ROCK SLOPES WITH OPEN FILTERS UNDER WAVE LOADING: EFFECTS OF STORM DURATION AND WATER LEVEL VARIATIONS

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Rubble mound breakwaters and revetments typically contain granular filters in one or more layers. The transition from the armour layer to the filter layer, and transitions between other layers within the structure, are normally geometrically tight to prevent material washout. This requires a limited ratio of the material size of the upper layer and neighbouring layer. An alternative is a geometrically open filter where in principle underlayer material can be transported into the upper layer, but if the hydraulic load at this transition between two layers remains low, the transition can be designed such that no or limited transport occurs, see for instance Van Gent and Wolters (2015), Van Gent et *al* (2015) and Jacobsen et *al*, (2017). This allows for larger ratios of material sizes, which can reduce the number of filter layers, and relax the material requirements with respect to the width of gradings. This can lead to considerable cost savings. In Van Gent and Wolters (2015) physical model tests for the transition between a layer of rock and an underlayer that consists of sand have been performed and design guidelines have been derived. Here, additional physical model tests are presented to study the influence of the storm duration and water level variations on the response of sand underneath a layer of rock.

Keywords: rock slopes; open filters; erosion; physical model tests; storm duration; water level variations

INTRODUCTION

Rubble mound breakwaters and revetments typically contain granular filters. These filters fulfill several functions. They prevent the erosion (washing out) of finer base material due to waves and currents, contribute to the energy dissipation by turbulent flow through the voids, and provide drainage. Granular filters can be designed as geometrically tight filters or as geometrically open filters. For geometrically tight filters (no material washout) often a relatively large number of filter layers and material volume is required. Each layer should have a minimum thickness of at least a few diameters but for practical reasons also a minimum thickness irrespective of the size of the material is required. For a granular filter of a number of layers, the mentioned minimum thickness may lead to a substantial size of the total filter.

Geometrically open filters in which no transport of material of the filter layer (base material) occurs because the hydraulic load is smaller than the threshold value for incipient motion (hydraulically closed filter), can be applied as alternative to geometrically tight filters. For the onset of base material removal reference is made to De Graauw et *al.* (1983), Bakker et *al.* (1994) and Klein Breteler et *al.* (1992), CUR Report 161 (1993), CUR Report 233 (2010), Sumer et *al.* (2001, 2013), Dixen et *al.* (2008), Stevanato et *al.* (2010), Van de Sande et *al.* (2014) and Jacobsen et *al.* (2017).

Another alternative is a transport filter where some movement of the base material within the granular filter layer is allowed. In this case the hydraulic load is larger than the threshold value for incipient motion. The design of a transport filter is based on the principle that the layer thickness is such that erosion of base material (or settlement) remains below an acceptable level. In practice, limited settlement is often permitted. For studies related to open transport filters under wave loading with sand as base material reference is made to Uelman (2006), Ockeloen (2007), Zoon (2010), Wolters and Van Gent (2012), Van Gent and Wolters (2015), Van Gent et *al.* (2015) and Jacobsen et *al.* (2017).

Figure 1. Open transport filters with rock on top of sand (from Van Gent and Wolters, 2015).

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For open transport filters where the toplayer consists of rock and the underlayer (base material) consists of sand, guidelines have been developed, see for instance Van Gent and Wolters (2015). These guidelines take effects of the wave loading as well as the geometry of the structure into account. However, a number of aspects have not been addressed. These include effects of the duration of the loading (storm duration and/or number of storms) and water level variations. Here additional physical model tests have been described based on the set-up of Van Gent and Wolters (2015), but now focussed on the duration of the wave loading and water level variations.

The 2D model tests by Van Gent and Wolters (2015) were focussed on one layer of rock on top of a sandy slope and on two layers of rock on top of a sandy slope. Tests were carried out for 1:4 and 1:7 slopes. Wide and narrow rock gradings were applied. The following parameters were measured:

$A_{e,r}$: Outer rock profile: Area of the eroded part of the top/filter layer of rock.
$A_{e,s}$: Internal interface: Area of sand erosion at the internal sand-rock interface.
A_{acc} : Internal interface: Area of sand accretion at the internal sand-rock interface.
z_s : Maximum erosion depth of sand (measured in vertical direction).
z_{acc} : Maximum accretion height of sand within the filter layer (measured in vertical direction).

Figure 2 shows a schematization of these parameters. The test results showed that if the rock is stable under direct wave loading (*e.g.* by applying high-density rock in the tests), the eroded part of the external surface of the rock layer ($A_{e,r}$) was more or less equal to the eroded part of the internal sand surface ($A_{e,s}$).

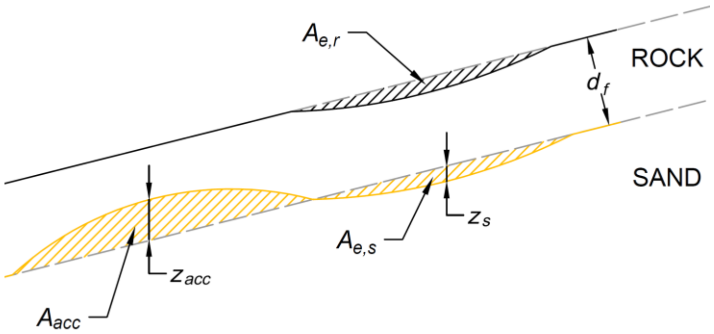

Figure 2. Erosion and accretion pattern (parameter definition).

The next chapter deals with the influence of storm duration and the subsequent chapter with the influence of water level variations. Finally, the main conclusions and recommendations for future research on open filters have been summarised.

INFLUENCE OF STORM DURATION

New physical model tests were performed to analyse effects of the storm duration and water level variations on the erosion and accretion of sand at the rock-sand interface. The experimental set-up was similar to the experimental set-up of the physical model tests as described in Van Gent and Wolters (2015). See Figure 3 for the model set-up.

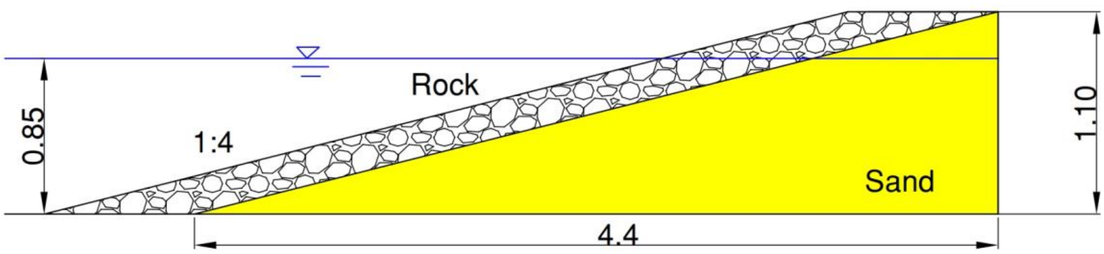

Figure 3. Model set-up for physical model tests (all dimensions are given in metres).

One of the earlier tested structure configurations was selected. A layer of rock on a 1:4 slope with a thickness of d_f = 0.2 m, a porosity of n_f = 0.38, a stone diameter of D_{n50} = 38 mm, a wide grading of D_{n85} / D_{n15} = 6.5, and a density of ρ_f = 3688 kg/m^3, was placed on top of sand with a diameter of D_{50} = 0.18 mm and a density of ρ_s = 2650 kg/m^3 (referred to as Configuration A in Van Gent and Wolters, 2015). Table 1 shows the values of the most important parameters.

Table 1. Parameters of the tests with a 1:4 slope.

Filter Thickness	Filter size	Filter thickness	Filter grading	Filter porosity	Wave height	Wave steepness	Number of waves
d_f (mm)	D_{n50} (mm)	d_f / D_{n50} (-)	D_{n85} /D_{n15} (-)	n_f (-)	H_{m0} (m)	s_p (-)	N (-)
200	38	5.2	6.5	0.38	0.12	0.04	52000

Also, one of the earlier tested wave conditions was selected. A water level of 0.85 m above the flume bottom was used, a spectral significant wave height of H_{m0} = 0.12 m, and a wave steepness of s_p = 0.04 where $s_p = 2\pi H_{m0}/gT_p^2$ (the foreshore was horizontal such that the wave steepness at the toe was equal to the wave steepness closer to the wave generator). This corresponds to $s_{m-1,0}$ = 0.048, with $s_{m-1,0} = 2\pi H_{m0} / gT_{m-1,0}^2$. The significant wave height of H_{m0} = 0.12 m has have been selected such that no motion of the high-density rock occurred due to direct wave loading. The spectral significant wave height H_{m0} and the spectral wave period $T_{m-1,0}$ ($T_{m-1,0} = m_{-1}/m_0$) were obtained from the measured wave energy spectra close to the toe of the structure. In Van Gent (2001) the wave period $T_{m-1,0}$ was found to appropriately describe the influence of wave energy spectra on wave run-up, while in later studies this wave period was found to be the most appropriate wave period for other coastal processes (wave overtopping, wave reflection, dune erosion, and the stability of rock slopes). A Jonswap wave spectrum has been applied.

In total N = 52000 waves have been generated corresponding to a total test duration of 18 hours. These 18 hours have been divided into 6 periods of 3 hours. After each period of 3 hours the outer rock profile (settlement) has been measured using a mechanical profiler (6 profiles over the flume width of 1 m). The profile of the interface between rock and sand (sand profile) was measured after 3, 6, 9 and 18 hours. To measure the sand profile, the stones above the sand surface were carefully removed. After the sand profile had been measured, the sand and filter layers were repaired. Through the glass wall of the flume sand profile changes were measured after each period of 3 hours, providing data also after 12 and 15 hours.

Figure 4 shows the profile development in time and Figure 5 shows the test results for the sand accretion (A_{acc} and z_{acc}) and sand erosion ($A_{e,s}$ and z_s) after each period of 3 hours of testing. The results show that during the first 9 hours of testing the accretion and erosion progresses relatively fast while after 9 hours the increase in accretion and erosion is relatively small or even absent. For an unknown reason a relatively large value of the accretion height was measured after 6 hours of testing (upper green triangle in left graph of Figure 5).

The observed dependency on the storm duration can be summarised in an expression. The data has been fitted to the following expression to account for the influence of the storm duration using the number of waves N:

$$f(N) = c_0 \ N \qquad \text{for } N \leq p$$
$$f(N) = c_1 - c_2 \ / \ N \qquad \text{for } N \geq p \qquad (1)$$

Continuity of $f(N)$ and its derivative determine $c_2=0.25\ c_1^2/c_0$ and $p=0.5\ c_1 / c_0$. The coefficients c_0 and c_1 were calibrated based on the experiments, see Table 2 (see also Figure 5).

Table 2. Calibrated coefficients for the storm duration expression.

	A_{acc}	z_{acc}	$A_{e,s}$	z_s
c_0	1.0 E-8	3.5 E-8	2.3 E-9	1.2 E-8
c_1	1.8 E-4	3.7 E-4	6.2 E-5	2.0 E-4

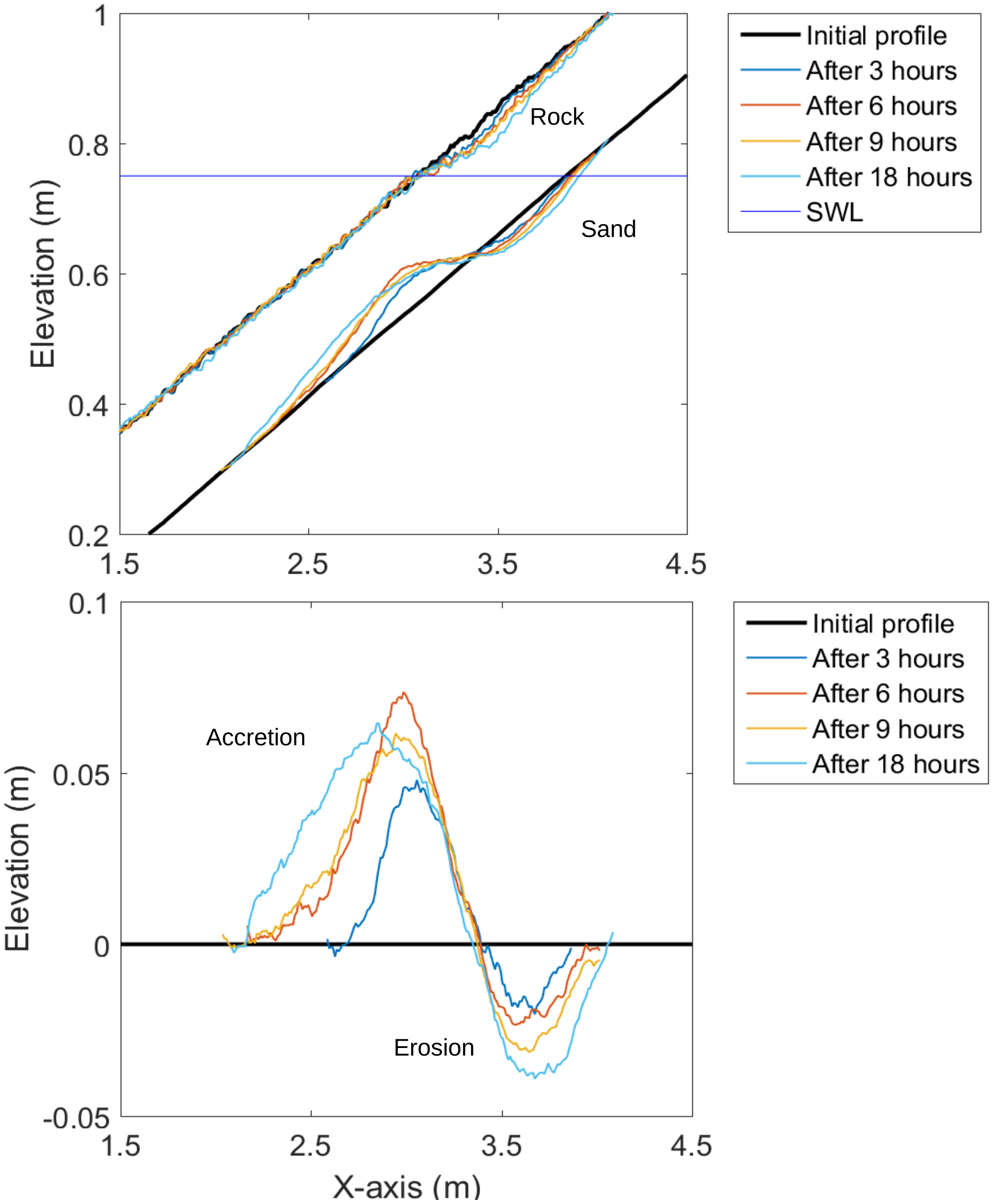

Figure 4. Profile development in time (upper graph denotes the profiles of the rock slope and of the sand slope; lower graph shows the erosion and accretion of sand, relative to the initial slope).

The formulae by Van Gent and Wolters (2015) were based on tests with 2 different wave steepnesses of which the one applied in the present tests was with a duration of N=8640 (3 hours). To incorporate an estimate of the effect of storm duration in the prediction formulae, the obtained values for $A_{e,r}$, $A_{e,s}$, A_{acc} , z_s and z_{acc} should be multiplied by $f(N) / f(8640)$ using Eq. 1.

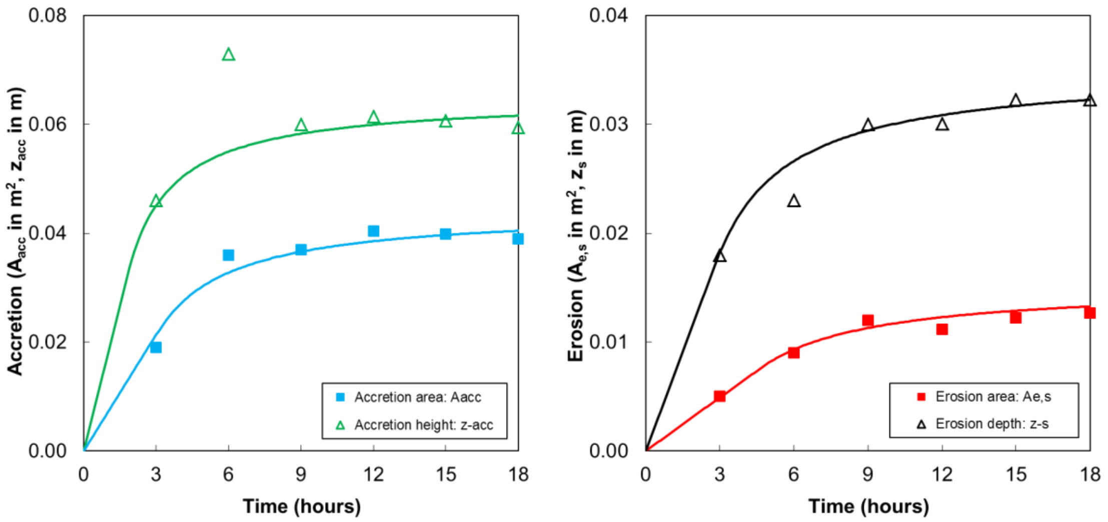

Figure 5. Influence of storm duration on accretion (left) and erosion (right).

INFLUENCE OF WATER LEVEL VARIATIONS

To study effects of water level variations on the erosion and accretion of sand underneath the rock, the same structure configuration as shown in Figure 3 has been used. One of the earlier tested wave conditions was selected: A spectral significant wave height of H_{m0} = 0.12 m and a wave steepness of s_p = 0.04, which corresponds to $s_{m-1,0}$ = 0.048.

Three scenarios of water level variations have been applied, see also Figure 6:

a) Increasing water levels: 3 levels with Δd=0.1m difference, each during 3 hours (total 9 hours).
b) Decreasing water levels: 3 levels with Δd=0.1m difference, each during 3 hours (total 9 hours).
c) Storm peak: 3 increasing levels with Δd=0.1m difference to the highest water level and 3 decreasing levels with Δd=0.1m difference to the lowest water level (total 9 hours).

The water level variations can be seen as water level variations within a storm or different water levels of subsequent storms.

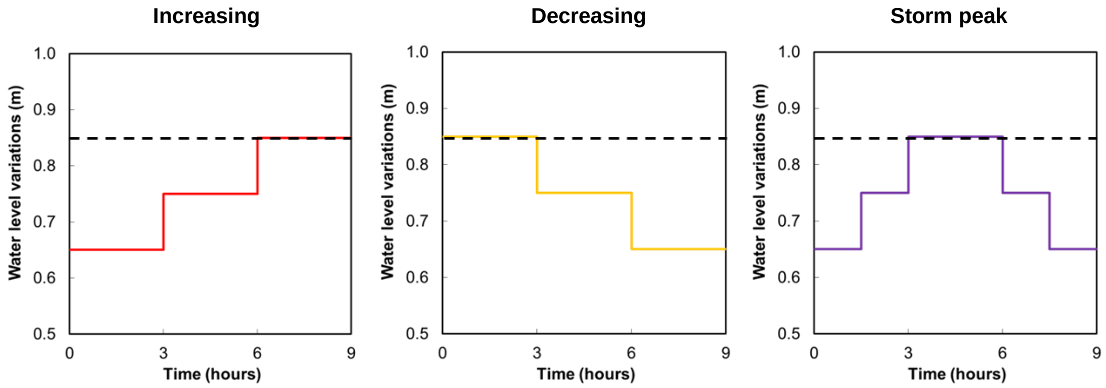

Figure 6. Scenarios of water level variations.

Figure 7 shows the resulting profiles after 9 hours of testing with each of the described scenarios, as well as the resulting profiles after 9 hours of testing with a constant water level (0.85m). Figure 7 shows that for each of the 3 scenarios the affected profiles are much wider compared to a constant water level. The scenario with a decreasing water level leads to larger erosion and accretion areas than all other scenarios. The erosion and accretion are about 50% larger than for a constant water level. Apparently during this scenario, the accretion area that appeared during the highest water level got eroded in the subsequent step, and the accretion area in the second step got eroded during in the last step, leading to a wide area of erosion and relatively large accretion area at a low position along the slope. For all three water level scenarios the erosion depth was less (10%-50%) than for the constant water level condition. The scenario with an increasing water level leads to less accretion but the area of erosion has about the magnitude as for the situation with a constant water level. The scenario with a storm peak leads to less erosion and less accretion than the situation with a constant water level, although the affected profile is wider.

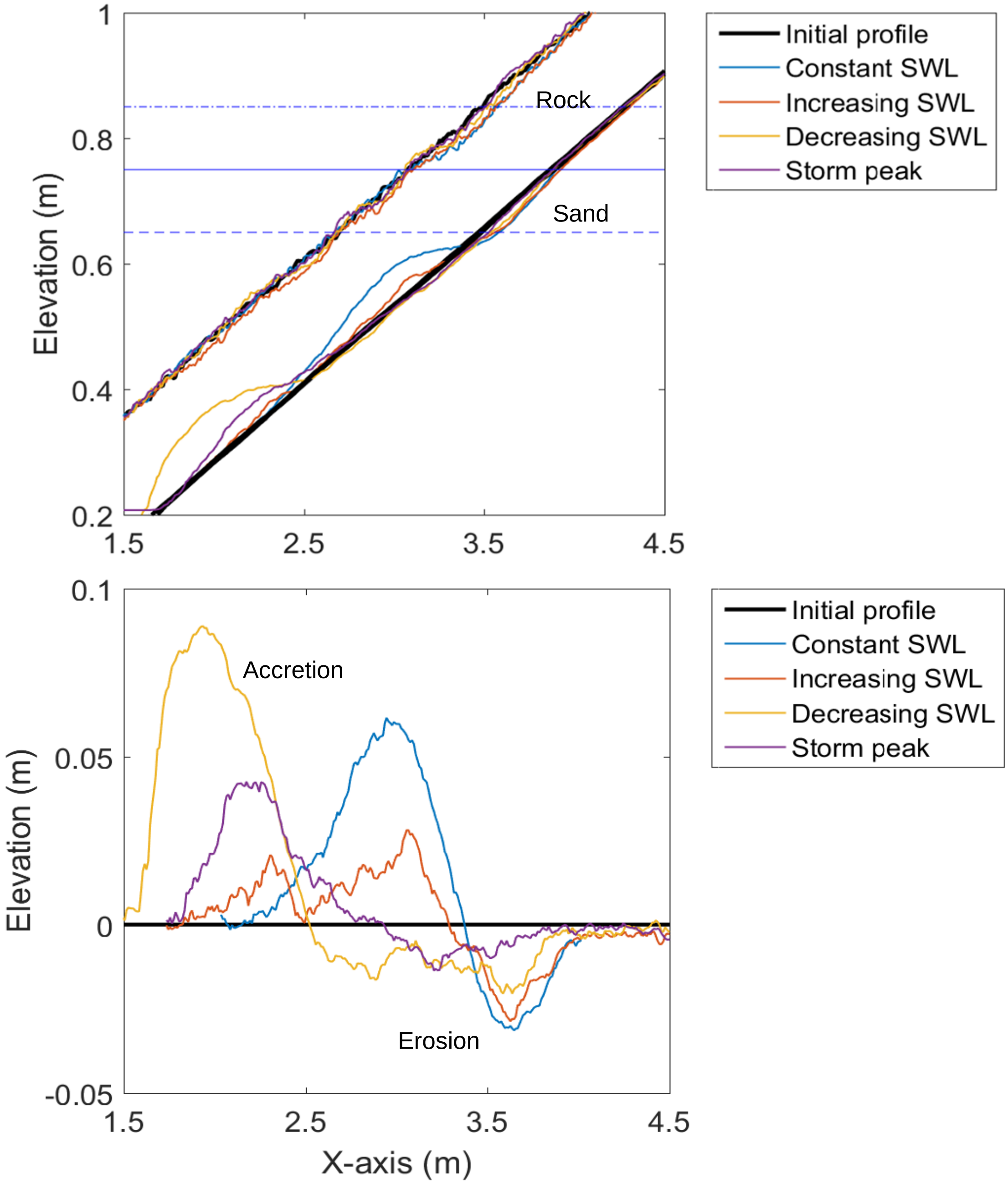

Figure 7. Influence of water level variations (upper graph denotes the profiles of the rock slope and of the sand slope; lower graph shows the erosion and accretion of sand, relative to the initial slope).

Figure 8 shows the relation between the accretion area and accretion height (left graph) and the relation between the erosion area and the erosion depth (right graph). The red symbols in Figure 8 show the three water level scenarios while all other data-points are those by Van Gent and Wolters (2015) with a constant water level. This figure indicates that, although accretion can deviate from the situation with a constant water level, the relation between the area and height of accretion is more or less similar, with the result for the storm peak scenario being on top of the earlier derived relation between accretion area and height. The relation for erosion is however quite different; for a specific erosion area, the erosion depth is much smaller for the scenario with a decreasing water level. As also shown in Figure 7, this is due to the erosion area being wider and less deep than for conditions with a constant water level.

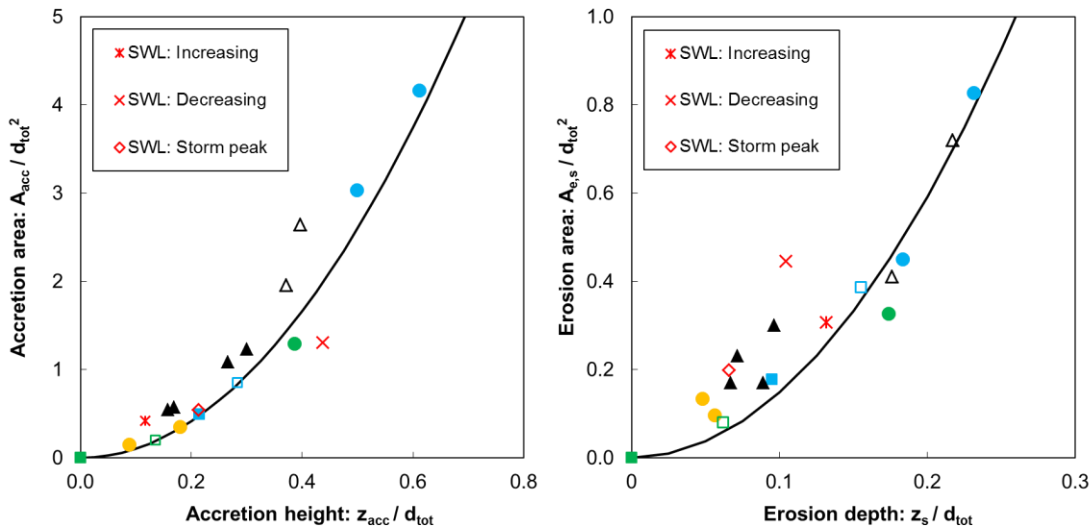

Figure 8. Relation between accretion area and height (left graph with $d_{tot} = d_f$) and between erosion area and depth (right graph with $d_{tot} = d_f$) for the three water level scenarios in red and conditions by Van Gent and Wolters (2015) with a constant water level.

Based on this set of model tests it can be concluded that water level variations play an important role in the erosion and deposition of sand. The worst case scenario is a series of conditions with a decreasing water level (for the parameters accretion area, accretion height, and erosion area). However, for the erosion depth the situation with a constant water level is the worst case scenario.

Increasing water levels and a storm peak lead to somewhat less erosion and accretion than a constant water level. For the latter two scenarios the expressions by Van Gent and Wolters (2015) provide conservative estimates. However, for scenarios in which storms occur with a sequence of decreasing water levels, those estimates are not conservative for the parameters accretion area, accretion height, and erosion area. For the example tested here with 3 subsequent water levels with a total variation of $\Delta d/H_{m0}$ =0.20m/0.12m=1.67, the accretion area, accretion height and erosion area increased by a factor 1.5 compared to a condition with a constant water level. For all tested water level scenarios the erosion depth was less than for a condition with a constant water level. For estimates of erosion and accretion with significant water level variations other than those tested here, dedicated physical model tests or numerical model computations with the model by Jacobsen et *al.* (2017) may provide valuable insight.

CONCLUSIONS AND RECOMMENDATIONS

For open filters with rock on top of sand guidelines have been developed by Van Gent and Wolters (2015):

- If the accretion of sand within the layer of rock reaches a level of two stone diameters or less underneath the outer rock profile, wave action on the slope causes that sand will be entrained directly into the water column. If this occurs, the application of open filters is not recommended.
- Sand accretion and sand erosion at the rock-sand interface can be predicted reasonably well by the derived expressions. Also the settlement of the outer rock profile as a result of the sand erosion can be predicted reasonably well. It is recommended to apply the expressions within the range of validity and to apply them only as first estimates for applications outside the range of validity.
- The sand erosion and accretion depend on the wave height, the thickness and permeability of the rock layer(s), the slope, and the critical hydraulic gradient at the internal rock-sand interface. Numerical model computations (Van Gent et *al.*, 2015) indicate that also the wave steepness is important. The critical hydraulic gradient at the rock-sand interface depends on the size and permeability of the rock material, and on the size, angle of repose and the relative density of the sand.

A number of important aspects were not taken into account in the guidelines. Therefore, new physical model tests have been performed to analyse the influence of storm duration and the influence of water level variations. From these (small-scale) physical model tests the following can be concluded:

- The erosion and accretion of sand underneath a layer of rock increase with the number of waves. After about 10000 waves the progress of erosion and accretion slows down while after about 25000 waves the increase in accretion and erosion is relatively small or even absent. The dependency on the number of waves (representing the storm duration or a sequence of storms) can be assessed by multiplying the expressions by Van Gent and Wolters (2015) for the erosion and accretion parameters $A_{e,r}$, $A_{e,s}$, A_{acc} , z_s and z_{acc} by $f(N) / f(8640)$ using Eq. 1.
- Effects of water level variations have been studied by testing three scenarios with different water level variations. The results show that water level variations play an important role. The affected profile becomes much wider if water level variations occur. The worst case scenario is a series of conditions with a decreasing water level (for the parameters accretion area, accretion height, and erosion area). However, for the erosion depth the situation with a constant water level is the worst case scenario; for all tested water level scenarios the erosion depth was less than for a condition with a constant water level. Increasing water levels and water level variations characterising a storm peak lead to somewhat less erosion and accretion than a constant water level.

For open filters with rock on top of sand, it is recommended to study also the influence of potential scale effects for open filters. Furthermore, it is recommended to analyse whether the approach to account for effects of oblique waves on the stability of armour layers, as presented in Van Gent (2014), can also be applied to account for the effects of oblique waves on the erosion of sand in open filters.

REFERENCES

Bakker, K.J., H.J. Verheij and M.B. de Groot. 1994. Design relationship for filters in bed protection, *J. of Hydraulic Engineering*, 120(9), 1082-1088.

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

CUR report 161. 1993. Filters in hydraulic engineering (in Dutch), CURNET, Gouda, The Netherlands.

CUR report 233. 2010. Interface stability of granular filter structures, Theoretical design methods for currents, CURNET, Gouda, The Netherlands.

De Graauw, A., T. van der Meulen, M. van der Does de Bye. 1983. Design criteria for granular filters, Publication 287, *Delft Hydraulics*, Delft, The Netherlands.

Dixen, F.H., B.M. Sumer, and J. Fredsøe. 2008. Suction removal of sediment from between armor blocks. II: waves", *J. of Hydraulic Engineering*, Vol 134, no 10, October 2008, ASCE.

Jacobsen, N.G., M.R.A. van Gent, and G. Wolters. 2015. Numerical analyses of the interaction of irregular waves with two-dimensional permeable coastal structures, Elsevier, *Coastal Engineering*, **102**, 13-29.

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

Klein Breteler, M., H. den Adel and M.A. Koenders. 1992. Placed (pitched) stone revetments, Filter design rules, report M1795/H195, XXI, *Delft Hydraulics & Geo Delft* (in Dutch), Delft, The Netherlands.

Ockeloen, W.J. 2007. Open filters in breakwaters with a sand core, M.Sc. Thesis, *TU Delft*, Delft, The Netherlands.

Stevanato, F., A.W. Nielsen, B.M. Sumer, J. Fredsøe. 2010. Flow velocities and bed shear stresses in a stone cover under an oscillatory flow, in: *Proceedings of the Fifth International Conference on Scour and Erosion*, I, pp. 609–618.

Sumer, B. M., S. Cokgor, and J. Fredsøe. 2001. Suction removal of sediment from between armor blocks, *J. of Hydraulic. Engineering*, 127(4), 293–306.

Sumer, B. M., H.A.A. Guner, N.M. Hansen, D.R. Fuhrman and J. Fredsøe. 2013. Laboratory observations of flow and sediment transport induced by plunging regular waves, *J. of Geophysical Research*, 118, 6161-6182.

Uelman, E.F. 2006. Geometrically open filters in breakwaters, M.Sc. Thesis, *TU Delft*, Delft, The Netherlands.

Van de Sande, S.A.H., W.S.J. Uijttewaal, H.J. Verheij. 2014. Validation and optimization of a design formula for geometrically open filter structures, *Proc. 34th International Conference on Coastal Engineering (ICCE)*, Seoul, Korea.

Van Gent, M.R.A. 2001. Wave run-up on dikes with shallow foreshores, *J. of Waterway, Port, Coastal and Ocean Engineering*, ASCE, Vol.127, No.5, pp.254-262.

Van Gent, M.R.A. 2014. Oblique wave attack on rubble mound breakwaters, Elsevier, *Coastal Engineering*, Vol. 88, pp. 43-54.

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

Van Gent, M.R.A., M.P. Herrera, J. Molines, and N.G. Jacobsen. 2015. Rock slopes on top of sand: Modelling of open filters under wave loading, *Proc. Coastal Structures 2015*, Boston, USA.

Wolters, G. and M.R.A. van Gent. 2012. Granular open filters on a horizontal bed under wave and current loading, *Proc. 33rd International Conference on Coastal Engineering (ICCE)*, Santander, Spain.

Zoon, A. 2010. Cobble sea defence: Hydraulic interface stability of sand underlying a single filter layer, M.Sc. thesis, *TU Delft*, Delft, The Netherlands.