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Effect of Fully and Partial Submerged Pile Cap on Local Scour Depth around Piles

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***Abstract*: Bridges are constructed in irrigation canals and drains using pile foundation to avoid throttling waterways. From investigation, the invert level of pile cap rises above the waterways high water level by about 0.5m. Recently, the flow rates of several canals and drains increase inasmuch the output of drainage treatment plants. As a result, numerous waterways water levels are rising from 0.5m to 1.5m. As a consequence, pile cap became fully or partial submerged. Therefore, the local scour around the bridge piles may be greatly affected. From this standpoint, different experimental tests to study the effect of submerged pile cap on the local scour around piles were performed. Furthermore, the pile cap entrance angles were investigated as an enhancement to the local scour around piles. The results indicate that, the higher pile cap submergence ratio, the deeper corresponding scour hole around piles. On contrary, reducing the pile cap entrance angle cause an improvement to the scour rate around piles. Finally, different charts were plotted describing the relationships between scour depth and pile cap submergence ratio.**

Keywords: Experimental analysis; Submerged pile cap; Local scour; Piles.

I. INTRODUCTION

Scour is a natural phenomenon caused by the flow of water in rivers and streams. It is the consequence of the erosive action of flowing water, which removes and erodes soil materials from the bed and banks of streams and also from the vicinity of bridge piles, piers and abutments. Also it can be defined as the lowering of the level of the river bed by water erosion such that there is a tendency to expose the foundations of structures such as bridges.

The basic mechanism causing local scour at piles is the formation of vortices at their bases. The vortex removes bed material from the base of the obstruction. As the sediment transport rate, which is outgoing from the scour hole is higher than the coming into, a scour hole develops. As the depth of the scour increases the strength of the vortices is reduced. On the other hand, there are vertical vortices downstream the structure called wake vortices. The intensity of wake vortices diminishes rapidly as the distance downstream of the structure increases, (Federal Highway Administration, 2001).
Piers and abutments are usually considered as similar in case of scour phenomena, (Melville, 1997). Local scour holes around bridge piers are developed by the down flow and horseshoe vortex, (as shown in Fig. 1). The maximum scour depth migrates from the element side to the pier axis or to the channel wall with time, respectively, (Graf, 1996).

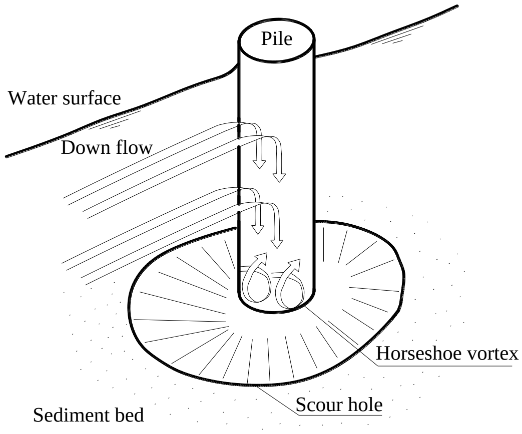


Fig. 1. General view of the scour around piles

The vortex system and the down flow, along with the turbulence, are the principle causes of the local scour. This vortex loses its strength passing along the structure (Kothyari et. al., 1992).

Many researches dealt with the scour mechanism around piles, Rambabu et. al., 2003; Mostafa and Agamy, 2011; Umeda, 2011; Zanke et. al., 2011; Ferraro et. al., 2013; and Ong et. al., 2013. In addition, others adopted models to simulate local scour around bridge piers and abutments, Abdel-Razek and Baghdadi, 1995; Kandasamy and Melville, 1998; Chaurasia and Lal, 2002; Oliveto and Hager 2002; and Khwairakpam and Mazumdar, 2009. It is however found that, there is a lack of researches exploring effect of submerged pile cap on scour around piles. Moreover, the effect of different pile cap upstream entrance angles on the performance and scour around piles were focused.

II. EXPERIMENTAL SETUP

The main components of the apparatus used in this study are the flume, tail gate, measuring device and flume bed material. The flow system is a closed loop. The pump section branch draws water from the sump tank and discharges first through the flow meter and then the control valve into feeding pipe to the inlet stilling tank which feeds the flume.

The study was carried out in a straight flume. The laboratory rectangular flume was 0.6m wide, 0.2m deep and 5.7m length, (see Fig. 2). The flume was made from a selfcolored glass reinforced plastic mounding. The inlet part of the flume has 0.6m wide and 1.0m deep at its first portion where the feeding pipe gives its capacity of water. A perforated plate baffle filled with a large and washed aggregate was fixed at the beginning of the inlet section to dissipate the kinetic energy of the high velocity water entering the inlet part from feeding pipe. The testing part of the flume has 0.6m wide and 0.2m deep. A measuring carriage moves through two aluminum rails fixed at the top of the two sides of the flume. The outlet part of the flume has a width of 0.6m wide and 1.0m deep at its end and has a capacity about 300 liters. A drain valve is fixed at the lower part of the flume to drain the water of the sump (outlet) tank when required, (as shown in Fig. 3).

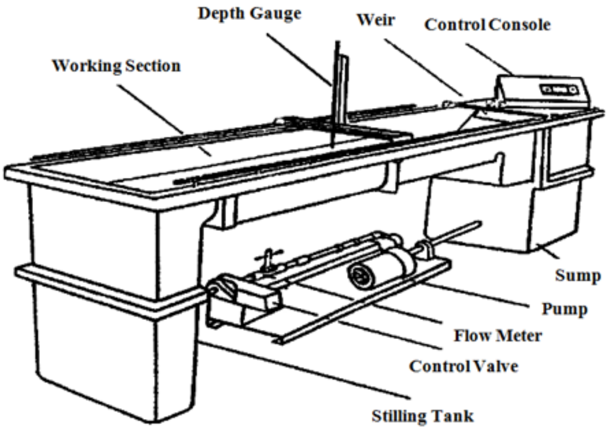


Fig. 2. Sketch of the flume

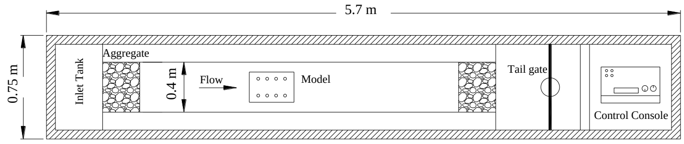
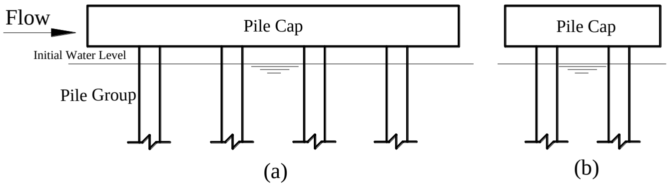


Fig. 3. Plan of the flume

The models of bridge pile cap and piles were built from wood and plastic pipes. The diameters of piles range from 1.5cm to 2.5cm and 3cm, see Fig. 4 (a) and (b). In addition, the pile cap submergence ratios range from free case to 0%, 25%, 50%, 75% and 100%, (as shown in Fig. 5), while the pile cap upstream entrance angles range from 90^o to 60^o,45^o,30^o and 15^o, (see Fig. 6).



(a) (b)

Fig. 4. Geometric of a pile cap and pile group: (a) Side view; (b) Front view

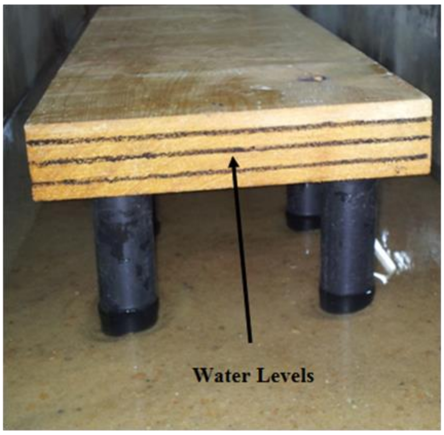


Fig. 5. Water submergence levels during tests

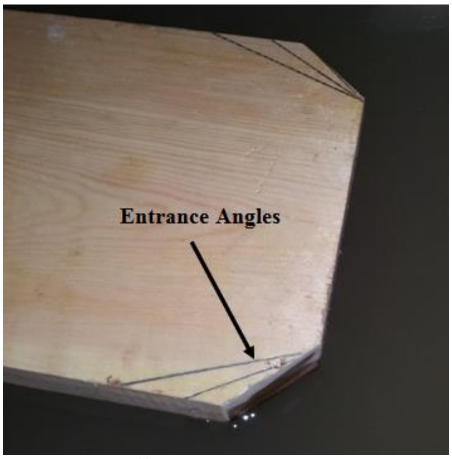


Fig. 6. Different pile cap entrance angles

The apron was followed by 3.5m long mobile bed consisting of sand layer. The thickness of sand layer is 7.0cm. The sieve analysis of the sand layer was shown, (see Fig. 7). The model sand is non-uniform (uniformity coefficient, D_{60}/D_{10}=1.52<6.0) with D_{50}=1.77mm, and geometric mean, D_{85}/D_{15}=1.54.

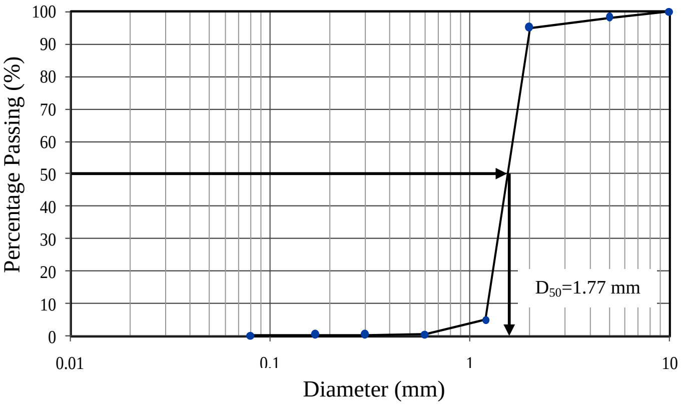


Fig. 7. Sieve analysis of the sand

III. SCOUR TIME RELATIONSHIP

Fig. 8, presents the required time for each test, in which the relationship between $d_s/d_{s\,Max}$ was plotted against the time. It was found that 90% of the maximum scour depth was achieved within 2 hours. So, each test was carried out through 2 hours.

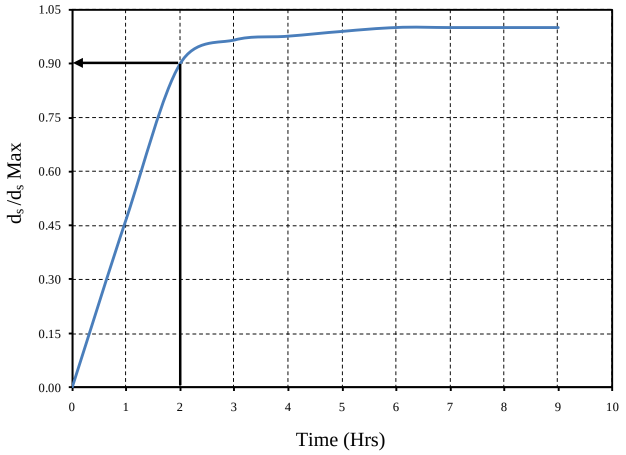


Fig. 8. Time scour relationship for Q=3.47 lit./sec

IV. DIMENSIONAL ANALYSIS

The scour around a pile is dependent on the flow conditions, sediment property and pile geometry. Assuming that the scour is around a smooth circular pile in uniform sand, the dependant variables of the phenomenon are:

$$d_s = f(\rho, \upsilon, U_b, T, D, D_{50}, \rho_s, w_s, g) \qquad (1)$$

Where d_s is the scour depth, ρ the density of water, υ the kinematic viscosity, ρ_s the density of sand, w_s the setting velocity of the sand and g the acceleration due to gravity. From dimensional analysis, the non-dimensional scour depth d_s/D is found to depend on several parameters:

$$\frac{d_s}{D} = f\left(KC, Re, \frac{D}{D_{50}}, \frac{\rho_s}{\rho}, \theta, \frac{w_s}{U_b}\right) \qquad (2)$$

In which KC is the Keulegan-Carpenter number,

$$KC = \frac{U_b T}{D} \qquad (3)$$

Re is the Reynolds number,

$$Re = \frac{U_b D}{\upsilon} \qquad (4)$$

And θ is the Shields parameter,

$$\theta = \frac{\rho\, U_b^{\,2}}{(\rho_s - \rho)\, g\, D_{50}} \qquad (5)$$

Where U_b is the maximum value of the undisturbed bed shear velocity. The range of KC number in the experiments was from 2 to 30. The range of the Reynolds number was from 6×10^2 to 1.3×10^3. The Shields parameter was $\theta < 0.2$, while the critical Shields parameter for mobilization of the sediment was θ_c= 0.05-0.06. The ratio of pile diameter to the sand size was D/D_{50} = 15-30. The specific density of the sand was ρ_s / ρ = 2.65. The ratio of the setting velocity to the friction velocity was w_s/U_b= 1.7-6.7.

V. TEST PROCEDURE

The runs were conducted during the experimental tests in the following sequence. First, the mobile bed was leveled. Then, the control valve was opened gradually to obtain the required discharge and the tail gate was adjusted at a certain position to achieve the required water depth. Starting test time of each run was recorded, and water surface profiles were measured. Furthermore, the pump was stopped after 2 hours, and the sand was drained from the water to survey the scour holes. Moreover, the mentioned steps were repeated for another submergence ratio. Finally, the runs were repeated for another pile cap entrance angle.

VI. ANALYSIS OF THE RESULTS

The effect of pile cap submergence ratio and upstream entrance angles are investigated for different pile diameters. Results show the effect of these parameters on local scour depth around piles, (as shown in Fig. 9).

Fig. 9. Scour holes around piles

The relationship between the maximum scour depth around piles and percentage of pile cap submergence ratio is plotted in Fig. 10 for upstream pile cap entrance angle 90°. It was found that, at the first row of piles, the scour has a significant effect than other rows, thus because of the current effect that is reduced while moving through the piles till reach the last row. The pile cap submergence ratio has an obvious effect on the maximum scour around piles. As the submergence ratio changes from freeboard to 0%, 25%, 50%, 75% and 100% the maximum scour around first row of piles increases by 25%, 33%, 41%, 50% and 66% of the freeboard case respectively. This may be attributed to the increase in reflected wave vertical velocity component which affected by the submergence ratio increase.

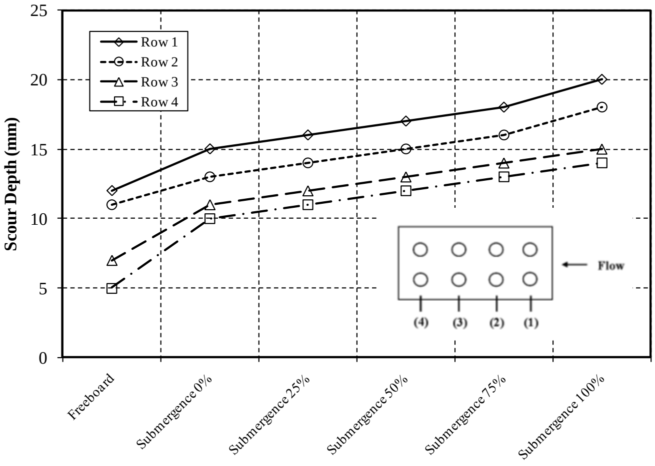


Fig. 10. Scour depth for different percentages of pile cap submergence Pile cap angle (90°), Pile diameter (1.5 cm)

The modification of pile cap upstream entrance angle is the main factor investigated to reduce the maximum scour generated around piles in case of submerged pile cap. Figs . From 11 to 14 describe the maximum scour depth around piles with the percentage of pile cap submergence ratio, during using different pile cap entrance angles changed from sharp angle 90^o that produces higher values of local scour to mild pile cap entrance angles of 60^o, 45^o, 30^o and 15^o.

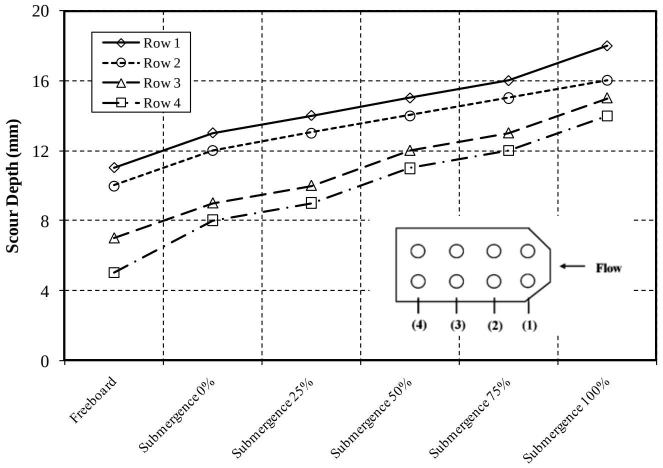


Fig. 11. Scour depth for different percentages of pile cap submergence Pile cap angle (60^o), Pile diameter (1.5 cm)

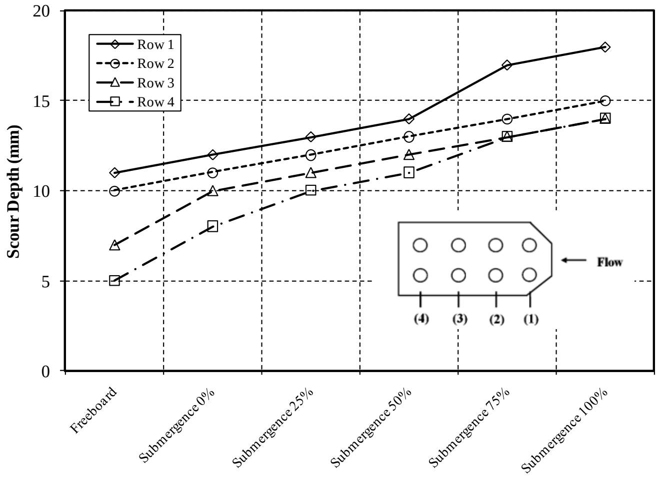


Fig. 12. Scour depth for different percentages of pile cap submergence Pile cap angle (45^o), Pile diameter (1.5 cm)

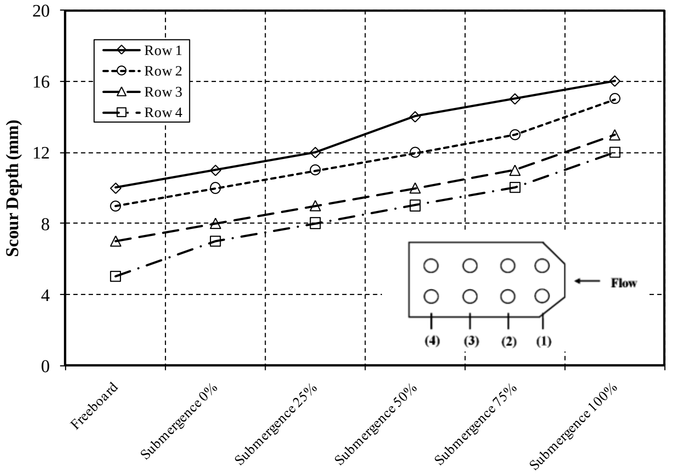


Fig. 13. Scour depth for different percentages of pile cap submergence Pile cap angle (30^o), Pile diameter (1.5 cm)

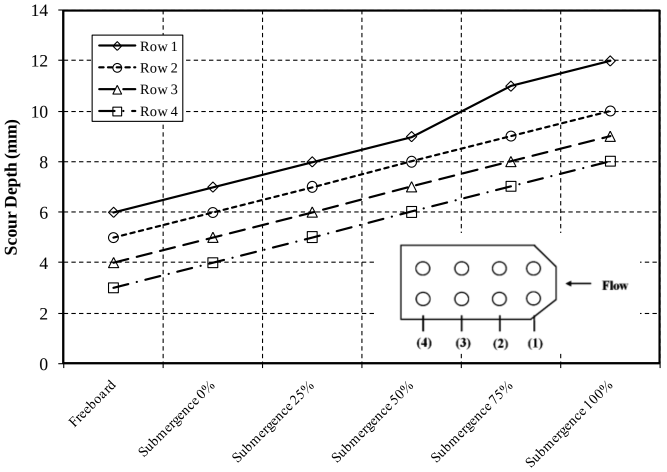


Fig. 14. Scour depth for different percentages of pile cap submergence Pile cap angle (15^o), Pile diameter (1.5 cm)

It was found that, changing the pile cap entrance angle from sharp angle 90^o to 60^o, 45^o, 30^o and 15^o reduces the local scour around first row of piles by 11%, 17%, 23% and 47% respectively.

Figs. from 15 to 17 present the maximum scour depth for different pile cap entrance angles at pile cap submergence ratio equals 50%, the pile diameters change from 1.5cm to 2.5cm and 3.0cm (D/t_{cap} equals 0.4, 0.6 and 0.75 respectively).

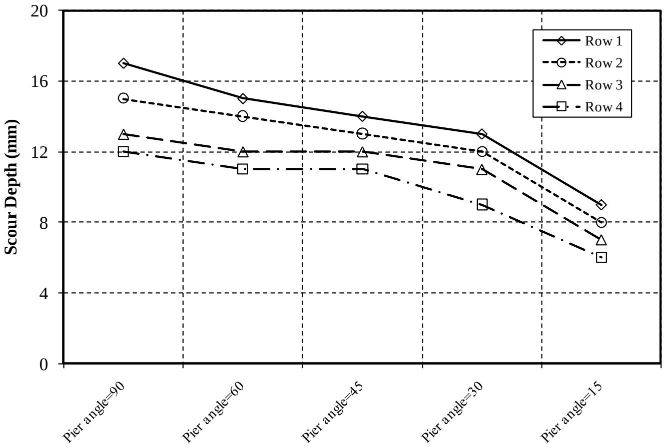


Fig. 15. Scour depth for different pile cap angles, Submergence =50%, Pile diameter (1.5 cm)

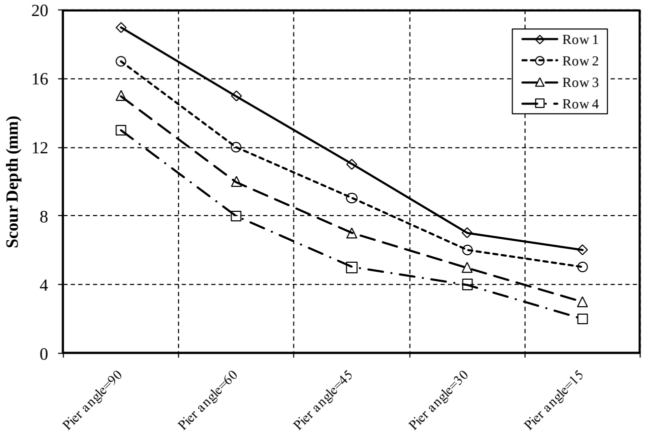


Fig. 16. Scour depth for different pile cap angles, Submergence =50%, Pile diameter (2.5 cm)

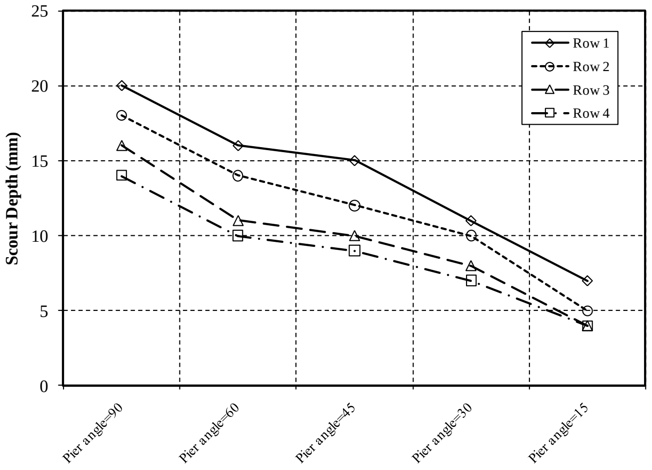


Fig. 17. Scour depth for different pile cap angles, Submergence =50%, Pile diameter (3 cm)

It is clear that, there is a significant effect for changing the pile cap entrance angle on the maximum scour depth around piles, thus because the smoothing pile cap entrance angle, the lesser effect of current impacting the system and lower flow vertical velocity component. At pile cap entrance angle 90° and for the first row of piles, the increase in pile diameter from 1.5cm to 2.5cm and 3.0cm causes increase in the maximum scour depth by about 9% and 17% respectively.

VII. CONCLUSIONS

From the previous analysis of the results, the following conclusions are obtained:

1- The maximum scour depth around piles increases as the pile cap submergence ratio increases. For fully submerged pile cap, the maximum scour depth around first row of piles increases by 66% of the freeboard case.
2- The first row of piles facing the flow is the most affected than the other rows.
3- The maximum scour depth around piles decreases as the pile cap entrance angle decreases. Changing the pile cap entrance angle from sharp angle 90° to 15° reduces the local scour around first row of piles by 47%.
4- The biggest enhancement to the local scour around piles in case of submerged pile cap was during using pile cap entrance angle of 15°.
5- There is a significant effect for changing the pile diameter on the maximum scour depth. In addition, increasing the pile diameter by 66% and 100% cause increase in maximum scour depth by about 9% and 17% respectively.

NOTATIONS

The following symbols have been adopted for use in this paper:

Q = The discharge [L^3T^{-1}];
d_s = The scour depth [L];
$d_{s\,Max}$ = The maximum scour depth [L];
ρ = The density of water [ML^{-3}];
υ = The kinematic viscosity of water [L^2T^{-1}];
ρ_s = The density of sand [ML^{-3}];
w_s = The setting velocity of the sand [LT^{-1}];
g = The acceleration due to gravity [LT^{-2}];
Re = Reynolds number [-];
θ = Shields parameter [-];
U_b = The maximum value of the undisturbed bed shear velocity [LT^{-1}]; and
D_{50} = The sand effective diameter [L].

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