# Roughening Elements as Abutment Scour Countermeasures

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## Introduction

Local scour is known to be one of the major causes of bridge failure or collapse. Therefore, a great deal of research effort in recent years has been put into devising appropriate countermeasures to reduce the expected scour levels at piers and abutments [see, for review, Melville and Coleman (2000) and Lagasse et al. (2001)].

Scour countermeasures are usually divided into (1) bed-armoring and (2) flow-altering devices. The former aim at increasing the resistance of the river bed using, for example, riprap blocks, cable-tied blocks, gabions, geobags, or similar tools [e.g., Melville et al. (2006a, b), Korkut et al. (2007), Cardoso and Fael (2009), and Sui et al. (2010)]. Bed armoring would ideally guarantee zero scour, if appropriately designed to avoid failure. On the other hand, flow-altering devices can also be proposed. These are designed to weaken the turbulent flow field responsible for the scour process: the bridge structure is provided with specific devices, including collars and/or slots [e.g., Dargahi (1990), Chiew (1992), Kumar et al. (1999), Zarrati et al. (2004), and Heidarpour et al. (2010)], vanes [e.g., Johnson et al. (2001) and Li et al. (2006)], sacrificial piles (Melville and Hadfield 1999; Haque et al. 2007), threading cables (Dey et al. 2006), and sills [e.g., Chiew and Lim (2003) and Grimaldi et al. (2009)]. Flow-altering devices typically result in a reduced, nonzero scour depth and thus would be less effective than bed armoring. Motivation for studying such devices is possibly related to lower cost and easier installation work in comparison with bed armoring. In some cases, it has been proposed to combine bed-armoring and flow-altering devices [e.g., Mashahir et al. (2010) and Zarrati et al. (2010)]. Most of the studies on scour countermeasures have been based on laboratory experimentation aimed at proposing devices able to guarantee a certain reduction of the erosion depth.

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This paper presents results obtained from a laboratory study on flow-altering countermeasures for abutment scour, a topic that received smaller attention in comparison with the analogous one for piers. The countermeasures investigated here are roughening elements on the upstream face of the obstacle. The paper is organized as follows. Conceptual arguments are discussed to support the choice of this kind of devices. Then, the framework for analysis is derived based on dimensional considerations. The laboratory facilities are described and the experimental campaign is outlined. The result presentation considers first experiment reliability, second scaling of the process temporal evolution, and finally countermeasure performance to arrive at the major conclusions. The full data set is provided.

## Concept and Dimensionless Framework

As is well known, local scour at an abutment is due to flow separation, downflow, and the resulting principal vortex. Roughening elements (in terms of beams attached to the upstream face of the abutment, see Fig. 1) may break the downflow, thus reducing the action of the principal vortex. Such elements may act similarly to dissipation structures in basins downstream of spillways and, in the context of bridge scour, the roughening elements are similar to the threading cables proposed for piers by Dey et al. (2006). Some preliminary experimental results on scour at roughened abutments were presented by Radice and Lauva (2012), showing that these elements may have similar performance to that of other flow-altering devices, such as slots.

The performance of roughening elements is likely dependent on their protrusion out of the abutment face because the more protruding the elements are, the more efficiently they can intercept the downflow. In this paper, an attempt to consider feasible solutions was made. For example, Dey et al. (2006) presented results for a ratio of cable diameter to pier diameter equal to 0.3, but they mentioned that in reality such a ratio would probably not exceed 0.1. In the present case, the ratio of element protrusion to abutment length in the transverse direction was not larger than 0.2, which was still considered a feasible ratio, at least for small structures. In addition, the abutment models were roughened down to an elevation corresponding to scour depths of twice the obstacle length, while for lower elevations the abutment face was not protected.

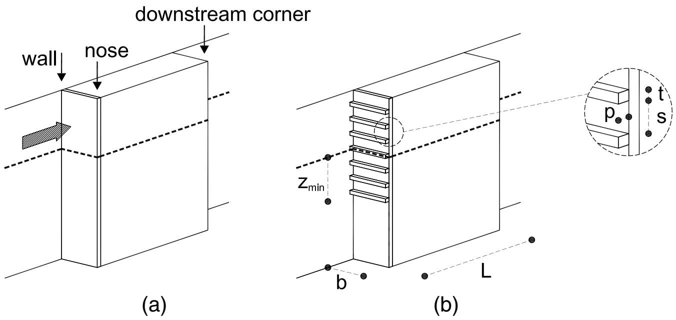


**Fig. 1.** Sketch of (a) an unprotected abutment; (b) one equipped with roughening elements on its upstream face; the thick dashed lines identify the nonscoured sediment level; the points where the scour depth was measured and the geometric parameters are indicated

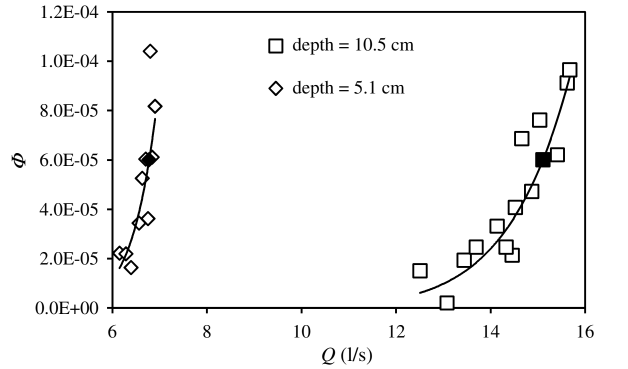


**Fig. 2.** Relationship $\Phi(Q)$ resulting from the preliminary tests, with threshold conditions highlighted by filled symbol

Another parameter that should significantly influence the countermeasure performance is the spacing between consecutive elements. Indeed, it is evident that elements very distant from each other could weakly alter the downflow because the latter would be able to reattach to the large flat portions of the abutment face. This would suggest using elements close to each other; on the other hand, for very small spacing these elements would simply create a new wall, just shifted upstream from the original one. It is therefore expected that a spacing for which maximum reduction can be obtained exists.

The scour depth ($d_s$) at a certain point can be represented as a function:

$$d_s = f_1(\rho, \mu, g, d, U, B, b, L, \mathrm{Sh}, \mathrm{Al}, t, p, s, z_{\min}, \rho_s, D_{50}, \sigma, T) \quad (1)$$

where $\rho$ = water density; $\mu$ = water viscosity; $g$ = gravity acceleration; $d$ = water depth; $U$ = flow velocity; $B$ = flume width; $b$ = abutment length; $L$ = abutment length in the streamwise direction; Sh, Al = parameters for abutment shape and alignment; $t$, $p$, $s$, $z_{\min}$ = element thickness, protrusion, spacing, and minimum elevation below the nonscoured sediment level; $\rho_s$ = sediment density; $D_{50}$ = sediment size; $\sigma$ = sediment uniformity parameter; and $T$ = time. After some manipulation one can obtain

$$\frac{d_s}{b} = f_2\left(\mathsf{R}, \mathsf{F}, \frac{b}{d}, \frac{b}{B}, \frac{L}{b}, \mathrm{Sh}, \mathrm{Al}, \frac{t}{b}, \frac{p}{b}, \frac{s}{b}, \frac{z_{\min}}{b}, \frac{\rho_s}{\rho}, \frac{b}{D_{50}}, \sigma, \frac{TU}{b}\right) \quad (2)$$

with $\mathsf{R} = \rho \times U \times d/\mu$; and $\mathsf{F} = U/(g \times d)^{0.5}$ as the Reynolds and Froude numbers, respectively. The length scale $b$ can be replaced with the water depth $d$ or with some combination of $d$ and $b$, as proposed in several studies [e.g., Melville (1992) and Oliveto and Hager (2002)]. Most suitable choice for the present analysis shall be discussed in the following. Finally, it can be shown that Eq. (2) embeds the effect of a flow intensity parameter defined as the ratio of water velocity to its threshold value for incipient particle motion [see, for e.g., Simarro et al. (2007)].

## Experimental Setup and Campaign

The experiments documented here were run at the Hydraulics Laboratory G. Fantoli of the Politecnico di Milano, using a 5.8-m-long rectangular flume with a width of 40 cm and slope of 0.04%. In the last 2 m of the flume, a 30-cm-deep recess section was filled with natural sand having $\rho_s = 2{,}570$ kg/m$^3$, $D_{50} = 0.9$ mm, and $\sigma = 1.2$ (nearly uniform). The same sediments were glued onto the bottom of the remaining part of the channel to ensure homogeneity of the bed roughness. Water discharge was measured by a magnetic flowmeter with an accuracy of 0.5%; water depth was measured with a precision of 0.5 mm by means of piezometric probes placed every 0.5 m along the flume and vertical rulers attached to the lateral wall. The water elevation in the channel was imposed by means of a downstream gate.

Only clear-water, nearly threshold conditions were investigated here. It is well known that the definition of a critical state for incipient particle motion is not straightforward [see, for example, Buffington and Montgomery (1997)]. The concept according to which threshold conditions may be associated with a vanishing sediment transport rate [e.g., Schvidchenko and Pender (2000) and Radice and Ballio (2008)] was followed here. The threshold flow discharge for given water depth was defined as that for which $\Phi = q_s/[g \times (\rho_s/\rho - 1) \times D_{50}^3]^{0.5} = 6 \times 10^{-5}$, where $\Phi$ and $q_s$ are the dimensionless and dimensional sediment transport rates per unit width, respectively. Preliminary tests were performed obtaining a relationship $\Phi(Q)$, with $Q$ as flow discharge, for fixed water depths. During these tests, $q_s$ was measured counting the number of sediments crossing a sight in a given duration. The results are depicted in Fig. 2, from which critical discharges were determined as equal to 15.1 and 6.8 L/s for depths of 10.5 and 5.1 cm, respectively.

The vertical-wall abutment model used here had rectangular base with $b = 5$ cm and $L = 20$ cm (see again Fig. 1). The contraction ratio resulted as $b/B = 0.13$, so that constrictions effects were supposed to be vanishing according to the analysis of Ballio et al. (2009). The abutment was made in acrylic material and its upstream face was covered with wooden plates to create the desired surface characteristics. For the unprotected abutments, only a plate was added; for the protected abutments, plates equipped with roughening elements characterized by different combinations of $t$, $p$, and $s$ were used. In all cases, the ratio $z_{\min}/b$ was as close as possible to $-2$. The abutment model was compound of two parts, the lower being buried in the sediment bed while the higher could be inserted into the former to activate the scour process.

Each experiment was run in the following way. First, the flume was filled with water at a very low rate to avoid disturbance to the loose sediment bed. In this phase, no scour occurred because only the lower part of the abutment was in place. Then, the test discharge and depth were achieved and, once the desired flow conditions were steady, the upper part of the abutment was inserted into the lower one and the experiment started. The scour depth was continuously measured at the channel wall, at the abutment nose and at the downstream corner by rulers attached to the obstacle and flume with a precision of 1 mm (comparable to the particle size and thus suitable for the purpose). Experiment duration was limited to 6 h

**Table 1.** Experimental Conditions

| Run | $Q$ (L/s) | $d$ (cm) | $U$ (m/s) | $t$ (cm) | $p$ (cm) | $s$ (cm) | $z_{\min}$ (cm) | $b/d$ | F | $p/\delta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| A-0 | 14.70 | 10.65 | 0.35 | — | — | — | — | 0.47 | 0.34 | — |
| A-1 | 14.61 | 10.60 | 0.34 | 1.0 | 1.0 | 1.0 | 11.0 | 0.47 | 0.34 | 0.15 |
| A-2 | 14.67 | 10.45 | 0.35 | 1.0 | 1.0 | 2.0 | 10.0 | 0.48 | 0.35 | 0.15 |
| A-3 | 14.70 | 10.40 | 0.35 | 1.0 | 1.0 | 3.0 | 9.0 | 0.48 | 0.35 | 0.15 |
| A-4 | 14.55 | 10.60 | 0.34 | 1.0 | 1.0 | 4.0 | 11.0 | 0.47 | 0.34 | 0.15 |
| B-0 | 14.65 | 10.50 | 0.35 | — | — | — | — | 0.48 | 0.34 | — |
| B-1 | 14.62 | 10.60 | 0.34 | 1.0 | 0.5 | 1.0 | 11.0 | 0.47 | 0.34 | 0.07 |
| B-2 | 14.67 | 10.45 | 0.35 | 1.0 | 0.5 | 2.0 | 10.0 | 0.48 | 0.35 | 0.07 |
| B-3 | 14.72 | 10.40 | 0.35 | 1.0 | 0.5 | 3.0 | 9.0 | 0.48 | 0.35 | 0.07 |
| B-4 | 14.65 | 10.50 | 0.35 | 1.0 | 0.5 | 4.0 | 11.0 | 0.48 | 0.34 | 0.07 |
| C-0 | 6.61 | 5.15 | 0.32 | — | — | — | — | 0.97 | 0.45 | — |
| C-1 | 6.67 | 5.15 | 0.32 | 1.0 | 1.0 | 1.0 | 11.0 | 0.97 | 0.46 | 0.20 |
| C-2 | 6.66 | 5.10 | 0.33 | 1.0 | 1.0 | 2.0 | 10.0 | 0.98 | 0.46 | 0.20 |
| C-3 | 6.66 | 5.05 | 0.33 | 1.0 | 1.0 | 3.0 | 9.0 | 0.99 | 0.47 | 0.20 |
| D-0 | 6.74 | 5.10 | 0.33 | — | — | — | — | 0.98 | 0.47 | — |
| D-1 | 6.77 | 5.05 | 0.34 | 1.0 | 0.5 | 1.0 | 11.0 | 0.99 | 0.48 | 0.10 |
| D-2 | 6.77 | 5.15 | 0.33 | 1.0 | 0.5 | 2.0 | 10.0 | 0.97 | 0.46 | 0.10 |
| D-3 | 6.78 | 5.10 | 0.33 | 1.0 | 0.5 | 3.0 | 9.0 | 0.98 | 0.47 | 0.10 |

because earlier results of Radice and Lauva (2012) showed that the percentage reduction of scour is significant at the first stages of the process, while later it diminishes due to increase in the scour depth. Thus, performing very long experiments would not have been relevant for the present investigation.

Four series of experiments were performed (indicated with A, B, C, and D), each of which was for one combination of water depth and element protrusion. In addition, in each homogeneous series all the parameters were kept constant except the spacing between the elements, according to the concept steering the analysis and mentioned in the previous section. The test characteristics are listed in Table 1, where the indicated water depth refers to the reference hydrodynamic condition achieved before inserting the upper part of the abutment into the lower one. The abutment was located 4.5 m from the flume inlet, corresponding to 45 and 90 times the flow depth for the latter's value of 10 and 5 cm, respectively. Therefore, the flow was expected to be fully developed or almost fully developed. For example, according to the law proposed by Kirkgöz and Ardiçlioğlu (1997) the length of the developing region would be approximately 65 and 72 times the flow depth, respectively. Finally, despite the relatively small dimension of the flume, scaling effects were not significant in the experiments.

## Results

### Experiment Repeatability

A check of the capability to control the experimental conditions was performed considering the result repeatability. Given how the campaign was structured, the experiments with unprotected abutments were performed twice and results of tests A-0 and B-0 could be compared as well as of C-0 and D-0. The latter comparison is depicted in Fig. 3, proving good repeatability of the measured scour trends at the monitored locations around the abutment. A similar comparison for the other two unprotected tests yielded analogous results.

### Scaling

As mentioned previously, there are several options for the reference length scale to be used for normalization of the scour depth. Such scale can be written as $\delta = b^{\alpha} d^{1-\alpha}$ and some proposals for the $\alpha$ value can be found in the literature. For example, Melville and Coleman (2000) proposed $\alpha = 0, 0.5$, or 1 depending on the $b/d$ ratio; Oliveto and Hager (2002) proposed instead $\alpha = 2/3$. Here the objective was to find a value yielding good collapse of the experimental data, and thus suitable for the following analysis of the countermeasure performance. The dimensionless temporal evolution of the scour depth for tests A-0 and C-0 is presented in Fig. 4, where a value $\alpha = 0.6$ was used. This value was the best one within a range of 0–1, in which values every 0.1 were tried. Calibration of the second decimal digit of the exponent was not attempted because such a job would not be crucial for the subsequent analysis.

It was not possible to find a parameter yielding good similarity of the scour values in the first experimental times. In addition, the most appropriate scaling was not the same for all the measured points. Indeed, best collapse of points for location D was obtained with $\alpha = 0.2$, indicating that the scaling behavior of different positions in the scour hole was different. Indeed, previous experience of the first author (unpublished) demonstrated that a self-similarity of the shape of the erosion hole, involving also the downstream portion of the latter, is attained only for very long experimental times. For the analysis of the countermeasure performance, the best scaling for the upstream part of the erosion hole was privileged because it is where largest scour depth values were measured.

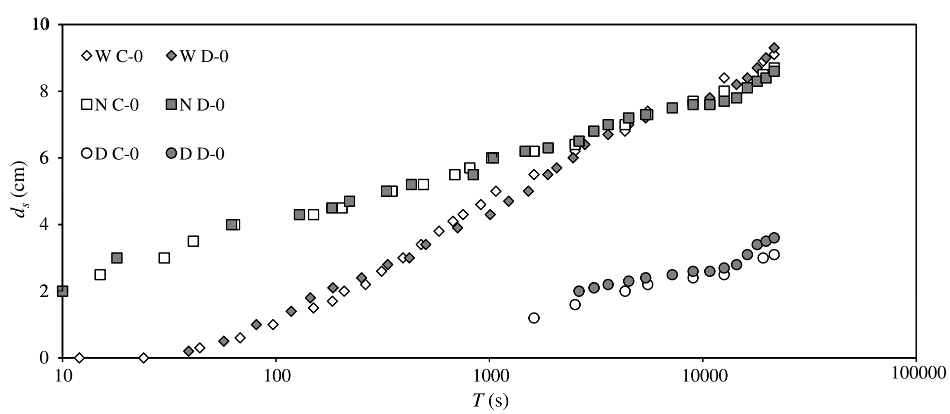


**Fig. 3.** Temporal trend of the scour depth at the three monitored points for tests C-0 and D-0 (W, N, and D are, respectively, flume wall, abutment nose, and downstream corner in Fig. 1)

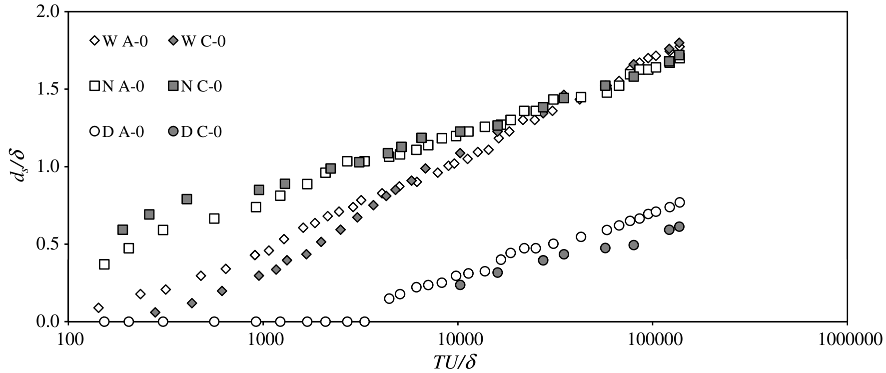


**Fig. 4.** Dimensionless time evolution of the scour depth for tests A-0 and C-0

## Countermeasure Performance

The analysis of countermeasure performance was based on a reduced version of Eq. (2):

$$\frac{d_s}{\delta} = f_3\left(\mathsf{F}, \frac{b}{d}, \frac{p}{b}, \frac{s}{b}, \frac{TU}{b}\right) \tag{3}$$

where viscous effects were discarded ($\mathsf{R}$ was larger than $1.7 \times 10^4$), a single abutment was used with perpendicular alignment (constant Sh, Al, $L/b$), measured scour depths were not sufficient for $z_{\min}$ to come into play, only one sediment was used (constant $\rho_s/\rho$ and $\sigma$), $b/D_{50}$ was constant and however larger than typical thresholds indicated for self-similarity of the process [e.g., Melville and Coleman (2000)], there was a constant relative thickness $t/b$, and there was a constant $b/B$ (and with however negligible effect as discussed previously).

Because the experiments were not run until attainment of an equilibrium condition, the scour reduction was quantified at three dimensionless times $\tau = TU/\delta = 1{,}000$, 10,000, and 100,000. Values of $d_s/\delta$ for those times were logarithmically interpolated based on the measured scour depths and are plotted in Fig. 5 as a function of $s/p$. The choice of the latter as the key geometric parameter deserves some discussion. Rigorously, based on the conceptual arguments given previously and Eq. (3), $p/b$ and $s/b$ should be used as independent geometric parameters of the roughening elements. However, the range of $p/b$ (or, in turn, of $p/\delta$) was limited to small values in order to preserve feasibility of the roughening elements. In addition, if the dimension of the vortex system is somehow assigned (the abutment length was kept constant), $s/p$ can be argued to be the parameter governing the possibility for the intercepted downflow to reattach. It thus would be possible to analyze the results with one parameter less than expected.

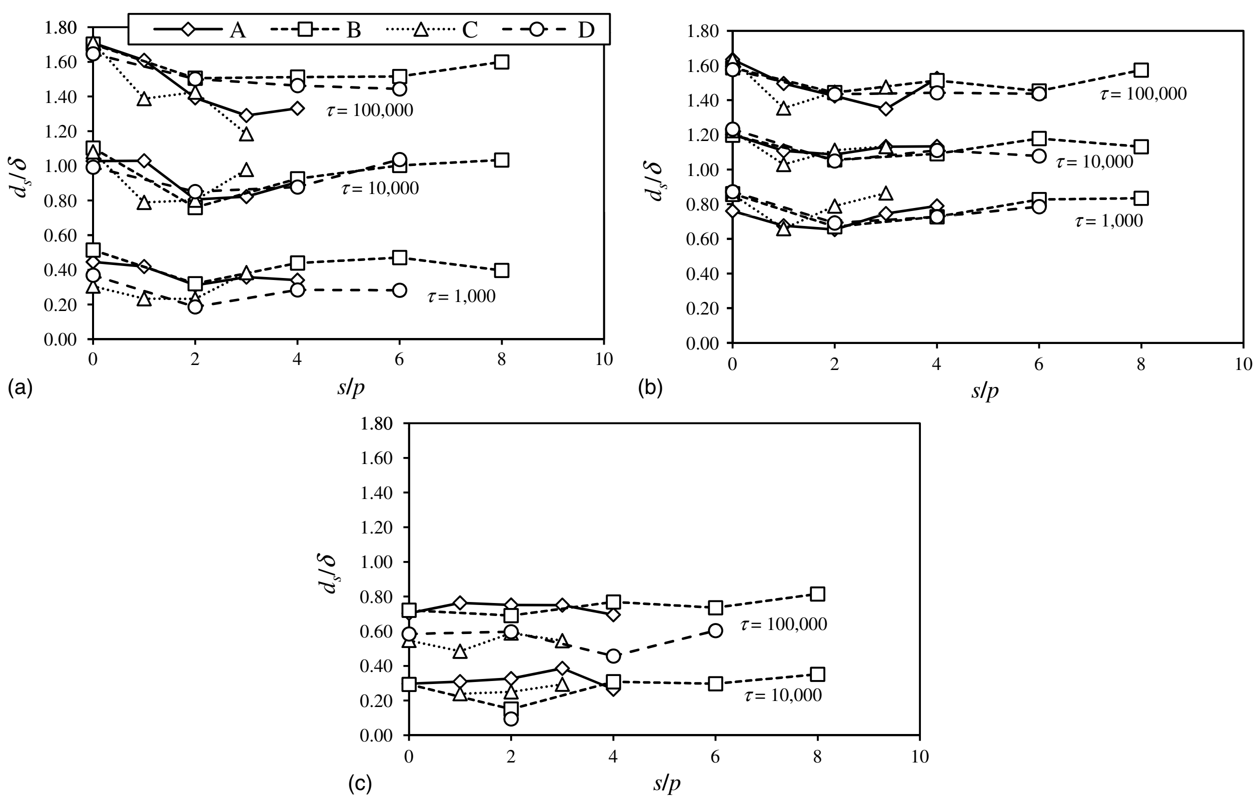


**Fig. 5.** Dimensionless scour depth at (a) channel wall; (b) abutment nose; (c) downstream corner as a function of $s/p$ for all the experimental series (in legend) and three different characteristic times $\tau = TU/\delta$ (values indicated); $s/p = 0$ corresponds to the unprotected abutments

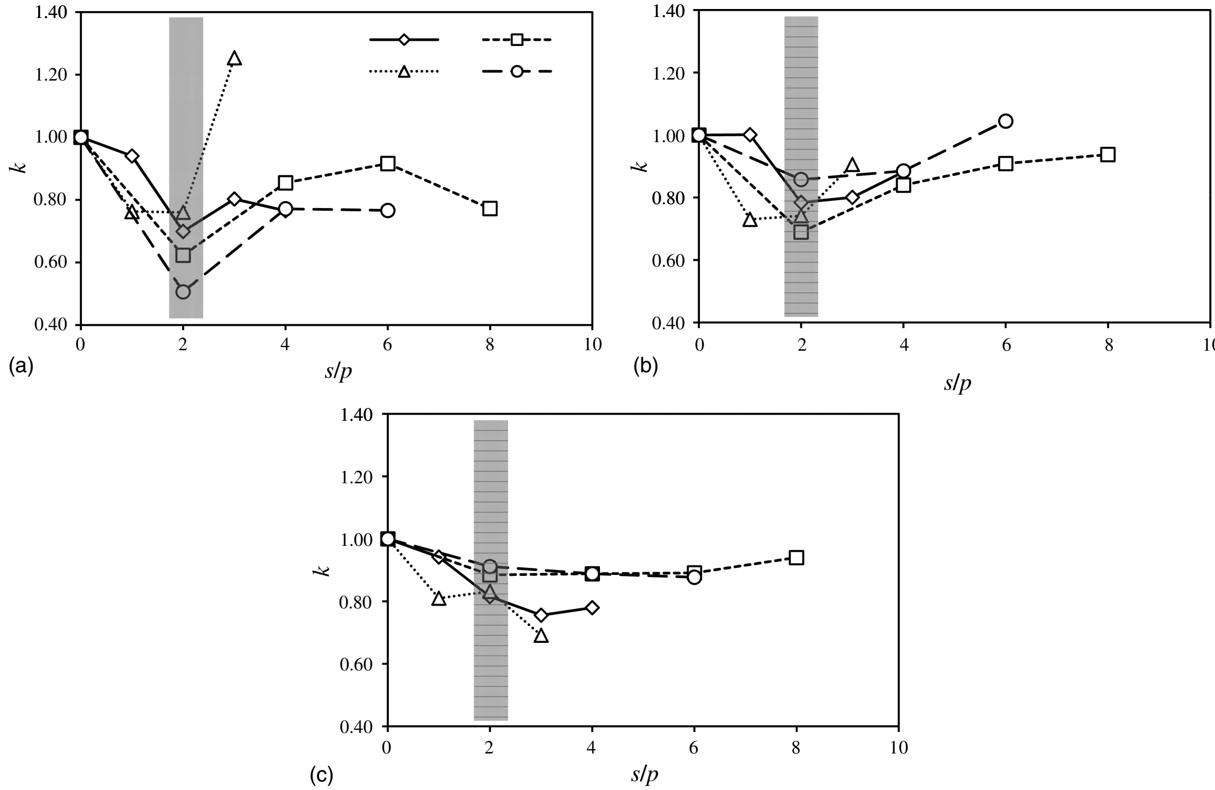


**Fig. 6.** Ratio of the scour depth at flume wall for the roughened abutments to those for the unprotected ones for (a) $\tau = 1{,}000$; (b) $\tau = 10{,}000$; (c) $\tau = 100{,}000$; $s/p = 0$ corresponds to the unprotected abutments

Indeed, in the present case plots in terms of $s/p$ enabled a reasonable collapse of data to be obtained. This behavior depended on the range of the other parameters and cannot be assumed as of general validity.

Results in Fig. 5 include all the experimental runs that were conducted. The curves for different series and the same $\tau$ are overlapping, thanks to the appropriate scaling found in the previous section. It can be seen that, in general, the roughening elements provided a protection of the wall point more than of the nose one, as already discussed by Radice and Lauva (2012). In addition, the scour depth at the downstream corner was in some cases larger for the protected abutments than for the unprotected ones. It has been indeed discussed in the literature than increase of scour at some locations may be the price to be paid to protect other ones, considered most important for structure safety [e.g., Johnson et al. (2001), Li et al. (2006), and Melville et al. (2006a)].

Data are depicted in Fig. 6 in terms of a scour reduction factor $k = (d_s/\delta)/(d_s/\delta)_{\text{unprotected}}$; just the point at the flume wall is considered at the same times previously used. From the plots, it emerges that the minimum scour values were measured for a $s/p$ ratio equal to 2. This is particularly true for $\tau = 1{,}000$ and $\tau = 10{,}000$, while for the largest times results are less clear. For large times, however, the scour reduction becomes lower than 10% due to increase in the scour levels. For $\tau = 1{,}000$, scour depths for $s/p = 2$ are between 51 and 76% of those for the unprotected abutments. Analogous values for $\tau = 10{,}000$ are 69 and 86%. Such values are consistent with those found by Dey et al. (2006), who obtained maximum scour reductions of 45% for threaded piles and a ratio of cable to pier diameter of 0.3.

As a final synthesis, for the range of parameters investigated here (vertical-wall rectangular abutments perpendicular to the flow; $b/d = 0.48$ and 0.98, short abutments; $b/D_{50} = 56$, negligible effect of particle size; $t/b = 0.2$; $\mathsf{F} = 0.34$ and 0.46; $p/b = 0.1$ and 0.2, or $p/\delta = 0.07$ to 0.2; $s/p = 1$–8) the best scour reduction was obtained for $s/p = 2$. Percentages of scour reductions were larger than 25% for $\tau = 1{,}000$ and larger than 15% for $\tau = 10{,}000$. Such times would correspond to short durations in real scale (for example, considering a $1/100$ scale with Froude similarity law, $\tau = 10{,}000$ would correspond to a few hours time). Such devices would then be suitable for small bridges on small creeks, where flood events would likely be characterized by short time scales, in case such bridge sites need protection for bank erosion (as one should have borne in mind that the roughening elements protect the location close to the flume wall and may thus be influent for stability of the bank).

Several issues that were not considered in this study can affect the countermeasure performance and should therefore be addressed in follow-up analyses. The expected reduction of the scour depth should be quantified, for example, in live-bed conditions, for skewed flow, and for different thickness of the roughening elements. Furthermore, another agent that can actually reduce the effectiveness of scour countermeasures but has received scarce attention in the literature is the presence of debris material, which can cover the flow-altering devices.

## Conclusions

This paper has explored the possibility to use roughening elements as abutment scour countermeasures. The performance of such devices has been investigated experimentally determining, for the range of conditions used, a best-configuration parameter and expected scour reductions. Suitability of the devices proposed here for real river situations has been argued.

The distinctive points of the present study within the context of research on scour countermeasures are (1) new devices with reasonable feasibility being proposed; (2) a laboratory campaign organized on the base of conceptual arguments; (3) carefully performed experiments, with particular account for data reliability; (4) data analysis following a well-defined dimensionless framework; and (5) full database made available to the scientific community and thus usable by other scholars in similar works.

## Acknowledgments

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## Notation

*The following symbols are used in this paper:*

Al = parameter for abutment alignment to flow;
$B$ = flume width;
$b$ = abutment length in transverse direction;
$D_i$ = sediment size at $i$th percentile;
$d$ = flow depth;
$d_s$ = scour depth;
$\mathsf{F}$ = Froude number;
$g$ = acceleration due to gravity;
$k$ = scour reduction factor = $(d_s/\delta)/(d_s/\delta)_{\text{unprotected}}$;
$L$ = abutment length in streamwise direction;
$p$ = protrusion of roughening elements;
$Q$ = flow discharge;
$q_s$ = solid discharge;
$\mathsf{R}$ = Reynolds number;
Sh = parameter for abutment shape;
$s$ = spacing between roughening elements;
$T$ = time;
$t$ = thickness of roughening elements;
$U$ = bulk flow velocity;
$z_{\min}$ = minimum elevation of roughening elements;
$\alpha$ = exponent;
$\delta$ = $b^{\alpha}d^{1-\alpha}$;
$\mu$ = dynamic viscosity of water;
$\rho$ = water density;
$\rho_s$ = sediment density;
$\sigma$ = sediment uniformity parameter = $(D_{84}/D_{16})^{0.5}$;
$\tau$ = $TU/\delta$; and
$\Phi$ = dimensionless solid discharge per unit width.

## Supplemental Data

The full database with the time development of the scour depth for the experiments described here is available online in the ASCE Library.

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