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Falling aprons at circular piers under currents

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Traditional guidelines on rock protection at circular piers predominantly focus on preventing shear failure (by choosing a sufficiently large rock size), winnowing failure (by designing an appropriate filter) and edge failure (by selecting a sufficient extent). In particular areas (e.g. in an eroding river channel or in an area with large-scale bed forms), the rock protection may also face a degradation (lowering) of the bed. As a result, the edges will be undermined and stones will roll down and cover the newly developed slope (a falling apron). This process is not well understood and theoretically-based design guidelines for falling aprons are not available, only empirical relationships for bank revetments.

Indicative laboratory experiments were conducted in order to derive guidelines to account for bed degradation in the design of rock protection at circular piers under currents. This paper summarizes the experimental set-up, monitoring techniques, test program and results of the conducted experiments. All tested rock protection layouts consisted of a single stone grading with a sufficient stone size and layer thickness to prevent shear failure and winnowing failure. In total, 7 live-bed tests were conducted with varying current velocities, bed degradation levels and rock layouts. During the tests, the bed protection level near the pier was monitored with video cameras. Before and after each test, the bathymetry was recorded by stereo-photography.

The analysis focussed on the successive failure stages, the redistribution of stones over the slope and the evolution in time. The results showed that, as the undermining progressed, the stones at the edges of the protection were redistributed through a combination of rolling, sliding and sinking. Finally, a protective mound was formed, with stones covering the slopes on all sides. The observed stone layer thickness on the slopes gradually reduced towards the outside. A design rule was derived to account for bed degradation by quantifying the stone volume required for a falling apron.

Key words
falling apron, scour, rock protection, pier, bed degradation, granular filter.

I INTRODUCTION

Scour represents a critical threat to infrastructure throughout the world. Apart from being one of the major causes of bridge failure, scour at circular piers is also becoming an increasingly important topic in view of the rising number of offshore wind farms. Although scour is occasionally dealt with by extending the pier length, in most cases scour protection is applied to prevent erosion and maintain the bed level around the pier. A large variety of scour protection alternatives have been developed and applied over the course of years. The selection of the most appropriate measure is usually based on a multiple criteria approach, including the local hydrodynamics, sediment characteristics, required safety level, construction and maintenance aspects and costs. Loose rock (riprap) is applied most frequently.

A well-designed scour protection will have to provide resistance against all potential failure mechanisms. The failure mechanisms that are relevant for scour protection consisting of loose rock are well described in [Chiew, 1999, 2004]. For live-bed conditions they are:

- shear failure, which refers to failure due to entrainment of stones by the local flow field around the pier;
- winnowing failure, which is related to erosion of the finer underlying bed material through the voids of the coarser stones (failure of the filter);
- edge failure, which is initiated by bed scouring at the edge of the scour protection;
- bed form induced failure, which refers to the destabilization of the scour protection due to its interaction with propagating bed forms;
- bed degradation failure, which occurs when the scour protection disintegrates due to undermining by a lowering of the bed;

The first two failure mechanisms have been thoroughly investigated in the past and are subject of various design guidelines. Edge scour was recently investigated based on field measurements at offshore wind farms [Raaijmakers, 2010]. The latter two, despite their importance under live-bed conditions, are less well studied. The available literature focuses on qualitative descriptions of their mechanisms. [Lauchlan, 2001] studied the influence of passing bed forms on scour protection at a circular pier. It was observed that as the trough of the bed form approached, stones rolled down into the trough and spread laterally. In the next stage, the crest of the bed form progressed over the scour protection. After a few of these sequences, the scour protection stones subsided low enough to remain undisturbed by further bed form progression. In a different paper of [Lauchlan, 2002] the effect of a degradation (lowering) of the bed was investigated. The experiment showed that the applied (very thin) stone layer fully disintegrated after the bed lowered, leading to the conclusion that loose rock is inadequate for protecting piers in rivers with significant bed degradation. However, another paper on this topic [Chiew, 2004] demonstrated that a stable mound can be formed after bed degradation. The stability was attributed to the reduction of bed shear stress that emerges after bed degradation.

In the design of river bank protections, a foreseen degradation of the river bed is either dealt with by constructing the protection down to the foreseen degradation level or by designing a falling apron, i.e. a volume of stones that will redistribute, cover and protect the newly formed slope. In the latter case, the required volume is calculated based on volumetric design formulae, which are mainly dependent on the assumed slope, layer thickness and safety factor. Although the falling apron approach could also be adapted for a circular pier in a degrading bed, to our knowledge its application has not yet been confirmed. The aim of the present study is therefore to:

- investigate the behaviour of falling aprons at circular piers under currents, and to
- develop a guideline to quantify the stone volume required to account for a given bed degradation.

The study was based on indicative laboratory experiments. This paper describes the conducted laboratory experiments (sections 2 and 3), analysis of the results (section 4), and conclusions (section 5).

II SETUP OF LABORATORY EXPERIMENTS

All tests were performed in the Atlantic Basin at Deltares. This basin has dimensions of 75 x 8.7m and contains a sandy test section of 15 x 8.7m in the centre of its long axis. The median grain size d_{50} of the applied sediment was 180µm. The basin has three pumps with an individual capacity of 1 m^3/s. For the present research project, the width of the test section was reduced to 6m (see Figure 1) to allow for a strong current in combination with a large water depth (see Table 1). No waves were generated.

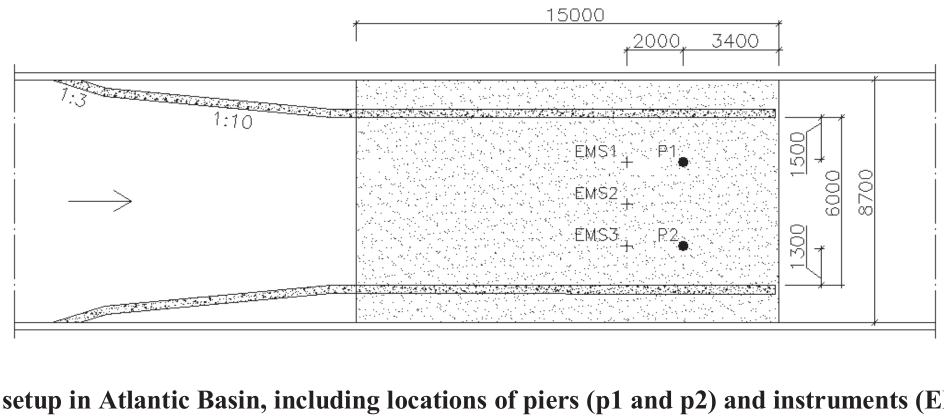

Figure 1: Test setup in Atlantic Basin, including locations of piers (p1 and p2) and instruments (EMS1-3). The arrow indicates the current direction.

In the experiment setup, two transparent circular piers with a diameter D of 200mm were mounted at the bottom of the test section. Both piers included an internal camera system with fish-eye lens for a 360 degree view from inside the pier during the test (see also [de Sonneville, 2010]). Around the piers, various layouts of loose rock were applied, in combination with various levels of bed degradation. The outer ring of scour protection was anticipated to redistribute (and become a falling apron) upon being undermined. The rocks were sized sufficiently large to prevent shear failure ($D_{50} \approx$ 10mm) and the layer thickness was estimated large enough to prevent winnowing failure (~10 times D_{50}) based on the approach of [Hoffmans, 2011]. The degradation of the bed was simulated by creating a local increase of the bed level (referred to as 'sill') near the piers (see Figure 2a). The influence of bed-forms and edge scour were found to be very limited during the tests.

Before and after each test, the bathymetry was recorded based on digital stereo-photography (see also [Hofland, 2011]). The layer thickness of the scour protection on the slopes was inspected by wedging a steel plate into the rock protection from the side, while removing a part of the protection and replacing the plate with a transparent gridded screen after selected tests. Three electromagnetic current velocity meters were installed at 40% of the water depth, 2m upstream of the piers (indicated by '+'s in Figure 1) to measure the depth-averaged current velocity.

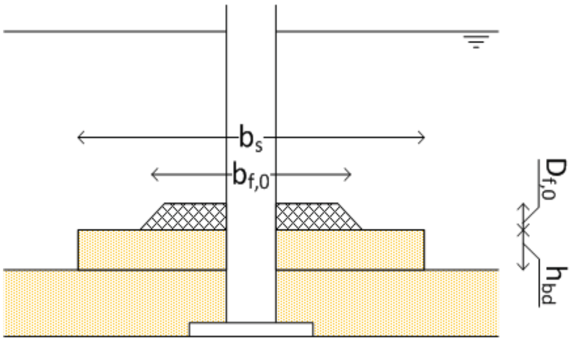

Figure 2a: Schematic overview of the pier, sill, rock protection and definitions.

Figure 2b: Photograph of typical layout at start of test.

The test program consisted of seven tests with two different layouts (see Table 1). Layout L03 was defined as the reference layout. All tests were performed with a constant unidirectional current of 0.5m/s and a water depth of 1.0m, which resulted in a sediment mobility in the order of four times the critical value (live-bed regime). The test duration was either 3 or 6 hours. In selected tests, the bathymetry was not repaired before starting the next test, to be able to study the bed evolution in time.

Test	Layout name	Extent $b_{f,0}$ [-]	Thickness $D_{f,0}$ [mm]	Sill height h_{bd} [mm]	Water depth h_w [m]	D.a. current velocity u_c [m/s]	Duration T [hr]
T-01	L01	6D	100	0.25D	1.0	0.50	3
	L02	6D	100	0.25D	1.0	0.50	3
T-02	L03	4D	100	0.50D	1.0	0.50	3
	L04	4D	100	-	1.0	0.50	3
T-03	L05	4D	100	1.00D	1.0	0.50	3
	L06	3D	100	0.50D	1.0	0.50	3
T-04	L05	4D	100	1.00D	1.0	0.50	3
	L07	2D	100	0.50D	1.0	0.50	3
T-05	L05	4D	100	1.00D	1.0	0.50	6
	L07	2D	100	0.50D	1.0	0.50	6
T-06	L08	4D	50	0.50D	1.0	0.50	3
	L03	4D	100	0.50D	1.0	0.50	3
T-07	L08	4D	50	0.50D	1.0	0.50	6
	L03	4D	100	0.50D	1.0	0.50	6

Table 1: Overview of test conditions and parameters.

III TEST RESULTS

III.1 Introduction

The test results contained visual observations, internal and external video recordings, cross-sections and bathymetrical recordings. First the results of the reference layout (L03) are described. Next, the effects of the varied parameters (extent, sill height and layer thickness) and the development in time are considered.

III.2 Behaviour of reference layout

Layout L03 had a scour protection extent of 4D (at top level) and a sill height of 0.5D. The video recordings showed that the stones remained stable before the outer perimeter of scour protection was undermined. Upon undermining of the edges, the redistribution predominantly consisted of stones rolling onto the newly formed slopes. As time progressed, the character of the redistribution progressed more and more into sliding and sinking. Most redistribution occurred within the first hour of the test.

Visual inspection of the patterns after the test revealed that the sills applied beforehand had eroded almost completely (see Figure 3), except at the downstream side. The top bed level around the pile remained equal to before the test (no pier scour occurred). The maximum redistribution of stones occurred at the sides perpendicular to current direction. The angle of the external slope after the test was about 1:2 at those sides, slightly steeper at the upstream side (about 1:1.5) and slightly less steep at the downstream side (about 1:3).

Figure 3: Photographs before (left) and after (right) test T-02 showing the redistribution of layout L03.

Inspection of the cross-sections revealed that the layer thickness of the newly formed slope reduced gradually towards the outside (see Figure 4 - left). Please note that this differs from the single layer thickness earlier observed at falling aprons at river banks [Van der Hoeven, 2002].

Figure 4: Photographs of cross-section of selected test (left) and the applied method (right).

The angle of the inner slope was calculated based on a volume balance (see Figure 5) in which the eroded volume (V_1) was assumed equal to the stone volume on the slopes (V_2). Both outer and inner slopes were assumed linear. The layer thickness was assumed to reduce in outward direction to a thickness of 1 times D_{50} at the toe of the mound. Figure 5 shows that with this method, the calculated inner slopes resembled the observed inner slopes reasonably well. The inner slope angle was in the order of 1:2.5.

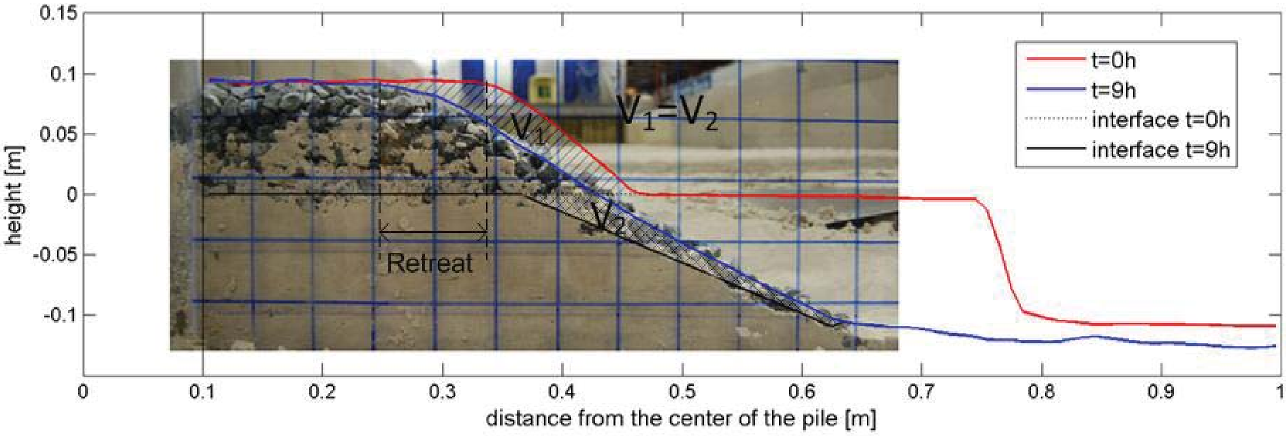

Figure 5: Schematic overview of applied volume balance, projected on photograph of cross-section.

III.3 Effects of extent, sill height and layer thickness

The layouts with a larger extent (layout L01; 6D) proved their conservativeness: only a relatively small part of the total volume was redistributed (see Figure 6; left). No scour (lowering of the top stone level) was observed at the pier. The tests with a smaller extent (layout L06; 3D) showed slight scouring near the pier (~0.25D). With an even smaller extent (layout L07; 2D), significant scouring at the pier occurred (0.5D). The newly formed slope reached the pier and the layer thickness at the pier boundary was reduced as result of the large volume of redistributed stones (see Figure 6; right). At the piers with smaller extents two downstream gullies developed. Occasionally, rocks had been transported into these gullies.

Figure 6: Photograph of results after test T-01 (layout L01) (left) and after test T03 (layout L06).

A larger bed degradation (layout L05; 1.0D) was found to cause a larger retreat, as result of the larger required volume of redistributed stones. Despite this extra retreat, layout L05 did not experience pier scour. The angle of the slope and the general shape of the mound was quite similar for a larger bed degradation.

Layout L08, which was the only test with a reduced layer thickness, experienced slight pier scour (~0.1D). The pattern suggested that it had been caused by winnowing, and not by the degradation of the bed.

III.4 Development in time

Selected tests were continued without repair. In these tests, the redistribution progressed but at a significantly lower pace. In contrast to the initial phase, where the erosion predominantly occurred at the sides perpendicular to the current direction, after 6 to 9 hours the largest developments were observed at the upstream and downstream side, where the remaining sill further eroded (see Figure 7). This caused additional retreat upstream and downstream as result of the additional required stone volume to cover the slopes. At the sides, some additional erosion occurred in the upper part of the slopes. Layout L03 appeared to have reached equilibrium after 9 hours of testing. For L05, equilibrium had not yet been reached after 12 hours.

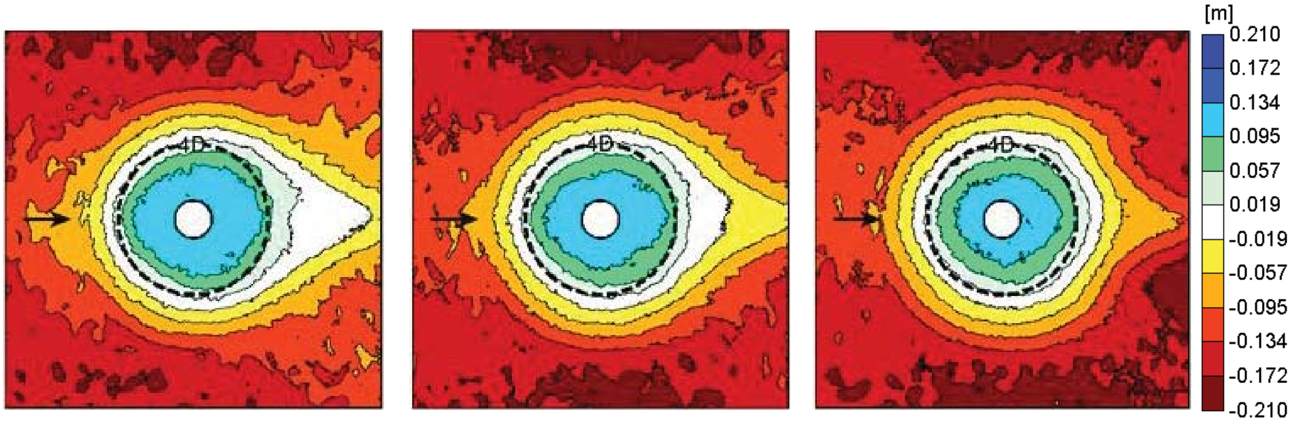

Figure 7: Bathymetry of layout L05, after respectively 3, 6 and 12 hours.

IV ANALYSIS

IV.1 Governing processes

Scour around a slender cylindrical pier is governed by three hydrodynamic phenomena [Sumer, 2002]: a horseshoe vortex upstream of the pier, vortex shedding at the downstream side of the pier and streamline contraction. The horseshoe vortex is the dominant phenomenon. As the current encounters the pier, pressure gradients drive it downward around the pier and scour occurs as result of a locally enhanced sediment transport gradient. In case a scour protection is present, the protected bed lies sheltered from the horseshoe vortex. Scour only occurs at the edges of the scour protection, where the horseshoe vortex, shed vortices and streamline contraction are weaker.

In our tests, a mound was formed with the shape of a submerged cone-shaped object. For this type of object, the flow patterns around the cone are dominated by downstream re-circulating flow [Sumer, 1994; Sadeque, 2008]. The component of vortex shedding is rather weak.

IV.2 Interpretation of test results

The videos during the test showed that the first part of the redistribution was induced by undermining. After the slopes were covered with stones, sinking occurred, likely as a result of winnowing. This sinking was strongest in the upper part of the profile. At the end of the tests, the slopes were quite linear, with a layer thickness reducing from top to bottom (in outward direction). It appears that the volume lost by winnowing is compensated by stone volume from above, until the layer thickness is sufficient to prevent further winnowing. The further away from the structure, the lower the hydraulic load and subsequently the required layer thickness. This supports the idea that at the end a stable situation can be achieved.

The tests with smaller extents showed that pier scour occurred when the extent at top level reduced below 3D. This extent is likely related to the size of the horseshoe vortex (separation distance). In our tests, no pier scour occurred when the extent at top level was maintained at 3D after redistribution.

A larger bed degradation induced a larger retreat with comparable external slope angles. However, on the longer term the downstream slope became significantly steeper. The erosion on the downstream side may be caused by a stronger re-circulating current, similar to scour patterns observed at a backward facing step. The tests with smaller bed degradations showed significantly less erosion downstream.

IV.3 Design formula

Pier scour was prevented in the tests where a sufficient volume was available to cover the side slopes, while maintaining the required layer thickness for an extent of least 3D. In our opinion, therefore, loose rock may well be adequate to provide protection against pier scour in case of bed degradation. We assume bed degradation can be accounted for in the design of a scour protection around piers, just as all other failure mechanisms.

For an estimate of the volume required for a falling apron, the mound is schematized as shown in Figure 8 (dark blue patch), with linear internal and external slopes, and a layer thickness of $1xD_{50}$ at the toe of the mound. The total volume required after bed degradation is a function of the level of bed degradation h_{bd}, the initial layer thickness $D_{f,0}$, the median rock size $d_{f,50}$, the minimal required extent after deformation $r_{f,A}$, the outer slope angle α and inner slope γ. The volume is calculated by subtracting multiple cone-shaped objects.

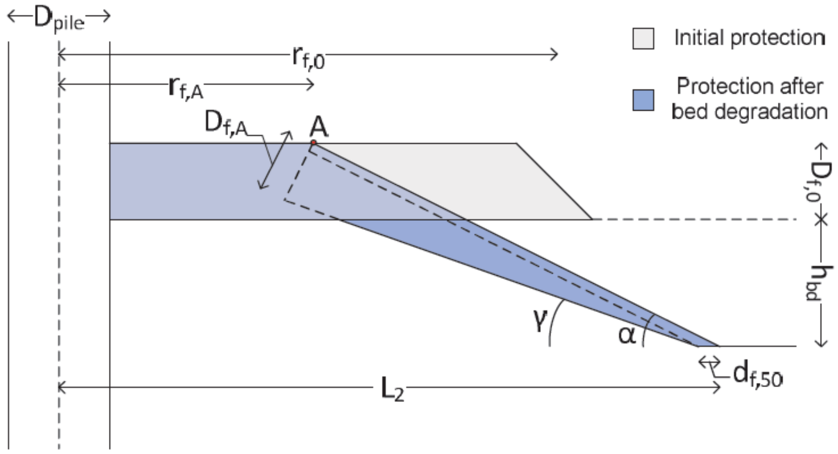

Figure 8: Schematization of volume balance with definition of parameters.

For practical reasons, the required volume is subsequently expressed as an initial extent $r_{f,0}$, which is required to maintain a minimal horizontal extent $r_{f,A}$ in case of a specified bed degradation h_{bd}:

$$r_{f,0}=\sqrt{\frac{\frac{\pi}{6}\left(L_2^3-r_{f,A}^3\right)-\frac{\pi}{3}\tan\gamma\left(\left(L_2-d_{f,50}\right)^3-\left(L_2-d_{f,50}-\frac{h_{bd}}{\tan\gamma}\right)^3\right)}{\pi D_{f,0}}} \qquad (1)$$

In this formula, h_{bd}, $D_{f,0}$, $d_{f,50}$ and $r_{f,A}$ are input parameters. α was consistently found to be very close to 1:2, a value which was also observed at falling aprons at river banks in field applications [Oberhagemann, 2008]. Instead of using the measured inner slope γ, we propose to base the inner slope on a parameter which we define as the theoretically required layer thickness to prevent winnowing failure at point A ($D_{f,A}$). We expect this parameter to depend on the hydraulic load and decrease with increasing $r_{f,A}$, due to the decreased influence of the pier. A simplified conservative method of dealing with this parameter is to assume it equal to the initial layer thickness, provided that this thickness was also defined in order to prevent winnowing failure. We note that equation [1] is only valid for the sides that are perpendicular to the current direction, where most undermining occurred in the tests.

Sensitivity analyses with this formula showed that the required extra extent increases with the level of bed degradation and decreases with increasing $D_{f,0}$ and increasing $r_{f,A}$. Assuming a conservative value for $r_{f,A}$ (4D) and for $D_{f,A}$ ($=D_{f,0}$), leads to the following (slightly conservative compared to equation [1]) design formula, which is based on the linear relation between retreat and bed degradation.

$$r_{f,0}-r_{f,A}=1.4\times h_{bd} \qquad (2)$$

Applying equation [2] when designing a falling apron results in a significant reduction of the stone mass compared to the traditional methods, as result of improved layer thickness formulation and the absence of a separate safety factor.

V CONCLUSIONS

Laboratory experiments were conducted to investigate the application of falling aprons to account for bed degradation at circular piers under currents. Two transparent piers (200mm) were installed in the Atlantic Basis at Deltares and equipped with internal video cameras. In total seven tests were performed with a constant (relatively high) current velocity, varying levels of bed degradation and varying scour protection layouts consisting of loose rock. During the tests, the stone redistribution was monitored with the internal and external video recordings. After the tests, the bathymetry was recorded with stereo-photography. Selected tests were not repaired in order to be able to study the development in time.

The experiments showed that as the undermining progressed, the stones at the edges of the protection were redistributed through a combination of rolling, sliding and sinking. Finally, a protective mound was formed, with stones covering the slopes on all sides. The observed stone layer thickness on the slopes gradually reduced towards the outside. Scouring at the pier occurred only in the tests for which the layer thickness around the pier reduced below an extent of three times the pier diameter.

These results indicate that bed degradation failure can be accounted for by designing a falling apron. Based on the observed behaviour, a design rule was derived to account for bed degradation by quantifying the stone volume required for a falling apron. However, it should be kept in mind that the formula is based on a limited number of indicative tests. A full validation should include a larger range of hydraulic conditions, durations, rock sizes, layer thicknesses and sediment properties. The responsible hydraulic processes should be confirmed by performing detailed measurements of the current patterns.

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