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Effects of Pile Caps on Local Scour at Bridge Piers

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The most existing pier-scour equations mainly apply to uniformly shaped piers (i.e. piers with a constant horizontal cross-section geometry over their length). However, actual bridge piers have composite shapes. Typical examples are piers founded on plinths, caissons, or piles. Pier footings may often project above the streambed because of scour. This may be caused by either long-term bed degradation or local scour. In such cases, the computation of the local bridge scour depth becomes complicated because of the difficulty in choosing an appropriate pier dimension. Referring to piers founded on piles, in previous papers (references [7] and [8]) some outcomes were achieved, mainly on the quasi-equilibrium scour depth. Based on additional experiments, this paper would like to come up with a deepening of the previous findings and provide new insights on the temporal evolution of the river-bed morphology around the pier. Tests typically lasted some days to provide a more effective interaction between the flow and the complex pier-plinth-piles. The results could provide useful tools in design, numerical modeling and field investigations.

I. INTRODUCTION

Bridge piers are often founded on piles mainly due to geotechnical and economic reasons. This kind of foundation is commonly considered a guarantee for the safety of the bridge structure against any scouring problems. However, pier footings may often project above the streambed as result of either long-term degradation, lateral shifting of the stream, contraction scour, or local scour during a runoff event. For such cases piles should be designed to resist to a certain exposure to the flow and the footing location should be designed on structural and hydraulic bases. Moreover, when general scour produces a significant bed lowering, the safety reassessment of the bridge requires a new local scour prediction that must consider the combined pier/foundation pile geometry. Figs. 1 and 2 provide two field examples of local and general scour around piers founded on piles.

Papers dealing with the effects of such a combined geometry on scour depth are rare in literature. Based on a laboratory study, the Authors of reference [3] evaluated how the effect of footing location can be taken into account in scour prediction equations that use a single characteristic pier size. They found that a weighted width technique provides simple and accurate estimations. Their analysis did not account for the scour-arresting effects for footings located below the streambed. HEC-18 [10] provides some guidelines for evaluating local scour at exposed pile caps. It is recommended that the pier width should be used in a scour equation if the top of the pile cap is at or below the streambed. If the pile cap is placed into the flow, its width should be considered instead of the pier width. However, the HEC-18 procedure is based on few data and many engineers consider it conservative, especially for large piers. An experimental investigation of scouring at rectangular piers founded on two circular cylindrical piles is [4]. That research was thus focused on a pure two-width problem, while disregarding more complex geometries. Preliminary results on physical models composed by pier, pile cap and pile group were given in [2]. A detailed references list is provided in [5]. More recently, a new methodology to predict local scour depth at a complex pier was presented in [1]. In particular, the method distinguishes the different scouring processes for different pile-cap elevations.

Figure 1. River Basento (Italy): Local scour around the plinth of a pier founded on piles

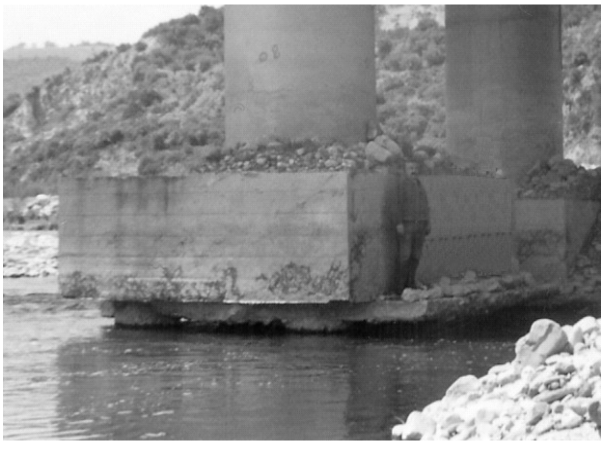


Figure 2. River Basento (Italy): General scour around a pier with consequent exposure of the piles

All these studies are mainly focused on conditions of quasi-equilibrium scour depth. Moreover, the proposed design procedures are specific and preliminary because of the complexity of the problem and the large number of parameters involved.

In this context, a research project was initiated at University of Basilicata for developing general and straightforward design criteria. This paper would like to provide some results on the temporal evolution of the scour depth around the pile cap and, in particular, upstream and downstream of it. This, by highlighting differences with uniform cylindrical piers.

II. EXPERIMENTAL SETUP

Experiments were conducted in a 1 m wide and 20 m long rectangular straight channel at the Hydraulic Engineering Laboratory, University of Basilicata, Italy. The working section was about 10 m. The bed material was a nearly uniform sand with density ρ_s = 2.65 t/m^3, grain size d_{50} = 1.7 mm and sediment gradation $\sigma = (d_{84}/d_{16})^{1/2}$ = 1.5. The scour elements were three-width models consisting of a cylindrical pier of diameter D, a square pile cap of width B and thickness T, and 4 cylindrical piles of diameter d, spaced each other by s. A definition sketch is given in Fig. 3.

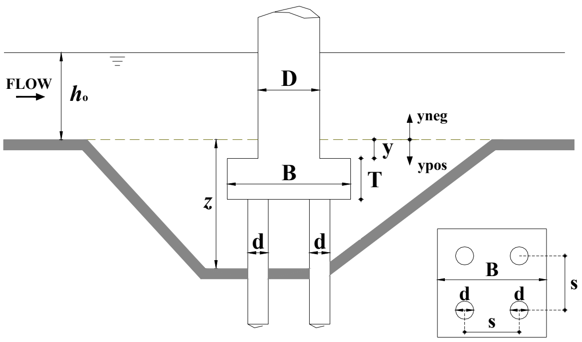


Figure 3. Definition sketch of the scour element and hydraulic variables

Two models were tested. One had D = 0.12 m, B = 0.24 m, T = 0.08 m, and d = 0.04 m. The other had D = 0.06 m, B = 0.12 m, T = 0.04 m, and d = 0.02 m. All model dimensions were multiples of the piles diameter.

All the experiments were run under plane bed conditions, steady flow, and clear-water scour regime. Moreover, the models were always set with the top elevation of the pile cap placed at the initial bed level.

Discharges Q were measured with an orifice plate with ±3% of accuracy. Water surface was surveyed with a conventional point gage, typically ±0.5 to 1 mm, whereas the bed morphology was surveyed with a so called shoe gage having 4 mm by 2 mm wide horizontal plate at its base. The tests were of long duration, typically 2 days up to 13 days, to ensure an adequate interaction between flow and the complex pier-plinth-piles and to get conditions of quasi-equilibrium. Measurements during the test were carefully taken in extensive regions around the pile cap.

The approach flow depth was controlled by an adjustable sharp-crested weir located at the channel downstream end. Once the bed was accurately leveled the experiment initiated submerging the working section by setting the sharp-crested weir up. This was lowered within 10 to 20 seconds to the pre-selected flow depth and the temporal start of the experiment was set at scour inception. Photograph in Fig. 4 is an upstream view of the experimental stand.

Figure 4. Upstream view of the experimental stand

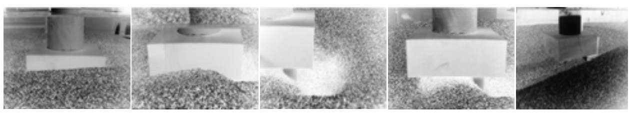
Test conditions and measured scour depths are presented in Tab. I, with h_o = approach flow depth, $\mathsf{F}_d = V_o/(g' d_{50})^{1/2}$ = approach densimetric Froude number, V_o = approach velocity, g = gravitational acceleration, , g' = $[(\rho_s-\rho)/\rho]$g, ρ = fluid density, z = maximum scour depth at the experiment's end, and t_t = test duration.

TABLE I. TEST CONDITIONS AND MEASURED SCOUR DEPTHS

Run	D	B	h_o	F_d	z	t_t
-	cm	cm	cm	-	cm	hours
1	12.0	24.0	5.6	1.99	9.8	47.8
2	12.0	24.0	11.6	2.36	18.5	313.2
3	12.0	24.0	13.3	2.05	14.2	66.7
4	12.0	24.0	21.8	2.22	13.1	52.5
5	12.0	24.0	29.2	3.01	22.4	21.5
6	6.00	12.0	5.5	2.35	10.8	43.0
7	12.0	24.0	10.6	2.63	18.3	271.3
8	6.0	12.0	10.8	2.37	12.0	216.4

III. EXPERIMENTAL EVIDENCES

Fig. 5 provides a typical evolution of the scour area around a pier founded on piles. At the beginning of the scour process the maximum scour depth tends to be located at the downstream edge of the pile cap. Successively, it migrates toward the pile cap front so that the exposition of the piles to the flow occurs first upstream and only after a long time downstream.



(a) (b) (c) (d) (e)

Figure 5. Run 2: Temporal scour evolution around a pier founded on piles after (a) 10 hours, (b) 20 hours, (c) 4 days, (d) 10 days, and (e) 12 days

Fig. 6 refers to the typical bed morphologies observed in the laboratory and in the field at the first phase of the scour process. Conditions encountered in the field were similar to those observed during the experiments.

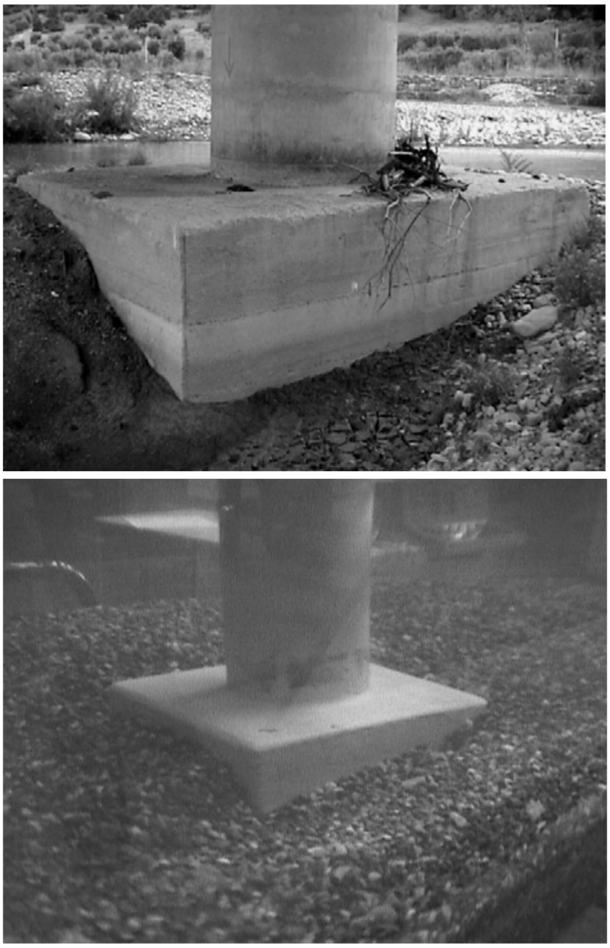


Figure 6. Local scour observed around a pile cap in the field (above) and in the laboratory (below)

Fig. 7 provides the bed contours during and at the end of the two runs 7 and 8. The first three plots show the bed morphology for the run 7 at 23, 142, and 271 hours after the run-start. It can be noted as the scour region tended to elongate downstream of the pile cap as two distinct and divergent ogival-shaped areas. The upstream part of the scour hole developed with slope almost equal to the angle of repose of the bed material. The bed configuration appeared to be satisfactorily symmetric. Similar bed morphologies were observed, but with less distinctness, also for the run 8. The second set of plots refers to this run at 0.5, 48, and 216 hours after the run-start. The aggradation zone tended to growing up axially downstream of the pile cap becoming shallow or even disappearing when the scour process approached its quasi-equilibrium phase. In both runs the maximum observed longitudinal extension of the scour region was remarkable and equal to about 6 times the pile cap width B. The hole's edges spanned significantly also in the transverse direction by about $4B$.

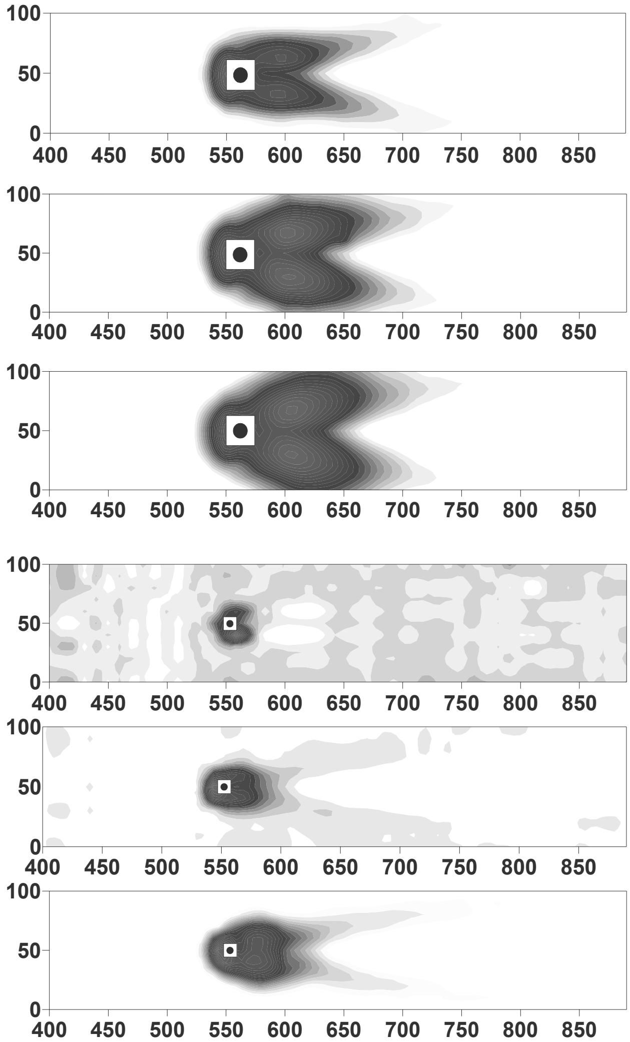


Figure 7. Bed contours during and at the end of the runs 7 (first three plots) and 8 (second set of plots)

IV. Data Analysis and Conclusions

The scour equation suggested in [6] for the temporal progress of scour at uniformly shaped piers was assumed as framework for this analysis. This equation was supported by an extensive experimental work. Tests were performed in two rectangular channels of width 1.0 and 0.5 m. Using three uniform and three non-uniform sediments of average grain sizes d_{50} between 0.5 and 5 mm, pier diameters D between 5% and 50% of the channel width, and approach flow depths h_o between 10 and 500 times the average grain size, the temporal scour evolution $z(t)$ around cylindrical bridge piers under clear-water conditions was investigated. It was found that the maximum scour depth z depends on three main parameters, namely the reference length $L_R = D^{2/3} h_o^{1/3}$; the densimetric Froude number $\mathsf{F}_d = V_o/(g' d_{50})^{1/2}$; and the relative time $T = [\sigma^{1/3}(g' d_{50})^{1/2}/L_R]t$ as

$$Z = 0.068\sigma^{-0.5}\mathsf{F}_d^{1.5}\log(T) \qquad \mathsf{F}_d > \mathsf{F}_{di}. \qquad (1)$$

Here $Z=z/L_R$ and F_{di} is the value of F_d for sediment entrainment around the pier. For square-shaped piers the second member of (1) should be multiplied for a shape factor N=1.25.

More recently, the following equation interpreting the temporal trend of the scour depth at rear of a cylindrical pier has been proposed in [9]

$$\frac{Z_r \sigma^{0.5}}{\mathsf{F}_d^{1.5}} = 0.086\log(T) - 0.16 \quad \mathsf{F}_d > \mathsf{F}_{di} \tag{2}$$

with subscript r = rear. Equation (2) applies for flows in transitional regime (i.e. 15<D*<150, where $D^*=(g'/\nu^2)^{1/3}d_{50}$ is the dimensionless grain size and ν is the fluid kinematic viscosity).

In the following the ratio $Z\sigma^{0.5}/\mathsf{F}_d^{1.5}$ will be denoted as ζ. More specifically ζ_D and ζ_B will denote the values of ζ when D and B are assumed as effective pier width, respectively.

With reference to the run 2 lasted 13 days, Fig. 8 shows the temporal trend for the scour depth upstream and downstream of the pile cap.

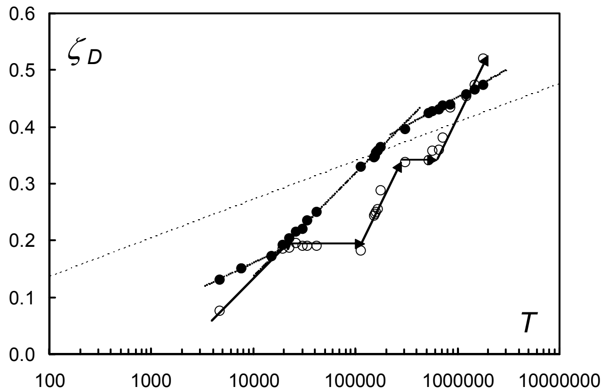


Figure 7. Run 2: $\zeta_D=Z\sigma^{0.5}/\mathsf{F}_d^{1.5}$ as a function of dimensionless time T by assuming D as the effective pier width. Temporal evolution of scour depth upstream (●) and downstream (○) of the pile cap. (········) Equation (1)

The analysis of the plot would involve the following considerations. With reference to the scour progress upstream of the pile cap one can observe that:

- Scour starts after a certain delay compared to a uniform cylindrical pier of the same diameter D, owing to the collar-like protection exerted by the plinth;
- Then, the scour process develops until about $T=2\cdot10^4$ at a similar rate as that of a uniform cylindrical pier of the same diameter D;
- Successively ($2\cdot10^4<T<2\cdot10^5$), the scour rate increases owing to the exposure of the plinth that would determine an increasing of the effective element width;
- Lastly ($T>2\cdot10^5$), the scour rate would tend to decrease again owing to the exposure of the piles with a consequent reduction of the effective obstacle width.

While, the scour evolution downstream of the pile cap exhibits a two-step trend probably connected to the upstream piles exposure first and to the exposure of the complete pile group afterwards. This exposure would imply a compression of the flow between the piles thus creating higher velocities and greater scour potential.

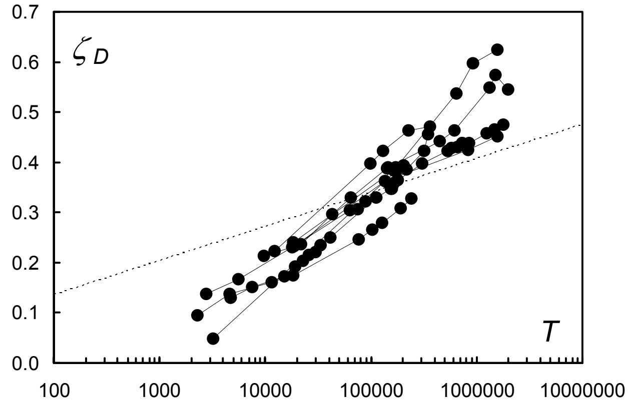


Figure 8. $\zeta_D=Z\sigma^{0.5}/\mathsf{F}_d^{1.5}$ as a function of dimensionless time T by assuming D as the effective pier width. (········) Equation (1)

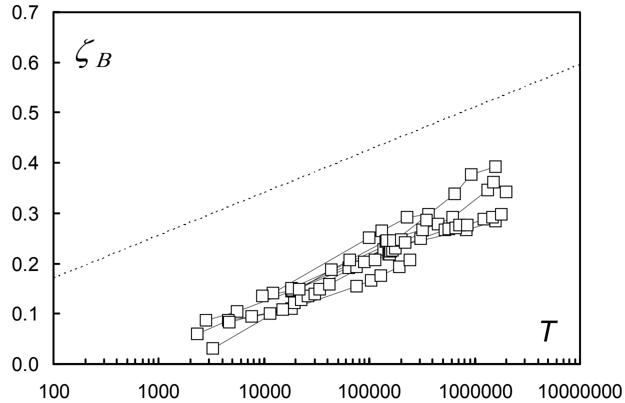


Figure 9. $\zeta_B=Z\sigma^{0.5}/\mathsf{F}_d^{1.5}$ as a function of dimensionless time T by assuming B as the effective pier width. (········) Equation (1) multiplied for the shape factor 1.25

The plot in Fig. 8 refers to the temporal trend of the maximum scour depth. Typically, such scour depth was located just upstream of the pile cap except for the initial phase of the process in which it localized at the lateral of the pile cap and for very high values of T ($T>10^6$) when it localized even downstream of the pile cap mainly because of the exposure of the piles. It can be observed that:

- For $T<10^3$ the pile cap performs as a good protection so that the scour process appears completely inhibited;
- For $10^3<T<10^5$ the pile cap performs as a scour mitigator because the scour depths tend to be smaller than those that would occur for a uniform cylindrical pier at the same flow conditions;
- For $T>10^5$ the pile cap is significantly exposed to the flow and thus the scour depths are greater than those for a uniform cylindrical pier of the same diameter D because of an increasing of the effective pier width;
- Lastly, for $T>10^6$, as above said, the maximum scour depth would tend to localize downstream of the pile cap mainly because of the pile group exposure.

The plot in Fig. 9 shows the discrepancies between observed and computed scour values when, as usual, data are interpreted by assuming the plinth width as the effective element width. Differences tend to be attenuated for T increasing. Nevertheless, overall such kind of method would appear too conservative.

Finally, the plot in Fig. 10 shows the temporal evolution of the scour depth downstream of the pile cap.

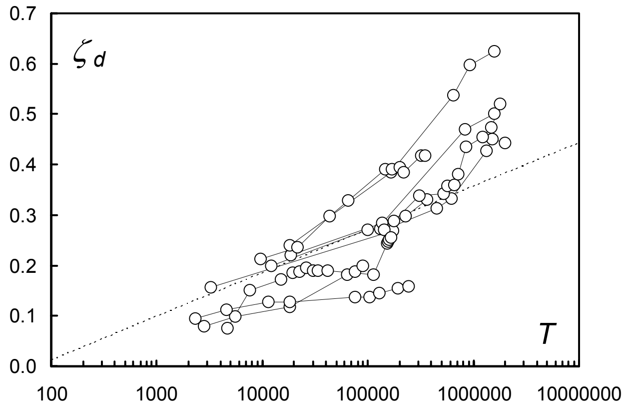


Figure 10. $\zeta_d=Z\sigma^{0.5}/\mathsf{F}_d^{1.5}$ as a function of dimensionless time T downstream of the pile cap and by assuming D as the effective pier width. (········) Equation (2)

In general, scour depths are significantly greater than those at uniform cylindrical piers with divergences increasing as T increases. The trend in the plane (ζ, log$T$) is manifestly not linear because the changing in the time of the effective element width would significantly affect the features of scour mechanisms.

Acknowledgment

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