scheldt Flume, Deltares

This set-up consisted of a non-overtopped rubble mound structure with an impermeable core, a filter (D_{n50} = 9.4 mm), a 1:3 two-layer rock armoured slope (D_{n50} = 16.3 mm and D_{n85}/D_{n15} = 1.19) and a foreshore (see Figure 2). In addition, the main particularity of these tests for shallow coastal areas is that the generated wave was equal for all test runs, and only the change in the water depth at the toe of the structure defined the incident wave height. This way, the effect of the sea level rise in the damage to the structure was clearly represented. Thus, this set-up provided a large amount of complementary data given the number of tests carried out, which allowed the testing of different slope configurations and a number of repetition tests. The testing conditions included the following:

- Currently sea level and sea level rise scenarios (in depth-limited conditions).
- Cumulative and non-cumulative damage.
- Damage variability: repetition tests.

The cross-section of the model set-up used in the Deltares tests is shown in Figure 3. During these tests, only the damage to the front slope was evaluated. In this study, only the straight slope configuration is considered. The test programme, including slope configurations with a berm, is described in Van Gent *et al*. (2018). Incident wave heights were depth-limited given that a 8 metres long foreshore was present in this model. The model (considering reference wave climate in the Dutch coast) followed the Froude criterion. Moderate Reynolds ($Re>1*10^4$) ensured turbulent conditions in the filter and armour (no permeable core) and negligible scale effects. In addition, the wave generation equipment included active compensation for the reflected wave at the wave board.

Figure 2. Deltares shallow water tests set-up.

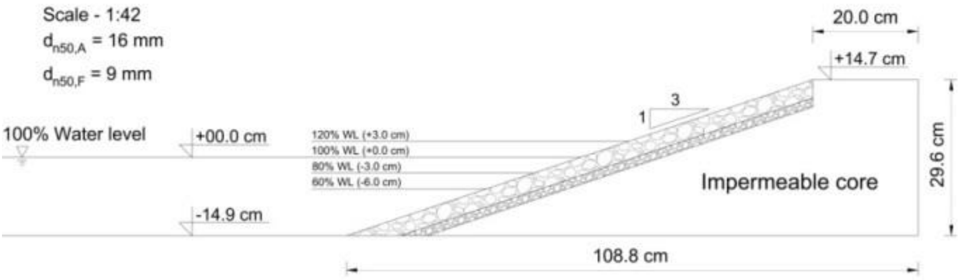


Figure 3. Deltares tests cross-section.

The (straight slope) tests included 25 runs in two series (repeated 5 times each) described in Table 1, where it is shown the type of damage (cumulative or non-cumulative), the water depth at the toe of the structure (h_T), the test condition (Cond.), the targeted generated wave height ($H_{s,g}$), the targeted wave height at the toe of the structure ($H_{s,T}$) and the targeted peak wave period (T_p).

Table 1. Deltares (right) test conditions.

Series	Run	Damage	h_T (m)	Cond.	$H_{s,g}$ (m)	$H_{s,T}$ (m)	T_P (s)
Series 1 (5 repetitions)	R1	Cum.	0.089	60%	0.087	0.037	1.27
	R2	Cum.	0.119	80%	0.087	0.050	1.27
	R3	Cum.	0.149	100%	0.087	0.062	1.27
	R4	Cum.	0.179	120%	0.087	0.074	1.27
Series 2 (5 repetitions)	R1	Non-cum.	0.149	100%	0.087	0.062	1.27

3 DAMAGE CHARACTERISATION METHOD

This section has the aim of validating the damage characterisation methods, which include the damage concepts (Section 3.1), damage parameters (Section 3.2) and measuring techniques (Section 3.3). For that, the physical modelling test results presented in the previous section are used. As a first step, the damage parameters considered in this study are described in more detail, including the procedure for their calculation (Figure 4).

The first parameter considered in S, as defined by Broderick (1984) (see Equation 1). This damage parameter is widely used and describes the damage to the structure as the number of units eroded in the width-averaged profile.

$$S\ (number\ of\ units) = \frac{\langle A_e \rangle_w}{D_{n50}^2} \tag{1}$$

where $\langle A_e \rangle_w$ (m^2) is the eroded area from the averaged profile obtained over a given characterization width w and D_{n50} (m) the nominal median diameter.

The following parameters E_{2D} (Melby and Kobayashi, 1998) and $E_{3D,m}$ (Hofland *et al.*, 2011; 2014) are show in Equation 2 and Equation 3 respectively. These two parameters estimate the damage to the structure considering the maximum erosion depth perpendicular to the slope. The distinction between them is that for E_{2D} this erosion depth is measured in the width-averaged profile, while for $E_{3D,m}$ this erosion depth is obtained as the maximum erosion depth recorded at any point of the structure. In addition, for $E_{3D,m}$ the initial profile and the profile after the test are averaged with a circular spatial moving average with mD_{n50} diameter.

$$E_{2D}\ (\ erosion\ depth\ in\ units) = \frac{max(\langle e \rangle_w)}{D_{n50}} \tag{2}$$

$$E_{3D,m}\ (\ erosion\ depth\ in\ units) = \frac{max(\langle e \rangle_{mDn50} \rangle_w)}{D_{n50}} \tag{3}$$

where $max(\langle e \rangle w)$ (m) is the maximum erosion depth from the averaged profile obtained over a given characterization width w, $max(\langle e \rangle_{mDn50})_w$ (m) the maximum erosion depth averaged over an area of mD_{n50} diameter obtained over a given characterization width w and D_{n50} (m) the nominal median diameter.

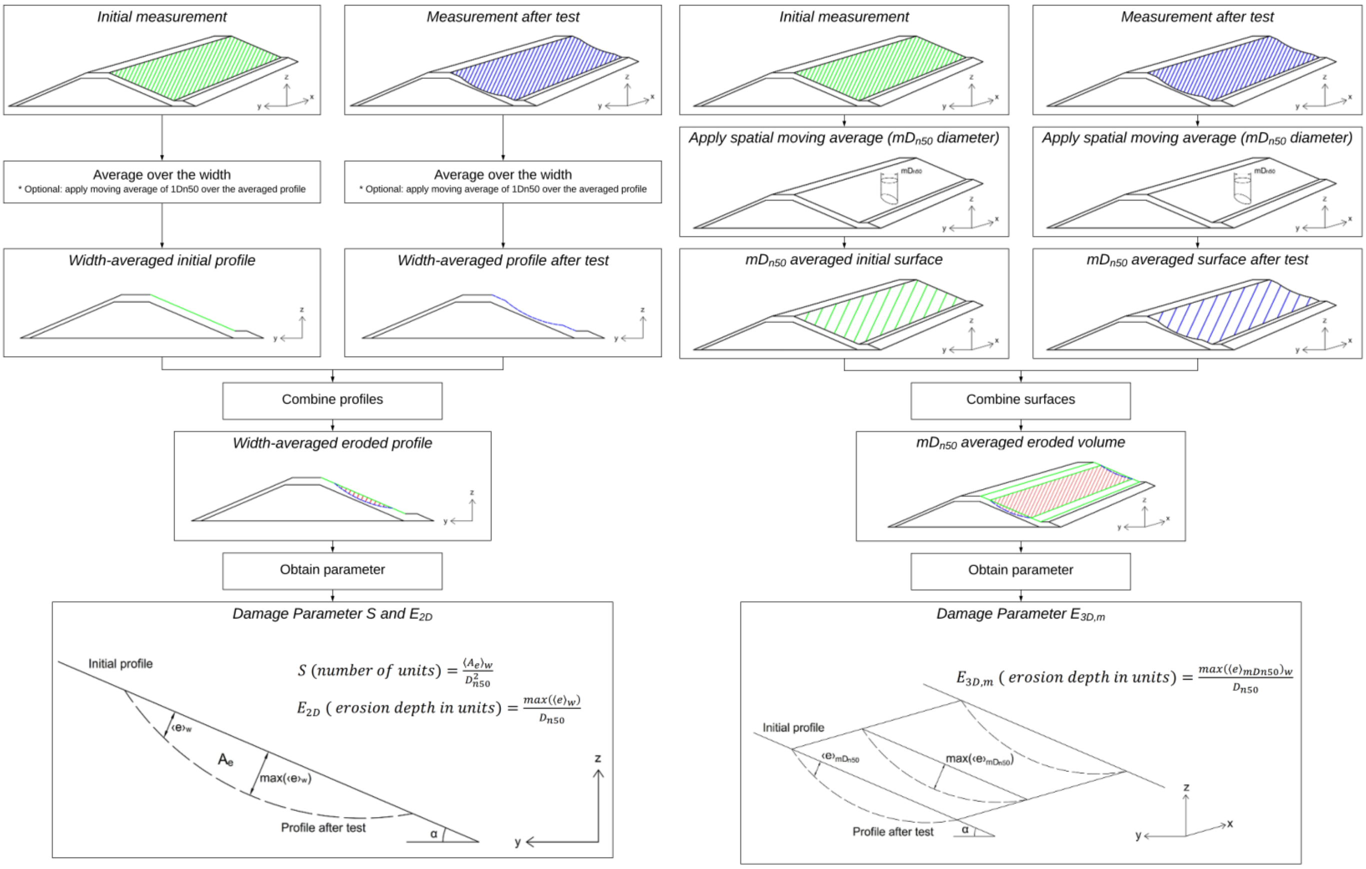


Figure 4. Damage parameters methodology.

3.1 Damage concepts

Two main damage concepts will be discussed here: characterization width (i.e. the width over which the damage is evaluated in a physical model) and the damage limits (i.e. damage initiation, intermediate damage and failure).

3.1.1 Characterization width

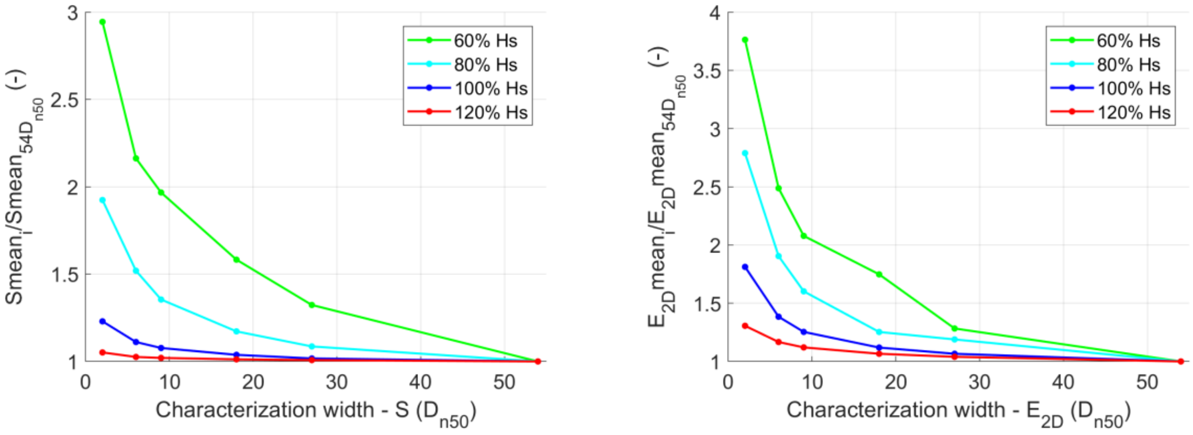
This is addressed given that using different characterizations widths in the assessment of coastal structures would lead to different damage results for all damage parameters and would influence the definitions of damage limits. Among others, Frostick *et al.* (2011) recommends the use of characterization widths larger than 15-20 rock diameters in order to achieve representative results, but does not discusses the influence it has in the measured damage.

Mean damage evolution:

The influence of the characterization width on the mean measured damage can be observed in Figure 5, obtained from the survey of a $54D_{n50}$ wide slope in the Deltares tests. The values for each characterization width are obtained as the average of all the values for that given width, being between 135 values for the 2 D_{n50} width and 5 value for the 54 D_{n50}. This average damage is then normalized by the damage obtained for the 54 D_{n50} characterization width.

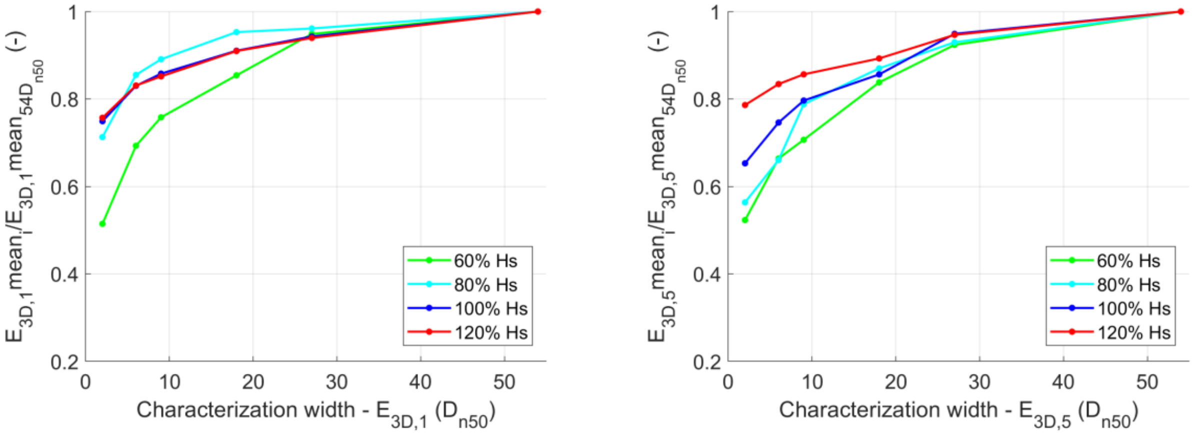
Regarding the parameters obtained from width-averaged profiles (S in Figure 5a and E_{2D} in Figure 5b), it can be observed that the measured mean damage reduces with increased characterization width since the damage to certain areas will be hidden by the accretion in other areas. Regarding the parameters obtained as the maximum erosion depth observed within a given characterization width ($E_{3D,1}$ in Figure 5c and $E_{3D,5}$ in Figure 5d), it can be observed that the measured damage increases with increased characterization width.

The main observation for the damage parameters $E_{3D,m}$ is that the measured damage continues to increase with increasing characterization widths. This suggests that there is no upper limit for the damage to the structure and that when considering wider structures the probability of observing a larger extreme damage will continue to increase. Thus, besides considering the characterization width, this length effect for the design and characterization of coastal structures should then be taken into account (see Section 3.2.2 and Van Gent *et al*. (2018)).



(a) S parameter

(b) E2D parameter



(c) $E_{3D,1}$ parameter

(d) $E_{3D,5}$ parameter

Figure 5. Characterization width. Mean damage variation – Deltares Series 1,2,3 (bias).

Damage variability evolution:

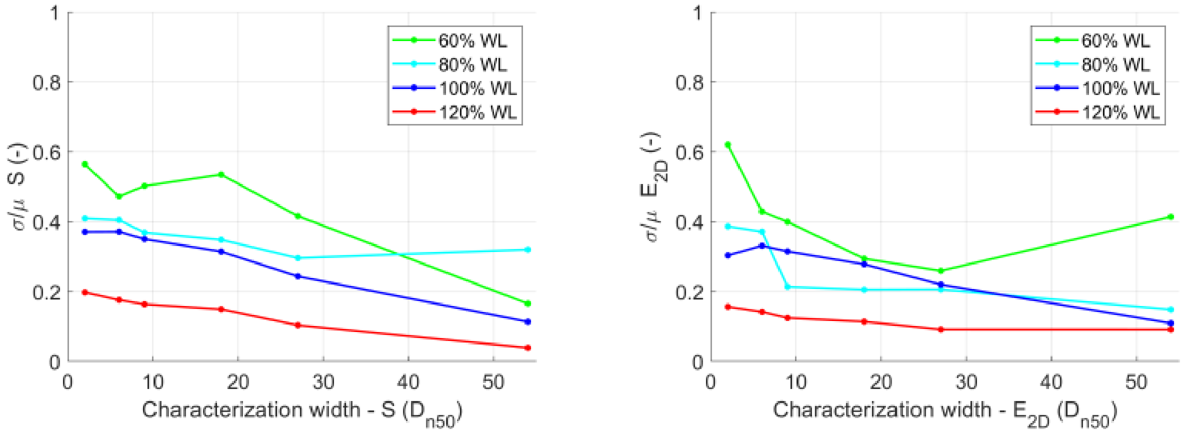
The variability of measured damage is evaluated for different characterization widths. The five identical realizations of Deltares tests Series 1 are considered, which consists of four test runs each (60%WL, 80%WL, 100%WL and 120%WL). In Figure 6 it can be observed the standard deviation normalized by the mean for the four parameters.

Regarding the parameters obtained from width-averaged profiles (S in Figure 6a and E_{2D} in Figure 6b), it can be observed that the increase in the characterization width leads to a general reduction of the variability in the measurements. Regarding the parameters obtained as the maximum erosion depth observed within a given characterization width ($E_{3D,1}$ in Figure 6c and $E_{3D,5}$ in Figure 6d), they also show a reduction in the variability (mainly due to an increase of the mean values) with increasing characterization width, with significantly less variability than for parameters S and E_{2D}. For additional details on damage variability consider Van Gent *et al*. (2018).

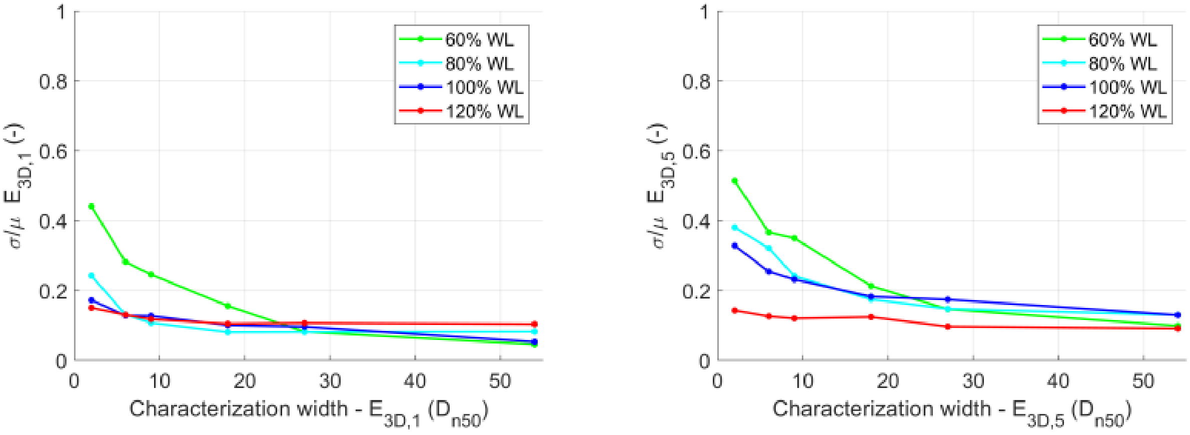
Conclusions regarding characterization width:

Following the previous results, it can be stated that the characterization width is an important factor in the definitions of damage to coastal structures. According to the present results, a characterization width of approximately $25D_{n50}$ is recommended, but the following aspects should be taken into account:

- Mean evolution: as shown in Figure 5, different characterization widths will affect the measured damage (bias). Thus, ideally, a suitable characterization width will be the one that shows a smaller difference in mean measured damage compared to what is obtained when considering different characterization widths.
- Variability evolution: as shown in Figure 6, it should be considered that different characterization widths will present different variability in the results when the same condition is tested repeated times (random error). Thus, ideally, a suitable characterization width will be the one that shows a smaller variability in the results.
- Laboratory conditions: the definition of the most suitable characterization widths should take into account the limited space available for physical modelling tests and the associated costs that limits the experiment dimensions. In addition, the implication of the scaling constraints which limit the possibility of reducing the units size in the armour of the structure should be taken into account. Thus, a suitable characterization width will be the one that could fit into general testing facilities without introducing scale effects.



(a) S parameter (b) E2D parameter



(c) $E_{3D,1}$ parameter (d) $E_{3D,5}$ parameter

Figure 6. Characterization width. Standard deviation divided by the mean – Deltares Series 1 (random error).

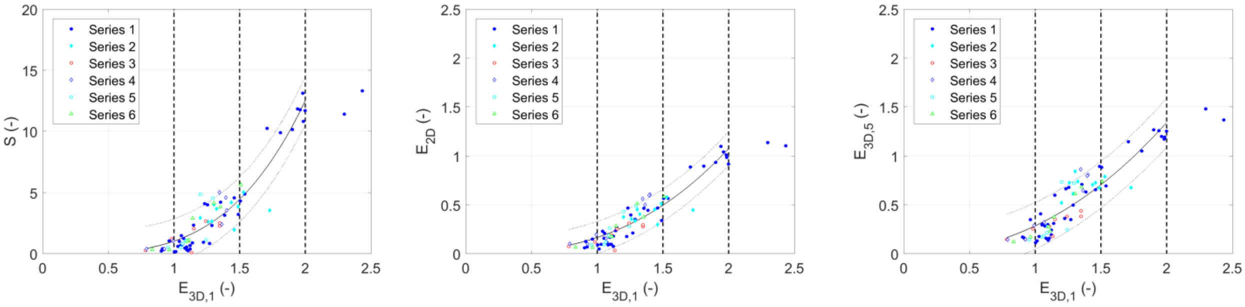
3.1.2 Damage limits

This study aims to establish unified damage limits for the characterization of coastal structures such as damage initiation, intermediate damage and failure. Based on the contributions and limitations found in literature (see Section 1.2) and the need of establishing unified concepts for damage characterization, the following damage limits are proposed for a nD_{n50} thick rock armoured slopes:

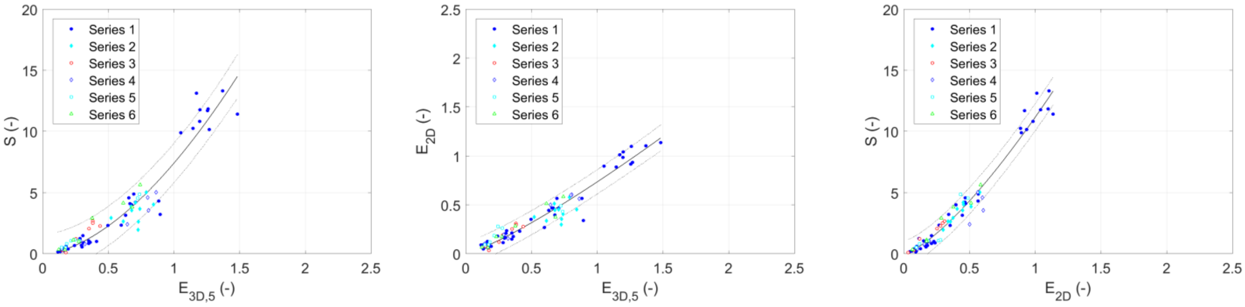
- Damage initiation: defined as the condition where a circular hole of $1D_{n50}$ diameter and a depth of $1D_{n50}$ is observed in the armour layer.
- Intermediate damage: defined as the condition where a circular hole of $1D_{n50}$ diameter and a depth of 1.5 D_{n50} is observed in the armour layer.
- Failure limit: defined as the condition where a circular hole of $1D_{n50}$ diameter and a depth of nD_{n50} is observed in the armour layer.

In order to characterize a given rock armoured slope according to these damage limits, the parameter $E_{3D,1}$ is used as the calibration method. This $E_{3D,1}$ parameter can be described as " the erosion depth measured in D_{n50} perpendicular to the slope averaged over a circular area of $1D_{n50}$", which allows to capture the damage limits describe above.

Traditional damage assessment methods were based on slope surveys with profilers with a limited number of profiles and the exposure of the filter layer for the failure limit: $D_{50}/2$ for Thompson and Shuttler (1975), $1D_{n50}$ for Melby and Kobayashi (1998) and less clear extent for other authors (see Section 1.2). According to such methods, damage initiation and intermediate damage is based on defined parametric limits while failure is determined by the visual observation of images such as Figure 1 left or using cylindrical gauge with a hemispherical foot. In contrast, the use of high resolution surveys such as the ones provided by DSP (see Figure 1 right) allows a more precise visualization of the state of the structure for all damage levels. In this case all the damage limits can be quantified according to the depth and extension of the damage area.



(a) $E_{3D,1}$ vs S parameter (b) $E_{3D,1}$ vs E_{2D} parameter (c) $E_{3D,1}$ vs $E_{3D,5}$ parameter



(d) $E_{3D,5}$ vs S parameter (e) $E_{3D,5}$ vs $E2_D$ parameter (f) E_{2D} vs S parameter

Figure 7. Comparison all damage parameters (for $27D_{n50}$ characterization width).

Thus, considering the measurements carried out with a high resolution technique (DSP) and the damage parameter $E_{3D,1}$, the damage limits can be calibrated based on the Deltares tests (characterization width of $27D_{n50}$), see Figure 7 and Table 2.

Table 2. Damage limits (for $27D_{n50}$ characterization width).

Damage limit	**$E_{3D,1}$**	**$E_{3D,5}$**	**E_{2D}**	S
Damage initiation	1.0	0.3	0.2	1
Intermediate damage	1.5	0.7	0.5	4
Failure	2.0	1.1 (90% conf.)	0.9 (90% conf.)	11 (90% conf.)

An important remark from the previously defined calibrated damage limits is the fact that, according to the available data, they are constant for the slopes applied (1:3 in Deltares tests). Nevertheless, this should be further investigated considering larger number of tests and different slope configurations in order to validate these conclusions.

3.2 Damage parameters

This section addresses the need of to establishing and validating a robust damage parameter able to accurately characterize the damage and remaining strength of rubble mound structures. This will be done analysing the Deltares shallow water test results in more detail and using a characterization width of 27 D_{n50} and the previously established damage limits. Only parameters S, E_{2D} and $E_{3D,5}$ will be evaluated ($E_{3D,1}$ calibration parameter will not be considered).

3.2.1 Damage parameters analysis

The analysis of damage parameters is done considering hereafter four criteria: bias, random error, distinction of damage range and its values for different structures.

Bias:

The first element to be considered, the bias in damage characterization of coastal structures, is related to the ability of the damage parameters to provide the most precise description of the state of the structure. This can be achieved with damage parameters that do not lead to hidden erosion, defined as the conditions were the damage in one location of the structure is hidden by the accretion in other location when considering width-averaged profiles.

Damage parameters based on width-averaged profiles (S and E_{2D}) are associated to larger bias since a larger characterization width will lead to an averaged profile which reduces (averages out) the magnitude of the maximum erosion areas, especially for smaller damage levels (damage initiation). On the contrary, damage parameters that capture the maximum erosion depth observed within a given characterization width ($E_{3D,5}$) have limited bias since they provide an assessment of the complete structure surface and identify all damaged areas.

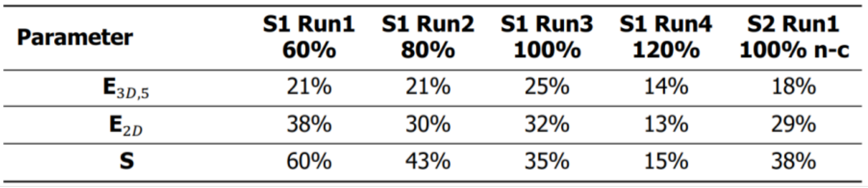
Random error:

This second aspect, the random error in the measured damage to coastal structures, is related to the ability of damage parameters to describe the state of the structure with the smallest variability and larger confidence in the measured result. This is going to be analysed further, in order to estimate the random error associated with each of the damage parameters.

The damage data for Series 1 (composed by four test runs of 60%, 80%, 100% and 120%) and Series 2 (composed by 1 test run of 100%) is described in the table below. For each test run 10 observations are considered, obtained from 5 realization in a model with a width of $54D_{n50}$ (2 times the considered characterization width of 27 D_{n50}). For these 10 observations and the three damage parameters, Table 3 shows the 80% confidence prediction interval applying a student-t distribution with critical t-value of 1.383 ($\delta = \pm 1.383\ \sigma/\sqrt{10}$) expressed as a % of the mean.

According to these results, it can be observed that damage parameters $E_{3D,5}$ present a lower variability (random error), especially for the lower conditions associated with a lower amount of damage (60% and 80%). Damage parameters S and E_{2D} present low variability in higher damage levels (120% in Series 1 run 4) but much higher variability (random error) in the other damage levels.

Table 3. 80% prediction interval respect to mean from Deltares tests Series 1,2 (for $27D_{n50}$ characterization width).



Parameter	S1 Run1 60%	S1 Run2 80%	S1 Run3 100%	S1 Run4 120%	S2 Run1 100% n-c
$E_{3D,5}$	21%	21%	25%	14%	18%
E_{2D}	38%	30%	32%	13%	29%
S	60%	43%	35%	15%	38%

Distinction of damage range:

The third element to be considered is the ability of damage parameters to distinguish the range of damage levels between initial damage, intermediate damage and failure. According to the experimental data from the tests, S, E_{2D} and $E_{3D,5}$ parameters were able to distinguish the different damage levels with a similar degree of scatter (for parameter $E_{3D,1}$ a larger scatter was observed). For additional details consider De Almeida (2017).

Values for different structures:

The fourth aspect to be considered in this analysis is the suitability of damage parameters to be used in different structures. In this case different structures do not only include variations in the characteristics of the rock slope, but also 3D features such as roundheads or slopes with a berm. Of the 3 parameters considered here, only the parameter that captures the maximum erosion depth observed within a given characterization width ($E_{3D,5}$) is suitable for describing damage to coastal structures with any geometry or 3D feature.

Conclusions on damage parameters analysis:

According to the four criteria previously discussed, the damage parameter $E_{3D,5}$ is considered as the most suitable damage parameter for the characterization of damage to coastal structures based on the four reasons:

- Low bias: the damage to the structure is clearly captured, without including hidden erosion present in the parameters that consider width-averaged profiles.
- Low random error: this parameter describes the damage to the structure with low variability also for a relatively low amount of damage, which increases the confidence in the measured and expected damage.
- Distinguish damage range: the different states of damage to the structure can be recognized according to the limits established.
- Constant value for different structures: for all structure configurations this parameter can be used without the need of any modification.

3.2.2 Extreme damage distribution for $E_{3D,5}$

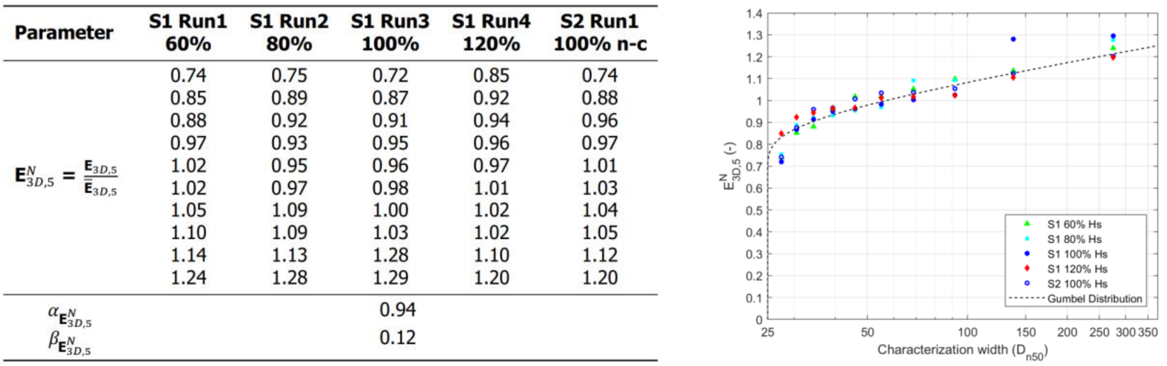
According to the results from this study, the measured damage with parameter $E_{D,5}$ can be adjusted to an extreme value distribution. This illustrates that for increasingly long structures a larger damage is expected, in the same way as for increasingly long time period a larger wave height is expected, or that for increasingly long dikes a larger probability exists that one section can fail (VNK, 2014).

In order to define an extreme value distribution for the measured damage with $E_{3D,5}$, the results shown in Figure 8a are considered. Each test condition (four for Series 1 and one for Series 2) had five realizations each with a width of $54D_{n50}$, which leads to 10 damage results for a characterization width $27D_{n50}$. For each test condition, the measured damage was normalized by the mean value, so all 50 measurements are combined in one single distribution. These values are adjusted to a Gumbel distribution, with the distribution parameters determined by the least square method.

The exceedance probability for the damage is translated to a return width in a similar form as used for the study of extreme wave climate (see Equation 4). The combined extreme distribution for the normalized damage parameter $E^{N}_{3D,5}$ is shown in Figure 8b.

$$R_w = \frac{\lambda}{1-F_X(x)} \tag{4}$$

where R_w (m) is the return width, λ (m) the characterization width (27D_{n50} in this study) and $1 - F_X(x)$ (-) the exceedance probability.



Parameter	S1 Run1 60%	S1 Run2 80%	S1 Run3 100%	S1 Run4 120%	S2 Run1 100% n-c
$\mathbf{E}^N_{3D,5} = \frac{\mathbf{E}_{3D,5}}{\overline{\mathbf{E}}_{3D,5}}$	0.74	0.75	0.72	0.85	0.74
	0.85	0.89	0.87	0.92	0.88
	0.88	0.92	0.91	0.94	0.96
	0.97	0.93	0.95	0.96	0.97
	1.02	0.95	0.96	0.97	1.01
	1.02	0.97	0.98	1.01	1.03
	1.05	1.09	1.00	1.02	1.04
	1.10	1.09	1.03	1.02	1.05
	1.14	1.13	1.28	1.10	1.12
	1.24	1.28	1.29	1.20	1.20
$\alpha_{\mathbf{E}^N_{3D,5}}$			0.94		
$\beta_{\mathbf{E}^N_{3D,5}}$			0.12		

(a) Distribution parameters

(b) Extreme damage distribution

Figure 8. Gumbel distribution $E^N_{3D,5}$ parameter from Deltares tests Series 1,2 (for 27D_{n50} characterization width).

Figure 8b shows that a single realization of a test run for a characterization width of 27D_{n50} is expected to present approximately a damage of 0.8 the mean damage (calculated from 10 realizations) while for a structure 10 times wider (approx. 270D_{n50} wide) it is expected a damage of 1.2 the mean damage. Thus, according to this study, the damage to a structure of 270D_{n50} wide is expected to present a damage up to 50% (1.2/0.8 = 1.5) larger than the one obtained in a single realization in a 27D_{n50} characterization width. Detailed guides on how to account for the length effect on rock armoured structures are presented in Van Gent *et al*. (2018).

3.3 Measuring technique

Significant differences can be observed in the damage characterisation outcome when using high resolution and high accuracy measurements techniques compared with low resolution measurements used in traditional surveys. In contrast to low resolution techniques, high resolution techniques (e.g. DSP) are able to measure the state of the whole structure surface and capture all the erosion areas.

These high resolution measuring techniques such as DSP present a number of advantages for the damage characterization of coastal structures. First, it allows the introduction of more precise damage parameters such as $E_{3D,5}$ and allows the improvement in the damage limits and definitions. Thus, these high definition measuring technique, together with suitable parameters and definitions, can describe the state of the full structure surface in order to identify the presence of weak areas that threatens the stability of the structure. Second, for parameters obtained from width-averaged profiles such as S and E_{2D}, high resolution surveys which captures the state of the whole structure surface are able to reduce the variability and uncertainty in the damage characterization results, especially for situations with a relatively low amount of damage.

In summary, high resolution measurement techniques, in combination with the use of other damage parameters, are able to reduce the bias related with hidden erosion and random errors related with the position of the measured profiles, which are present in the damage characterization methods carried out with low resolution techniques. Thus, it can be concluded that such innovative measuring techniques such as DSP are able to improve significantly the damage characterization of coastal structures.

4 CONCLUSIONS

Damage characterization for rock armoured slopes were addressed in this paper with focus on 3 key elements: damage concepts, damage parameters and measuring techniques. It is highlighted that for a reliable damage assessment, these 3 elements should be taken into account. For this research, a physical modelling campaign were carried out within the EU Hydralab+ framework. The Deltares shallow water tests were carried out in a wave flume with a foreshore (depth-limited waves), a 1:3 slope and an impermeable core.

On damage concepts, the characterization width was discussed, since this influences the measured damage and the associate assessment description. The main effect is that for parameters obtained from width-averaged profiles (S and E_{2D}), the measured damage reduces with increased characterization width since the damage to certain areas will be hidden by the accretion in other areas, while for parameters obtained as the maximum erosion depth observed within a given characterization width ($E_{3D,1}$ and $E_{3D,5}$), the measured damage increases with increased characterization width. Considering this and other factors, it is recommended to carry out laboratory experiments with a characterization width of around 25D_{n50}.

The calibrated damage limits and damage parameters for rock armoured slopes with a characterization width of about 25D_{n50} and with an armour thickness of nD_{n50} are:

- Damage initiation: defined as the condition where a circular hole of $1D_{n50}$ diameter and a depth of $1D_{n50}$ is observed in the armour layer: $E_{3D,1} = 1$; $E_{3D,5} = 0.3$; $E_{2D} = 0.2$; $S = 1$.
- Intermediate damage: defined as the condition where a circular hole of 1 D_{n50} diameter and a depth of $1.5D_{n50}$ is observed in the armour layer: $E_{3D,1}= 1.5$; $E_{3D,5} = 0.7$; $E_{2D} = 0.5$; $S = 4$.
- Failure limit: defined as the condition where a circular hole of $1D_{n50}$ diameter and a depth of nD_{n50} is observed in the armour layer: $E_{3D,1}= 2.0$; $E_{3D,5} = 1.1$; $E_{2D} = 0.9$; $S = 11$.

Regarding damage characterization parameters different parameters were considered. It was found that $E_{3D,5}$ is the parameter that can better describe the damage and remaining strength of conventional and non-conventional structures. The key reasons for defining this parameter as the most suitable damage characterization parameter are the following:

- Low bias: the damage to the structure is clearly captured, without including hidden erosion present in the parameters that consider width-averaged profiles.
- Low random error: this parameter describes the damage to the structure with low variability also for a relatively low amount of damage, which increases the confidence in the measured and expected damage.
- Distinguish damage range: the different states of damage to the structure can be recognized according to the limits established.
- Constant value for different structures: for all structure configurations this parameter can be used without the need of any modification.

In addition, the results from this study show that the damage measured with the damage parameter $E_{3D,5}$ presents an extreme value distribution. This illustrates that for increasingly long structures a larger damage is expected

Regarding damage characterization measuring techniques, the importance of high resolution measuring techniques for delivering accurate damage characterization of coastal structures was demonstrated. These techniques (such as DSP) allow the use of the most precise damage parameter: $E_{3D,5}$.

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