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Granular slopes with open filters under wave loading

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A B S T R A C T

Permeable hydraulic structures that consist of rock material typically contain granular filters in one or more layers. These filters are normally geometrically tight to prevent material washout. Geometrically tight filters are often difficult to realize in the field and expensive. An alternative is a geometrically open filter. A geometrically open filter has a large ratio of the size of toplayer material (rock) and underlayer material (e.g., sand) and is designed in such a way that only minimal base material loss or settlement occurs. Potential applications of open filters include bed protections, toe structures, and slope protections. Proper guidelines on the design of open filters under wave loading could lead to significant cost and material savings, and to more practical applications of filters in the field. Physical model tests were conducted in a wave flume of Deltares. The analysis of the tests with 1:4 and 1:7 slopes and fixed test durations of 3 h (<10,000 waves) has led to a method of predicting the amount of erosion of the sand underneath granular filters and of the sand accretion within a granular filter. Ranges of applicability have been provided for the underlying formulae. The tested material ranges included filter rock sizes close to prototype scale. In addition, a criterion has been developed to define the amount of acceptable transport in open filters.

1. Introduction

Permeable hydraulic structures that consist of rock typically contain granular filters. These filters fulfil several functions. They prevent the erosion (washing out) of finer base material or sub-layers 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.

The design of geometrically tight filters (no material washout) is relatively straightforward (see e.g., CUR Report 161/233, 1993; CIRIA-CUR-CETMEF, 2007), but in many instances a 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 (e.g., 0.5 m) is required. For a granular filter of a number of layers, the latter minimum thickness may lead to a substantial size of the total filter.

One alternative is a geometrically open filter in which no transport of sand occurs because the hydraulic load is smaller than the threshold value for incipient motion (hydraulically closed filter). Another alternative is a transport filter where some movement of sand 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 in many instances permitted. Typical applications of transport filters include toe structures, slope protections as well as bed protections. Although geometrically open filters have been applied in practice (e.g., underneath a cobble beach in the Port of Rotterdam and at the toe of dikes in the southern part of The Netherlands), a solid design method in which the amount of erosion and accretion is predicted accurately does not exist yet. An example of a transport filter under wave loading can be seen in Fig. 1.

In the 1980s and 1990s a large number of tests have been performed by for instance De Graauw et al. (1983), Bakker et al. (1994) and Klein Breteler et al. (1992) to determine criteria for the initiation of motion in granular filters. These criteria are based on estimates of the hydraulic gradients parallel or perpendicular to the interface between sand and the granular filter. This resulted in various formulae and a design diagram for interface stability of granular filters; see for instance CUR Report 161 (1993). Furthermore, new criteria for interface stability were for instance introduced in CUR Report 233 (2010) and Van de Sande et al (2014). Wörman (1989) provided a stability formula for granular filters around bridge piers under non-uniform flow conditions.

Sumer et al (2001) employed an approach based on the Shields parameter to determine the onset of base material removal from between armour blocks subject to currents. Investigated was a filter layer of regularly placed armour blocks on a base of sand and a fixed bottom. Cokgor and Albayrak (2005) conducted tests similar to those of Sumer et al (2001), focussing on tests with currents with varying non-uniform bed material. The filter consisted of a single layer of crushed stones (of single size).

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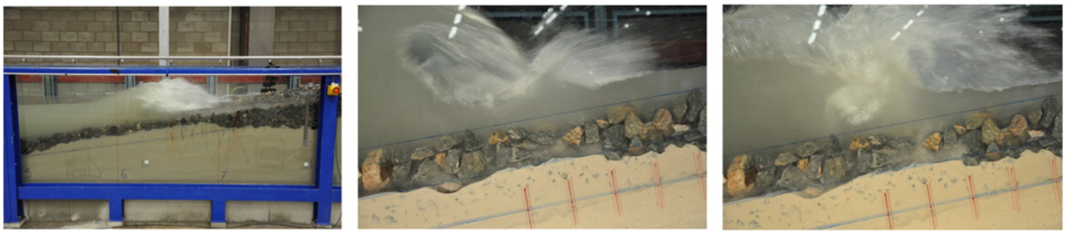

Fig. 1. Physical model tests with open filters with rock on top of sand under wave loading (1:7 slope).

These studies have been conducted with a focus on steady flow and the beginning of base material transport through the filter. The studies do not specifically address material transport itself or effects of filter settling. However, several transport measurements have been conducted but these were mainly conducted during conditions with small transported volumes. As described in the analysis of the performed model tests, the information on the initiation of motion for steady flow condition has shown to be a valuable starting point for estimates of transport under cyclic conditions.

Regarding cyclic loading very little knowledge is available. De Graauw et al (1983) and Klein Breteler et al (1992) conducted several wave tunnel experiments with a granular filter on a sand base under cyclic (wave) loading. Based on these experiments Klein Breteler et al (1992) concluded that the previously developed formulae for the initiation of motion in steady currents can also be applied to cyclic flow. Uelman (2006) investigated a sloped granular filter structure (1:3) on a sand core using wave flume experiments with regular waves. Ockeloen (2007) continued the research by Uelman (2006) with irregular wave loading and proposed an equation for the erosion area based on the pressure gradient parallel to the slope (estimated from video recordings of the water surface measured above the filter layer), the relative filter thickness (i.e., the filter thickness divided by the rock diameter: d_f / D_{50f}) and the wave loading (wave height, wave length, number of waves). Dixen et al (2008) extended the study of Sumer et al (2001), which determined the onset of base material removal from between armour blocks for currents, to waves and combined waves and currents. The behaviour of a filter layer of regularly placed armour blocks (very rough) on a base of sand was investigated. The filter consisted of both a single and multiple layers of the same armour stones (various sizes and forms were tested). Zoon (2010) analysed various large scale tests in the Delta Flume (cobble beach) and the GWK (Elastocoast revetment experiments) regarding the stability of sand underlying a single filter layer under wave loading. Finally Wolters and Van Gent (2012) studied granular open filters on a horizontal sand bed under wave and current loading. Based on their study they proposed formulae for base material transport in horizontal granular filters based on the hydraulic gradient parallel to the filter–bed interface and the filter velocity respectively.

Proper guidelines on the design of open transport filters, which allow an acceptable and predictable loss of base material under wave and current loading, could lead to significant cost and material savings, and to more practical applications of filters in the field. As a step towards guidelines for open filters under wave loading a Joint Industry Project (JIP Topfilter) has been carried out. Within this initiative physical model tests were initiated by Deltares, Boskalis and Van Oord, and reported in Wolters et al (2014). These model tests were focussed on a layer of rock on top of a 1:7 sandy bed. The data-set by Wolters et al (2014) has been extended by results of physical model tests with a 1:4 slope. The testing of these two slopes was considered a good benchmark for typical slope applications of open filter structures. Here, the combined data-set of the tests with 1:4 and 1:7 slopes is presented and the erosion of the base layer respectively the accretion of sand within the filter layer is analysed. Tested material ranges included filter rock sizes close to prototype scale. The focus of the tests was on wave loading. Current loading and combined current and wave loading are not discussed in this paper.

In the subsequent chapters the experimental set-up and test programme are presented first, followed by a description of the tested rock layer configurations, the observations during the tests, and the analysis of the test results. Formulae are presented to assess sand erosion and accretion based on the hydraulic loading at the sand–filter interface. Finally, the ranges of validity of the formulae are presented and criteria of acceptable damage are proposed.

2. Experimental set-up

The objective of the physical model tests was to gather data on the physical processes within a granular filter that trigger the erosion process, on (critical) hydraulic gradients at the sloping interface of sand and filter, and on the amount of base material erosion and filter settlement. The tests were carried out in the Scheldt Flume of Deltares (110 m long, 1.2 m high and 1 m wide). Two slopes were used, a 1:4 slope and a 1:7 slope. The slopes were extended above the waterline to ensure an even erosion process. Furthermore, the constant filter layer thickness over the slope allowed for a systematic investigation of the involved hydraulic gradients and erosion processes.

Fig. 2 shows the model set-up for the 1:4 and 1:7 slopes. The foreshore was horizontal and the waves at the toe are equal to those closer to the wave generator. In the tests the configuration of the rock layer varied but the sand material was kept the same in all tests.

Measurements were performed of the incident waves, the base material (sand) erosion and filter (surface) settlement using a mechanical profiler, and of the pressures and hydraulic gradients at the sand–rock interface.

Fig. 3 shows a picture of the test set-up with the mechanical profiler. Six individual profiles were measured over the flume width of 1 m; the distance between the individual profiles was 0.143 m. The entire outer profile (rock slope) was measured at the beginning and end of each test series. Between subsequent tests within the test series only a limited (outer) profile measurement was performed at the position where the maximum settlement was found. The profile of the interface between rock and sand (sand profile) was measured at the beginning and the end of each series of tests. To measure the sand profile, the stones were carefully removed up to the sand surface. 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 monitored after each test.

As previous investigations have indicated (e.g., CUR Report 161, 1993; Klein Breteler et al., 1992; Ockeloen, 2007; Wolters and Van Gent, 2012) can the hydraulic gradient measured parallel to the filter–bed interface be a good tool to assess the hydraulic loading and erosion potential at the interface to the bed. The start of erosion is hereby expressed by the critical hydraulic gradient, which is a function of both filter and bed material parameters. The latter is further discussed in the Analysis section.

To measure slope-parallel hydraulic gradients at the sand–rock interface a frame with 16 pressure transducers was used for the 1:7 slope (10 sensors in the filter and 6 below the filter–sand interface)