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METHODS FOR LOCAL SCOUR DEPTH ESTIMATION AT COMPLEX BRIDGE PIERS

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ABSTRACT
Four methods for the prediction of the local scour depth at complex bridge piers are evaluated by using new experimental data. New tests were carried out in clear-water conditions by systematically varying the pile-cap elevation of a complex pier. Six simple-pier scour formulas were combined with the four methods; the comparison of predictions and measurements allows establishing that the method by Sheppard (2005), combined with its original scour formula, performs the best. The method by Melville and Coleman (2000) seems to be the most conservative and achieves its best prediction in combination with the CSU scour formula. The methods by Richardson and Davis (2001) and Coleman (2005) potentially lead to both overestimations and underestimations, depending on the position of the pile cap and on the adopted scour formula.

INTRODUCTION
Local scouring at bridge piers is a complex phenomenon about which several studies and research are available in the literature; it is considered one of the main causes of damaging or failure of bridges. Accurate predictions of the scour depth are crucial for designing bridge foundations: underestimation may lead to bridge failure, including collapse; overestimation leads to unnecessary extra construction costs.

The complexity of the local scouring phenomenon is due to the complex flow field and turbulence around the pier (see, *e.g.* Dargahi, 1987; Graf & Istiarto, 2002; Dey & Raikar, 2007). The formulae for the scour depth estimation are usually based on experimental investigations; the majority of them refer to a simple pier, and few methods allow the scour depth assessment at piers changing in dimensions and shape along the vertical axis: structures very common in the reality, namely "complex pier". A complex pier is frequently composed of up to three elements, presently referred to as column, pile-cap and piles (or pile group) (Figure 1A), while a simple pier is assumed to be a single cylindrical column.

In the present work, the methods developed for complex piers by Melville and Coleman (2000), Richardson and Davis (2001), Coleman (2005) and Sheppard (2005) are considered. These methods treat a complex pier as a single cylindrical pier by using an equivalent pier diameter, b^*. This equivalent cylindrical pier is such that, for the same flow and sediment conditions, produces the same scour depth, d_s, as the complex pier (Figure 1B). The effective equivalent diameter depends on the position of the pile cap and the piles with respect to the initial bed level.

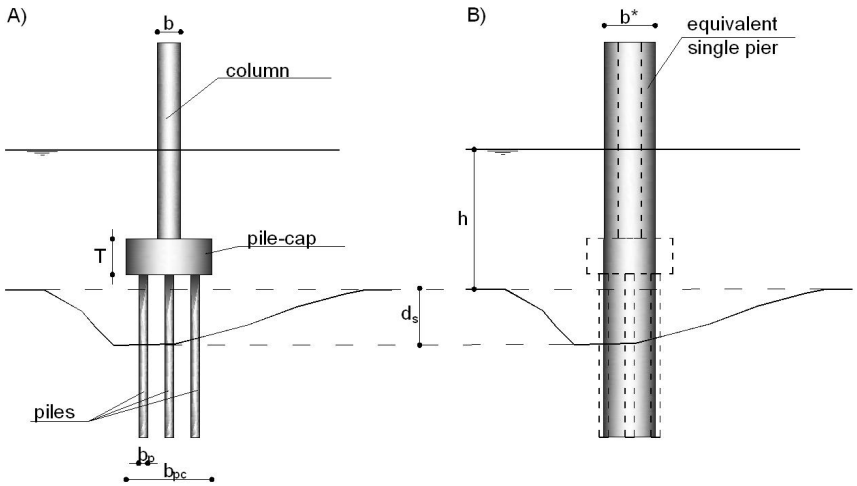

Figure 1. Sketch of a complex pier and its equivalent single pier.

The following elementary configurations may be assumed as reference (Figure 2):
1) the column is exposed to the approach flow; the distance between the pile-cap top and the initial bed level, Y, is greater than the scour depth ($Y<-d_s$; Y is negative when the pile-cap is below the initial bed level);
2) the pile-cap is exposed inside the scour hole; the distance between the pile-cap top and the initial bed level is greater or at limit equal to the column diameter, b, ($Y>-d_s$; $Y<-b$;);
3) the pile-cap is entirely exposed inside the scour hole; the distance between the top of the pile-cap and the initial bed level is shorter than the column diameter, b, or at limit equal to zero *($Y>-d_s$; $Y>-b$)*;
4) the pile-cap is exposed to the approach flow; its the extension above the initial bed level is smaller than its thickness, T, ($Y<T$); the piles may be exposed once the scour hole matures;

5) the pile-cap is entirely exposed to the approach flow and outside the scour hole; the piles are exposed; the distance between the water surface and the top of the pile-cap ranges from the water depth, *h*, minus the pile-cap thickness to zero (*Y*>*T*);
6) the pile-cap is partially exposed to the approach flow and its top is above the water surface (*Y*-*T*)<*h*;
7) only the piles are exposed to the approach flow; the pile-cap is entirely above the water surface *(Y*-*T*>*h*).

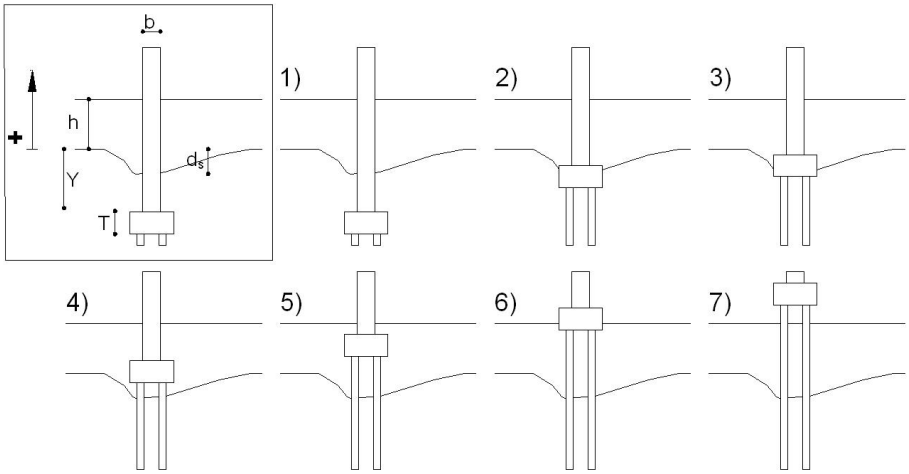

Figure 2. Schema of the elementary configurations for a complex pier.

SCOUR PREDICTION AT COMPLEX PIERS

Melville and Coleman (2000) (hereafter MC) identify five configurations for complex piers, corresponding to five ranges of *Y*: 1) $Y<-d_s$; 2) $Y>-d_s$; 3) $Y>T$; 4) $Y<h+T$; 5) $Y>h+T$. For cases 1) to 4), they consider the complex pier as a column founded on a caisson constituted by the pile cap as if the pile-cap extended down to the base of the scour hole and the pile group did not exist. In particular, for case 1), they assume $b^*=b$; for cases 2) and 3), b^* is given by:

$$b^* = b\left(\frac{h-Y}{h+b_{pc}}\right)+b_{pc}\left(\frac{b_{pc}+Y}{h+b_{pc}}\right) \tag{1}$$

For case 4), the scour depth is estimated by assuming $b^*=b_{pc}$; for case 5) b^* is assumed equal to the dimension of the piles group, as a whole, as seen from upstream, b_{pg} (pg stands for pile group) and corrective factors are assumed in the scour formula as a function of the number of rows, the pier alignment and the relation between spacing of piles and pile diameter. In the original contribution, the equilibrium scour depth is estimated by using the equivalent diameter in the scour predictor of Melville and Coleman (2000) for simple (single column cylindrical) piers.

In Richardson and Davis (2001) method (hereafter RD), the scour depth at a complex pier depends on the scour produced by each components of the complex pier (*i.e.*, column, pile-cap and piles): the "superposition of the scour components" is considered. Details are not included here due to lack of space; the method includes graphical procedures. The authors assess the scour depth through the Colorado State University (CSU) formula, as derived for simple piers.

Coleman (2005) (hereafter Co) distinguishes four different cases to estimate the effective pier diameter:

$$b^* = b \qquad \text{if } Y \le -b \tag{2}$$

$$b^* = b\left(\frac{b}{b_{pc}}\right)^{\left\{\left(\frac{b}{b_{pc}}\right)^3+0.10-\left[0.47\left(0.75+\frac{Y}{b}\right)^{0.5}\right]\right\}} \qquad \text{if } 0>|Y|\ge|Y_T|, \tag{3}$$

Y_T being pile-cap elevation Y at which cap is undercut and piles exposed to flow.

$$b^* = \left[\frac{0.52Tb_{pc}+(h-0.52T)b_{pg}}{h}\right] \qquad \text{if } Y = h \tag{4}$$

$$b^* = b_{pg} \qquad \text{if } Y \ge h+T \tag{5}$$

The equilibrium scour depth is estimated by using the equivalent diameter in the formulation of Melville and Coleman

(2000).

Sheppard (2005) proposes a method for complex piers (hereafter Sh) based on the evaluation of the effective diameter of each component, depending on their size, shape, location and orientation relative to the flow. The equivalent diameter for the complex pier can be approximated by the sum of the effective diameters of each component.

$$b^* = b^*_c + b^*_{pc} + b^*_p \tag{6}$$

In the equation b^*_c, b^*_{pc} and b^*_p are the equivalent diameters for column, pile-cap and a single pile respectively. They are given by empirical relationships. Once b^* is calculated, d_s can be obtained as:

$$\frac{d_s}{b^*} = 2.5 \tanh\left[\left(\frac{h}{b^*}\right)^{0.4}\right]\left\{1 - 1.75\left[\ln\left(\frac{U}{U_c}\right)\right]^2\right\}\left[\frac{b^*/d_{50}}{0.4(b^*/d_{50})^{1.2} + 10.6(b^*/d_{50})^{-0.13}}\right] \tag{7}$$

where U is the approaching flow velocity; U_c is the critical velocity for the beginning of sediment motion; and d_{50} is the median grain size.

When the shape of the structure exposed to the flow changes as scour progresses (as in piers with buried or partially buried pile caps), the scour depth prediction involves iterative computations. The author assumes three cases: 1) pile cap above the initial bed; 2) partially buried pile caps; and 3) completely buried pile caps.

Apart from the formulations inherent to the described methods, three other formulae for local scour at a simple piers were considered, namely those of Breusers *et al*. (1977), Hancu (1971) and Shen *et al*. (1969).

EXPERIMENTAL FACILITIES

Twelve laboratory experiments were carried out in order to collect data for evaluating the performance of the four complex pier methods. A rectangular flume was used (see Sousa, 2007 for details). It is made of steel with glass sidewalls. The flume length and width are respectively 8.00m and 0.70m. The bottom is horizontal. The flume has a working reach with a 2.00m long, 0.70m wide and 0.26m deep bed recess; it is located 4.50m downstream of the entrance. The approach reach is sparsely covered with gravel so as to favour the development of the rough boundary layer. The flume is equipped with a drainage system, a downstream tailgate and a moving carriage. Uniform sand was used in the tests to fill the recess. It is a coarse sand with median grain size d_{50}=0.83mm and geometric standard deviation $\sigma_g=(d_{84}/d_{16})^{0.5}$=1.48; the submerged sediment specific gravity $\Delta=\rho'_s/\rho\approx1.65$ being ρ'_s the buoyant sediment density and ρ the water density. No sediment feeding needed to be provided during the experiments.

A PVC complex pier was placed in the centre of the recess box (Figure 3). It was composed by a column, a pile-cap and four piles, all of cylindrical shape, whose diameters were 0.048m, 0.150m and 0.025m, respectively.

An electromagnetic flowmeter, positioned on the feeder pipe, allowed obtaining discharge measurement; flow depths and the bed levels in front of the pier were measured using point gauges with decimal vernier installed on the moving carriage.

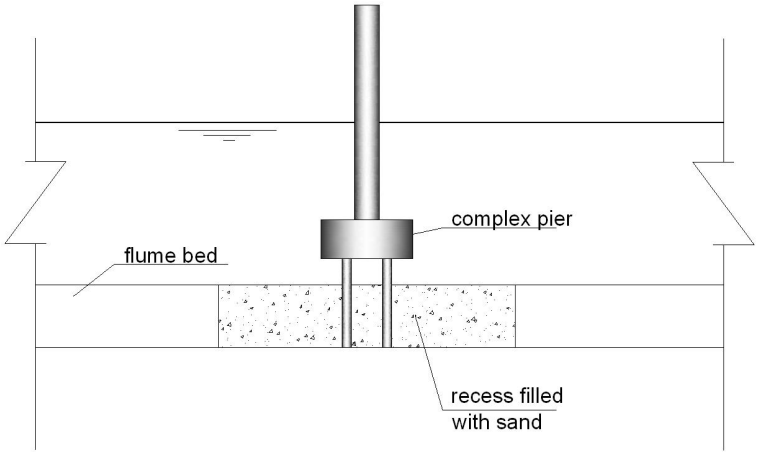

Figure 3. Schema of the complex pier installation.

DESIGN OF THE TESTS

Tests were designed in order to experimentally reproduce all the seven configurations described in Figure 1. The complex pier dimensions, the flow depth and the discharge were chosen so as to satisfy the following conditions (see, e,g., Grimaldi, 2005):

- for the column: i) $Re_{p(b)}= Ub/\nu>7000$ (Re_p and ν being the pier Reynolds number and the water kinematic viscosity respectively) to avoid viscous effect; ii) $h/b\geq2$ to avoid the flow shallowness effect; iii) $B/b\geq10$, not to have contraction scour; iv) $b/d_{50}\geq50$, to render the local scouring independent of d_{50};
- for the pile-cap: $Re_{p(bpc)}= Ub_{pc}/\nu>7000$; $b_{pc}/d_{50}\geq50$;
- for the piles group: $Re_{p(bpg)}= Ub_p/\nu>7000$; $h/b_{pg}\geq2$; $B/b_{pg}\geq10$; $b_{pg}/d_{50}\geq50$.

In addition, the ratio B/h was taken into account in order to guarantee that the flume behaves as wide ($B/h>5$; B being the flume width).

It is to be noted that no flow shallowness and the contraction scour effect were assumed as related with the pile-cap.

Tests were performed under the condition of beginning of sediment motion, with $U/U_c\approx1$, so as to maximize the scour depth. Each test was run until the equilibrium was reached, according to the method suggested by Cardoso and Bettess (1999) on the issue. Summing up, tests were designed according to the values reported in Table 1, where b_p is the diameter of a simple cylindrical pile, n is the number of piles and p the distance between axes of adjacent piles.

Table 1. Design of the tests.

B (m)	h (m)	d_{50} (mm)	b (m)	b_{pc} (m)	b_p (m)	b_{pg} (m)	T (m)	n	p (m)	$U\approx U_c$ (m/s)	Q (m^3/s)
0.70	0.10	0.83	0.048	0.15	0.025	0.05	0.05	4	0.075	0.29	0.020

Fr	$Re_{p(b)}$	$Re_{p(bpc)}$	$Re_{p(bpq)}$	h/b	h/b_{pq}	b/d_{50}	b_{pc}/d_{50}	b_{pq}/d_{50}	B/b	B/b_{pq}	B/h
0.29	13714	42857	14286	2	2	58	181	60	15	14	7

RESULTS AND DISCUSSION

Figures 4 and 5 show the variation of measured and predicted scour depths with the pile cap elevation, Y. Structural collapsing situations potentially occur in the cases where predicted values are smaller than the measured ones.

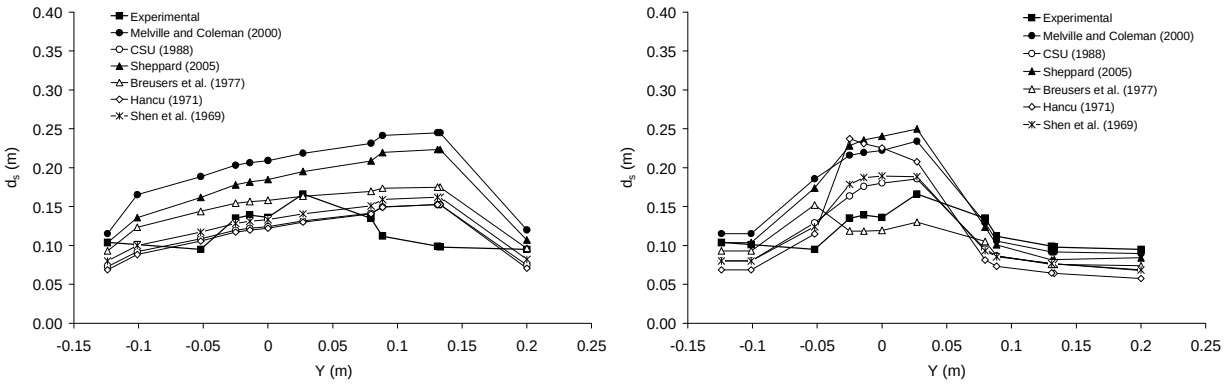

Figure 4. Measured and computed local scour depths with the MC (left graph) and RD (right graph) complex pier methods.

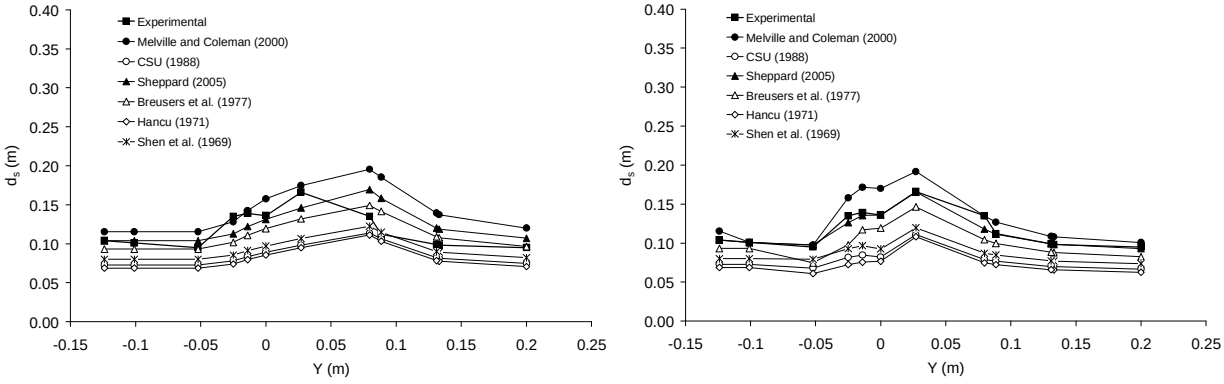

Figure 5 . Measured and computed local scour depths with the Co (left graph) and Sh (right graph) complex pier methods.

From Figure 4 and 5 it is clear that the calculated scour depth varies with Y. The six curves calculated via the Sh method – one per scour formula – display the same overall shape as the experimental curve; on the contrary, the MC and Co methods do not follow the experimental trend irrespective of the scour formula they were combined with. Finally, depending on the formula combined with the RD method, some reproduce the observed trend and some others do not.

The performance of each complex pier method plus scour formula combination was further evaluated through three statistical parameters: the Theil's coefficient, *E*, the Mean Absolute Error, *MAE*, and the Root Mean Square Error, *RMSE*,

$$E = \frac{\left[\frac{1}{n}\sum_{i=1}^{n} e_i^2\right]^{\frac{1}{2}}}{\left[\frac{1}{n}\sum_{i=1}^{n}\left(d_{se(i)}\right)^2\right]^{\frac{1}{2}} + \left[\frac{1}{n}\sum_{i=1}^{n}\left(d_{s(i)}\right)^2\right]^{\frac{1}{2}}} \tag{8}$$

$$MAE = \frac{\sum_{i=1}^{n}|e_i|}{n} \tag{9}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n}} \tag{10}$$

where

$$e_{(i)} = d_{se(i)} - d_{s(i)} \tag{11}$$

$d_{se(i)}$ and $d_{s(i)}$ being the predicted and the measured scour depth at a given *Y*.

Tables 2 to 5 report the values of *E*, *MAE* and *RMSE* for each method and formula. The simple-pier scour formula originally associated with a given complex-pier scour method is identified in bold; the grey squares indicate the lower values of each statistical parameter.

It is interesting to note that the MC method achieves the lower values of *E* and *RMSE* in combination with the CSU formula. However, Figure 4 (left graph) shows that the CSU formula largely underestimates the scour depth largely for some *Y* values; the best performance with no underestimation is obtained with the formula of Breusers *et al*. (1977).

The RD and Co methods render to the lower values of all the statistical parameters when combined with the formula by Breusers *et al.* (1977). The RD method predicts scour underestimations in combination with all the scour formulae. The Co method produces the most reliable predictions, with no underestimation, if combined with the formulation of Melville and Coleman (2000); consistent overestimations appear for piles exposed to the flow.

The Sh method produces rather precise predictions in combination with its original formula of scour for simple piers.

Table 2 – Values of *E*, *MAE* and *RMSE* for the MC method.

	Melville and Coleman (2000)	*CSU*	*Sheppard (2005)*	*Breusers et al. (1977)*	*Hancu (1971)*	*Shen et al. (1969)*
E	0.282	0.123	0.236	0.154	0.128	0.128
MAE	0.081	0.025	0.059	0.033	0.027	0.024
RMSE	0.091	0.030	0.071	0.042	0.031	0.032

Table 3 – Values of *E*, *MAE* and *RMSE* for the RC method.

	Melville and Coleman (2000)	***CSU***	*Sheppard (2005)*	*Breusers et al. (1977)*	*Hancu (1971)*	*Shen et al. (1969)*
E	0.189	0.122	0.211	0.119	0.217	0.135
MAE	0.039	0.029	0.044	0.024	0.051	0.032
RMSE	0.053	0.030	0.060	0.027	0.057	0.034

Table 4 – Values of *E*, *MAE* and *RMSE* for the Co method.

	Melville and Coleman (2000)	*CSU*	*Sheppard (2005)*	*Breusers et al. (1977)*	*Hancu (1971)*	*Shen et al. (1969)*
E	0.129	0.182	0.088	0.085	0.201	0.145
MAE	0.027	0.032	0.018	0.016	0.036	0.025
RMSE	0.034	0.037	0.022	0.020	0.041	0.031

Table 5 – Values of *E*, *MAE* and *RMSE* for the Sh method.

	Melville and Coleman (2000)	*CSU*	***Sheppard (2005)***	*Breusers et al. (1977)*	*Hancu (1971)*	*Shen et al. (1969)*
E	0.071	0.211	0.024	0.088	0.243	0.160
MAE	0.014	0.040	0.003	0.018	0.045	0.031
RMSE	0.018	0.042	0.006	0.020	0.047	0.033

CONCLUSIONS

Four methods commonly used for estimating the depth of local scour at complex bridge piers were selected for evaluation against new experimental data. The four methods were combined with six formulae for the scour depth estimation at simple cylindrical piers. In particular, the following scour formulae were considered: Melville and Coleman (2000), CSU, Breusers *et al.* (1977), Sheppard (2005), Hancu (1971), Shen *et al.* (1969).

Sh method, combined with its original scour formula, is the most adequate to predict the scour depth at tested the complex pier. Its predictions led to the lower values of *E*, *MAE* and *RMSE*. MC method seems to be the most conservative and renders the lower values of *E* and *RMSE* in combination with the CSU formula.

RD method potentially leads to both important overestimations and underestimations of the scour depth, depending on the position of the pile cap.

Co method predicts no underestimation in association with the formulation of Melville and Coleman (2000) but overestimates scour in the case of piles exposed to the flow, irrespective of the adopted simple pier scour predictor.

REFERENCES

Breusers H.N.C., Nicollet, G., Shen, H.W. (1977). Local scour around cylindrical pier, *J. Hydr. Res.*, IAHR, 15(3), 211-252.

Cardoso, A.H., Bettess, R. (1999), Effects of time and channel geometry on scour at bridge abutments, *J. Hydr. Engrg.*, ASCE, 125(4), 388-399.

Coleman, S.E. (2005). Clearwater local scour at complex piers, *J. Hydr. Engrg.*, ASCE, 131 (4), 330-334.

Dargahi, B. (1987). Flow field and local scouring around a cylinder, Bulletin No. TRITA-VBI-137, Royal Institute of Technology, Stockholm, Sweden.

Dey, S., and Raikar, R.V. (2007). Characteristics of horseshoe vortex in developing scour holes at piers, *J. Hydr. Engrg.*, ASCE, 133(4), 399-413.

Graf, W.H., Istiarto, I. (2002). Flow pattern in the scour hole around a cylinder, *J. Hydr. Res.*, IAHR, 40(1), 13-20.

Grimaldi, C. (2005). Non-conventional countermeasures against local scouring at bridge piers. Dissertation for Doctorate degree in Hydraulic Engineering for Environment and Territory. Cosenza, Italy: University of Calabria.

Hancu, S. (1971). Sur le calcul des affouillements locaux dams la zone des piles de ponts, *XIV IAHR Congress*, Paris, France.

Melville, B.W., Coleman, S.E. (2000). Bridge scour, Water Resources Pub., LLC, Highlands Ranch, CO, USA.

Richardson, E.V.; Davis, S.R. (2001). Evaluating scour at bridge - Fourth Edition, Hydraulic Engineering Circular No. 18, Publication No. FHWA NHI 01-001, U.S. Department of Transportation, USA.

Sheppard, D. M. (2005). Bridge Scour Manual, Florida Department of Transportation, Florida.

Shen, H.W., Schneider, V.R., Karaki, S.S. (1969). Local scour around bridge piers, *J. Hydr. Div.*, ASCE, 95(6), 1919-1940.

Sousa, A. M. (2007). Erosão localizada em pilares cilíndricos complexos, M.S. Thesis, Instituto Superior Técnico, Lisboa.

U.S. Department of Transportation (1988), Interim Procedures for Evaluating Scour at Bridges, Federal Highway Administration, Washington, D.C.

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