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Effects of storm duration and oblique wave attack on open filters underneath rock armoured slopes

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ABSTRACT

Underneath rock slopes of rubble mound structures often one or more granular filter layers are present. These filter layers prevent base material washout. In contrast to traditional filters, geometrically open filters allow for some movement of base material. In order to design such open filters the amount of erosion and accretion of base material needs to be predicted. Based on 2D physical model tests Van Gent and Wolters (2015) presented a method to estimate the erosion and accretion of sand underneath rock slopes. Since the developed method was only valid for perpendicular wave attack, a new study has been performed to assess effects of oblique wave attack on the amount of erosion and accretion of sand underneath a rock slope. For that purpose 3D physical model tests were performed in a wave basin with 5 different wave angle between 0° (perpendicular wave attack) and 75°. Based on the test results it was shown how the effects of wave obliquity can be taken into account in the design of open filters. In addition, the effect of the storm duration on open filters has been studied. This led to an extended design method to predict the amount of erosion and accretion of sand underneath rock slopes under wave loading.

1. Introduction

Rubble mound structures that consist of rock typically contain granular filters. The filter layers prevent washout of finer base material due to waves and currents. Granular filters can be designed as geometrically closed filters or as geometrically open filters. The design of geometrically closed filters (no material washout) is relatively straightforward, but in many instances a large number of filter layers and material volume is required. Geometrically open filters, with a larger ratio of toplayer material and base material, can be divided into hydraulically closed filters and open transport filters. For hydraulically closed filters no transport of base material occurs because the hydraulic load is smaller than the threshold value for incipient motion. For the threshold value of base material removal reference is made to Bezuijen et al. (1990), Bakker et al. (1994), Sumer et al. (2001, 2013), Dixen et al. (2008), Stevanato et al. (2010) and Jacobsen et al. (2017). For open transport filters some erosion of base material is allowed if the erosion remains below an acceptable level. Interface stability for structures with open filters was for instance studied in Wörman (1989), Uelman (2006), Ockeloen (2007), Zoon (2010), Van de Sande et al. (2014) and Van Gent et al. (2017). Applications of transport filters include slope protections and bed protections, for which the toplayer material is rock and the base material is sand.

In order to design open transport filters the amount of erosion and accretion of base material needs to be predicted. Adequate guidelines on the design of open transport filters could lead to significant cost savings, and therefore to more applications of open transport filters in the field. Van Gent and Wolters (2015) provide an overview of recently conducted research on filters and first guidelines on the design of open transport filters. The work has been limited to perpendicular wave attack. Here, the extension of the method to account for oblique wave attack and for storm duration will be described. Both improvements are based on new physical model tests in a wave flume (storm duration) and in a wave basin (oblique waves).

The 2D model tests by Van Gent and Wolters (2015) were focussed on one or 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 toplayer 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 layer of rock, measured in vertical direction.

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Fig. 1 shows a schematization of these parameters, where d_f is the thickness of the layer of rock (in the case of a system with two layers of rock this is the filter layer, *i.e.* the second layer with smaller stones underneath the toplayer). 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 ($A_{e,s}$). Erosion of sand at the internal rock–sand interface occurred in the part just below SWL.

Equations to estimate the magnitude of these erosion and accretion parameters were provided by in Van Gent and Wolters (2015) as well as the ranges of validity of these equations. In this work these equations will be extended to incorporate effects of storm duration and oblique wave attack. Also a criterion was proposed on the amount of transport of sediment that can be regarded as acceptable. 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: The accretion of sand should be limited: $z_{acc} < (d_{tot} - 2\,D_{n50,a})$ where d_{tot} is the total thickness of the rock layer(s) and $D_{n50,a}$ is the median nominal toplayer diameter (*i.e.* the equivalent cube size), based on weight; $D_{n50,a}=(M_{50,a}/\rho_a)^{1/3}$, where $M_{50,a}$ is the mass of toplayer stones for which 50% of the granular material (by weight) is lighter and ρ_a is the mass density of stones in the toplayer.

Effects of the storm duration and oblique wave attack are studied based on new physical model tests that will be presented in Chapters 2 and 3. In Chapter 4, extended formulae are presented to assess the sand erosion and sand accretion including effects of storm duration and oblique wave attack.

2. Storm duration

2D physical model tests were performed in the Scheldt Flume of Deltares to analyse effects of the storm duration on the erosion and accretion of sand at the rock-sand interface; see also Van Gent et al. (2016). 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 Fig. 2 for the model set-up.

One of the earlier tested structure configurations was selected: A layer of irregular rock on a 1:4 slope with a thickness of $d_f = 0.2$ m, a porosity of $n_f = 0.38$, a nominal stone diameter of $D_{n50,f} = 38$ mm, a wide grading of $D_{n85,f}/D_{n15,f} = 6.5$, (with $D_{nx,f} = 0.84\,D_{x,f}$ and D_x being the x% value of the sieve curve) and a density of $\rho_f = 3688$ kg/m^3, was placed on top of sand with a sieve diameter of $D_{50,s} = 0.18$ mm and a density of $\rho_s = 2650$ kg/m^3 (referred to as Configuration A in Fig. 5 of Van Gent and Wolters, 2015). Table 1 shows the values of the most important parameters. The number of waves is hereby based on the mean wave period (T_m).

A water level of 0.85 m above the flume bottom was used, a spectral significant wave height of $H_{m0} = 0.12$ m (*i.e.* the spectral significant wave height calculated from the spectrum of the incident waves, $H_{m0} = 4\sqrt{m_0}$ where m_0 is the zeroth moment of the wave spectrum), 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 $s_m = 0.049$, with $s_m = 2\pi H_{m0}/gT_m^2$ with $H_{m0} = 0.12$ m and $T_m = 1.25$ s. The significant wave height of $H_{m0} = 0.12$ m has been selected such that no motion of the high-density rock occurred due to direct wave loading. The movements in the layer of rock are only due to the settlement as a result of the erosion of sand underneath. The spectral significant wave height H_{m0} was

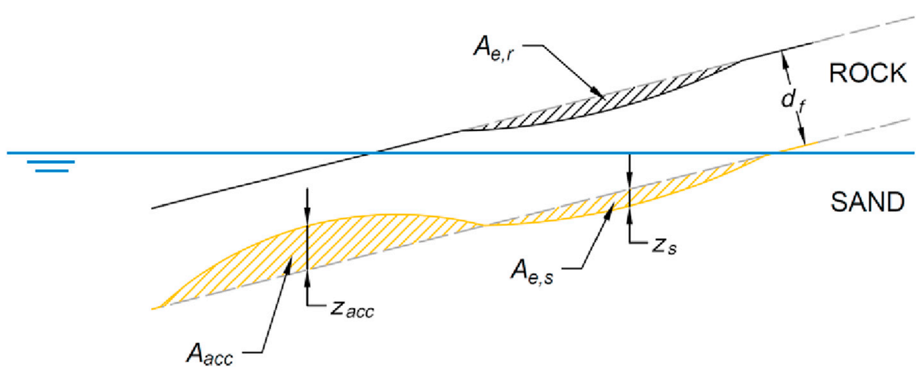

Fig. 1. Erosion and accretion pattern (parameter definition).

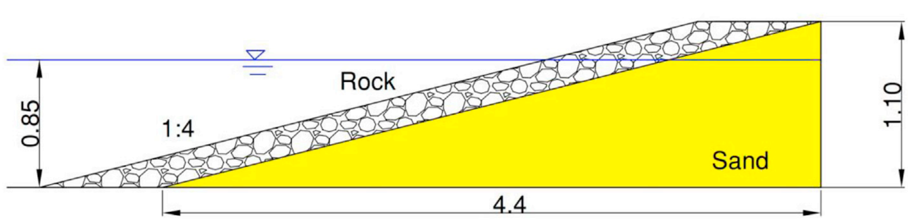

Fig. 2. Model set-up for physical model tests on storm duration (all dimensions are given in metres).

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

Filter thickness	Filter size	Filter thickness	Filter grading	Filter porosity	Wave height	Wave steepness	Number of waves
d_f	$D_{n50,f}$	$d_f/D_{n50,f}$	$D_{n85,f}/D_{n,15f}$	n_f	H_{m0}	s_p	N
(mm)	(mm)	(−)	(−)	(−)	(m)	(−)	(−)
200	38	5.2	6.5	0.38	0.12	0.04	52000