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# Effect of pier shape and pier alignment on the equilibrium scour depth at single piers

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ABSTRACT

The equilibrium scour depth at uniform single bridge piers depends on a large number of variables, including the pier horizontal cross-section shape and its alignment angle towards the flow direction. The influence of these variables has been studied by only a few researchers, mostly, on the basis of tests that were far from approaching equilibrium. This experimental study aims at revisiting the influence of piers' shape and alignment on local scouring for length–width ratios smaller than or equal to 4, by increasing the experimental evidence. Fifty five long-duration laboratory tests were run under steady, clear-water flow, close to the threshold for initiation of sediment motion. Five pier shapes were considered: circular, rectangular square-nosed, rectangular round-nosed, oblong, and zero-spacing (packed) pile-groups; the tested skew-angles were 0°, 30°, 45°, 60°, and 90°. It was concluded that i) the shape factor can be taken as 1.0, for rectangular round-nosed and oblong cross-section piers, and as 1.2, for rectangular square-nosed and packed pile-group cross-section piers, ii) the shape factor does not vary significantly with the duration of tests, this way confirming the robustness of the shape factors reported to date, iii) the effect of shape is present at skewed piers although the associated coefficients remain in the narrow range of 1.0–1.2, and iv) for length–width ratios smaller than 4, the shape factor is of the same order of magnitude as the skew angle factor and should not be neglected.


## 1. Introduction

Local scour at bridge foundations is a rather common cause of bridges' failure. Consequently the prediction of the ultimate "equilibrium" scour depth is a key issue in bridge engineering. In spite of the progresses made on this topic during the last five or six decades, it remains a subject of concern in hydraulic engineering.

According to Lança (2013), among others, the scour depth, $d_s$, around uniform single piers depends on the flow depth, $d$, slope of the energy line, $S$, and acceleration of gravity, $g$; fluid density, $\rho$, and kinematic viscosity, $\nu$; median grain size, $D_{50}$, gradation coefficient, $\sigma_D$, and density, $\rho_s$, of the bed material; pier width, $D_p$, alignment, and shape of the horizontal cross-section; channel width, $B$, bed slope, $S_0$, cross-section geometry; and time, $t$. Piers' alignment and shape are usually accounted for through the coefficients $K_\theta$ and $K_s$, respectively.

For fully developed, clear-water uniform flow, in a wide rectangular flatbed channel whose bed is composed of uniform, non-ripple forming sand, the non-dimensional scour depth can be shown to read (Lança, 2013):

$$\frac{d_s}{D_p} = \varphi\left(\frac{d}{D_p}, \frac{U}{U_c}, \frac{D_p}{D_{50}}, \frac{Ut}{D_p}, K_s, K_\theta\right) \tag{1}$$

In this equation, $U$ is the average velocity of the undisturbed approach flow and $U_c$ is the approach flow velocity for the threshold condition of the sediment entrainment. Eq. (1) applies if scouring is free of viscous effects. Compared, for instance, with the framework suggested Ettema et al. (2011), the above equation does not include the Froude number or any Froude-like number since this is not compatible with the simultaneous inclusion of flow intensity, $U/U_c$, and $D_p/D_{50}$. This is clear, *e.g.*, in Melville (1992). For constant $U/U_c$ (usually $U/U_c \approx 1.0$ in laboratory conditions so as to

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maximize the scour depth), the non-dimensional equilibrium scour depth becomes:

$$\frac{d_{se}}{D_p} = \phi\left(\frac{d}{D_p}, \frac{D_p}{D_{50}}, K_s, K_\theta\right) \tag{2}$$

since the scour depth no longer evolves at equilibrium.

The effect of flow shallowness, $d/D_p$, on scouring is unanimously recognized as inescapable and it has been the subject of many studies on scouring. Most of these studies have successively assumed that the equilibrium scour depth does not depend on sediment coarseness, $D_p/D_{50}$, for $D_p/D_{50} > 25$–$50$ and this is still the prevailing view in the hydraulics community. However, Sheppard et al. (2004) and Lee and Sturm (2009) have shown that the effect of $D_p/D_{50}$ cannot be discarded for much higher values of $D_p/D_{50}$. Lança et al. (2013b) have corroborated these findings. The predictors issued from these recent studies account for the simultaneous effects of the flow shallowness, $d/D_p$, and sediment coarseness, $D_p/D_{50}$. For practical use, such predictors necessarily require the application of multiplying factors to include the effects of flow intensity, pier shape, pier alignment, gradation coefficient and density of bed the material, flow contraction, cross-section shape and time.

The pier shape multiplying factor is defined as the ratio between the scour depth at a pier with a given shape of the horizontal cross-section and the scour depth at the standard section-shape pier, all the other parameters kept constant. Likewise, the pier alignment or orientation factor is defined as the ratio between the scour depth at a pier aligned at a given angle (angle of attack) with the flow direction and the scour depth at an equal pier aligned with the flow direction (zero angle of attack), all the other parameters kept unchanged.

The effects of pier shape and alignment have been studied by few researchers (the most well-known being Laursen & Toch, 1956). Yet, a variety of pier shape factors, $K_s$, were suggested by different researchers (*e.g.*, Melville, 1997 or Melville & Coleman, 2000), based on very limited experimental data. With the exception of Laursen and Toch (1956), who have used the rectangular pier as the standard shape, all the others have chosen the circular pier for that purpose. Richardson and Davis (2001) suggested the following expression that fits the multiplying factor for the angle of attack, $K_\theta$, obtained by Laursen and Toch (1956):

$$K_\theta = (\cos\ \theta + L/D_p\ \sin\ \theta)^{0.65} \tag{3}$$

where $\theta$ is the angle of attack, $D_p$ stands for the pier width and $L$ is its length.

According to Richardson and Davis (2001), $K_\theta$ should only be used if the angle of attack, $\theta$, is higher than 5° and $2 \le L/D_p \le 16$. It should be noted here that, according to Laursen and Toch (1956), $K_s$ and $K_\theta$ must not be used together since, in the above domain, the shape effect becomes negligible.

To the authors' best knowledge, no systematic studies other than those of Laursen and Toch (1956) were performed on the effect of angle of attack on local scour. Therefore, improving and updating the angle of attack factor is essential, in particular, for values of $L/D_p \le 4$, close the lower validity limit of Eq. (3).

This experimental study aims at revisiting the influence of piers' shape and alignment on local scouring, for uniform piers defined by $L/D_p \le 4$, by increasing the experimental evidence. It should be stressed here that most of the tests performed by Laursen and Toch (1956) lasted 3 h, under the assumption that, from there on, the pier alignment or orientation factor does not change. This is equivalent to assume that the scour holes remain self-similar, *i.e.*, that their non-dimensional geometry does not change in time irrespective of the pier shape and alignment. This specific point is also addressed in this study.

## 2. Experimental setup and procedure

Fifty five tests were performed in a 28.00 m long, 2.00 m wide and 1.00 m deep flume of the Universidade da Beira Interior. Sixteen of these tests were already published by Lança et al. (2013a) in a different context: four correspond to cylindrical piers, twelve correspond to special (packed) pile-groups, where piles touch each other ($s/b=1$, $s$=spacing between pile axes; $b$=pile diameter, *cf.* Table 1).

At the entrance of the flume, two honeycomb diffusers aligned with the flow direction smoothed the flow trajectories and guaranteed the uniform cross-wise flow distribution. Immediately downstream the diffusers, a 5.00 m long bed-reach was covered with small gravel to provide proper roughness and guarantee fully developed rough turbulent flow. The central reach of the flume, starting at 14.00 m from the entrance, included a 3.00 m long, 2.00 m wide and 0.60 m deep recess box in the channel bed. A uniform quartz sand ($\rho_s$= 2650 kg m$^{-3}$; $D_{50}$=0.86 mm; $\sigma_D$=1.36) was used to fill the recess box. At the downstream end of the flume, a tailgate allows the regulation of the water depth, which was kept equal to 0.20 m.

Five different pier shapes were considered in the study, according to Table 1, where the associated values of $D_p$ are summarized. All pier, except those circular shaped, were 200 mm long and installed with different angles of attack at 1.0 m from the upstream boundary of the bed recess box: these angles were $\theta$=0°, 30°, 45°, 60° and 90° for $\theta$ defined according to Table 1.

Prior to each experiment, the sand bed in the recess box was carefully leveled with the contiguous concrete bed. The area located around the pier was covered with a thin metallic plate to avoid uncontrolled scour at the beginning of each experiment. The flume was then filled gradually, imposing a high water depth and a low flow velocity. The discharge corresponding to the chosen approach flow velocity, measured by an electromagnetic flow meter with an accuracy of $\pm$0.5% of full scale, was then adjusted to pass through the flume. The flow depth was regulated by adjusting the downstream tailgate and measured with the help of a point gauge to the accuracy of $\pm$1 mm. Once the discharge and flow depth were established, the metallic plate was removed and the experiment started.

Scour immediately initiated and the depth of scour hole was measured, to an accuracy of $\pm$1 mm, with another(adapted) point gauge, approximately every 5 min during the first hour. Afterwards, the interval between measurements increased and, after the first day, only a few measurements were carried out each day. In agreement with Simarro et al. (2011), when at least 7 days had passed, the experiments were stopped. Fig. 1 shows the scour depth time evolution for test 50, which is similar to all the others.

The sand bed approach reach located upstream the piers stayed undisturbed through the entire duration of the experiments; this long term stability ensured that the scour depth was not supplemented by upstream bed degradation, as documented in Fig. 2. It should be noted here that no ripples developed along the tests because a practically uniform sand, characterized by $D_{50}$=0.86 mm, was used, which is physically incompatible with development of those bed forms (see, *e.g.*, Simons & Sentürk, 1992).

## 3. Results and discussion

### 3.1. Data characterization

The values of the most important control variables and non-dimensional parameters characterizing the experiments, including those reported by Lança et al. (2013a), are summarized in Table 2. It can be concluded that a high relative flow depth ($d$=0.200 m;