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Comparative Study of Slot Shapes Effects on the Scour around Bridge Pier

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Abstract- Scour caused by a decrease in crossing section increases the flux per width unit which all cause rising shear stress in narrowed section. Local scour depth around bridge circular piers located in rivers in uniform sediment and clear water condition has studied in this paper. In order to prevent potential failure of pier and consequently superstructure collapse, a slot in the pier is considered. For the coherent comparison 3 different slot shapes with same areas, however in 3 levels of stream depth were located in pier in current direction and 2 amounts of flow discharge were considered. Entirely 20 scenarios were defined then the results were comprised to find the best answer. Following to the novelty experimental modeling in workshop, the approach of finite volume method, FVM, and ANSYS Fluent software were used to ascertain and solve equations of the issue. The variation of equilibrium scour depth with approached velocities indicates that the decrease at velocity, wider width and shorter height of slot where located near the surface has caused to minimum amount of scour depth.

Keywords- *Local Scour, Bridge, Pier, Slot, River, Vortex, CFD*

I. Introduction

Bridge scour as one of the main causes of bridge failures is a natural phenomenon caused by erosion or removal of stream bed or bank material from bridge foundations due to flowing water. This phenomenon is created locally as a result of mutual effect of water stream geometry, bed and current specifications around the pier. Actually scouring is displacement of particles from initial position to another location. Scour development has four stages of Initial phase where scour begins, Development, Stabilization and Equilibrium phases. That is to say, after movement of particles from their initial place, if they encounter a pier, a scour hole will be drilled around it. Although developing depth of the hole is inevitable, in third phase of scouring walls are going to be reduced till in equilibrium phase. Then particles move in the scour hole without getting out of it [4, 6, 7].

In local scour, as it can be inferred from figure 1, vortexes are created in 5 classes; Horseshoe vortex system that would be created by local pressure and separate flow lines after the flow contacts pier. Thus, interfering of these eddy currents lines with intact lines and concentration of them in front of the pier, causes drilling a hole where the Rotation of water is stretched in two side of pier. This whirlpool makes the horseshoe vortex. Wake vortex system is against horseshoe vortex and created by layers roll on the pier surface to make and upward flow. In lower Reynolds numbers, (50<Re< 3-5) system is stable and downstream makes up a robust system near the pier. The third one is surface roller vortex system. The mechanism of this type of vortex is based on the pressure between two water levels which influence each other in a corner. The next is Downflow vortex system. This system occurs when the flow is striking the pier and moves down and transport bed's materials with itself. Bow wave vortex system can be considered as the last system. As it would be created in water surface and because of turning direction of flow, it is against horseshoe vortex. The bow wave flow is significant in shallow streams where the swirl system is synchronized as the main stream, so if the power of flow reduces, the system will reverse. The occurrence of these vortexes, either individually or as a combination, makes a wake vortex region behind the pier [3, 7].

Wake region is an area which can be established behind the pier when flow pattern encounters with pier. This is because just in front of pier the velocity comes down into minimum and kinetic energy is not able to increase the pressure [3, 10].

The parameters affecting on the scour can be divided into four main categories regarding flow and channel characteristics; Geometric parameters as width (b), length (l) and shape of pier, pier angle with the flow (α), piers distance and protection system of pier. 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 with unit width, flow section surface (A) and Manning roughness coefficient. Parameters 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 (D_{50}), and grain size distribution of bed, particles shape and static angle. In addition to above mentioned factors there is some significant information about basin's floods intensity and the period of flood [1, 2, 8].

As a general statement, considering of being a slot and passing stream through it, the depth of scouring would decrease. If this condition coincides with short–term flood, the risk of pier failure would considerably be reduced. The depth of local scour around the bridge piers is strongly time-dependent and partly increases over time [7, 8, 12].

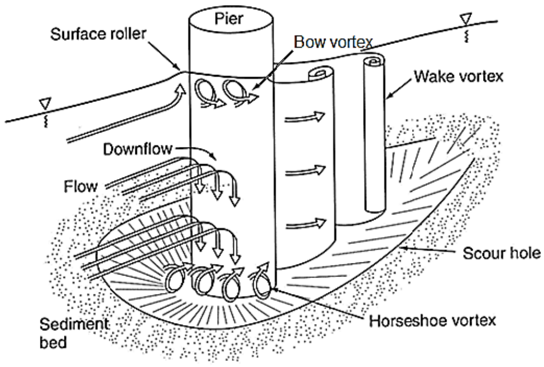

Figure 1. Schematic view of vortexes around a pier

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Figure 2 shows scour depth diagram in terms of time around a bridge pier. Richardson and Davis (1995); had expressed that the maximum depth of local scour in clear water is 10% more than equilibrium scour depth at the sediment–containing water [3, 6, 13, 14].

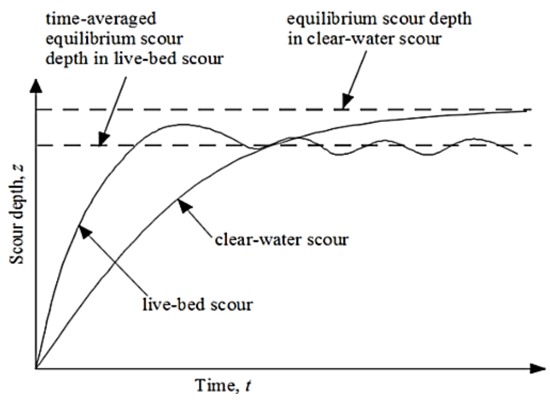

Figure 2. Scour depth as a function of time

Melville B.W. and Chiew Y. M., (1999); had studied on the effect of time on final scour depth around a circular bridge pier and derived an exponential function for changes of scour time as follow:

$$\frac{y_{s,t}}{y_s} = 1 - e^{\left[-0.028\left[\frac{u_t}{a}\right]\right]^{1/3}} \tag{1}$$

In above equation' $y_{s,t}$' is scour depth in time' t', 'y_s' is maximum scour depth, 'a' is diameter of pier and 'u_t' is velocity in time 't' [7, 9].

A. Objective

The aim of this study is to determine the effect of slot and measure and comprise the amount of local scour depths and finally issue the best solution. For this objective, a method which has been used in current paper against the phenomenon of scour is using a slot on the pier in front of the flow path. It is one of the novel engineering solutions which are used to protect bridge pier against scouring. Slot has 2 main duties; the first one is repelling scour by changing flow rotation, and the second is delaying the occurrence of the phenomenon of scour by preventing flow streams from encountering channel bed. Slots could be in various shapes like quadrangle or orbicular with different dimensions, and in dissimilar levels of positions [5, 11, 15]. Figure 3 illustrates the physical model of cylindrical slotted pier and it's around vortexes.

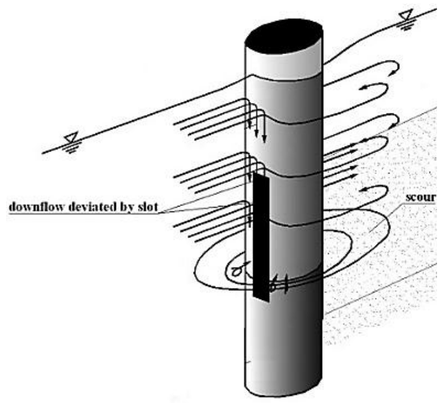

Figure 3. Schematic view of slotted pier and vortices around it

II. Methodology for Prevention of Scour

A. Approach

A fundamental method for solving numerical analysis was CFD-based (Computational Fluid Dynamic) 3D simulation technique. This technique is divided into three main methods as Finite Element Methods (FEM), Finite Volume Methods (FVM) and Finite Difference Methods (FDM). FVM has been used for solving the present problem. In a CFD-based modeling and FVM, the region of interest (the domain) is sub-divided into an interconnected mesh of small cells (control volumes). The net flux through the control volume boundary is the sum up of integral over the four control volume faces (Six in 3D), the value of the integrand is not available at the control volume faces, so it is determined by interpolation. Within each individual cell the fluid flow equations are solved by using information from its neighboring cells.

Iterating from initial conditions, ANSYS Fluent computer software was used to perform many millions of repetitive operations and the results are a fluid flow simulation, velocity and pressure in all directions which are obtained through replicating the performance of the prototype system. ANSYS Fluent provides a comprehensive suite of computational fluid dynamics software for modeling fluid flow and other related physical phenomena.

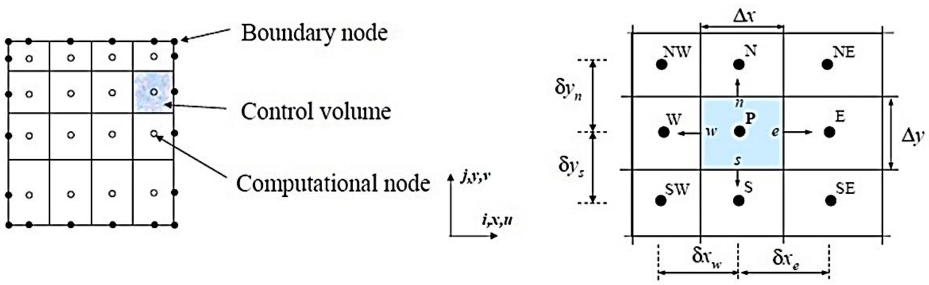

Figure 4. Cells and nodes in control volume

Governing equations of the continuation and momentum equations in constant density and incompressible flow which were solved in this paper are as follow:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial u_i}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\rho u_j u_j\right) = \frac{\partial}{\partial x_i}\left(\sigma_{ij}\right) + \rho b_i \tag{3}$$

represents velocity in ‘i’ direction and $\partial / \partial x_i$ is spatial derivatives of the components ‘i’ of Cartesian coordinate system, ‘ρ’ density, bi volumetric force in xi direction and σij is stress tensor.

There are many equations to calculate scour depth; however, no equation has been issued merely for slotted bridge piers yet. So to calculate this value, calculation was done by six equations, as Liu et al., 1961; Chital 1962; Hancu, 1971; Colorado State University (CSU), 1975; Jain and Fisher, 1979; and Jain, 1982; which have been mentioned respectively as below:

$$y_s/y = 2.0\, (a/y)^{2/5} .Fr^{2/3} \tag{4}$$

$$y_s/y = -5.49Fr^2 + 6.65Fr - 0.51 \tag{5}$$

$$y_s/a = 2.422\, u/u_c\, (u/ga)^{1/3} \tag{6}$$

$$y_s/y = 2.0\, .(a/y)^{0.65}.(Fr)^{0.43} \tag{7}$$

$$y_s = 1.85a(Fr_c)^{0.25}.(y/a)^{0.5} \tag{8}$$

$$y_s/a = 1.41 (y/a)^{0.3} Fr^{0.25} \tag{9}$$

For all of these equations ‘y_s’ refers to scour depth, ‘y’ is depth of flow, ‘a’ is diameter of pier, ‘u’ is average velocity of flow, ‘u_c’ is critical velocity of flow, ‘Fr’ is Froud number and ‘Frc’ is critical Froud number. Froud number calculated by following equation:

$$Fr = \frac{u}{\sqrt{gy}} \tag{10}$$

In above equation, ‘g’ is acceleration of gravity which is equal to 9.81 m/sec2. [6 ,16]

B. *Modeling Process*

A large amount of experimental data was gathered from the Iranian Soil Conservation Institute’s laboratory in Watershed Management Research center (ISCWMR) for modeling scour depths in piers based on different slots elevations. This data has been compared with none slotted pier’s scour. In this project, models include a rectangular flume, with width of 0.25 m, length of 5 m and depth of fluid 0.09 m, where w×d (0.25 × 0.09) is equal with flume section area (0.022 m2). The mentioned figures are constant along the flume for all models. From the study conducted by Ettema and Raudkivi, it was found that to avoid wall effect on scouring, flume width should be 6.25 times more than pier diameter. The size of pier was determined to meet the criterion which had been defined by other investigations. A cylindrical pier with 0.03 m diameter and 0.3 m height was fitted on the centerline of the flume in 2.5 m length and 0.125 m width based on flume coordination (as shown in figure 5). The bed type material D50 is 0.84mm, Geometric deviation standard is s=1.45 and Sediment distribution be classified as uniform.

Planned levels for slot fitted in locations of flow depth ‘y’ that equal to (0–1/3y); (1/3y–2/3y) and (2/3y-y). Also scour depth has been calculated in all models for 2 counts of 5 and 7 lit/sec discharge. Table 1 illustrates above information. In this table discharge in litter/second, depth, width and diameter in ‘meter’ and velocity are in meter/second.

TABLE I. HYDRAULIC CHARACTERISTICS OF CHANNEL AND FLOW

Discharge	Depth of flow	Width of flow	Diameter of pier	U	Fr
5	0.09	0.25	0.03	0.222	0.23
7	0.09	0.25	0.03	0.311	0.33

For modeling purposes and according to figure 4, three physical models of slotted piers with different geometric shapes were selected, while the area of slots(S) was constant in them. If we assume ‘l’ is height and ‘b’ (figure 4) is the width of slot, in all slots the ratio of (l/b) is different. As illustrated in figure 4, diameter of pier is ‘B’ and level of slot where fitted, is called ‘d’, thus dimension of slot would be specified by (l×b). Slot No.1 with dimension of 30 × 7.5 mm, ratio of 4 for (l/b), slot No.2 with dimension of 15 × 15mm, ratio of 1 for (l/b) and slot No.3 with dimension of 11.5 × 20 mm, ratio of 0.57 for (l/b) have been considered. Table 2 shows the geometrical characteristics of bridge pier with and without slot.

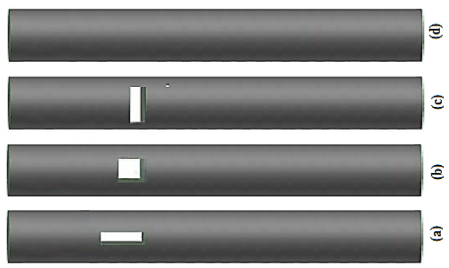

Figure 5. Piers with different slot shapes and without slot

TABLE II. GEOMETRICAL CHARACTERISTICS OF SLOTTED PIER

No. of slot	Length of slot	Width of slot	Area of slot (S)
	m	m	m2
Slot No.1	0.03	0.0075	0.000225
Slot No.2	0.015	0.015	0.000225
Slot No.3	0.01125	0.02	0.000225
Without slot	NA	NA	NA

All modeling has been done under clear water condition. 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/UC), a number of different models and methods have proposed.

For calculation, 20 scenarios were considered. These scenarios have been divided into two main series which are different in count of discharge. In each series, 9 scenarios are different in kind and location of slots and 1 scenario is pier without slot. Table 3 expresses the Characteristics of scenarios.

TABLE III. CHARACTERISTICS OF SCENARIOS

Scenarios		Model	Slot	Level	Slots geometry		elevation of slots
Q=5 l/s	Q=7 l/s				Height	Width	
First	Eleventh	S_1H_1	No. 1	0	0.03	0.0075	0-1/3y
Second	Twelfth	S_1H_2	No. 1	B	0.03	0.0075	1/3y-2/3y
Third	Thirteenth	S_1H_3	No. 1	2B	0.03	0.0075	2/3y-y
Fourth	Fourteenth	S_2H_1	No. 2	0	0.015	0.015	0-1/3y
Fifth	Fifteenth	S_2H_2	No. 2	B	0.015	0.015	1/3y-2/3y
Sixth	Sixteenth	S_2H_3	No. 2	2B	0.015	0.015	2/3y-y
Seventh	Seventeenth	S_3H_1	No. 3	0	0.01125	0.02	0-1/3y
Eighth	Eighteenth	S_3H_2	No. 3	B	0.01125	0.02	1/3y-2/3y
Ninth	Nineteenth	S_3H_3	No. 3	2B	0.01125	0.02	2/3y-y
Tenth	Twentieth	Without Slot	-	-	-	-	-

The time for calculating scour depth is very important because scour depth is strongly time dependent (Figure 2). In current study, by using Fluent software as a main application of modeling and solving, calculating time has been estimated 60 minutes which it is divided into 60 parts of 60 seconds that calculation was repeated in each part. To select best procedure a sensitivity analysis has been performed before modeling on available known turbulence models in Fluent software as k-ε Standards, k-ε RNG, k-ε Realizable, k-ω’ Standard and k-ω SST and 2 Pressure and Velocity relation algorithms as Piso and Coupled. Subsequently for data calibration and best solving model selection, based on Froude Number, Drag Force, Shear Stress and Converge Time of software outcomes with comparing to lab results, model type k-ε RNG and Piso algorithm were selected.

Figure 6 shows the result of sensitivity analysis result based on k-ε RNG and Piso algorithm around the bridge pier with slot.

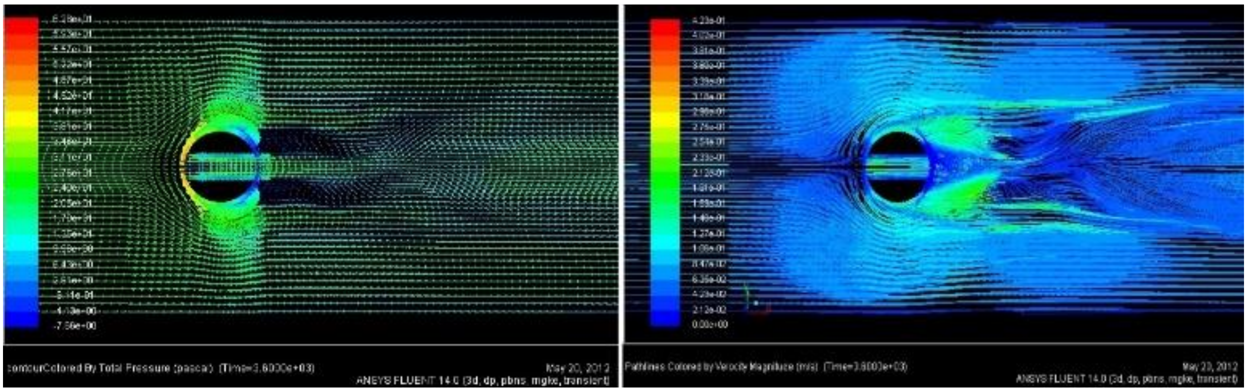

Figure 6. Counter and Path line of Pressure and velocity in k-ε RNG

To define the geometry of the scenario's models and meshing, ICEM CFD software was used. ICEM CFD, a product of ANSYS Inc., in compatible with Fluent and final model is exported to other group products of ANSYS.

To compute scour depth, after modeling and simulation in software with above mentioned models and algorithm obtained parameters are Bed shear stress, Velocity magnitude and Total pressure respectively.

III. Results and Discussion

Turning to analyzing all the scenarios by using CFD modeling by Fluent software and aforementioned 6 equations, it had been inferred 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 would be 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 would 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 in their lowest amount. In greater distances of slot from bed, shear stress become smaller and velocity and total pressure reach in extreme value. Changes in discharge value do not affect above results.

Based on results observed in the same models, the equations of Jain (Eq. 9) were used as the basis of comparisons as this equation have uniform and a steady rate in results with comparison to lab outcomes. Results from models and scenarios are shown in table 4 and figures 7.

TABLE IV. Results for scour depth basis on (ys/b)

Discharge	Models									
	S1-L1	S1-L2	S1-L3	S2-L1	S2-L2	S2-L3	S3-L1	S3-L2	S3-L3	WS
Q=5 lit/s	2.84	2.83	2.75	2.65	2.72	2.68	2.70	2.69	2.62	2.77
Q=7 lit/s	3.17	2.96	2.88	2.99	2.98	2.96	2.96	2.94	2.81	3.1

For slot No. 1 the maximum scour depth in the 5 lit/sec discharges occurred in the 1th level and the minimum scour depth occurred in 3rd level. The same results were seen for the 7 lit/sec discharge.

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

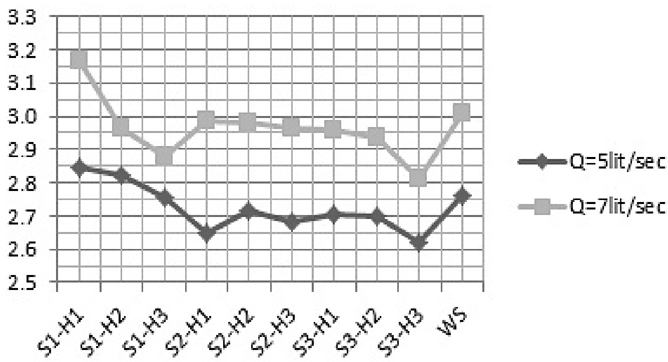

Figure 7. Scour depth around bridge pier by "Jain 1961"

Generally, it was likely found that for all slots the maximum scour depth occurred in the 1st level and except some cases the minimum scour depth occurred at the 3rd level. For both discharges of 5 and 7 lit/sec, the maximum scour occurred in slot No. 1 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 where length of slot is less than its width and the slot is far from the channel bed. As shown in figure 8 scenarios S3L3 has the minimum scour depth around the pier.

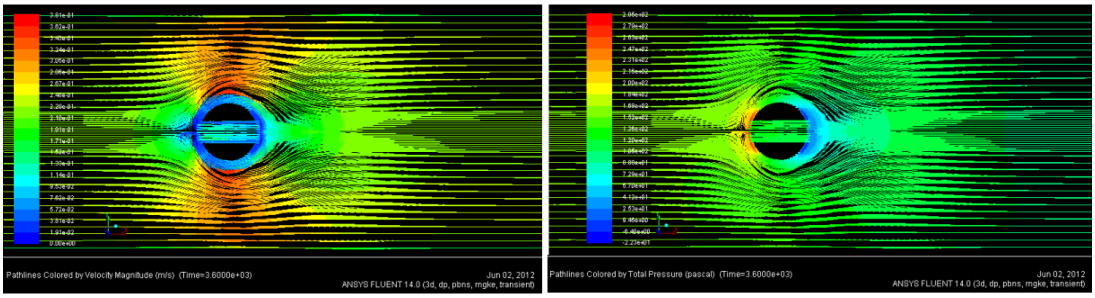

Figure 8. Path lines by Velocity and Pressure for S3L3

IV. CONCLUSIONS

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 use of slots in the piers. In the present study; 3 configurations of slots with different dimension and different elevations on the pier, and in 2 different amount of discharge has been carried out. The effectiveness of the slot dimensions has also been 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 its 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).

In addition to the slot's dimensions, those slots which were installed near the bed level resulted in maximum scour depth compared to other elevations. Locating the pier slot from the bed level to the 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. Thus, among the all scenarios which were studied, 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 depth. Specific studies shall be carried out on every case taking the dimensions of the piers and configuration of the slots into account.

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