Local Scour Around Bridge Piers- A Study Of Its Effects Around Cylindrical Pier Groups

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Abstract

Laboratory experiments were conducted to measure local scour around cylindrical piers in different arrangements. Also experimental data was compiled for each arrangement to develop semi-empirical equations by means of statistical analyses. The methodology of Salim & Jones (1996) was tested with the experimental data and a new equation to predict scouring in pile groups is proposed. Finally the goodness of piers with slot is verified as a mechanism to minimise the scouring phenomenon.

Introduction

One of the main causes of failure of bridges in service conditions is the phenomenon of local scouring around the piers, making the prediction of the scouring depth a very important issue during the design procedure. The complexity of the theoretical analysis varies as different physical phenomena occurring are taken into account, such as vorticity and conditions of the sediments of the bed, among others.

As a result, experimentation is needed as an alternative of acquiring knowledge of this aspect of fluvial hydraulics. This activity has been initiated at the Universidad de los Andes through its hydraulics laboratory from 80's. The present study considers different arrangements to study the phenomenon in cylindrical pier groups and the protection given by a rectangular slot through the pier. The study reported is confined to scour in clear water.

Experiments

Experimental conditions

The experiments were conducted in a flume 10-m long and 1.20-m wide having a horizontal slope. The flume had a working section with a sediment recess 0.15-m deep, 1.20-m wide, 3 m long and located 4.0 m downstream from the flume entrance. Details of the water recirculation system, discharge measurement, tailgate control, etc are given in Espinosa (1999).

The arrangements tested are shown in Figure 1. The arrangement I is a single pier 0.17 m diameter. The arrangement II is a pier group transverse to the approach flow, the diameter of the individual piers (D) is 0.17m with a similar gap between them. The arrangement III is also a pier group that has the piers at an angular spacing of 120°. The diameter of the individual piers of the group in relation to that of the circumscribing circle of the pier group is such that any one of them can just pass through the gap between the other two. In such an arrangement, it can be shown that the ratio of pier diameter to that of the circumscribing circle is 0.302.

Finally the arrangement IV is a single pier with a rectan-

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gular slot. The width (ω) of the rectangular slot equal to 0.33D extends to the full height of the solid pier. The sediments used were cohesionless natural sands from a riverbed, with relative density of 2.65 and geometric mean size (d_{50}) of 0.52mm.

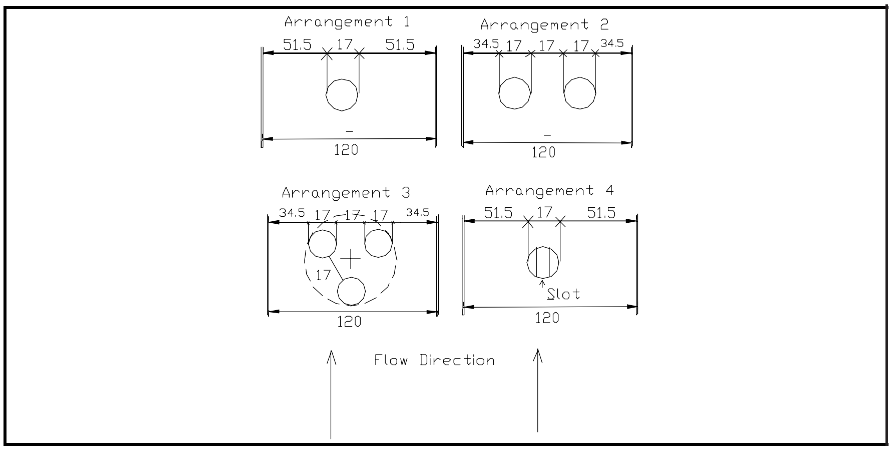


FIG. 1- Experimental Arrangements (all dimensions in cm).

Rojas (1998) and Martínez (1998) established 10 combinations of discharge and flow depths relating to clear-water conditions. Details of the hydraulic computations and calibration of the experimental conditions are given in Espinosa (1999). Before the start of each run, the particular arrangement of pier groupings was inserted centrally and vertically in the flume and the sediment in the working section was leveled perfectly around the arrangement. The experimental database is also described in Espinosa (1999).

Keeping in view the duration of experimental runs adopted by researches in the past at the Universidad de los Andes, a duration of 2 h was adopted in the present study.

Analysis Of Results

Identification of Parameters

Arrangement I

For the arrangement I, one can write the following functional relationship for maximum scour depth (*ds*) due to clear water flow, that is, $\tau_b/\tau_c<1.0$ (Breusers & Raudkivi 1991; and Espinosa 1999)

$$\frac{d_s}{Y_o} = f\left(\frac{\tau_b}{\tau_c}, \mathrm{Re}, Fr, \frac{b}{d_{50}}, \frac{Y_o}{b}, \Delta_s\right) \tag{1}$$

where Δ_s; $(\rho_s - \rho)/\rho$; and ρ being the densities of sediment and water respectively and $\mathrm{Re} = V.Y_0/\nu$, approach flow Reynolds number. Since b/d_{50} Δ_s and τ_b/τ_c are constant in the present study, equation (1) reduces to

$$\frac{d_s}{Y_o} = f\left(\mathrm{Re}, \mathrm{Fr}, \frac{Y_o}{b}\right) \tag{2}$$

The influence of each of the parameters show in equation (2) can be seen in Espinosa (1999). Apart from these parameters, the importance of the parameter b/d_{50} over the parameter d_s/Y_0 is observed with the aid of the

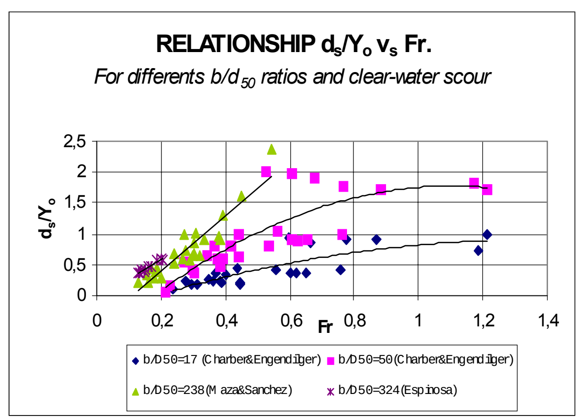


FIG. 2- Relationship between ds/Yo and Froude number for different relations of b/d50.

data found in the literature, and compared with the present value - see Figure 2.

Figure 2, leads to the observations:

- As the ratio b/d_{50} increases at a given Froude number, the value of the parameter d_s/Y_0 also increases. This is due to the capability of the flow moving the finest material with respect to the pier width for a given Froude number.

- There appears to be a limiting Froude number after which, the value of d_s/Y_0 is independent of Froude number for a given b/d_{50} ratio.

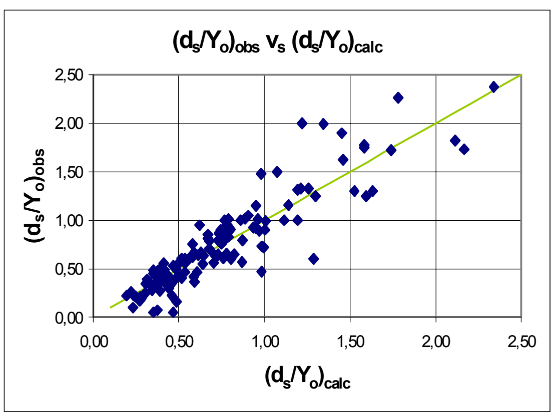
Incorporating this information on the influence of the parameter b/d_{50} and using statistical package (SSPS for Windows) the following equation is written as:

$$\frac{d_s}{Y_o} = 0.611 \cdot Fr^{0.659} \cdot \mathrm{Re}^{0.028} \cdot \left(\frac{Y_o}{b}\right)^{0.543} \cdot \left(\frac{b}{d_{50}}\right)^{0.152} \quad \text{with } (R^2) = 0.83 \tag{3}$$

Changing the dependent variable (d_s/Y_0) for one relating to the scouring depth with the mean diameter of the sediment (d_s/d_{50}) and ignoring the effect of Reynolds number due to its little significance in the phenomenon (see the exponent in equation (3)), is possible to get a better fit of the experimental data. Suggesting:

$$\frac{d_s}{d_{50}} = 0.946 \cdot \left(\frac{b}{d_{50}}\right)^{1.237} \cdot Fr^{0.966} \cdot \left(\frac{Y_o}{b}\right)^{0.603} \cdot \Delta_s^{-0.499} \quad \text{with } (R^2) = 0.98 \tag{4}$$

Figure 3 shows the goodness of fit of the experimental data as for equations (3) and (4)



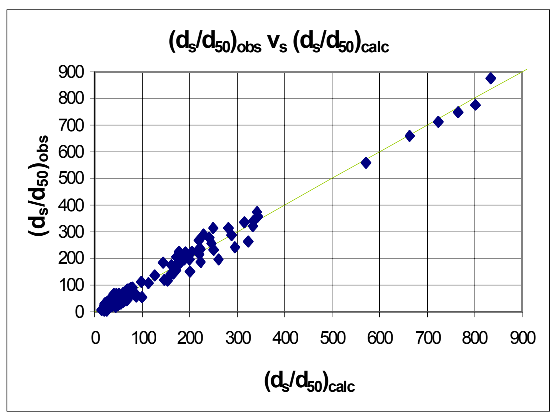


FIG. 3 - $(d_s/Y_o)_{obs}$ v_s $(d_s/Y_o)_{calc}$ and $(d_s/d_{50})_{obs}$ v_s $(d_s/d_{50})_{calc}$ according to eq. (3) - Fig 3(a)- and eq. (4) - Fig 4(b).

Equations (3) and (4) are only valid for clear-water scour around circular piers. For other geometrical shapes the shape correction factors given in the literature can be applied.

ARRANGEMENT II

Salim & Jones (1996) (see Figure 4) developed a methodology that can be used to determine scour depth at pile groups. Taking the local pier scour equation recommended by Federal Highway Administration (FHWA, Circular HEC-18) as a frame of reference, they introduced a new correction factor (K*s*, *spacing correction factor*) which is the ratio of scour depth at a particular value of the relative separation (*s/b*), where *b* is width of the pier, to that of equivalent solid pier for the same pile group configuration. The equation is stated as:

$$\frac{d_s}{Y_o} = \left[2.0K_1K_2K_3 \left(\frac{D}{Y_o} \right)^{0.65} (Fr)^{0.43} \right] K_s \qquad (5)$$

where:

K_1 = shape factor (1.1 for square nose, 1.0 for round nose, 0.9 for sharp nose).

K_2 = angle of attack factor.

K_3 = dune factor (varies from 1.0 to 1.3).

K_s = spacing correction factor estimated from:

$k_s = A(1 - e^{(1\text{-}s/b)}) + e^{0.5(1\text{-}s/b)}$ where A varies from 0.47 to 0.57.

D = width of the equivalent solid pier or the width of the pile group if the piles were packed to touch one another; and

F_r = Approach Froude number $= V/\sqrt{gY_0}$.

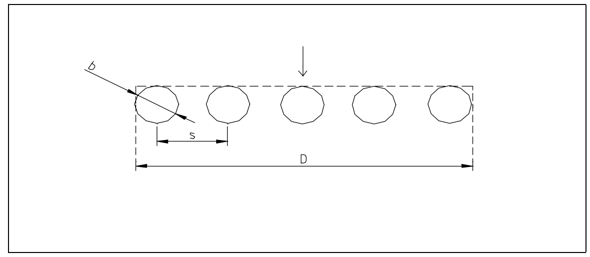
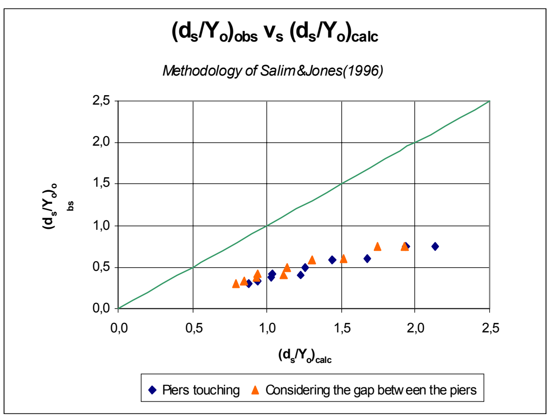
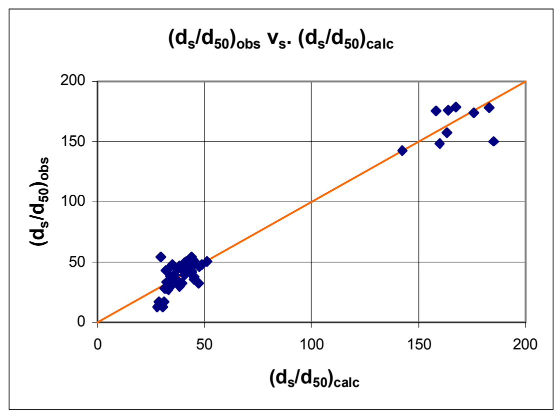


FIG. 4 - Definition sketch for Methodology of Salim & Jones (1996).

Applying these concepts to the present experimental data, Figure 5 (a) suggests that this methodology overestimates the observed scour, even if the span between piers is taken into account. This may be explained because the methodology is based on the local pier scour equation recommended by Federal Highway Administration -Salim & Jones (1996) - which is known to be conservative in predicting the scour.



(a)Results after the methodology of Salim&Jones (1996).



(b)Results from equation (7).

FIG. 5- Local Scour equations for arrangement II.

Keeping in mind the concept of spacing correction factor (K_s) introduced by these authors, one can modify the functional relationship for scour depth proposed for arrangement I (see equation (1)) into the following form:

$$\frac{d_s}{b_{50}} = f\left(\frac{\tau_b}{\tau_c}, \mathrm{Re}, Fr, \frac{b'}{d_{50}}, \frac{Y_o}{b'}, \Delta_s \right) \qquad (6)$$

where $b/D.K_s$ or in other words b' is the effective width of the pile. Based on statistical analysis and recompiled data equation (7) can be established (ignoring again the approach Reynolds number to get better fit) - see Figure 5 (b):

$$\frac{d_s}{d_{50}} = 377.73 \cdot Fr^{1.336} \cdot \left(\frac{b'}{d_{50}} \right)^{0.278} \cdot \left(\frac{Y_o}{b'} \right)^{0.802} \cdot \Delta_s^{0.450}$$

with $(R2) = 0.98$ (7)

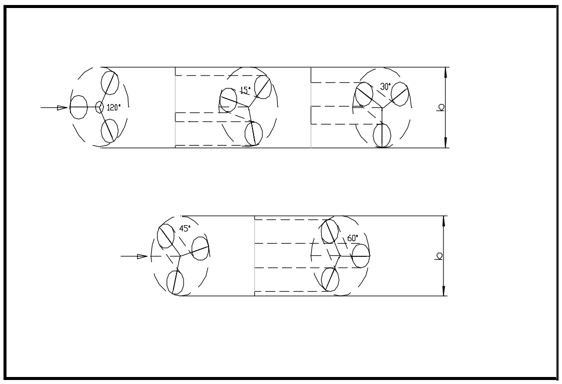
Equation (7) is only valid for clear-water scour and circular piers aligned transverse to the approach flow. For other geometrical shapes and orientations, the respective correction factors (Salim &Jones - 1996) can be applied.

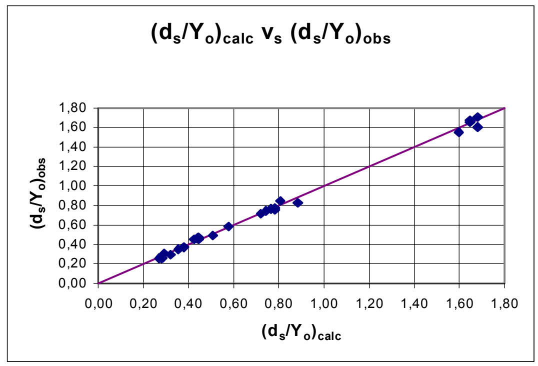
Arrangement III

For this arrangement, the width (b) of the group will be taken as the one associated to the diameter of the circumscribing circle of the pier group. According to what was reported by Vittal et al (1994), it is known that for this sort of arrangement the orientation of the group with respect to the flow is a significant variable in the expected value for local scouring. For the arrangement III, one can write the following functional relationship for scour depth (ds) due to clear water flow, that is, τ_b/τ_c <1.0 (Espinosa 1999).

$$\frac{d_S}{Y_O} = f\left(\frac{\tau_b}{\tau_c}, \mathrm{Re}, Fr, \frac{b}{d_{50}}, \frac{Y_o}{b}, \frac{B}{b}, \Delta_s\right) \tag{8}$$

where B is that represented by the portion of the width of the single piers which is projected in a plane perpendicular to the direction of the approaching flow and is a function of the orientation of the group with respect to approach flow. See Figure 6 (a) (*width B represented by the summation of gray lines in each case*).





(a) Diagramatic sketch *(b) Results for arrangement III.*

FIG. 6 - Diagramatic sketch and results for arrangement III.

Using the functional relationship of equation (8) the following empirical equation (model) is deduced (The parameter τ_b/τ_c is now included because is not constant in the experimental database for this arrangement and the approach Reynolds number is ignored due to its little influence):

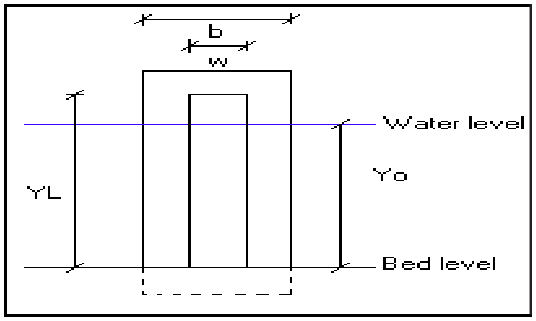
$$\frac{d_S}{Y_O} = 3.414 \cdot Fr^{0.0087} \cdot \left(\frac{Y_o}{b}\right)^{-1.146} \cdot \left(\frac{b}{d_{50}}\right)^{-0.316} \cdot \left(\frac{B}{b}\right)^{0.125} \cdot \left(\frac{\tau_B}{\tau_C}\right)^{1.118} \tag{9}$$

with a correlation coefficient of 0.99 (see Figure 6 (b)). The reason for not including the submerged specific gravity of the material (as it had been done for the previous arrangements) is because the available data in the literature for this type of configuration are only for sand; equally, the influence of Fr seem to be negligible in equation (9).

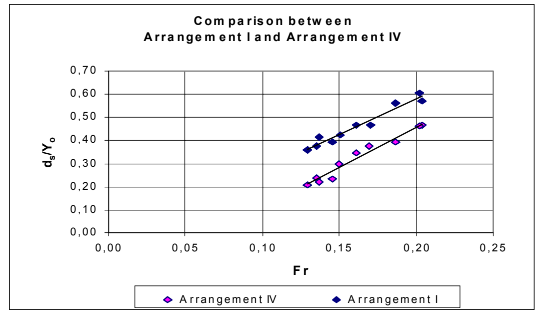
Arrangement IV

In order to include the effect that the slot has, the functional relation should comprise (besides the parameters previously mentioned) relationships indicating the effect the height of the slot has with respect to the depth of the approaching flow Y_L/Y_0 and the width of the slot with respect to the pier size w/b . (*Vittal et al* (1994)) - see Figure 7(a). Based on this, the functional relationship of the variables involved in the phenomenon for this type of arrangement has the following structure:

$$\frac{d_S}{Y_O} = f\left(\frac{\tau_b}{\tau_c}, \mathrm{Re}, Fr, \frac{b}{d_{50}}, \frac{Y_o}{b}, \frac{w}{b}, \frac{Y_L}{Y_o}\right) \tag{10}$$



(a) *Definition sketch.*



(b) *Protection given by slotted systems.*

FIG. 7 - Definition sketch and results for arrangement IV.

Comparing the functional relationships proposed for arrangements I and IV (equations (1) and (10)), and according to what was stated by Vittal et al (1994) the relationship between the observed scouring in arrangement I (d_{sI}) and the one observed for arrangement IV (d_{sIV}) can be expressed as:

$$\frac{d_{sIV}}{d_{sI}} = f\left(\frac{w}{b},\frac{Y_L}{Y_o}\right) \tag{11}$$

In addition, the parameters w/b and Y_L/Y_0 were kept constant in the present study, which implies that equation (11) will transform to:

$$\frac{d_{sIV}}{d_{sI}} = cte \tag{12}$$

As it can be observed, what was found in equation (12) is partially confirmed, with the lines tending to be parallel -see Figure 7 (b)- suggesting a mean value of 0.69 for this ratio.

Conclusions

The study reveals the following:

· The adimensional parameters of that determine the scouring depth are: the relationship of the width of the pier (or group) to the mean diameter of the bed material (b/d_{50}); Froude number for the approaching flow (Fr); relationship of the approaching flow depth to the width of the pier (or group) (Y_0/b); the submerged specific gravity of the bed material (Δ_s); and the relationship between the shear stress of the bed and the critical shear stress for movement to initiate (τ_b/τ_c).

· For arrangement III, in addition to the parameters previously mentioned, the orientation of the group with respect to the approaching flow is also a significant variable. In arrangement IV, the relationships between the width of the slot to the width of the pier (w/b) and between the height of the slot to the approaching depth (Y_L/Y_0) also intervene.

· In contradiction to that was reported in the literature, using the dimensionless parameter (d_s/d_{50}) in the functional equations, implies a better fit than to the equations that use (d_s/Y_0) as dependent variable for arrangements in *I* and *II*.

· The slot system results in an effective protective mechanism (around 30% reduction in scour depth for $w/b = 0.302$ and $Y_L/Y_0 = 1$) for the phenomenon of local scouring. However, its efficiency depends of the parameters w/b and Y_L/Y_0 which need further investigation for a better generalisation.

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