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The Effect of Slots on Scouring Around Piers in Different Positions of 180-Degrees Bends

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Abstract: Scouring around the bridge piers causes a great deal of damage every year. To control this, a number of different methods have been proposed. However, these studies have been conducted on direct channels. This study investigates the application of slots in the reduction of pier scouring in 180-degree river bend. Toward this end, four models of slotted bridge piers and a model of non-slotted bridge pier were studied in the position of 60-degree of the mild 180-degree bend. The findings revealed that the average amount of decrease in the depth of scouring occurred in slotted pier type 1 which was the highest amount of depth decrease amounting to 24%. However, the scouring depth decrease was the lowest in slotted pier type 4 corresponding to 12%. Moreover, this study showed that the effects of slots on decreasing the scouring depth declined with the increase in the proportion of the average flow velocity to threshold velocity of sediments movement.

Key word: Scour · Pier · River bend · Slot

INTRODUCTION

Many factors can lead to river bridge failure such as overtopping, structural failure, debris accumulation, embankment erosion and scouring. Statistics and information obtained in some countries show that scouring is the most important factor in the destruction of bridges.

Pier scouring occurs when rapid water flows wash away big amounts of soil materials adjacent to bridge piers and this can in turn result in the destruction of the structure [1].

Different types of scouring occurring around the bridge piers include, general scouring or erosion which occurs regardless of the presence or absence of the bridge on the river bed, contractive scouring (constriction) which occurs as a result of section constriction when different structures like bridge piers block the water flow and local scouring which occurs by means of local flow field around the bridge piers. Although there are different types of scouring, local scouring of piers is the main reason explaining why bridges constructed on alluvial sediments collapse [2].

The main factor in local scouring consists of a series of secondary flows which comprise wake vortex system, trailing vortex system, horseshoe vortex system and bow wave vortex. Wake vortex system acts as a vortex and moves the bed sediments upward to the floor. This systems' strength depends on the piers' shape and water velocity. This

System does not exist. Practically, trailing vortex system is of little significance and often occurs in completely submerged piers. Horseshoe vortex system forms due to fragmentation in the piers upstream flow. In other words, the system forms when high pressure gradient is created by the collision between the water flow and the pier. It is important to note that the piers' shape plays an important role in the creation and the strength of the system [3].

Bow wave system forms on the water surface and it rotates in an opposite direction to horseshoe vortex system. Bow wave system is especially important in shallow water flows where the water flow crashes into the pier and adjusts the strength of the downward flow. Figures 1 and 2 depict different types of systems around the bridge piers and embankments.

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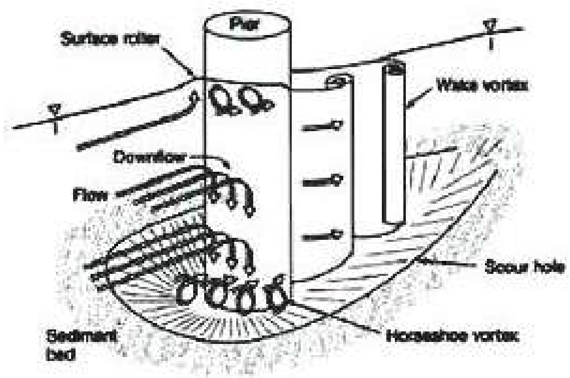


Fig. 1: Flow pattern around the pier [2].

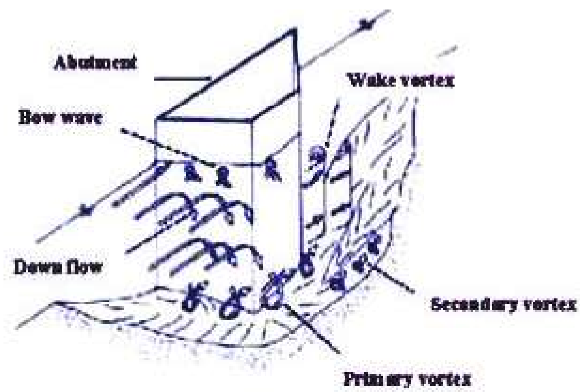


Fig. 2: Flow pattern around the Embankment [4].

Today, different methods are used to control and reduce local scouring among which ripraps, collars and slots are a few.

Chiew [5] studied the protection bridge piers against scouring using slots and collars. The test results demonstrated that using only one slot can lead to a 20% -reduction in scouring specially if the slot is close to the water surface or bed surface.

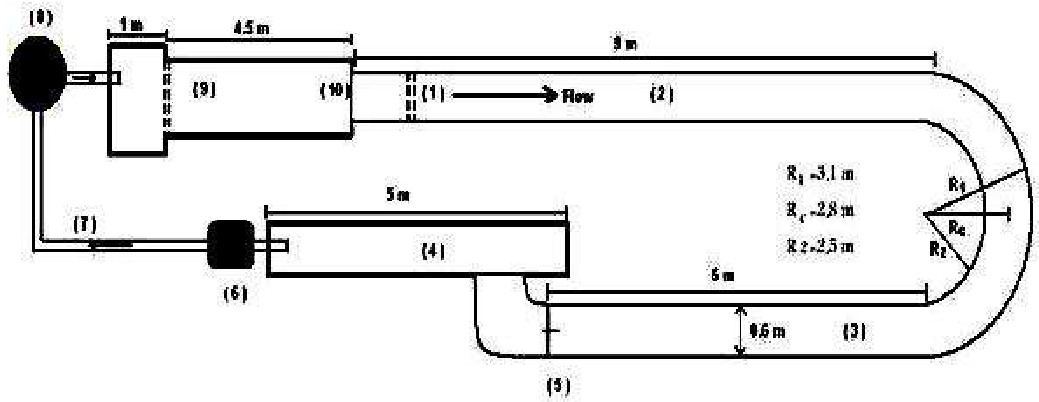
He also found that the combination of slot and collar can reduce scouring depth to greater extent. Kumar, *et al*. [6] investigated the reduction of local scouring around bridge piers in a direct stream with the use of a slot and a collar. Their findings showed that the slot was effective in decreasing scouring but the slotted pier would not be effective if the flow approaching the pier shows great deviation. The application of slot to control scouring in a group of circular bridge piers in a direct canal was studied by Heidarpoor, *et al*. [7]. The findings revealed that the group of bridge piers has a great impact on the depth of scouring on the front part of the pier compared with an individual pier. They also concluded that the effect of the slot on reducing scouring depth increases in parallel with the increase in the pier area.

The numerous studies to date have often been carried out in direct channels. In some special cases, however, due to the necessity in the construction of the proposed projects or the changes caused by the river, some bridges are built on river bends about which research studies are still scarce. Concerning hydraulic conditions and sediments around bridge piers in bends, one can review the experiment done by Emami [8] in which the flow patterns and scouring around a cylindrical pier in 180-degree bend were studied. Testing the maximum scouring depth at different points, he showed that the highest amounts of scouring occur in the first half of the bend and the amounts of scouring depth approximate the amounts at the direct point in the end sections of the second half of the bend. In light of the above-mentioned, the present study endeavors to test the effects of slots in bridge piers at different points of 180- degree river bends under laboratory conditions so that the effects of slots on decreasing scouring depth with respect to the characteristics of the water flow patterns in bends compared to the direct position might be revealed.

MATRRIALS AND METHODS

In order to investigate the mentioned purpose in this study, the researchers made use of a physical hydraulic model under clear water conditions in non-adhesive materials. This model, located in the hydraulic laboratory in Islamic Azad University of Ahvaz, included a rectangular flume with a 180-degree bend. Figure 3 and Table 1 depict the details such as length, width, bend radius, etc.

For laboratory purposes, the flume width must be at least as eight times as the size of the pier for scouring conditions in clear waters so that the effect of the channel walls on scouring depth can be eschewed [9]. Therefore, to determine the extent of the effects of the slots in reducing local scouring around bridge piers, a diameteral cylindrical 60 mm (b) was utilized as the pier model. All the experiments of the study were conducted in clear water condition to readily observe the maximum scouring depths [10]. The scouring mechanism in clear waters occurs in a manner that the bed sediments do not move with the upstream water flow. To put it differently, when the sediments are removed from the scouring hole,



1-Dissipator 2-Inlet canal 3-Outlet canal 4-Ground water reservoir 5-Tail Gate
6-Centerifugal Pump 7-Transition Pipe 8-Surge Tank 9-Stilling Basin 10-Triangular Weir

Fig. 3: Physical hydraulic model

Table 1: physical hydraulic model

Discharge Be Use (l/s)	Angle bend maximum (Degree)	Depth channel (m)	Radius of curvature to channel Width $\left(\frac{R_C}{w_t}\right)$	Width Channel (m)	Length bend Foreign (m)	Length bend Internal (m)	Radius Curvature Central (m)	Length Channel Output (m)	Length Channel Input (m)
35	180	0.45	4.67	0.6	9.74	7.85	2.8	5.5	9.1

it is not filled again by the sediments from the approaching currents [11]. While in moving bed scouring, the scouring hole is refilled by the sediments carried by upstream currents [12]. Clear water scouring for average flow velocity (u) and threshold velocity for bed sediments (u_c) occurs under $u/u_c \leq 1$ condition [13]. In contrast, moving bed scouring occurs under $u/u_c \rangle 1$ condition but maximum scouring occurs under u=u_c and clear water conditions. In other words, unlike moving bed conditions, clear water scouring occurs in a long period and reaches its maximum [14]. To calculate the critical velocity and the $\frac{u}{u_c}$ ratio, a number of different experiments and methods have been proposed. However, in this study, Chang's [15] method was employed. According to this method, the curves and diagrams suggested by Neil [16] are transformed into a series of relationships to calculate the critical velocity based on the flow depth and the average diameter of the particles. These relationships are:

For: $d_{50} \rangle 0.03(m)$

$$u_c = k_u (11.5) y^{1/6} d_{50}^{1/3} \quad (1)$$

For: $0.03(m) \rangle d_{50} \rangle 0.0003(m)$

$$u_c = k_{u1} (11.5) y^{x} d_{50}^{0.35} \quad (2)$$

Value of x the relationship (3) is to be calculated:

$$x = k_{u2} \frac{0.123}{d_{50}^{0.20}} \quad (3)$$

For: $0.0003 \rangle d_{50}$

$$u_c = k_u \sqrt{y} \quad (4)$$

u_c = critical velocity, $\left(m/s\right)$, y =flow depth (m), d_{50} = average size of sediment particles(m) k_u =0.55217, k_{u1} = $0.3048^{(0.65-x)}$, k_{u2} = 0.788.

In laboratory studies of phenomena, the relationships between effective factors of those phenomena are analyzed. In this study, the important role of dimensionless groups in interpreting and presenting experimental results and establishing links between the other factors involved in understanding the phenomena under study will be made clear. Meanwhile, applying dimensionless groups in different unit systems is quite simple so that the need to unit conversion coefficients is dispensed with.

In this study, it was assumed that local scouring (d_s) in a circular and cylindrical slotted pier and 180-degree river bend is the function of the following parameters:

$$d_s = f\left(\rho, \upsilon, \rho_s, d_{50}, y, b, w_t, t, t_e, u, u_c, \theta_p, w, y_l, \theta_A\right) \quad (5)$$

d_s = Scouring depth, ρ , v = Kinematics viscosity and water density, d_{50}, ρ_s = sediment size (assumed uniform sediment) and sediment density, y = water depth, b = pier diameter, w_t =section width, t= time, t_e=equilibrium time, u= average flow velocity, u_c= threshold velocity for bed sediment, θ_p = 180-degree bend position, w = slot width, y_1 =slot length and θ_A= angle of the flow approaching the slotted pier.

Creating suitable sand bend was a key factor in all experiments since irregularities and defects in the channel bed could result in inappropriate and untimely development of the bed. Researchers believe that if the ratio of the pier width (b) to particle size (d_{50}) is 25 times greater, the impact of particle size on scouring depth will be trivial [17]. In this study, a 15-cm thick and 2mm average diameter sand layer was used. Using sediments with this size prevents the development of deformity on the bed surface such as Ripple or Dunes which may exacerbate the estimation of scouring depth.

In addition, temperature and its effects on the changes in water density and viscosity which may influence the scouring depth have been assumed insignificant because studies have shown that there are not significant differences in scouring depth at different temperatures [2].

Consequently, with respect to the above-mentioned conditions, we can consider (d_s) only as a function of the following parameters:

$$d_s = f\left(y\ , b, w_t, t, t_e, u, u_c, \theta_p, w, y_l, \theta_A\right) \quad (6)$$

Applying the Buckingham theory and the dimensional analysis to equation (6), we can obtain the relationship (7):

$$d_s/b = f\left(u/u_c, t/t_e, w/w_t, y/y_l, \theta_p, \theta_A\right) \quad (7)$$

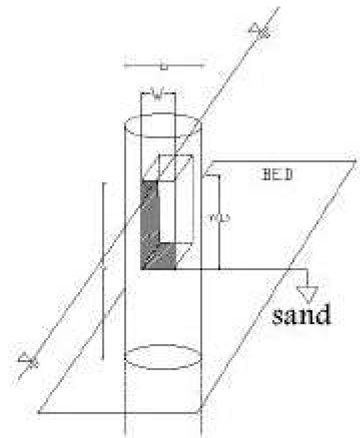


Fig. 4: slotted bridge pier

In order to test the effects of slots on scouring, four different slots were evaluated, each of which had a width corresponding to 0.25 of the pier diameter. The lengths of the slots are y_t and the depth of the uniform flow is y (Figure 4). Table 2 displays the characteristics of the different model piers and the slots according to b (pier diameter).

In this table, the bed surface is considered as the base level.

The equilibrium time plays a major role in the results of a scouring experiment [18]. Because equilibrium conditions must be achieved, this equilibrium time and the experiments must be prolonged. Bozkus and Osman [19] considered the maximum time for the experiments as two hours and found that the amount of increase in the depth of the scouring hole is insignificant after two hours. Ettema [20] considered the equilibrium time for scouring in a manner that during a four-hour period, the scouring depth would not increase more than 1mm. Sheppard *et al*. [21] and Melville and Chiew [13] ended their experiments when the scouring depth was not more than 5% of the pier diameter over a 24-hour period. Kumar, *et al*. [6], considered the time at which the changes in the scouring depth were not more than 1 mm, during a 3-hour period. In the present study, the equilibrium experiment was conducted under the most adverse conditions (discharge amounting to 31 litters per second and pier without slot).

Table 2: types of pier model

Number pier	pier status and slot	height slot
1	slot pier and slot length of the bed surface to surface 0-2b	0-2b
2	slot pier and slot length of 1 / 2 pier diameter of 3 / 2 diameter pier b/2-3/2b	b/2-3/2b
3	slot pier and slot length of the bed surface to the pier diameter 0-b	0-b
4	slot pier and slot length of the pier diameter equal to two pier diameter b-2b	b-2b
0	regular pier without slot	0

In the present study, the bridge pier model in each experiment was first installed in an appropriate position on the flume. Prior to each experiment, to make the bed surface uniform, the sand bed surface was leveled using a wooden leveler as wide as the flume which moved on the roller next to the flume. Also, a point gauge was used to measure the scouring depth. Before starting the experiment, the primary measurements of the bed in different locations of section were done and their average was considered as the primary measurements of the bed. Having started the experiment, the researchers gradually filled the flume with water to reach the desired flow depth. It is important to take a lot of heed while filling the flume so that clear water conditions are arrived at. When the pump was started, the upstream valve was slowly opened to obtain the optimal flow. At the same time, the tail gate was opened and regulated to reach the optimal flow depth. The flow was measured through triangular weir installed on the front part of the flume. After periodic measurements of the scouring depth during the experiment and after the two-hour equilibrium time, the tail gate was gradually opened to slowly discharge the flume without disturbing the bed. Moreover, the flume bed was left to dry. Maximum scouring in each experiment was finally recorded with a point gauge. It is important to note that the slotted bridge piers were tested at an angle of attack, in a river bend position of(60 degree) and four different discharges of (22,25,28,31) litters per second. Then, among these slots with respect to maximum reduction of scouring depth, one of the piers was selected as the most appropriate one. In order to test the effect of the selected slot position on scouring depth around slotted piers, those discharges were used at three 180-degree river bend positions(60, 90, 120 degrees). Afterward, the same experiments were repeated with non-slotted piers in the same positions.

RESULTS AND DISCUSSION

The diagram obtained from equilibrium experiments showed that the amount of increase in the depth of the scouring hole was insignificant after two hours (Figure 5). Consequently, in all of the remaining tests, the equilibrium was considered as two hours.

Table 3 illustrates the results of calculating the critical velocity and u/u_c ratio with the application of relationship 2.

H is the equivalent flow height based on Q-H in triangular weirs. Clear water scouring occurred because the changes were $\left(0.69 \langle U/U_C \langle 0.97\right)$ Figure 6 shows the ds/b changes (scouring depth ratio to pier width) according to the slot type for different flow conditions in 60-degree bend.

As illustrated in figure 6, from the four types of slotted piers, pier type 1 creates the slightest amount of scouring depth compared to other types of slotted piers and non-slotted pier. Also, comparing the impacts of the slots demonstrates that slot type 1(slotted pier and slot length from bed level to water surface) and slot type 3(slotted pier and slot length from bed level to pier diameter) which begin from the bed were the most effective ones. These results are compatible with Chiew [5] who acknowledges that slots which are close to water surface or bed level have greater effects on decreasing scouring around slotted piers. However, in Chiew's, study, the amount of reduction in scouring depth for the slots close to water surface or bed in direct channels or u/u_c was approximately 20% and the average decrease in the present study was varying between 12 to 24% in the bend with regard to $0.69 \langle u/u_c \langle 0.97$ changes. Table 4 and Figure 7 show the percentages of slotted pier scouring depth reduction compared with the non- slotted pier.

Table 3: Results of the critical velocity ratio calculated based on the relationship 2

N	*Q(1/s)*	*H(cm)*	*A(m²)*	*U(m/s)*	*KU₂*	*X*	*KU₁*	*U_C*	*U/U_C*
1	22	23.43	0.072	0.305	0.788	0.336	0.688	0.44	0.69
2	25	24.67	0.072	0.347	0.788	0.336	0.688	0.44	0.79
3	28	25.82	0.072	0.388	0.788	0.336	0.688	0.44	0.88
4	31	26.89	0.072	0.43	0.788	0.336	0.688	0.44	0.97

Table 4: The percent reduction of scour depth Slotted piers to without slot pier

Pier number	Slot types	U/Uc=0.69	U/Uc=0.79	U/Uc=0.88	U/Uc=0.97
1	0-2b	43.95	21.42	18.4	11.82
2	b/2-3b/2	29.15	18.55	15.56	6.88
3	0-b	40.36	20.58	18.02	9.25
4	b-2b	21.53	12.99	7.74	5.74

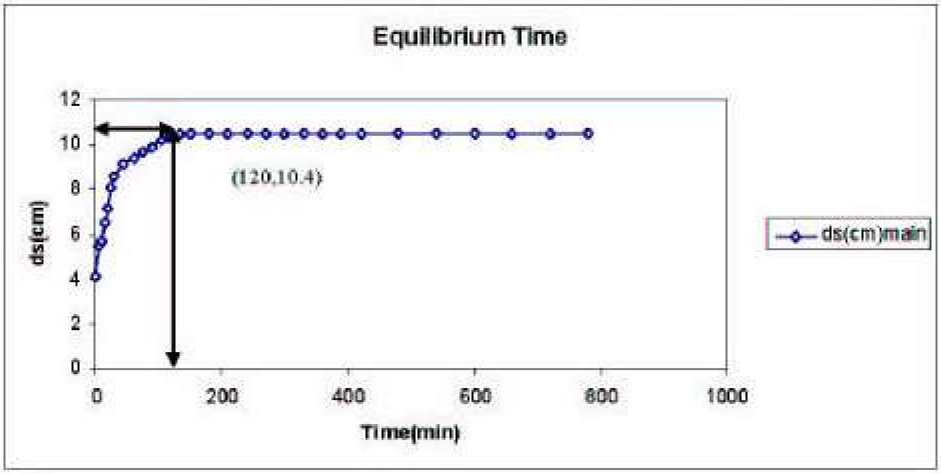


Fig. 5: equilibrium time

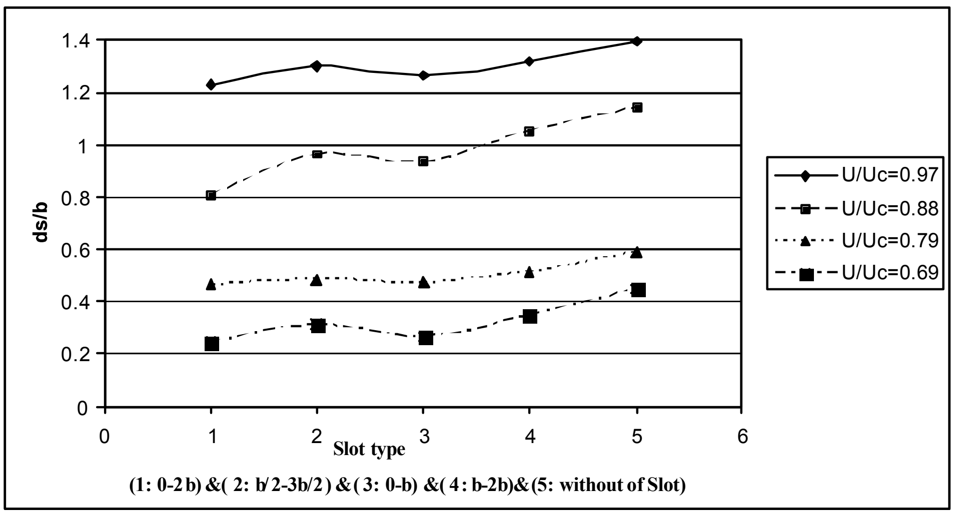


Fig. 6: Comparison of maximum depth scour four piers types of slotted and non - slotted pier position 60 degrees bend

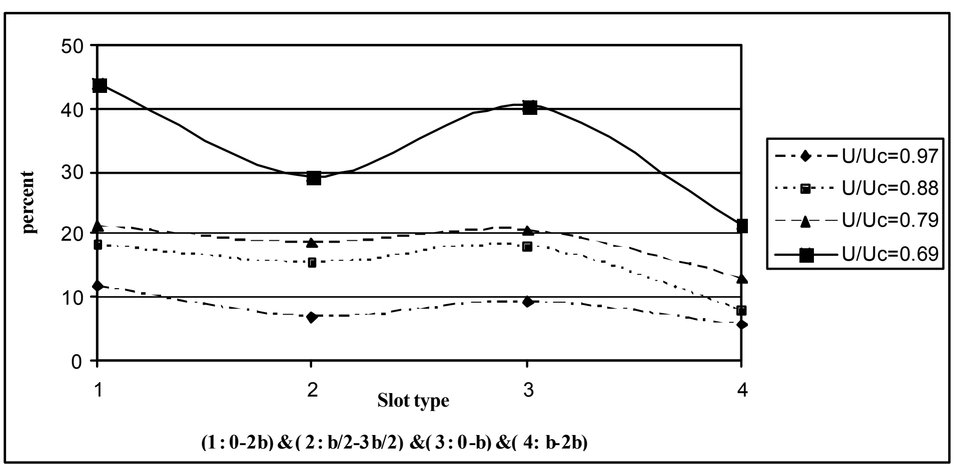


Fig. 7: The percent reduction of scour depth Slotted piers to without slot pier

Figure 7 illustrates that scouring depth reduction percentage increases as u/u_c ratio decreases in a way that this reduction percentage for slotted pier type 1 and $u/u_c = 0.97$ will maximumly reach 11.82% and for $u/u_c = 0.69$ for the same pier will reach 43.95%.

The figure, too, shows that the average reduction in slotted pier scouring depth compared to the non-slotted piers was 23.89% (0-2b) for slotted pier type 1, 17.53% (b/2-3b/2) for slotted pier type 2, 22.05% (0-b) for slotted pier type 3 and 12% (b-2b) for slotted pier type 4. when analyzing and interpreting these changes, it can be said that because in piers 1 and 3 the pier lengths begin from the bed level, the direction of downward horizontal flow which is the main cause of horseshoe vortex and one of the main factors of erosion around piers was deviated from the pier which in turn lead to the reduction of scouring depth. However, in slots type 2 and type 4, in which the slot length begin from a level higher than the bed level, the slots appeared less effective. On the other hand, when comparing piers 1 and 3, due to the fact that in pier type 1 the slots were close to water surface, the effective flow depth and the pressure-gradient decreased and thus the downward flow strength decreased and this in turn reduced the scouring depth.

CONCLUSION

The present study scrutinized the effects of slots on scouring depth in 180-degree river bend. The findings demonstrated that using slots in bridge pier is effective in reducing scouring in a manner that in piers type 1 and type 3 in which the slot lengths began from the bed level, the slots were more effective while in slots type 2 and type 4 in which the slot lengths begin from a level higher than the bed level, the slots were less effective. Quantitatively, as well, the average scouring depth reduction around the slotted pier type 1 (0-2b) was the highest amounting to 23.8% whereas for slotted pier type 4 (b-2b), it was the lowest equaling to 12%. Moreover results show that scouring depth is a function of average flow velocity (u) ratio to threshold velocity of bed sediments (u_c) so that the effects of slots on scouring reduction improve when this ratio decreases.

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Notation:

b Pier diameter
u Average flow velocity
u_c Threshold velocity for sediment bed
y Flow depth
d_{50} The average particle size of sediment
d_s Depth Scouring
υ Kinematics viscosity
ρ Density of water
ρ_s Density sedimentation
w_t Section width
t Time
t_e Equilibrium time
θ_p Position in bend
w Slot width
y_ι Slot length
θ_A Flow-pier approach angle slot
R_c Curvature radius of the central bend

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