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CONTRIBUTION OF COMPLEX PIER COMPONENTS ON LOCAL SCOUR DEPTH

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Abstract

An experimental campaign of 8 long-duration tests on scouring at complex piers was carried out under steady clear-water flow conditions. The aim was to evaluate the contribution of complex pier components on the total local scour depth. Data was also used to describe the temporal evolution of scour. A new approach to evaluate the maximum scour depth associated with a subtraction concept is suggested which considers the different sets of complex piers components. Two predictors (FDOT and HEC-18), based on a scour depth superposition concept are discussed, concluding that FDOT leads to similar results as the measured values, while HEC-18 leads to underestimation of the total scour depth.

Keywords: Local scour; Complex pier; Bridge foundation; Scour depth; Laboratory tests.

1. Introduction

Local scour around bridge foundations can lead to the partial failure or to the collapse of bridge piers and decks. Due to physical, geotechnical and economic considerations, bridges are frequently constructed with foundations of complex geometries. The most common geometry, used in the new large bridges, consists of a column founded on a pile cap supported by an array of piles. This geometry is commonly referred to as complex pier, Figure 1. Studies on scour at complex piers were mostly carried out during the last few years, providing the basis of the scour depth predictors.

Presently, three methods are used to predict the equilibrium scour depth at complex piers: Auckland method (Coleman, 2005), FDOT method (Sheppard and Renna, 2010) and HEC-18 method (Arneson *et al.*, 2012). The first method suggests a local scour predictor that combines expressions for scouring respectively at uniform piers, piers founded on a caisson or slab footing and at an unsubmerged pile group with debris raft at the water surface. In the second and third methods a conceptual procedure was developed (called superposition of the scour components, each corresponding to a structural element of the complex pier, *i.e.*, column, pile cap and pile group), in which it was considered that the individual scour depth components of a complex structure can be combined to obtain the prediction for the compound structure.

The aim of this study is to evaluate the contribution of complex pier components on local scour depth, in which a new approach to assess the components contribution is introduced. For this reason, only the superposition predictors of FDOT and HEC-18 will be retained for analysis.

2. Conceptual approaches in the predictors

The HEC-18 design method for complex piers was suggested by Richardson and Davis (2001) and revised by Arneson *et al.* (2012). According to Jones and Sheppard (2000), a superposition approach, comprising the conceptual separation of the pier components (*i.e.*, column, pile cap and pile group, see Figure 1) and the determination of the scour depths for individual components is adopted. The scour depth is calculated by adding the scour depth produced by each component of the complex pier exposed to the flow, as illustrated in Figure 1. The method has some limitations in the cases where the pile cap is partially or completely buried at the beginning of the scour process. In those cases the pile group is completely buried and, consequently, the correspondent experiments with isolated pile group are not feasible.

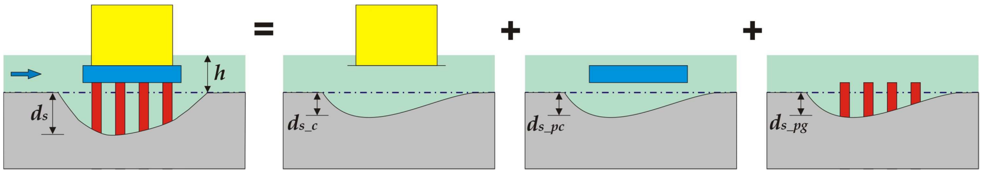

Figure 1. Conceptual hypothesis for superimposing scour components (Jones and Sheppard 2000).

Concerning the FDOT method, in accordance with Sheppard and Renna (2010), the scour depth associated with each pier component can be evaluated as the scour depth at one equivalent single cylindrical pier that would induce the same scour depth as that pier component, for the same sediment and flow conditions. This, in turn, depends on pier shape, size, location and alignment relative to the flow direction as well as on flow characteristics and sediment properties. The equivalent diameter of the complex pier can be approximated by the sum of the equivalent diameters of the complex pier components, as illustrated in Figure 2.

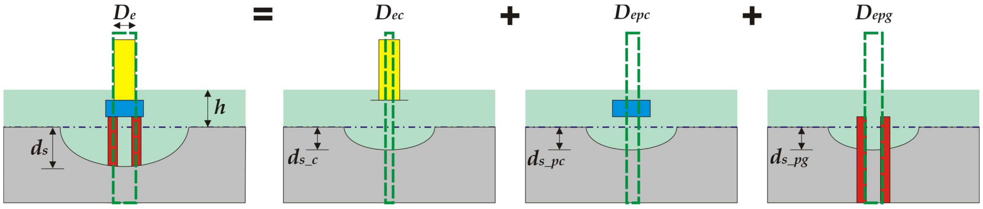

Figure 2. Conceptual hypothesis of summing equivalent diameters (Sheppard and Renna 2010).

The two predictors were developed on the basis of different types of experiments (*e.g.*, Jones 1989, Salim and Jones 1996, Smith 1999, Jones and Sheppard 2000): (i) tests with isolated structural components (*i.e.*, isolated columns, pile caps and pile groups) at various positions in the flow and (ii) tests with compound structures, consisting of suspended column founded on pile cap above the initial bed.

3. Contribution of complex pier components on total scour depth. A new approach

The experiments with isolated components, used in the development of the two referred predictors, both applying the so called superposition approach, lead to a loss of interaction of the flow structure between the column and the pile cap and between the pile cap and the pile group. In this aspect, the downflow generated in the upper elements is most affected.

These interactions with the flow structure can increase or decrease the scour depth, depending on the complex pier geometry and on the flow characteristics. Figure 3 represents schematically the flow structure around the complex pier and the isolated components.

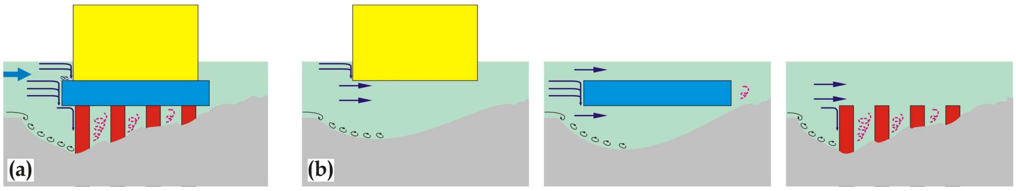

Figure 3. Interpretation of the flow structure around: (a) the complex pier and (b) the isolated components.

Since this seems to be an important issue, a new approach, believed to retain the flow interactions with the components of the complex pier was attempted in this study. With this purpose, three basic configurations were studied for a certain position of the complex pier: the first configuration with the three components (C1), the second without the column (C2) and the third without the pile group (C3) as illustrated in Figure 4.

The configurations C2 and C3 do not represent real situations of the complex pier but they are specific experimental configurations used to calculate, by subtraction, the contribution of the missing complex pier component on total scour depth (henceforth termed scour depth subtraction concept).

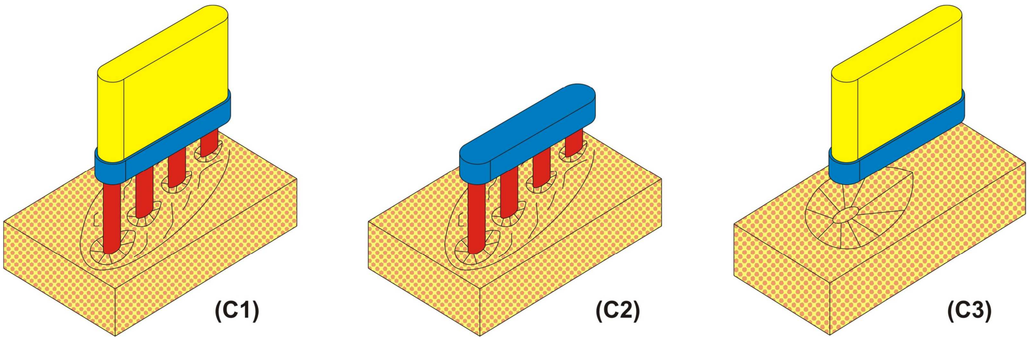

Figure 4. Complex pier configurations.

Consequently, the scour depth contribution of the three components of the complex pier is calculated from the following equations:

$$d_{s\_c} = d_{s\_C1} - d_{s\_C2} \tag*{[1]}$$

$$d_{s\_pg} = d_{s\_C1} - d_{s\_C3} \tag*{[2]}$$

$$d_{s\_pc} = d_{s\_C1} - d_{s\_c} - d_{s\_pg} \tag*{[3]}$$

where, d_{s_c}, d_{s_pg} and d_{s_pc} are the scour depth contribution of the column, pile group and pile cap respectively, and d_{s_C1}, d_{s_C2} and d_{s_C3} represent the scour depth due to configurations C1, C2 and C3 respectively. It seems reasonable to assume, for instance, that the contribution of the column to the total equilibrium scour depth can be isolated by subtracting the equilibrium scour depth due to configuration C2 (without column) from the equilibrium scour depth associated to the complete complex pier (C1), as soon as the approach flow, fluid, sediment and pier configuration and alignment remain unchanged.

4. Experimental setup and procedure

Eight laboratory experiments were carried out at the Faculty of Engineering of the University of Porto, FEUP, in order to collect data to validate this new approach. Additionally, data was used to evaluate the performance of the HEC-18 and FDOT predictors. A 33.2 m long, 1.0 m wide, and 1.0 m deep, rectangular flume was used; the test reach started at 16.0 m from the entrance, including a 3.2 m long, 1.0 m wide, and 0.35 m deep bed recess box. In order to achieve the most unfavorable conditions in terms of equilibrium scour depth, the tests were carried out with constant approach average velocity, U = 0.31 m/s, near the critical velocity, U_c ≈ 0.32 m/s (as calculated according to Neil 1967). Hence the flow intensity was U/U_c ≈ 0.97. The approach flow depth, h, was kept constant and equal to 0.18 m.

An acrylic complex pier model was placed at the center of the bed recess box as shown in Figure 5a. The model included a 0.089 m wide round-nose column founded on a 0.120 m wide and 0.058 m thick round-nose pile cap, supported by an array of cylindrical piles (one row of four piles). The pile diameter was 0.05 m and the piles were spaced by 2.5 times the pile diameter (distance between the centerlines of adjacent piles). The bed recess box was filled with uniform quartz sand of median size, d_{50} = 0.86 mm, and geometrical standard deviation, σ_g = 1.34.

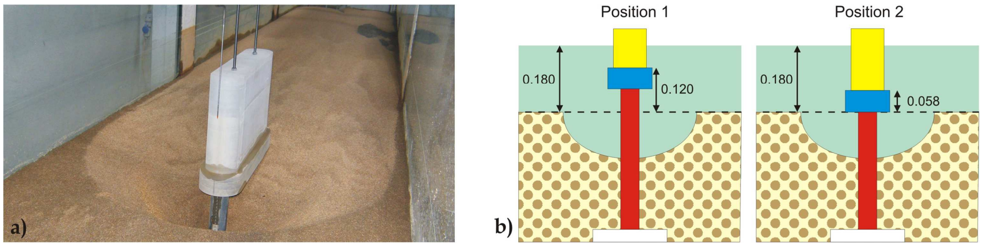

Figure 5. a) Experimental setup and b) Pile cap positions tested.

Two different top pile-cap positions relatively to the initial bed level, H_c, were tested. One position with H_c = 0.120 m (corresponding to the pile cap under the water and above the initial bed level) and the other position with H_c = 0.058 m (corresponding to the bottom of the pile cap being initially leveled with the sand bed) as shown in Figure 5b. Three experiments were performed in each of the two positions corresponding to tests for configurations C1, C2 and C3 (schemes of Figure 4). Two additional experiments were carried out and used as reference tests: in one of them only the column was present (corresponding to the case when the top of the pile cap remains buried below the bottom of the scour hole, henceforth referred as column reference test); in the other one, only the pile group was present (corresponding to the case where the bottom of the pile cap is above and out the water column, henceforth referred as pile group reference test).

Prior to each test, the sand of the recess box was leveled with the adjacent bed. The area located around the complex pier was covered with a thin plate (*i.e.*, filter fabric combined with a thin metallic grid) to avoid uncontrolled scour at the beginning of each test. The flume was filled gradually imposing high water depth and low flow velocity. Once the flow depth and discharge were established, the thin plate was carefully removed and the tests started.

Scour was immediately initiated and the scour hole depth was measured every ≈ 10 minutes during the first hour to an accuracy of ± 0.1 mm, with an adapted point gauge or a metric tape glued to upstream piles. Afterwards, the interval between measurements increased and, from the first day, two or three measurements were made per day. The minimum duration of the experiments was 7 days.

5. Results and Discussion

5.1 Scour depth evolution

In the pile group reference test, the scour process showed to be analogous to the one normally observed around single piers (*e.g.*, the column reference test), in which the time evolution of the maximum scour depth is characterized by a unique trend, as shown in Figure 6a. The scour depth evolution for the two pile cap positions with the complete complex pier (configuration C1) is displayed in Figure 6b. In the position 1, corresponding to the case where the pile cap is under the water and above the initial bed level, the scour depth evolution is similar to the pile group reference test, in which the scour hole starts in front of the upstream piles. In the position 2, corresponding to the case where the pile cap is founded over the initial bed level, the scour depth evolution does not follow a unique trend, as described for position 1, but presents two different phases: one corresponding to the first stage of the scour process, when the maximum scour depth occurs in front of the pile cap (represented by a continuous curve in Figure 6b and which corresponds to the first hour of test); the other corresponding to the maximum scour depth occurrence in front of the upstream piles (dashed curve, Figure 6b).

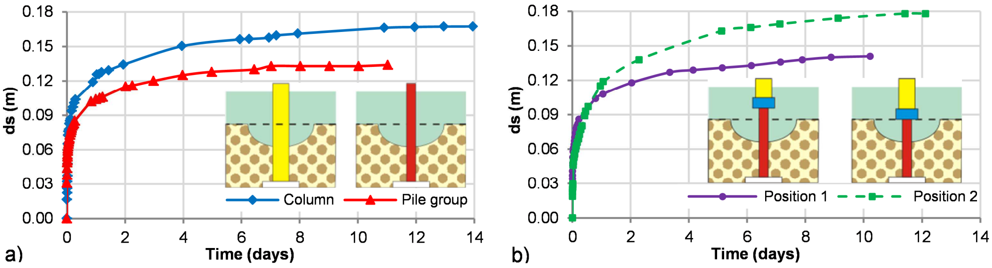

Figure 6. Scour depth evolution: a) reference tests and b) complex pier positions (Configuration C1).

Figure 7a shows the scour depth evolution and the respective scour hole at the end of the tests, for the three configurations (C1, C2 and C3), carried out in the position 1. Figure 7b shows the equivalent results for position 2. In both positions, the scour depth evolution for configuration 2 (C2) shows a trend relatively similar to the respective configuration 1 (C1). This is not the case when a similar comparison is made considering the scour depth evolution for configuration 3 (C3), where a different behavior of the scour depth evolution does occur, which is more evident in the case of position 1.

This particular trend for this last case (configuration C3, position 1) may be explained by a much slower scour rate occurring for this configuration as a result of the low intensity horseshoe vortex formed, due to the interaction of the downflow occurring in front of the column and pile cap with the predominant horizontal flow below the pile cap (in comparison with configuration C1).

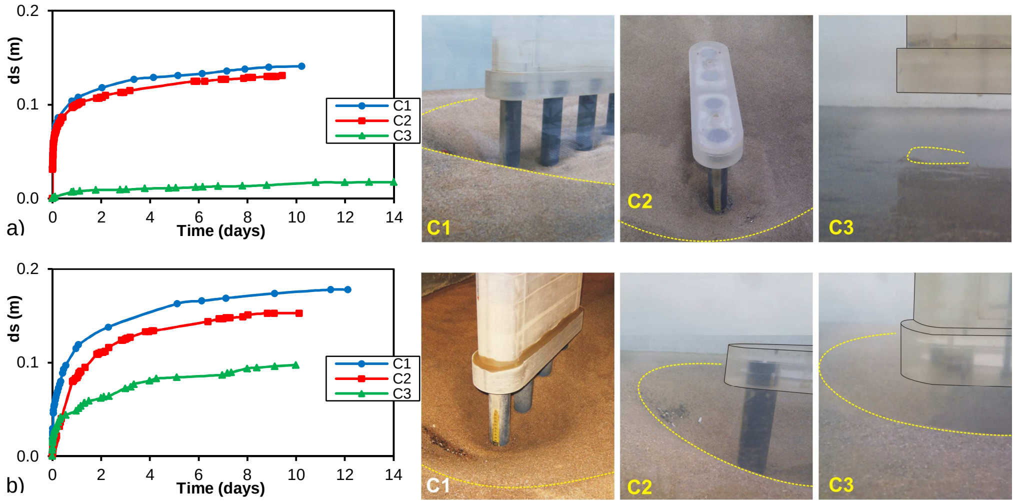

Figure 7. Scour depth evolution and final scour hole in the three configurations (C1, C2 and C3): a) position 1 and b) position 2.

5.2 Equilibrium scour depths

According to Ettema (1980) it can be assumed that the equilibrium stage in the scour evolution is attained asymptotically. The recorded experimental scour depth values were extrapolated to time infinite through the Franzetti *et al.* (1982) equation as suggested by Simarro *et al.* (2011) to estimate the equilibrium scour depth, d_{se}. Table 1 illustrates the deepest scour depths measured at the end of the tests, d_{sm}, and the equilibrium scour depths (extrapolated values) for the two studied positions.

Table 1. Scour depth values for configuration C1, C2 and C3.

	CONFIGURATION 1		CONFIGURATION 2		CONFIGURATION 3	
	d_{sm}	d_{se}	d_{sm}	d_{se}	d_{sm}	d_{se}
POSITION 1	0.141 m	0.151 m	0.131 m	0.140 m	0.018 m	0.025 m
POSITION 2	0.178 m	0.189 m	0.153 m	0.165 m	0.098 m	0.118 m

In the column reference test, the values of d_{sm} and d_{se} were 0.167 m and 0.178 m respectively, while, in the pile group reference test, those values were 0.134 m and 0.143 m respectively. Table 2 includes the equilibrium scour depths associated to each complex pier component for the two studied positions. These values were calculated through equations 1 to 3 (scour depth subtraction concept) using the extrapolated values obtained for the equilibrium scour depths correspondent to the three configurations (Table 1).

Table 2. Equilibrium scour depths associated to each complex pier component.

	Column	Pile cap	Pile group	Total
Position 1	0.011 m	0.014 m	0.126 m	0.151 m
Position 2	0.024 m	0.084 m	0.081 m	0.189 m

5.3 Contribution of complex pier components

In both predictors (*i.e.*, HEC-18 and FDOT), the column contribution to the local scour depth is calculated as the product of the scour depth developed for a single pier (with the same dimensions of the column) by a suspended column height factor, K_{h_c}, as designated in Jones and Sheppard (2000). Figure 8a provides this factor variation with the relative column position, H_c/h (distance measured from the bottom of the column to the initial bed level), according to results of Jones and Sheppard (2000), as well as the corresponding fitted curve. Figure 8b shows K_{h_c} values based on the experiments performed on the present study (for positions 1 and 2, P1 and P2 respectively). In this case, this factor is calculated as the relation of the equilibrium scour depth associated with the column (Table 2) and the equilibrium scour depth of the column reference test (0.178 m). Figure 8b pictures also the fitted curve from Figure 8a for comparison purposes. The results reveal that the column contribution associated to K_{h_c} is approximately the same either using the superposition concept or the subtraction concept.

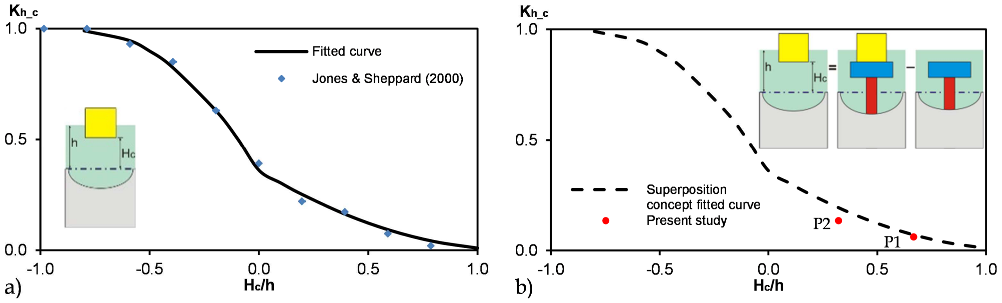

Figure 8. Suspended height column factor obtained by: a) superposition concept and b) subtraction concept.

Few studies have been published concerning the specific contribution of the pile cap on the scour process. Jones and Sheppard (2000) and Amini *et al.* (2011) presented experimental data for isolated pile caps in situations where this structural element is within the flow and above the bed or partially buried in the bed. Figure 9 shows the scour depth normalized by the pile cap width, D_{pc}, as a function of the relative pile cap position, H_{pc}/h (distance measured from the bottom of the pile cap to the initial bed level) correspondent to the results of the three studies analyzed (*i.e.*, Jones and Sheppard, Amini *et al.*, and the present study). This figure makes it clear that those results do not follow a single tendency. Hence, it may be concluded that other parameters than H_{pc}/h affect the scour depth pile cap contribution, and those can be the main factors that varied from the different studies, namely the shape of the pile cap, the flow shallowness and the sediment coarseness ratio.

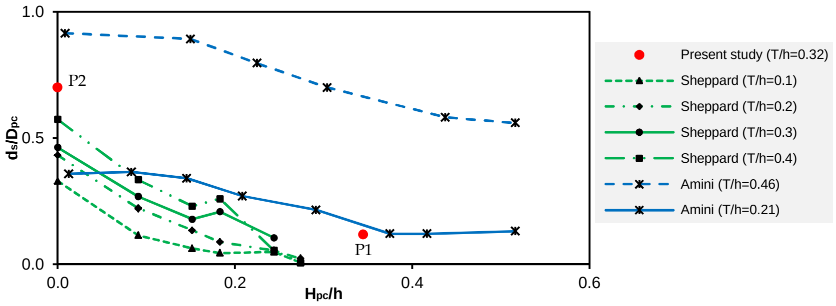

Figure 9. Pile cap contribution to complex pier local scour depth, as a function of H_{pc}/h.

Some authors established that the contribution of the pile group on local scour depth is calculated as the product of the scour depth for unsubmerged pile group by the submergence factor, K_{h_pg}. Figure 10a provides values of this factor, according to results of tests with submerged cylinders (Dey *et al*. 2008) and with submerged pile groups (Salim and Jones 1996, Smith 1999, Amini *et al*. 2012), as a function of the submerged pile group position relatively to the initial bed level, H_{pg}/h.

The figure includes the envelope curve of these data which is relevant as some of the tests may have been carried out with relatively short durations. Figure 10b shows the submergence factor, K_{h_pg}, for the two positions considered on the present study (P1 and P2). This factor is calculated as the relation of the equilibrium scour depth associated with the pile group (Table 2) and the equilibrium scour depth of the pile group reference test (0.143 m).

In this figure, the envelope curve given in Figure 10a was used for comparison purposes. The results reveal that the pile group contribution according to the superposition concept tends to give scour depth values lower than those obtained with the subtraction concept (present study).

Figure 10b enables also to conclude that the higher difference between the two concepts occurs when the top of the pile group is near to the initial bed level ($H_{pg}/h \approx 0$). In that case, the contribution of the pile group on local scour depth is close to zero in the superposition concept (envelope curve crossing the x axis in Figure 10b), while in fact the pile group may strongly contribute to the scour process once it has been exposed inside the cavity, what is taken into account in the subtraction concept.

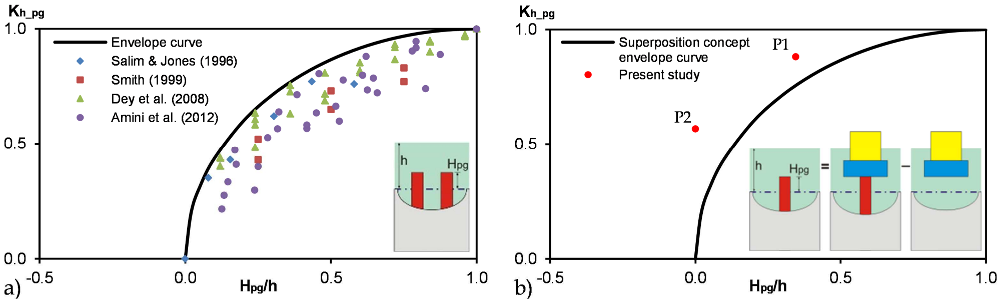

Figure 10. Pile group submergence factor by: a) superposition concept and b) subtraction concept.

5.4 Comparison between measured and predicted scour depths

As mentioned in section 2, the FDOT predictor calculates the equivalent diameters of the complex pier components, which implies that is necessary to obtain scour depths for each component for its comparison with the measured values. In this study, the scour depth values associated with each component, according to FDOT predictor, were considered through the following approximation:

$$d_{s\_i} = d_s \times (D_{ei}/D_e) \qquad [4]$$

where, d_{s_i} is the scour depth contribution of each component, d_s is the scour depth calculated for the complete complex pier configuration (in function of D_e), D_{ei} is the equivalent diameter calculated for each component and D_e is the total equivalent diameter calculated for the complex pier, given by the method as the sum of the calculated D_{ei}.

Figure 11a and Figure 11b show the contribution of the three components of the complex pier, calculated by the subtraction concept (labelled as present study) and calculated by the two referred predictors, for position 1 and position 2 respectively.

In terms of the total scour depth, the HEC-18 method provides underestimation values while the FDOT method provides similar values in comparison with the extrapolated values of the present study for the two pile cap positions. In position 1, the contribution of the column is similar in the present study and in the two predictors, in line with the results shown in Figure 8; on the other hand, values of the pile cap contribution have small differences for the same comparison; furthermore, the contribution of the pile group in HEC-18 method is smaller than the values of the FDOT method and the present study, which can be explained by the fact that this predictor uses the factor K_{h_pg} shown in Figure 10. In position 2, the column contribution is similar in both the present study and the two predictors, in accordance with Figure 8, whereas the contributions of the pile cap and the pile group do not keep the same proportions. These differences, clearly more significant than for position 1, may be due to the fact that the pile group is completely buried at the beginning of the scour process and in this situation the tests with isolated pile groups used in those predictors have some limitations as discussed in 5.3.

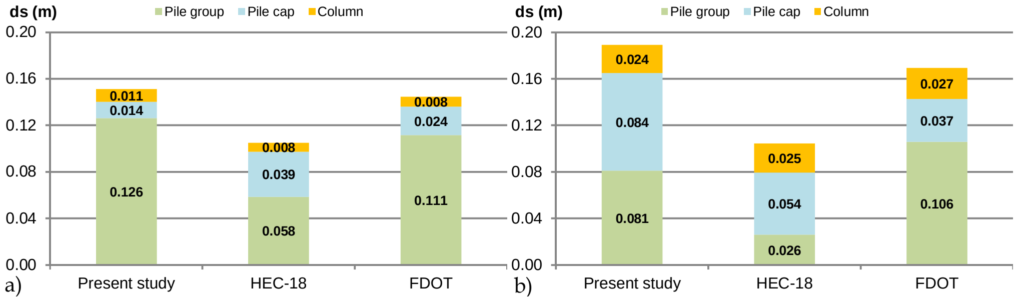

Figure 11. Comparison of the complex pier component contribution on: a) position 1 and b) position 2

6. Conclusions

From the previous discussion, the following important conclusions can be drawn:

1. For complex piers with one row of piles (the pier geometry used in the present study), the temporal scour depth evolution is similar to that obtained in experiments with single piers, which is characterized by a unique logarithmic trend;

2. The comparison between the superposition concept (tests with isolated components used in the predictors) and the subtraction concept (based on tests of the present study) shows that: the column contribution is similar in the two concepts; the pile group contribution is underestimated in the superposition concept, and; the pile cap contribution is more difficult to analyze because it depends on various factors, deserving further research;
3. The HEC-18 method provides underestimated scour depth predictions compared to the measured values while the FDOT method provides a similar scour depth prediction for the complete complex pier configuration.

Acknowledgments

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References

Amini, A., Melville, B.W., Ali, T.M., and Ghazali, A.H. (2012). 'Clear-water local scour around pile groups in shallow-water flow'. *Journal of Hydraulic Engineering*, Vol. 138 (2), 177 – 185.

Amini, S.A., Mohammad, T.A., Aziz, A.A., Ghazali, A.H., and Huat, B.B.K. (2010). 'A local scour prediction method for pile caps in complex piers'. *Water Management*, 164 (2), 73 – 80.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F. and Clopper, P.E. (2012). 'Evaluating scour at bridges'. Fifth edition. U.S. Depart. of Transportation, Federal Highway Administration.

Coleman S.E. (2005). 'Clearwater local scour at complex piers'. *Journal of Hydraulic Engineering*, Vol. 131 (4), 330 – 334.

Dey, S., Raikar, R.V., and Roy, A. (2008). 'Scour at submerged cylindrical obstacles under steady flow'. *Journal of Hydraulic Engineering*, Vol. 134 (1), 105 – 109.

Jones J.S. (1989). 'Laboratory studies of the effects of footings and pile groups on bridge pier scour'. Proceedings of the Bridge Scour Symposium, U.S., 340 – 359.

Jones J.S. and Sheppard D.M. (2000). 'Local scour at complex pier geometries'. Proceedings of World Environmental and Water Resources Congress 2000, ASCE, USA, May.

Neil, C. R. (1967). 'Mean velocity criterion for scour of coarse uniform bed-material'. Proc., 12th IAHR Congress, IAHR, Fort Collins, CO, 46 – 54.

Richardson, E.V., and Davis, S.R. (2001). 'Evaluating scour at bridges'. Fourth edition. National Highway Institute, U.S. Department of Transportation, Federal Highway Administration.

Salim, M., and Jones, J.S. (1996). 'Scour around exposed pile foundations'. Proc. of the American Society of Civil Engineers, Anaheim, USA.

Sheppard, D.M. and Renna, R. (2010). 'Florida bridge scour manual'. Florida Department of Transportation, Tallahassee.

Smith, W.L. (1999). 'Local structure-induced sediment scour at pile groups'. 83p., M.S. Thesis, Florida Univ, Gainesville, FL.