# RIPRAP PROTECTION OF VERTICAL-WALL AND SPILL-TROUGH BRIDGE ABUTMENTS

**António Cardoso[1], Cristina Fael[2], Gonzalo Simarro[3] & Anton Schleiss[4]**

[1] CEHIDRO & DECivil, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal.
e-mail: ahc@civil.ist.utl.pt

[2] Department of Civil Engineering and Architecture, Universidade da Beira Interior, Edifício II das Engenharias, Calçada do Lameiro, 6200-001, Covilhã, Portugal. e-mail: cfael@ubi.pt

[3] Instituto de Ciencias del Mar (CSIC), Passeig Marítim de la Barceloneta 37-49, 08003, Barcelona, Spain.
e-mail: simarro@icm.csic.es

[4] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), Station 18, 1015 Lausanne, Switzerland. e-mail: anton.schleiss@epfl.ch

## Abstract

Scour around bridge abutments frequently leads to the collapse of bridge superstructures. Consequently, scour countermeasures are usually designed and installed by river engineers, riprap matting being the most widespread solution. The associated design criteria must attend to two groups of failure mechanisms: i) those associated the abutment body stability, which include particle erosion, translational slide failure, modified slump and slump failure; ii) those associated with the riprap apron stability, including shear, winnowing, edge failure, bed-form undermining and river bed degradation. The work presented in this communication consists on the review of design criteria recently published by the authors to face particle erosion, shear, winnowing and edge failure mechanisms at vertical-wall and spill-trough bridge abutments, under clear water flow conditions. These are the key aspects to be faced as soon as abutments are located in flood plains, their side slopes are not too steep and pore pressure is negligible. The work is based on a large experimental campaign carried out at several facilities and allows the specification of blocs' diameter, plan layout and thickness of riprap mattresses.

## Introduction

For a long time engineers have used riprap as a countermeasure against scour at bridge piers and abutments. Riprap is designed to create a physical barrier intended to resist the erosion capacity of the flow. In the case of abutments, blocks are placed on the river bed, around their toes, to create horizontal aprons. At spill-through abutments, depending on the structural solution, blocks can also be placed directly on their side slopes.

In general, riprap design must attend to two groups of potential failure mechanisms: the first group is associated with the riprap apron stability; the second is associated with the abutment body stability.

According to Chiew (1995), riprap aprons are prone to four failure modes: *shear failure*, occurring where the individual riprap blocks are not heavy enough to resist entrainment by the flow; *edge failure*, which occurs as riprap blocks fall into the scour hole that, though reduced in depth by the presence of the apron, still develops at the apron's edge; *winnowing failure*, consisting in soil uplift from beneath the apron blocks; *bed-form undermining*, due to the movement of crests and troughs of bed-forms (dunes or anti-dunes) that may occur in the main-channel. Riprap aprons can also fail due to *river bed degradation* (general erosion), this being the fifth failure mechanism of these structures.

According to Melville and Coleman (2000), four failure modes exist for riprap placed on sloping abutments. These are *particle erosion failure*, *translational slide failure*, *modified slump failure* and *slump failure*. Assuming that (i) side slopes are not too steep, (ii) pore pressure is negligible, (iii) loss of support at the toe of the riprap due to undermining does not occur, (iv) there is no disturbance of critical support material in the lower levels of the riprap layer and (v) there is no base material with layers of impermeable material that act as fault lines, then the only failure mechanism of riprap placed on sloping abutments is *particle erosion failure*. In practice, this means that, if the abutment body is properly designed, the only concern is its protection against erosion of riprap blocks induced by the surrounding flow. Particle erosion failure occurs when individual blocks are dislodged by the hydrodynamic forces of the flowing water. To a large extent, this mechanism is similar to shear failure of riprap aprons.

Though failure modes are frequently interdependent, there is a reasonable consensus that (i) shear failure may be mitigated through the specification of sufficiently large blocks, (ii) edge failure may be avoided by the proper design of the apron plan configuration, (iii) winnowing failure may be avoided by placing a synthetic or a granular filter beneath mattresses of appropriate thickness, (iv) bed-form undermining can be prevented by founding the apron at or below the level of the migrating bed-form troughs (v) river bed degradation failure can be mitigated through actions that stabilize the longitudinal river bed profile (*e.g.*, bed sills). These remedies are specified by assuming that failure modes do not interact.

The work presented herein is directed to cover situations where riprap aprons are not subjected to bed form undermining or river bed degradation, while the only failure mechanism prone to occur on the abutment body is erosion failure. In other words, apron *shear, edge and winnowing failure* as well as abutment slope *particle erosion failure* will be covered. The study only applies to vertical-wall and spill-through abutments. It is based on experiments whose results were published by Fael (2007), Cardoso and Fael (2009), Cardoso *et al.* (2010.a), Cardoso *et al.* (2010.b) and Simarro *et al.* (2012).

Next, the experimental facilities and granular materials used in the experiments will be described. Then, the procedures adopted in the study and the most important design criteria will be presented.

## Experimental facilities and granular materials

Three horizontal-bed flumes were used in the studies, each including a central reach containing a recess box in the bed, where the abutment models were placed, protruding at right angle from one of the vertical side walls. The main features of the flumes are shown in Table 1, where $B$ = flume width, $\Lambda$ = flume length, $\lambda$ = distance from flume entrance to the abutment, $\Gamma$ = length of bed recess box and $\delta$ = its depth. The fix bed of the approach reaches was roughened with loose gravel to guarantee the development of rough-bed boundary layers upstream the recess boxes.

Table 1: Main features of flumes

| Flume | $B$ (m) | $\Lambda$ (m) | $\lambda$ (m) | $\Gamma$ (m) | $\delta$ (m) |
|---|---|---|---|---|---|
| EPFL | 1.50 | 7.10 | 3.70 | 3.00 | 0.30 |
| UCLM | 3.00 | 7.00 | 3.60 | 4.00 | 0.60 |
| UBI | 4.00 | 28.00 | 15.40 | 3.00 | 0.60 |

Tests on spill-through abutments were carried out in flumes of Ecole Politechnique Fédérale de Lausanne (EPFL) and Universidad de Castilla la Mancha (UCLM); abutment side slopes, H:V, were equal to 1:1, 3:2 and 2:1. The spill-through abutments were impervious to water and roughened with a 7 mm thick layer of glued riprap; the height of the models, measured from the surrounding bed, and their top widths were 130 mm and 100 mm, respectively. Backwater did not induce overtopping. Tests on vertical-wall abutments were conducted in the flume of Universidade da Beira Interior (UBI). These were simulated by 140 mm wide, parallelepiped Perspex boxes with smooth vertical walls. All abutment models extended downwards vertically from the reference bed level so that their bases were directly placed on the floor of the recess boxes.

In the experiments, four different sand mixtures and eight different mixtures of riprap blocks have been used. They are characterized, respectively, in Tables 2 and 3, which also include the values of the gradation coefficient, $\sigma_D$ = $(D_{84.1}/D_{50} + D_{50}/D_{15.9})/2$. In Table 2, $D_n$ = sand particle sieving diameter for which n% are finer by weight; in Table 3, subscript $r$ of $D_{rn}$ stands for riprap. All sands and riprap mixtures can be considered as uniform, since $\sigma_D < 1.5$. The specific gravity was verified to be s ≈ 2.65 in all cases.

Table 2: Diameters and gradation coefficient of sand mixtures

| Sand | $D_{15.9}$ (mm) | $D_{50}$ (mm) | $D_{84.1}$ (mm) | $\sigma_D$ (–) |
|---|---|---|---|---|
| sB1 | 0.64 | 0.86 | 1.17 | 1.35 |
| sB2 | 0.87 | 1.28 | 1.87 | 1.46 |
| sL | 0.71 | 0.96 | 1.25 | 1.33 |
| sM | 0.87 | 1.19 | 1.68 | 1.39 |

Table 3: Diameters and gradation coefficient of riprap mixtures

| Sand | $D_{r15.9}$ (mm) | $D_{r50}$ (mm) | $D_{r84.1}$ (mm) | $\sigma_D$ (–) |
|---|---|---|---|---|
| rB1 | 2.7 | 3.6 | 5.8 | 1.48 |
| rB2 | 5.3 | 7.5 | 10.9 | 1.44 |
| rB3 | 13.4 | 15.7 | 18.7 | 1.18 |
| rL1 | 4.2 | 4.8 | 5.5 | 1.15 |
| rL2 | 5.8 | 6.9 | 8.2 | 1.19 |
| rM1 | 3.3 | 4.5 | 5.6 | 1.31 |
| rM2 | 6.4 | 7.6 | 9.1 | 1.19 |
| rM3 | 10.6 | 11.9 | 13.4 | 1.12 |

The discharge $Q$ was measured using electromagnetic flow-meters at EPFL and UBI flumes, and using a triangular thin-plate weir at the UCLM flume. The flow depth was measured with point gages and regulated by hand-operated tailgates at the downstream end of the flumes. In some cases, scour depth was measured with adapted point gages.

## Design criteria revisited

### Apron thickness

The main objective of this section is to assess the minimum mattress thickness, $t$, needed to *avoid winnowing failure*. The assessment is made on the basis of the experiments carried out in UBI flume for vertical-wall abutments.

The study was carried out with a practically constant flow depth ($d$ ≈ 0.12 m). Two types of riprap stones (rB2 and rB3) and two types of sand (sB1 and sB2) were used. For a given test, the bed recess was almost filled with sand; then, a horizontal riprap layer was placed around the abutment, covering the entire recess box. The thickness of the riprap layer varied from test to test but it was always levelled with the adjacent concrete flume bed. Abutment lengths, $L$ = {0.30 m; 0.51 m; 0.72 m; 0.93 m; 1.13 m} were used. The top of the vertical-wall abutments (Perspex boxes) was kept open, allowing for the manipulation of a video camera to record images from inside. A ruler was fixed to the transparent wall of the abutments.

Forty two tests were performed: 21 with sB1 and 21 with sB2. No filter fabric was used. Several riprap layer thicknesses, $t$, were tested: $t = \{D_{r50};\ 2D_{r50};\ 3D_{r50}\}$ for rB2 and rB3 on sand sB2; $t = \{2D_{r50};\ 3\ D_{r50}\}$ for rB2 on sand sB1; $t = \{2D_{r50}$ to $20D_{r50}\}$ for rB3 on sand sB1.

The approach flow velocities, $U$, were kept equal to 90% of those verified to induce shear failure at the abutments' nose, $U_s$. Since the experiments were run for $U \approx 0.9U_s$, shear failure was never observed; as the recess box was entirely covered with riprap, edge failure was also not possible. Thus, *only winnowing failure* could be expected.

Scouring was monitored with the video camera recording the riprap and sand levels at the ruler, until equilibrium had been achieved. The original results of this study can be found in Fael (2007). The most important conclusions are as follows:

- Scour is nonexistent for rB2 on sB2, regardless of the layer thickness. The same is true for rB2 on sB1 and rB3 on sB2, provided $N \geq 3$. These results show that, in the mentioned circumstances, both riprap layers act as granular filters relative to the underlying sands, in spite of the fact that the criterion of Terzaghi-Vicksburg,

$$D_{r15}/D_{85} < 5; \quad 5 < D_{r15}/D_{15} < 20; \quad D_{r50}/D_{50} < 40$$

  is not fully respected for rB3 on sB2.
- When riprap rB3 is placed on the finer sand sB1, winnowing occurs for thicknesses, $t$, as large as $20D_{r50}$.

Granular filters respecting the criterion of Terzaghi-Vicksburg are difficult to build underwater. Since, in the absence of filters, winnowing is potentially active for mattresses' thicknesses as high as $20D_{r50}$ – which is the most valuable conclusion of this study –, synthetic filters tend to impose as the solution to avoid winnowing failure. These filters are kept in place by riprap aprons whose thicknesses is of the order of $2D_{r50}$, typically between $D_{r100}$ and $3D_{r50}$, as suggested by Richardson and Davis (1995) or Melville and Coleman (2000).

It should be stressed that, in this study, $L/d$ varied between 2.46 and 9.42, $d/D_{r50}$ = {7.6; 16.0}, while $L/B$ ranged from 0.075 to 0.283.

**Mattress plan configuration**

The objective of this section is to assess the minimum apron width, $w$, needed to *avoid edge failure*. Five series of experiments, involving various combinations of $L/B$ and abutment side slopes, H:V (see Figure 1), were performed. Flow depth was kept practically constant at 0.09 m in Series 1 to 4 and equal to 0.12 m in Series 5. The abutment top length, $L_t$ varied between the limits listed in Table 43, at increments of 0.10 m, except for Series 5 (vertical-wall abutment), were $L_t = L$ took the same values as for the tests on winnowing. For a given abutment configuration, riprap aprons of different plan sizes were embedded in the sand around the abutment nose, their top being leveled with the surrounding sand. Sand and riprap blocs used were those identified in Table 4.

Table 4: Main features of the experiments on the plan configuration of mattress aprons

| Series | Flume | $H:V$ | Sand | Riprap | $L_t$ (m) |
|---|---|---|---|---|---|
| 1 | EPFL | 2:1 | sL | rL2 | 0.20 – 0.30 |
| 2 | EPFL | 1:1 | sL | rL2 | 0.10 – 0.50 |
| 3 | UCLM | 2:1 | sM | rL2 | 0.30 – 0.60 |
| 4 | UCLM | 1:1 | sM | rL2 | 0.10 – 0.50 |
| 5 | UBI | 0 | sB2 | rB3 | 0.30 – 1.13 |

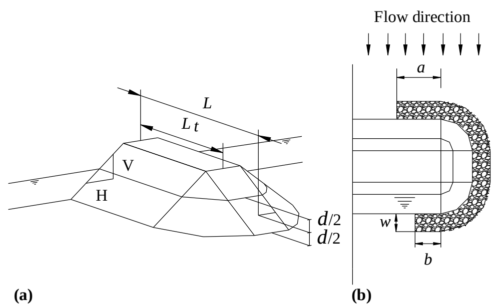


Figure 1 (a) Perspective and (b) schematic plan-view of spill-through abutments

For a given apron plan configuration, the volume of riprap stones was calculated by assuming a mattress thickness of $t = 3D_{r50}$, downstream apron length $b = 3D_{r50}$, and upstream apron length $a = \min\{L_t, 2d\}$ (see Figure 1). A thin flexible plate was inserted vertically in the sand bed along the external perimeter of the idealized apron, and the same sand volume was carefully removed from the space that the stones were to fill. For Series 1 to 4, the calculated riprap volume was finally poured into the excavated sand bed, to guarantee the same top level as the surrounding sand bed. Since riprap blocks were verified to act as granular filters, winnowing failure was avoided. For Series 5, riprap blocks did not perfectly conform to the criterion of Terzaghi-

Vicksburg for granular filters, since $D_{r15}/D_{85} \approx 7.2 > 5$; consequently, in this series, the lower one-third of the riprap aprons was replaced by a granular filter composed of riprap rB2, to also inhibit winnowing failure. In all tests, a row of yellow painted stones was carefully hand-placed around the abutment perimeter (white strip around the abutment in Figure 2).

Figure 2 Apron configuration after a failure test (yellow painted stones dislodged in the encircled zone)

Once the abutment, sand bed and riprap apron were placed, the flumes were slowly filled with water up to approximately the prescribed flow depth. Tests were carried out for $U \cong U_c$, namely for $0.95U_c < U < U_c$, in which $U_c$ is the critical velocity of beginning of motion of the surrounding sand as computed through the criterion of Neill (1967). Riprap blocks were much heavier than sand grains and shear failure never occurred. Bed-form undermining did not occur either since, in the absence of bed particles motion, bed-forms could not develop, such that *only edge failure* was allowed.

Since armouring aprons tend to divert scour holes from abutments, reducing the scour depth, it was assumed that edge failure occurred if at least one yellow painted block was dislodged from its original position and had fallen into the scour hole (encircled area in Figure 2). Experiments were continued until failure was observed or equilibrium scour depth was identified.

From a practical point of view, the most important results of the study refer to *w*, as derived from the narrower stable and the wider failing tests, to identify the failure limit. Their non-dimensional form, $w^+ = w/d$, are plotted against $L^+ = L_t/d$ in Figure 3, where black symbols refer to narrower stable tests and white symbols refer to wider failure ones. It should be pointed out that the effect of abutments' geometry could not be identified.

Figure 3 also assesses the applicability of existing *w* predictors, namely those of Richardson and Davis (1995), and Cardoso and Fael (2009). Richardson and Davis' predictor simply reads $w^+ = 2$. Since (i) the safety of the predictor of Richardson and Davis (1995) necessarily conflicts with economy and (ii) the predictor of Cardoso and Fael (2009), based on limited experimental evidence, seems unsafe, a new predictor is proposed as

$$w^+ = 0.75(L^+)^{0.55} \tag{1}$$

This equation constitutes an envelope curve to the *w* data for stable aprons (Figure 3). It should still be stressed that, though no systematic evaluation of *a* and *b* was performed herein, there was sufficient evidence in the reported experiments that (i) *b* can be taken as $b = 0$ without risk of edge failure and (ii) $a = \min\{L_t, 2d\}$ was frequently observed to nearly produce edge scour (not edge failure), particularly if $L_t > 2d$.

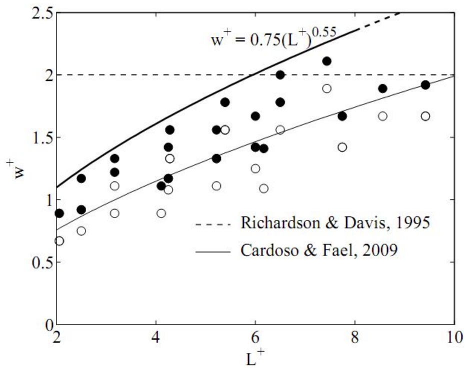


Figure 3 Variation of $w^+$ with $L^+$.

Figure 4 presents an alternative plan configuration of riprap aprons that considers the apron to be squared in its downstream part. This configuration was recently studied too, and results will be published by Simarro *et al.* (2012).

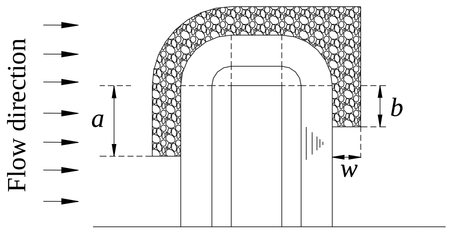


Figure 4 Schematic plan configuration of riprap apron

As long as $L_t/d < 5$, this geometry has shown to allow riprap reductions of up to 25% in volume and of up to 30% in width as compared to the traditional display (Figure 1).

The above results are valid for abutments that protrude at right angles from the walls of sand bed channels; $2.51 < L_t/d < 7.83$, $7.65 < d/D_{r50} < 22.22$, $0.22 < Fr < 0.50$ and $L_t/B < 0.28$ where $Fr$ is the approach Froude number. Experiments were performed under clear water flow conditions. This choice corresponds to the common situation encountered in floodplains where abutments are most frequently built.

## Size of riprap stones

The objective of this section is to assess the minimum block diameter, $D_{r50}$, needed to avoid *apron shear failure* and abutment slope *particle erosion failure*. Tests were performed at EPFL and UCLM flumes for the described spill-through abutments and at UBI flume for vertical-wall abutments.

The recess boxes were filled with sand; $3D_{r50}$ thick layers of riprap stones were placed on top of the sand such that the upper surface of the riprap was leveled with the adjacent fixed bed of the flumes. For the spill-through experiments, the $3D_{r50}$ riprap layers within the recess boxes were verified to act as granular filters with respect to the under-laying sands; for the vertical-wall abutments at UBI flume, the filtering effect was created by a filter fabric placed between the sand and the riprap mixtures. In any case, winnowing failure could not occur; since the recess boxes were entirely covered with riprap, edge failure and bed form undermining were also avoided.

The tests on shear failure of riprap at aprons involved the replacement of a $1D_{r50}$ thick layer of riprap by yellow painted stones of the same size in the zone where shear failure was expected to occur. Tests started with very low flow velocities. The velocity was successively increased by increasing the discharge and adjusting the downstream tailgate to maintain the flow depth approximately constant in a given test. This procedure was continued until the riprap stones close to the abutment began to move. A typical bed at the end of a test is shown in Figure 5.

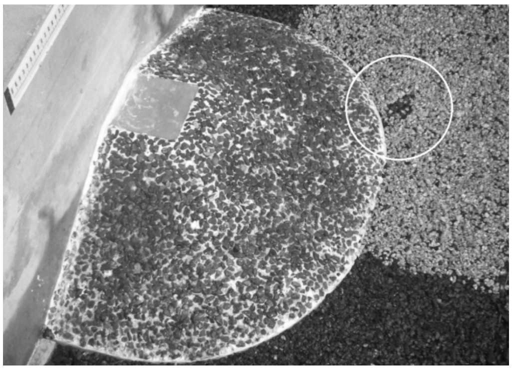

Figure 5 Abutment after a shear failure test.

Depending on the experiment, the flow depth varied in the range 0.09 m $\leq d \leq$ 0.12 m for spill-through abutments, while it was fixed at $d$ = 0.12 m for vertical-wall abutments. The beginning of motion is difficult to identify in the laboratory because of its stochastic nature resulting in its visual evaluation being somewhat subjective. Hence, two approximate values of the approach flow velocity, $U_s$, above which shear failure occurs were recorded: a lower one, where motion was about to take place but had not yet been observed, and an upper one, corresponding to very weak sediment motion (incipient motion). The velocity intervals were very small though containing the true $U_s$ value.

Fourteen shear failure tests were carried out in UCLM flume, for H:V = 2:1, corresponding to abutment top lengths, $L_t$ = {0.10 m; 0.20 m; 0.30 m; 0.40 m; 0.50 m; 0.60m}. For each length, at least two riprap block sizes – rM1 and rM2 – were tested; for $L_t$ = {0.40 m; 0.50 m}, block size rM3 was tested too.

At the end of each shear failure test, the bed was re-leveled and the side slopes of the abutment were covered with a $\approx 1D_{r50}$ thick layer of riprap stones which imbricate on the 7 mm thick layer of riprap blocks glued on the side slopes. The resulting configuration was stable for both dry and underwater conditions, which means that translational slide failure and slump failure were absent. Then, the same experimental procedure as described for the shear failure tests was adopted, now based on a few riprap stones being dislodged from the side slope of the abutment (Figure 6) as the way of identifying critical particle erosion failure condition. Fourteen particle erosion tests were performed, one per shear failure test.

Figure 6 Abutment after a particle erosion failure test

Similarly, six shear failure tests were carried out in the EPFL flume, for H:V = 3:2, corresponding to abutment top length, $L_t$ = {0.10 m; 0.20 m; 0.30 m}. Two different riprap stones – rL1 and rL2 – were tested. An equal number of particle erosion tests were performed in the same facility.

Fifteen shear failure tests were carried out for vertical-wall abutments in UBI flume with three riprap mixtures – rB1, rB2 and rB3 – and $L_t$ = {0.30 m; 0.51 m; 0.72 m; 0.93 m; 1.13 m}. For obvious reasons, no tests on particle erosion failure were carried out for vertical-wall abutments.

Since the 1990´s some authors have suggested formulations for the evaluation of the median size, $D_{r50}$, of stable riprap stones to place at abutment aprons. They have suggested empirical formulas that can be written as:

$$\frac{D_{r50}}{d} = \frac{C}{(s-1)^m} Fr^n \qquad (2)$$

where $Fr = U/\sqrt{gd}$ is the approach flow Froude number or the contracted cross-section Froude number, depending on the author; $g$ is the acceleration of gravity; $C$, $m$ and $n$ are empirical coefficients.

Within the experimental range of the present study, it was concluded that the predictor of Pagán-Ortiz (1991) – where $C$ = 0.535; $m$ = 1.00; $n$ = 2.00 – provides an excellent upper envelope curve to the spill-through data. In this formulation, $Fr$ is defined at the contracted cross-section.

In many practical circumstances, it is convenient to make predictions on the basis of the approach flow variables instead of the contracted cross-section variables. In that case, the study has shown that the relative abutment length, $L_t/d$, plays a paramount role, as implied by Equation (3):

$$I_S = \frac{U_s}{U_c} = I_{S0} - a\left(\frac{L}{d}\right)^b \qquad (3)$$

where $I_{S0}$, $a$ and $b$ are coefficients that depend on the abutment side slope. This dependence was established in this study as indicated in Table 4.

Table 4: Coefficients $I_{S0}$, $a$ and $b$ of Equation (3) for apron riprap stones.

| Abutment type | $I_{S0}$ | $a$ | $b$ |
|---|---|---|---|
| Vertical-wall | 1.00 | 0.400 | 0.250 |
| Spill-through; H:V = 3:2 | 1.00 | 0.355 | 0.275 |
| Spill-through; H:V = 2:1 | 1.00 | 0.300 | 0.300 |

Summing up, Equation (2) with $C$ = 0.535, as suggested by Pagán-Ortiz (1991), seems a good predictor of $D_{r50}$; alternatively, Equation (3) with constants $I_{S0}$, $a$ and $b$ as given in Table 3 may be used.

The results on particle erosion failure on the side slope of spill-through abutments have shown that the size of riprap stones capable of preventing erosion failure also be assessed through Equation (2), with $C$ having a value of 0.720. This value reflects the higher propensity for failure at side slopes than at horizontal aprons, where $C$ = 0.535.

Erosion failure results were also analysed in the framework of Equation (3). It was concluded that this equation constitutes an excellent lower envelope curve for the erosion failure data, with the values of $I_{S0}$, $a$ and $b$ as recorded in Table 5.

Table 5: Coefficients $I_{S0}$, $a$ and $b$ of Equation (3) for blocks on abutment side slopes

| Abutment type | $I_{S0}$ | $a$ | $b$ |
|---|---|---|---|
| Spill-through; H:V = 3:2 | 0.71 | 0.12 | 0.60 |
| Spill-through; H:V = 2:1 | 0.85 | 0.21 | 0.40 |

It should, finally, be noticed here that the above conclusions are valid within the experimental range of this study, i.e., 7.6 < $d/D_{r50}$ < 33, $L_t/d$ < 9.4, $F_r$ < 0.57 ($F_r$ = approach flow Froude number), with special emphasis to the fact that $L_t/B$ < 0.28 for vertical-wall abutments and $L_t/B$ < 0.20 for spill-through abutments.

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