Influence of the Slot Elevation on the Scour around the Bridge Pier Using CFD

Naser Mahan (Corresponding author)  
School of Civil Engineering, Islamic Azad University, Central Tehran Branch, Iran  
Tel: +98-912-644-0701, Email: n.mahan@gmail.com

Seyed Habib Musavi-Jahromi  
Associate Prof., School of Water Sciences Engineering, Shahid Chamran University, Iran  
Tel: +98-916-618-0911, E-mail: dr.hmusavi@yahoo.com

Abstract
The phenomenon of scour, cause erosion around bridge piers and consequently may result in failure of foundations and bridge collapsing. Bridge piers through flow streams, reduce flow path, increase the flux per unit width and increase shear stress in narrowed section. Eventually collision of flow with bridge pier causes the precession of the normal current to the side of the pier and channel bed. To prevent or to reduce occurrence of such a phenomenon a range of solutions are presented. One of the engineering approaches to reduce the local scour involves locating slots in the bridge piers. In the current paper the effectiveness of introducing slots on the piers in reduction of the scour depth around the cylindrical bridge piers, under clear water condition with time development has been studied. To determine the scour depth 2 numerical methods and CFD-based modeling have been used. A large amount of data were gathered from the Soil Conservation in Watershed Management Research Institute (SCWMRI) laboratory for modeling and the scour depths in the piers based on different slots elevations have been compared with none slotted pier’s scour. Imaginary three sizes of slots are used; slot No.1 with dimension 30x10 mm (1*b), slot No.2 with dimension 15x15 mm and slot No.3 with dimension 7.5x20 mm. The slots are positioned at 3 levels of 0, 1/3 and 2/3 of flow depth which equals to 0, B and 2B of circular pier diameter (B) compared. Two amounts of discharges; 5 lit/sec and 7 lit/sec were used on all the models. With the non-slotted piers 20 scenarios were studied in total. At the end of analyses it was found that, slots with wider width and shorter height which are located in near the flow surface would result in minimum scour depth. In this case, the scour depth would be reduced by 20% compared to the pier without any slot. Also slots with greater heights and less width which are located near the channel bed are the worst scenarios.

Keywords: local scour, Slot, Bridge pier, CFD, Elevation

1. Introduction
Scour is a usual occasion which happens around bridge pier. Actually scouring is displacement of particles by the initial location to another position. In totally scouring is due to the interaction forces such as dynamic force which is in the direction of the flow that works to discrete particles in the bed, and also resistance force due to particles friction and weight against movement of particles. Particles begins to move when the forces imposed by flow like Drag force and Lift force which cause separation between particles and bed, comes the dominant to particles resistance forces. In overall scour development has four stages as, Initial phase, Development phase, Stabilization phase and Equilibrium phase. Scouring in various views, shared in 3 main views, first one is scouring in view of the causing, that comprise General Scour, this type of scouring occurs when whole of the river bed where bridge is in this interval to the causes of forces interaction is going down. During of this interval of river, flow is able to move and carry particles along the river, which reduce the level of the river in bed from the primary balance at the same interval, Constriction effect, the cross section at a crossing is often reduced by piles and embankments. If the bed of the river is mobile, the concentration of flow at the constriction will result in an increase in flow depth through scouring. The increase in depth at a long constriction can be computed from the equation of motion and continuity for sediment and water, and Local Scour, local scour occurs around the structural components
due to barriers such as bridge and abutment. These barriers can increase flow local speed and confusion and also vortex can be created depending on structure shape which cause extra erosion forces on the bed. Thus local scour occurs around the piers due to create a complex 3D vortex system, all components illustrated in figure 1, second one is scour in view of the sediment transport condition which comprise scour in Clear water scour where sediment is removed from the scour hole and not replaced. Maximum scour occurs when the flow is no longer capable of moving the sediment out of the scour hole, and scour in Sediment water, where the sediment is continuously supplied to the scour hole from the general sediment transport. The maximum scour is reached when the sediment transport out of the scour hole equals the supply of sediment into the hole, and third one is scour in view of sediment particles condition which in laboratory, usually two types of scour are considered, Static Scour depth are measured hole depth at the end of experiment which is after setting of particles and suspended solids in scour hole and Dynamic Scour depth is calculating through testing and before location of sediment in scour hole.

As presented in figure 2 vortexes are created in 5 sorts, as Horseshoe vortex system, where after dealing flow with pier, would be created local pressure and will be separated flow lines. Thus these eddy currents lines interference with intact lines and concentrated in front of the pier, that cause drilling a hole in front of the pier. Rotation water in the hole stretched to two side of pier. In total, whirlpool makes the horseshoe vortex. Wake vortex system, this system is against horseshoe vortex and created by layers roll on the pier surface to up direction of flow. In lower Reynolds number (50<Re<3-5) system is stable and in downstream near the pier makes up a robust system. Trailing vortex system, formation mechanism of this system is the pressure between two levels which are interrupting together in a corner. Down flow vortex system, this system occurs when flow striking the pier and moves down and transport bed’s materials. Bow wave vortex system, this system created in water surface and turning direction is against horseshoe vortex. The bow wave flow is significant in shallow streams, because where the swirl system is synchronized with the main stream, in terms of reduce power, the system is downward.

Parameters affecting on the scour can be divided into four main categories: Geometric parameters as width (b), length (l) and shape of pier, pier angle with the flow (α), piers distance and protection system of piers. Hydraulic parameters such as discharge of flow (Q), depth of flow in upstream (y), the average velocity of flow in the upstream (v), slope of channel, discharge of flow per unit width, flow section surface (A) and Manning roughness coefficient. Parameter’s related to fluid characteristics as mass per unit volume of fluid (ρ), kinematic viscosity (ν) and acceleration of gravity. Sediment parameters such as specific gravity of bed materials (Ps), sedimentary material size (D50), and grain size distribution of bed, particles shape and static angle. In addition to above mentioned factors also significant information are about the basin’s floods intensity and period of flood. When a slot is installed on the pier, since it causes some stream passes of pier structure, therefore, the down flow vortex will be reduced. In addition to, decrease of the maximum scour depth, the rate of scouring is similarly reduced considerably. Reduction in the rate of scouring reduces the risk of pier failure when the duration of floods is low. Depth of local scour around the bridge pier is time dependent and increase over time. Figure 3 shows scour depth diagram in terms of time and shear velocity around a bridge pier. Richardson and Davis (1995) expressed that the maximum depth of local scour in clear water is 10% more than equilibrium scour depth at the sediment–containing water. Frantz et al (1982) were studied on effect of scour time in final scour depth around a circular bridge pier and derived an exponential function for changes of scour time as follow:

\[
y_{st} = 1 - e^{-0.02\left[\frac{D50}{a}\right]^{1/3}}
\]

In above equation \(y_{st}\) is scour depth in time \(t\), \(y_s\) maximum scour depth, \(a\) is diameter of pier and \(u_s\) is velocity in time \(t\).

2. Materials and method

Using slot is one of the solutions which were issued to prevent bridge pier in contradiction of scouring. Slot has 2 main duties, first preventing of scour by changing flow streams motion, then delaying the occurrence of phenomenon scour by deceleration of dealing flow streams to channel bed. Slots could be in various
shapes like quadrangle or orbicular and different dimensions and moreover in dissimilar levels of fitting. In whole state, slots could be fixed or variable in dimension. Figure 4 illustrate physical model of cylindrical pier with and without slot and figure 5 shows schematic view of pier with slot.

2.1 Methods and Equations

A method for solving is CFD-based (Computational Fluid Dynamic) 3D simulation technique. In a CFD-based simulation, the region of interest (the domain) is sub-divided into an interconnected lattice of small cells (control volumes). Within each individual cell the fluid flow equations are solved using information from its neighboring cells. Iterating from initial conditions, a computer is used to perform many millions of repetitive operations and the result is a fluid flow simulation which replicates the performance of the prototype system. There are many equations to calculate scour depth, but as yet no equation issued for slotted bridge piers. So to calculate this value, calculation is done by six equations, as Lee et al (1961), Chital (1962), Hanku (1971), Colorado State University(CSU) (1975), Jain and Fisher (1979) and Jain (1982) and Colorado State University(CSU) (1975) which mentioned respectively as bellow:

\[ \frac{y}{y} = 2.0 \left( \frac{d}{y} \right)^{2/5} \left( Fr \right)^{2/5} \]  
LIU (1961) (circular)  
(2)

\[ \frac{y}{y} = -5.49Fr^2 + 6.65Fr - 0.51 \]  
CHITALE (1962)  
(3)

\[ \frac{y}{a} = 2.42 \left( \frac{u_c}{u} \right)^{4/9} \left( u / ga \right)^{1/3} \]  
HANKU (1971)  
(4)

\[ \frac{y}{y} = 2.0 \left( \frac{a}{y} \right)^{0.65} \left( Fr \right)^{0.43} \]  
Colorado State University (1975)  
(5)

\[ y_s = 1.85a \left( Fr_c \right)^{0.25} \left( \frac{y}{a} \right)^{0.5} \]  
JAIN and FISHER (1979)  
(6)

\[ \frac{y}{a} = 1.41 \left( \frac{y}{a} \right)^{0.2} \left( Fr \right)^{0.25} \]  
JAIN (1981)  
(7)

2.2 Modeling procedure

In this project, model includes a rectangular flume, with width of 0.25m, length of 5m and depth of fluid 0.09m, where \( w*d \) (0.25*0.09) is equal to \( S \) (0.0225 m²) and constant along the flume for all models. From the study conducted by Ettema and Raudkivi, was found that to avoid wall effect on scouring, flume width should be more than 6.25 times of pier diameter. The size of pier in this study was defined to meet the criteria which have been defined by other investigations, a cylindrical pier with 0.03m diameter and 0.3m height was fitted on the centerline of the flume in 3m length and 0.125m width of flume coordinate.

Diameter, as \( B \) is diameter of pier, planned levels are 0, \( B \) and 2\( B \). As well as scour depth calculated in all models for 2 counts of discharge, 5 and 7 lit/sec. Table 1 illustrate the above information.

For modeling purposes and according to figure 4, three physical models of slotted piers with different geometry of slot were selected, while the area of slots was constant in them. If we assume that the length of slot be \( l \) and the width of slot be \( b \) (figure 5), in all slots the ratio of \( l/b \) is different. As illustrated in figure 5, diameter of pier is \( B \) and level of slot where fitted, is called \( d \), thus dimension of slot be specified by \( l/b \). Slot type one with dimension of 30*10mm, ratio of 3 for \( l/b \), slot type two with dimension of 15*15mm, ratio of 1 for \( l/b \) and slot type three with dimension of 7.5*20mm, ratio of 0.375 for \( l/b \). Table 2 shows the Geometrical characteristics of bridge pier with and without slot.

All modeling had been done under clear water condition. Clear water scouring for average flow velocity (\( U \)) and threshold velocity for bed sediments (\( U_c \)) occurs under condition \( (U/U_c) \leq 1 \). In contrast, moving bed scouring occurs under \( (U/U_c)>1 \) Condition. But maximum scouring occurs under \( (U=U_c) \) and clears water conditions. In other words, unlike moving bed conditions, clear water scouring occurs in a long period and reaches its maximum depth. To calculate the critical velocity and the ratio of \( (U/U_c) \), a number of different models and methods have been proposed.

For calculation 20 scenarios was considered. These scenarios are divided into two series as are different in count of discharge and in per series 9 scenarios are different in kind and location of slots and 1 scenario is pier without slot. Table 3 expressions the Characteristics of scenarios.

Time for calculating scour depth is very important as scour depth is time dependent. In current study time for calculations are considerate 60 minutes, and this time shared into 60 part of 60 minute, where
calculation repeated in every one minute. To computing scour depth, parameters which obtained are Bed shear stress, Velocity magnitude and Total pressure. By the initial velocity and critical velocity which obtained after modeling, resulted (U/Uc) ratio which shows condition (U/Uc ≤ 1) for all models.

3. Results and Discussion

After analyzing all the scenarios by using CFD modeling and aforementioned 6 equations, it was determinate that in the ratio of (l/b) if width of slot increased and length of that decreased, shear stress would be maximum and velocity and total pressure are in minimum value,. In reverse direction if width of slot decreased and length of that increased the least shear stress and maximum velocity and total pressure will be achieved. In ratio of d/y where d is slot distance from bed and y is depth of flow, in shorter distances of slot from channel bed, shear stress is maximum and velocity and total pressure are the lowest. In greater distances of slot from bed shear stress is smallest and velocity and total pressure are in extreme value. Changes in discharge value do not affect the above results.

Based on the observed results in the same models, the equations of Jain and CSU were used as the basis of comparisons. Results for models and scenarios by the 2 equations are shown in table 4 and figures 6 and 7. For slot No.1 the maximum scour depth in the 5 lit/sec discharge occurred in the 3rd level and the minimum scour depth occurred in 2nd level. Also in the 7 lit/sec discharge the maximum scour depth was in for the 1st level and the minimum value was similar to the low discharge.

In slot No.2 the maximum scour depth in the 5 lit/sec discharge was measured in the 2nd elevation and the minimum value was in the 1st level. For the 7 lit/sec discharge the maximum depth was in the 1st level and the minimum value was in the 3rd level.

For slot No.3 the maximum and minimum scour depth occurred in same elevation regardless of the discharge rates. The maximum scour depths were in the 1st level and the minimum scour depths were in the 3rd level for both the discharge rates.

In general, it is found that in a high discharge and for all slots, the maximum scour depth occurred in the 1st level and the minimum scour depth occurred at the 3rd level. For the low discharges and velocities, no regulation was found.

For both discharges of 5 and 7 lit/sec, the maximum scour occurred in slot No.1 and in the 1st level where length of slot is greater than its width and the slot is located near the bed. The minimum scour depth happened in slot No.3 and in the 3rd level where length of slot is less than its width and the slot is far from the channel bed. In this level, the velocity value is in maximum state as shown in the velocity variation vs. depth of flow diagram,

4. Conclusion

Scour is a normal phenomenon which occurs around most of the bridge piers. Many factors are involved in this event. One of the solutions to protect bridge piers and minimize the volume of the scour depth is the use of slots in the piers. Slots can be of various characteristics. In the present study; 3 configurations of slots with different dimension and different elevations on the pier, and in 2 different series of discharge were reviewed.

Those slots which were installed in the bed level resulted in maximum scour depth compared to other elevations. Moving the pier slot from the bed level to the fluid flow surface and with increasing the current velocity, the scour depths were reduced. It was concluded that the scouring depth for slots near the water surface were less than the other slot locations.

In addition to the slot’s elevation the effectiveness of the slot dimensions were also investigated. Among all the slots at any elevation from the bed surface, the minimum depth of scour occurred in slot No. 3. Therefore, increasing the slot width seemed to be more efficient than increasing slot’s height. Order of effectiveness of slot dimensions on scour reduction in the bridge piers are slot No. 3 (width greater than height), slot No. 2 (width equal to height), and slot No. 1 (width smaller than height).
Thus the best configuration is slot No.3 at 3rd level which reduces the scour depth by 20%.

It should be noted that the existence of slots on the piers do not automatically guarantee to result in reduced scour depths. Specific studies shall be carried out on every case taking the dimensions of the piers and configuration of the slots into account.

References


Christensen, Z.M., (2009), Reduction of local Scour Around Bridge Pier Combined System of Aero foil and Slot, B.Sc. Research Project, University of Southern Queensland, Civil Engineering Department, 35-42.


Melville, BW & Coleman, SE (2000), Bridge Scour, Water Resources Publications, LLC, Highlands Ranch, Colorado, USA.
Table 1. Hydraulic and geometric characteristics of channel and flow

<table>
<thead>
<tr>
<th>Discharge (lit/sec)</th>
<th>Length of channel (m)</th>
<th>Width of channel (m)</th>
<th>Pier diameter (m)</th>
<th>Pier height (m)</th>
<th>Depth of flow (m)</th>
<th>Section area (m^2)</th>
<th>U (m/sec)</th>
<th>Fr</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>0.25</td>
<td>0.03</td>
<td>0.3</td>
<td>0.09</td>
<td>0.0225</td>
<td>0.222</td>
<td>0.23</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>0.25</td>
<td>0.03</td>
<td>0.3</td>
<td>0.09</td>
<td>0.0225</td>
<td>0.311</td>
<td>0.33</td>
</tr>
</tbody>
</table>

This table illustrates the hydraulic and geometric characteristics for considered channel and flow in this article.

Table 2. Geometrical characteristics of bridge pier

<table>
<thead>
<tr>
<th>Number of slot</th>
<th>Height of pier (m)</th>
<th>Diameter of pier (m)</th>
<th>Length of slot (m)</th>
<th>Width of slot (m)</th>
<th>Area of slot (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot No.1</td>
<td>0.3</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.0003</td>
</tr>
<tr>
<td>Slot No.2</td>
<td>0.3</td>
<td>0.03</td>
<td>0.015</td>
<td>0.015</td>
<td>0.000225</td>
</tr>
<tr>
<td>Slot No.3</td>
<td>0.3</td>
<td>0.03</td>
<td>0.0075</td>
<td>0.02</td>
<td>0.00015</td>
</tr>
<tr>
<td>Without slot</td>
<td>0.3</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 shows Geometrical characteristics for slotted and non-slotted bridge pier.

Table 3. Characteristics of scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Model</th>
<th>Slot</th>
<th>Level</th>
<th>Slots geometry</th>
<th>Location of slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>S1-H1</td>
<td>No.1</td>
<td>0</td>
<td>0.03 0.01</td>
<td>y-1/3y</td>
</tr>
<tr>
<td>Second</td>
<td>S1-H2</td>
<td>No.1</td>
<td>B</td>
<td>0.03 0.01</td>
<td>1/3y-2/3y</td>
</tr>
<tr>
<td>Third</td>
<td>S1-H3</td>
<td>No.1</td>
<td>2B</td>
<td>0.03 0.01</td>
<td>2/3y-y</td>
</tr>
<tr>
<td>Fourth</td>
<td>S2-H1</td>
<td>No.2</td>
<td>0</td>
<td>0.015 0.015</td>
<td>y-1/3y</td>
</tr>
<tr>
<td>Fifth</td>
<td>S2-H2</td>
<td>No.2</td>
<td>B</td>
<td>0.015 0.015</td>
<td>1/3y-2/3y</td>
</tr>
<tr>
<td>Sixth</td>
<td>S2-H3</td>
<td>No.2</td>
<td>2B</td>
<td>0.015 0.015</td>
<td>2/3y-y</td>
</tr>
<tr>
<td>Seventh</td>
<td>S3-H1</td>
<td>No.3</td>
<td>0</td>
<td>0.0075 0.02</td>
<td>y-1/3y</td>
</tr>
<tr>
<td>Eighth</td>
<td>S3-H2</td>
<td>No.3</td>
<td>B</td>
<td>0.0075 0.02</td>
<td>1/3y-2/3y</td>
</tr>
<tr>
<td>Ninth</td>
<td>S3-H3</td>
<td>No.3</td>
<td>2B</td>
<td>0.0075 0.02</td>
<td>2/3y-y</td>
</tr>
<tr>
<td>Tenth</td>
<td>Without slot</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 displays the scenarios characters where applied for modeling in present article.
Table 4. Results for scour depth basis on (ds/b)

<table>
<thead>
<tr>
<th>Discharge</th>
<th>Equation</th>
<th>S1-H1</th>
<th>S1-H2</th>
<th>S1-H3</th>
<th>S2-H1</th>
<th>S2-H2</th>
<th>S2-H3</th>
<th>S3-H1</th>
<th>S3-H2</th>
<th>S3-H3</th>
<th>WS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q=5l/s</td>
<td>Jain</td>
<td>2.8</td>
<td>2.7</td>
<td>2.9</td>
<td>2.6</td>
<td>2.7</td>
<td>2.7</td>
<td>2.8</td>
<td>2.7</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>CSU</td>
<td>3.7</td>
<td>3.5</td>
<td>3.9</td>
<td>3.4</td>
<td>3.5</td>
<td>3.4</td>
<td>3.6</td>
<td>3.5</td>
<td>3.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Q=7l/s</td>
<td>Jain</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.1</td>
<td>3.0</td>
<td>3.1</td>
<td>2.7</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>CSU</td>
<td>4.4</td>
<td>4.1</td>
<td>4.2</td>
<td>4.1</td>
<td>4.1</td>
<td>4.4</td>
<td>4.1</td>
<td>4.1</td>
<td>3.6</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 4 displays the results for all models and scenarios which obtained by two equations of Jain 1961 and CSU 1975 and showed by ratio (ds/b).

Figure 1. Scour Components

Figure 1 show the schematic view of scour components when description of scour is in view of the causing.

Figure 2. Elements present around a pier (Melville & Coleman 2000)

Figure 2 present vortexes around bridge pier which occurs via local scour.
Figure 3 shows scour depth development as a function of time, where scour depth is strongly time dependent. It is a difference between clear water and sediment water (Live bed) development, which display in diagram.

Figure 4 and 5 shows section of bridge piers with and without slot and characteristics of slotted pier in front of flow.
Figure 6. Scour depth around bridge pier by “Jain 1961”

Figure 6 shows the results of scour depth by equation of “Jain 1961” for both discharges and all scenarios.

Figure 7. Scour depth around bridge pier by “CSU 1975”

Figure 7 shows the results of scour depth by equation of “Colorado State University 1975” for both discharges and all scenarios.