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The effect of slot dimensions and its vertical and horizontal position on the scour around bridge abutments with vertical walls

SEYED ABBAS HOSSEINI[1,*], MEHDI OSROUSH[1], AMIR ABBAS KAMANBEDAST[2] and AMIR KHOSROJERRDI[3]

[1]Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Department of Water Science and Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran
[3]Department of Agricultural Systems Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
e-mail: abbas_hoseyni@srbiau.ac.ir; mehdi.osroush@srbiau.ac.ir; ka57_amir@iauahvaz.ac.ir; khosrojerdi@srbiau.ac.ir

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Abstract. Scouring is one of the major threats to the stability of bridge abutments constructed over rivers. The present study investigated the usefulness of abutment slots in reducing the scour depth around bridge abutments with vertical walls, experimentally. Nine experiments with no slot and hundred experiments with slots were conducted in clear water conditions. Four subcritical flow conditions (Froude number less than 1) were investigated. For each flow condition, 25 different slot models having different sizes, and vertical and horizontal positions were considered. The results indicated that the slots having heights equivalent to half of the flow depth are more effective in reducing scouring if they are located closer to the bed. Increasing the slot height improves the performance. The best performance is achieved when the slot begins from the water surface and extends below the bed (equal to the scour depth in the model without the slot). Further, the results showed that the greater the distance of the slot is from the abutment nose and closer it is to the channel wall, the more effective the slot would be. Therefore, the most effective slot model is the model in which the slot height equals the distance from the water surface to below the bed, and when it is attached to the channel wall. For different slot models, in different flow conditions, the percentage of reduction of scour depth varies from 20 to 100%.

Keywords. Bridge; abutment; scour; slot.

1. Introduction

Bridges are among the earliest engineering structures and are usually built across rivers. Many of these structures, which are among the most important and vital connecting structures, fail annually due to various reasons. One of the most important factors responsible for the failure of bridges is the local scour phenomenon around the piers and abutments. According to a study conducted in the United States on the failures of 383 bridges by Richardson and Abed [1], 25% of the bridge failures resulted from the failure of piers, and 72% resulted from the failure of their abutments. Also, Melville [2] conducted a study on 108 bridge failures that occurred between 1960 and 1984 in New Zealand. Among the results, 29 bridge failures were attributed to the scour around the abutments.

The flow pattern and local scour process around bridge piers and abutments are considered as complex phenomena. In fact, in scour phenomenon, the interactions of structure, flow and sediment are observed, so that bridge abutments or piers can change the flow pattern, create 3-D flows and multiple vortices, increase hydrodynamic forces, create a hole around them, and ultimately, change the riverbed sediment pattern at the bridge abutments or piers location. This type of erosion can be identified with a hole formed around the structure, and this hole, if developed in depth, can cause damages and eventually lead to bridge collapse.

Studies such as Wong [3], Kwan [4], and Dongol and Mellvile [5] have shown that scour process around bridge abutments is similar to the scour process around bridge piers. However, there is a difference between both processes, that is, under the same conditions, the boundary layer created by the channel wall on the upstream abutment reduces the scouring compared to the bridge piers [6].

Down flow, bow flow, the main vortex at the upper corner of the upstream bridge abutment (horseshoe vortex), secondary vortex and wake vortex are considered as the factors involved in the scour occurred around bridge

*For correspondence
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abutments. The flow velocity becomes a pressing agent on the abutment, when the water flow collides with the bridge abutment. Since in general the velocity decreases from the surface to the bed, the dynamic pressure on the abutment nose also decreases from the top to the bottom, and the pressure gradient thus generated causes a flow towards the floor. This down flow digs the bed after colliding with it and is distributed in different directions. Some part of this flow, which returns to the upstream, is forced to move in the flow direction due to its collision with the general flow. This circulation of flow and its return create a vortex. The spin of this vortex extends downwards. In total, it looks like a horseshoe in plan. That is why it is called a "horseshoe vortex". Due to the flow separation around the bridge abutments, some vortices are formed, the axes of which are perpendicular to the riverbed, which are called wake vortex. [7, 8]. Figure 1 shows the flow field around a bridge abutment [7].

In order to prevent the potential and irreparable damages, it is necessary to carefully examine the scour process and apply proper methods for its effective control. The methods used to control and reduce the scour around bridge piers and abutments are classified into two categories: those increasing the bed resistance and those changing the flow pattern. In the method of increasing the resistance of the bed sediment particles or reinforcing the bed, riprap, prefabricated concrete pieces, cement grout bags, etc. are used to increase the resistance of the bed sediment particles, so that the bed cannot be easily scoured by the flow, thus preventing erosion. In the method of changing the flow pattern, the power of down flow and horseshoe vortex, which are the main causes of scour phenomenon, is decreased. Some of these methods include the use of crowns, slots, submerged plates, cables, sacrificial piles, etc. The down flow at the upstream face of the abutment and the development of secondary vortices are the most important factors causing the scour. Thus, a major application of slots is deviation of down flow at the upstream face of the abutment and the lateral flows around the bridge abutments. On the other hand, creating a slot results in formation of shear stresses on the floor of the flow direction, and the critical shear stress regions get smaller. These

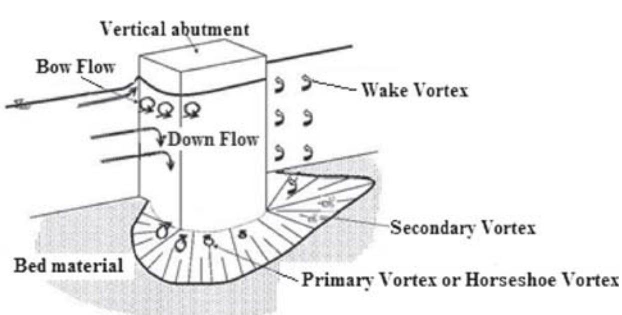


Figure 1. The flow field around a bridge abutment [7].

phenomena lead to decreased strength of the destructive vortices occurring around the structure [9].

Many studies have been conducted on the use of slots around bridge structures. Chiew [10] examined the effect of slots in the pier on reducing the local scour depth around a circular bridge pier by using slots with rectangular section and different slot widths and lengths, .The slots were made in the piers in the following two different positions: near the water surface and near the channel bed. The results showed that the use of a slot with a width of 0.25 times the bridge pier diameter and a slot height of more than 2 times the pier diameter reduced the scour depth by 20% and 5% in the two positions of near the channel bed and near the water surface, respectively. Kumar *et al* [9] created some slots with a width of 0.25 times the bridge pier diameter and different heights of $Y = y_0$ and Y = y_0+ d_s (where $y_0$is the flow depth and $d_s$is the scour depth in the control experiments) in the middle piers. They concluded that increased slot height will reduce the scour depth, and if the slot height exceeds the flow depth, it will be more effective in reducing the scour depth. Monocad *et al* [11] examined the function of crowns and slots in reducing the scour around bridge piers. Their results showed that increasing the slot height and using the slots featuring a crown with a width twice the pier diameter lead to scour reduction by 55-96%.

Grimaldi *et al* [12] examined the effect of slot usage in reducing the scour depth around the bridge piers. The results showed that for the best scenario, where the slot penetration in the substrate was 1/3 times the water depth, the scour depth could be reduced up to 30%. Radice and Lauva [13] examined the use of slots as a means for scour reduction around bridge abutments. In their study, only the position of the slot was examined by keeping the dimensions and position of the slot to the abutment nose constant. The results indicated that the slot located near the channel bed is more effective in reducing scour. Tafarojnoruz *et al* [14] examined the effect of slot usage in reducing scour around the bridge piers. The results showed that the most effective slot, which has the maximum height, starts from the water surface and penetrates to an acceptable level under the sediment bed and could reduce the scour depth by 35%. Gaudio *et al* [15] investigated various methods of reducing the scour around the bridge piers including the submerged vanes and bed sill, slot and sacrificial piles, collar and sacrificial piles, slot and collar, and bed sill and collar. The results showed that the slot-collar combination has the best performance among these methods. Setia and Bhatia [16] conducted a study on reducing the depth of scour around rectangular bridge piers using four types of slots: parallel slots (with an angle of 0 to ±180°), Y-shaped slots (with an angle of 0 to ±120°), slit T-shaped slots (with an angle of 0 to ±90°) and sigma-shaped slots (with an angle of 0 to ±45°). They also made a comparison with piers having no slots. The results showed that the parallel and Y-shaped slots (both with a width of 0.25D and the height of 1D above the erodible bed and 0.75D at the bottom of the sedimentary bed that D is the pier diameter) could reduce the scour depth by up to 50% and 40%, respectively. T- and sigma-shaped slots had no significant effect on reducing the scour depth. Azevedo *et al* [17] examined the effect of using slots in circular and elongated circular bridge piers. The comparison of both bridge piers showed that the elongated circular bridge pier had a greater effect on scour depth reduction. Also, it was shown that the maximum scour depth in the slot-mode was lower compared to the piers having no slots. Mehrzad and Hakimzadeh [18] investigated the effect of slots on scour reduction in cone-shaped bridge abutments and compared the results with the scour rates in circular piers. The results indicated that the use of cone-shaped piers with the lowest lateral slopes (78.69°) can cause reductions in scour depth up to 32% and that the scour depth can be decreased by over 55%, if the same cone-shaped abutment is used along with a slot with a width of 0.4 times the pier diameter and a height equal to the diameter of the circular abutment positioned at the middle of the water surface to the sedimentation bed. Hajikandi and Golnabi [19] studied the effect of straight slots, Y-shaped slots and T-shaped slots on reduction of scour in bridge piers. Their results demonstrated that decreasing the angle between the slot faces in the downstream side of the flow led to reduced scour rate when using Y-shaped slots. On the other hand, the results indicated that the straight slots showed higher efficiency compared to the Y-shaped slots, and the Y-shape slots showed higher efficiency compared to the T-shaped slots, such that the maximum percentages of scour depth reduction were 38% and 33% in straight slots and T-shaped slots, respectively.

Osroush *et al* [20], by creating slots at the center of bridge abutments, investigated the effect of the slot on reducing scour. Slot models had different heights relative to the bed and a fixed position relative to the tip of the abutment nose. The results showed that the scour depth decreases with increasing the slot height and its proximity to the bed. As seen in the above references, most of the studies conducted on the application of slots are related to the bridge piers, and the number of studies on bridge abutments is limited. For example, Osroush *et al* [20] examined only the effect of the position of the slot to the bed and its effect on scouring. Therefore, in the present study, slot dimensions and position to the bed, as well as the distance of slot from the tip of the abutment nose were examined for different flow conditions using different slot models.

2. Materials and methods

2.1 *Specifications of flume*

The experiments were conducted in a straight flume with a length of 13 m, a width of 0.5 m and a height of 0.6 m. The channel walls are made of Plexiglas material with a thickness of 1 cm. The flume body is placed at a height of 0.7 m from the ground. The flume bottom resembles a fixed bed with a zero slope. It also contains two tanks at its beginning and end, and a 90degree triangular spillway is embedded after installing the reservoir at the beginning of the flume in order to measure the discharge. The water depth in the flume is adjusted by a sliding gate at the bottom of the channel. The water is pumped from the main tank of the laboratory to the flume using a pump with a maximum discharge of 16 liters per second. To adjust the pump outlet flow, a valve is placed before the entrance of the inlet tank. Also, at a distance of 70 cm from the beginning of the tank, a gate controls the water entering the flume, though this is not used in the present study and is always left open, since another valve controls the inlet discharge into the tank. The water flow passes through the end part of the flume and enters the end tank and is then transferred back to the main tank of the laboratory through two 4inch tubes, and then, flows back into the flume using the pump. Therefore, water flows within the flume all the times. According to figures 2(a) and (b), a metal box with a length of 1.2 m, a width of 0.5 m and a height of 20 cm is installed at a distance of 6.5 m from the beginning of the flume. This box is filled with uniform sediments, so that its surface is aligned with the flume surface. The position of the sedimentary box and abutment relative to the upstream is selected such that the flow is fully developed. In order to calculate the length of the developed flow, Kirkgöz and Ardiçlioğlu's equation [21] is used. Figure 2(c) shows pictures of different parts of the flume.

2.2 *Dimensional analysis*

The maximum scour depth around an abutment with vertical wall and a slot under clear-water condition is a function of the following parameters:

$$F1\{(d_s)_{max},(d_s)_{s\,max},V,g,y,\rho,\rho_s,B_a,L_a,d_{50},\mu,W_s,B_s,H_s,X_s,Y_s,\emptyset_s,B,\alpha,t,t_e,V_c,\sigma_g\}=0 \tag{1}$$

where $(d_s)_{max}$: the maximum scour depth without using a slot, $(d_s)_{s\,max}$: the maximum scour depth with a slot, V: average flow velocity, g: gravitational acceleration, y: flow depth, ρ: flow density, ρ_s: density of the sediment particles, B_a: abutment width, L_a: abutment length, d_{50}: median particle size,μ: Dynamic viscosity, W_s: slot width, B_s: slot depth, H_s: slot height, X_s: the distance of slot from the nose, Y_s: slot position related to the bed, $\emptyset_s$: angle of slot, B: channel width,α : the angle of collision of the flow with the abutment, t: scour time, t_e: equilibrium time, V_c: critical velocity at the movement threshold of the sediment particles, σ_g: geometric standard deviation of sediment particles.

Using dimensional analysis and Buckingham's π theorem, Eq. (2) can be presented as follows:

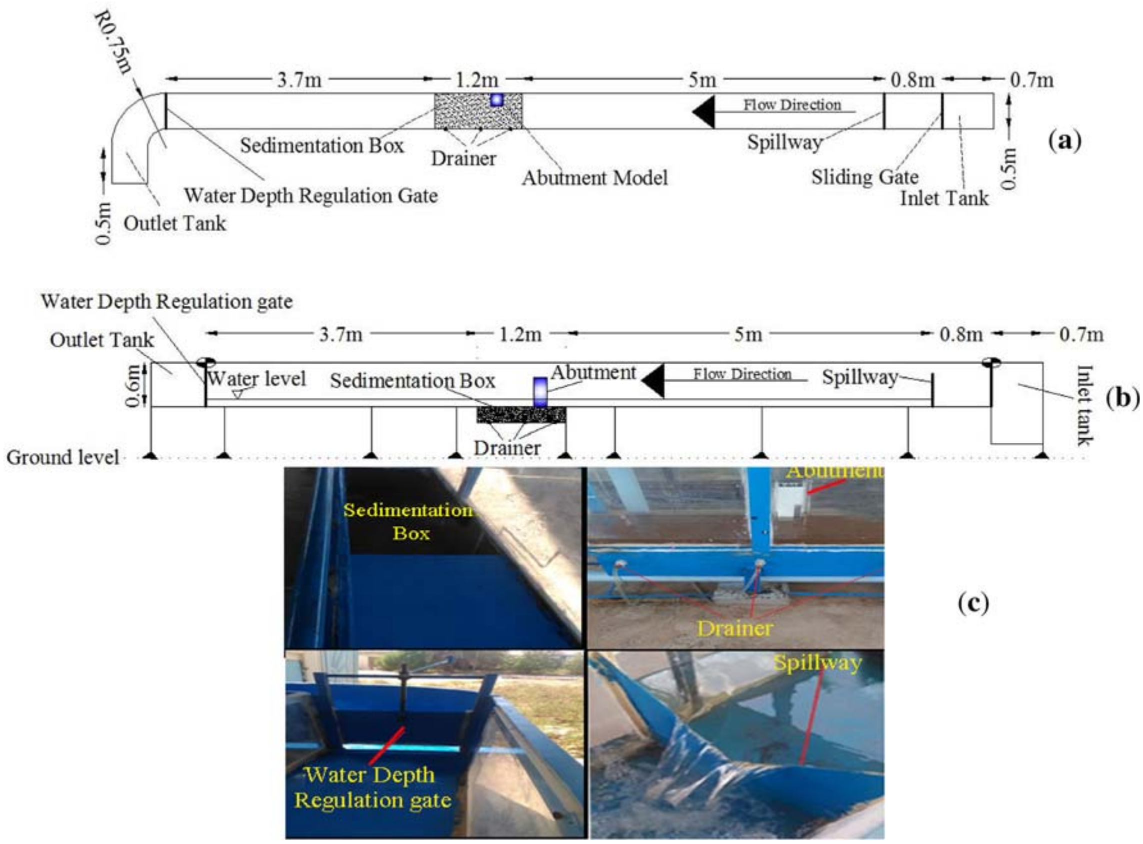


Figure 2. (a) Flume plan and experimental set-up, (b) cross-sectional view of the flume and (c) pictures of different parts of the flume.

$$(Pr)_s = F2\left\{Fr, Re, G_s, \frac{B_a}{L_a}, \frac{d_{50}}{L_a}, \frac{W_s}{L_a}, \frac{B_s}{L_a}, \frac{H_s}{y}, \frac{X_s}{L_a}, \frac{Y_s}{y}, \emptyset_s, \frac{B}{L_a}, \alpha, \frac{t}{t_e}, \frac{V}{V_c}, \sigma_g\right\} \quad (2)$$

where Fr: Froude number of the flow, *Re*: Reynolds number of the flow, G_s: density of sediment particles, and $(Pr)_s$: percentage of scour depth reduction, calculated as follows:

$$(Pr)_s = \frac{(d_s)_{max} - (d_s)_{s\,max}}{(d_s)_{max}} * 100 \quad (3)$$

In the present study, among the dimensionless parameters presented in Eq. (2), $G_s.\frac{B_a}{L_a}.\frac{d_{50}}{L_a}.\frac{W_s}{L_a}.\frac{B_s}{L_a}.\emptyset_s.\frac{B}{L_a}.\alpha.\frac{t}{t_e}.\sigma_g$ are considered constant, because they were not varied during the experiments. Thus, Eq. (3) can be presented as follows:

$$(Pr)_s = F\left\{Fr, Re, \frac{H_s}{y}, \frac{X_s}{L_a}, \frac{Y_s}{y}, \frac{V}{V_c}\right\} \quad (4)$$

Given the constant parametersy, V_c in this manuscript, the Froude Number is only dependent on. Thus:

$$(Pr)_s = F\left\{Fr, Re, \frac{H_s}{y}, \frac{X_s}{L_a}, \frac{Y_s}{y}\right\} \quad (5)$$

All the experiment were for turbulent flow conditions, thus the effect of viscosity or Reynolds Number can be neglected.

2.3 *Experiments set-up and conditions*

The studies by Dongol and Melville [5] showed that the greatest scour depth occurs around the abutment with vertical walls. Therefore, the studied abutment is a rectangular one with a vertical wall. It is galvanized and has a width and length of 9 cm. Concerning the size of sediments, various criteria have been specified. For example, according to the research by Dongol and Melville [5], in order to prevent the effect of sediment particle size on the scour depth as well as the formation of bed form, $\frac{L_a}{d_{50}} > 25$should be satisfied, where $L_a$is the abutment length (an element perpendicular to the flow), and d_{50} is the median diameter of the sediment particles. The more uniform is the particle size distribution, the higher the scouring dimensions will be. The particles uniformity can be expressed as $\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} < 1.3$, where σ_g represents the geometric standard deviation of the sediments [2]. Therefore, sediment particles used in the present study are non-cohesive sandstones with a median diameter of 1.37 mm, geometric standard deviation of σ_g= 1.13 and a density of 2.6.

All the experiments in this study were performed for uniform sand, under subcritical (Fr <1) and turbulent (R_e> 2000) flow conditions. All the experiments were conducted under clear water conditions, because the highest scour depth occurs under the same conditions. According to these conditions, $\frac{V}{V_c} < 1$, where V is the average flow velocity, and V_c is the critical velocity at the threshold of sediment particles movement [22]. In order to determine the threshold velocity for sediment particles using the critical velocity method, an experiment was conducted without abutment (Due to its importance, this experiment was repeated four times). In this method, a critical velocity is defined for the conditions in which erosion of the bed begins, and the average velocity available is compared with the critical velocity. At this stage, the critical flow velocity was calculated in several steps by keeping a constant discharge of 11 liters per second and a gradual decrease in flow depth, and its value was estimated as 0.33 m/s. Therefore, the velocities of 0.30, 0.26, 0.23 and 0.18 m/s were selected for the experiments. In the experiments on the abutments with slots, 25 models (combining five models of X_s, the distance of slot from the nose or horizontal distance, with five models of Y_s, the distance of slot from the bed or vertical distance) were considered. The slot positions in various experiments are presented in table 1. The slot height, H_s, is also listed in table 1. It is considered in three modes: equal to half the water depth, equal to the water depth, and equal to the water depth plus the scour depth. In table 1, *i* represents the slot position to the bed or vertical position, and *j* represents the slot position to the tip of abutment nose or horizontal position. Accordingly, for each slot, four velocities, that is, four Froude numbers were considered, and 100 experiments were conducted. In addition, nine experiments were conducted as control experiments, and a total of 109 experiments were conducted in the present study.

Figure 3(a) gives an example of a model of abutment with a slot at the position of $\frac{X_s}{L_a} = 0.5, \frac{Y_s}{y} = 0 \sim 0.5$, $\frac{H_s}{y} = 0.5$ (S_{63}), and figure 3(c) illustrates how the parameters of different slot models are defined at a cross-section, such as A-A, on the abutment and perpendicular to flow direction.

First, before starting each experiment, the surface of the sedimentary bed was completely flattened. After closing the terminal gate of the channel and turning the pump on, the valve was opened to some extent that water could enter the channel with very little discharge, and the water surface was raised to some extent that erosion due to sheet flow was prevented at the beginning of the experiment. Then, the discharge was increased until the desired discharge was reached. After adjusting the discharge by a 90degree triangular spillway, the water depth was adjusted at the desired value of 7 cm using the terminal gate. After completing each experiment within the time determined, the pump was switched off, and drainer was opened to slowly drain the water without disturbing the bed form. At the end of each experiment, the sediment bed profile was recorded using a digital depth gauge with an accuracy of ± 1 mm on meshes with dimensions of 1cm × 1cm for Froude numbers of 0.28, 0.31 and 0.36, and meshes with dimensions of 0.5cm × 0.5cm for Froude number=0.22.

3. Results and discussion

3.1 *Results of experiments without slot (control experiments)*

After determining the threshold velocity for the movement of sediment particles and flow characteristics, to determine the equilibrium time for each flow Froude number, an experiment and in total, four experiments were conducted for 13 hours. The results showed that 99% of the equilibrium scour depth occurred within 13 hours. In all experiments, according to figure 3(b), erosion occurred due to the down flow from the upstream corner of abutment in the vicinity of its nose tip, the front face of the abutment, or the point "b" at an approximate angle of 45°, and the bed particles were gradually transferred downstream and behind the abutment due to the development of scour process and creation of horseshoe vortexes.

During the test period, the scour depth at the base point, or point "b", where the maximum scour depth occurred, was recorded at different intervals, and at the end of the thirteenth hour, the topography of the erodible bed was recorded. As the scour hole deepened, the hole developed around the channel wall. The deepening rate of the scour hole was higher in the early stages of the experiment and gradually decreased, so that, after 60 minutes from the start of the experiment, with Froude numbers of 0.36, 0.31, 0.28, and 0.22, about 68.39%, 72.82%, 79.40% and 82.69% of the scour depth occurred, respectively. During the experiment, the sediments fell into the hole from the wall of scour hole and were added to the sedimentary hill. The sedimentary hill moved down, and development of the scour hole continued during the experiment. According to the results of the experiments, although the depth of the scour hole will not deepen further over time and reach equilibrium, the dimensions of the scour hole will increase over time even in flows with low Froude numbers.

After 4 hours from the beginning of the experiment, with Froude numbers of 0.36, 0.31, 0.28, and 0.22, about 95.28%, 97.99%, 97.61%, and 98.22% of the equilibrium scour depth occurred, respectively. Therefore, for all the

Table 1. Introduction of the experiments based on height, horizontal, and vertical positions.

S_{ij}	Number	Slot model	$\frac{X_s}{L_a}$	$\frac{Y_s}{y}$	$\frac{H_s}{y}$
i=6,7,8,9,10	1	S_{61}	0	$0\sim0.5$	0.5
j=1,2,3,4,5	2	S_{62}	0.25	$0\sim0.5$	0.5
	3	S_{63}	0.5	$0\sim0.5$	0.5
	4	S_{64}	0.75	$0\sim0.5$	0.5
	5	S_{65}	1	$0\sim0.5$	0.5
	6	S_{71}	0	$0.25\sim0.75$	0.5
	7	S_{72}	0.25	$0.25\sim0.75$	0.5
	8	S_{73}	0.5	$0.25\sim0.75$	0.5
	9	S_{74}	0.75	$0.25\sim0.75$	0.5
	10	S_{75}	1	$0.25\sim0.75$	0.5
	11	S_{81}	0	$0.5\sim1$	0.5
	12	S_{82}	0.25	$0.5\sim1$	0.5
	13	S_{83}	0.5	$0.5\sim1$	0.5
	14	S_{84}	0.75	$0.5\sim1$	0.5
	15	S_{85}	1	$0.5\sim1$	0.5
	16	S_{91}	0	$0\sim1$	1
	17	S_{92}	0.25	$0\sim1$	1
	18	S_{93}	0.5	$0\sim1$	1
	19	S_{94}	0.75	$0\sim1$	1
	20	S_{95}	1	$0\sim1$	1
	21	S_{101}	0	$\frac{d_s}{y}\sim1$	$1+\frac{d_s}{y}$
	22	S_{102}	0.25	$\frac{d_s}{y}\sim1$	$1+\frac{d_s}{y}$
	23	S_{103}	0.5	$\frac{d_s}{y}\sim1$	$1+\frac{d_s}{y}$
	24	S_{104}	0.75	$\frac{d_s}{y}\sim1$	$1+\frac{d_s}{y}$
	25	S_{105}	1	$\frac{d_s}{y}\sim1$	$1+\frac{d_s}{y}$

Froude numbers mentioned, the duration of 4 hours was selected as the test time. Figure 4 shows the equilibrium time chart for Froude numbers of 0.36, 0.31, 0.28, and 0.22. In this graph, the horizontal axis represents the time in minutes and the vertical axis represents the ratio of scour depth to the equilibrium scour depth. Then, for each of the four Froude numbers, four other experiments were conducted for 4 hours, and the topography of bed during this period was recorded for each experiment.

3.2 *Results of the experiments with a slot*

As previously stated, 100 experiments were conducted for four discharges defined by making 25 different slot models on the abutment. In all experiments, the slot depth was constant and was considered equal to $B_s = B_a$ throughout the abutment width. According to the suggestion by Kumar *et al* [9], Chiew [10], Monocad *et al* [11] and Grimaldi *et al* [12] which was mentioned in the introduction, concerning the slot width in the bridge piers, the slot width was considered equal to $W_s = 0.25L_a$. In the following, the results of scour phenomenon for different slot models are presented in terms of slot height and slot position relative to the bed and abutment nose.

3.2a *Slot Dimensions and its vertical position on scouring:* In figures 5(a-e), the longitudinal profiles of the changes in bed around the abutment for Fr = 0.36, as an example, for the five slot models of S_{6j}, S_{7j}, S_{8j}, S_{9j}, and S_{10j}, along with an abutment model having no slots, are compared for different vertical positions of slot to the bed corresponding to j = 1, 2, 3, 4, 5 separately. Also in figures 6(a-e), the percentages of scour depth reduction are presented for the four flow conditions with the corresponding Froude numbers of 0.22, 0.28, 0.31 and 0.36.

Like a model with no slot abutment, in all models of abutment with a slot, the flow close to the water surface moves down and, near the erodible bed, its direction changes towards the direction of the main flow after its collision with the channel bed. This causes initial vortex and erosion to begin from the upper corners of the abutment, and the depth and dimensions of the scour hole gradually increase. As seen in figures 5(a-e), in all models of abutment with slot, the maximum scour depth occurs at the base point. It can be concluded that the general shape of the sedimentary bed topography created by the scour around the bridge abutment with slots is similar to an abutment with no slot.

However, due to the partial passage of the flow from within the slot, the power of effective flows and pressure

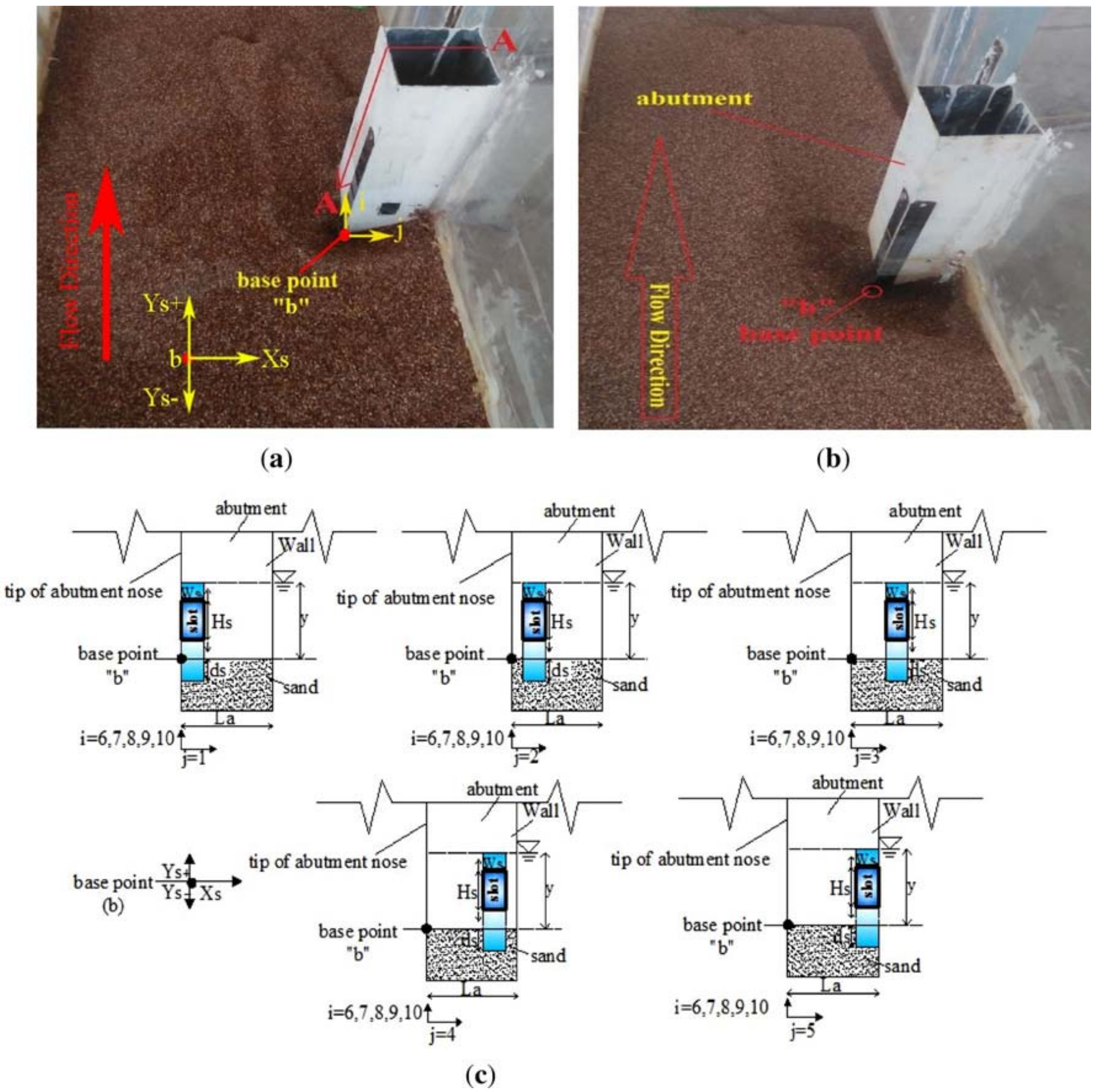


Figure 3. (a) An example of a model of abutment with a slot. (b) Display of base point (starting point of scour phenomenon and location of maximum scour depth). (c) Cross section A-A, different parameters of slot at different positions to the tip of abutment nose.

gradient decrease, which makes significant changes in depth and dimensions of the scour hole around the abutment and sedimentary hills to be deposited downstream the abutment in different slot models and flow conditions. In figures 6 (a-e), the scour depth reduction percentage is shown at different heights above the bed in five different positions to the abutment nose. These figures indicate that, as the Froude number increases, the percentage of scour depth reduction also decreases. Therefore, the lower is the Froude number, the better the performance of slot will be. For example, in models S_{91}, S_{92}, S_{93}, S_{94} and S_{95}, with Froude number of 0.36, the maximum reduction percentages of scour depth for these models are 33.61%, 36.3%, 38.72%, 44.29% and 49.58%, respectively. For Froude number of 0.31, percentages of scour depth reduction are 34.67%, 37.31%, 40.56%, 47.52% and 55.16%, for Froude number of 0.28, they are 45.23%, 48.28%, 51.32%, 55.38% and 59.03%, and for Froude number of 0.22, they are 56.46%, 75.49%, 100%, 100% and 100%, respectively. As can be seen, in all Froude numbers, the maximum scour depth decreases when the slot is located near the bed and the depth of its penetration into the scour hole is extended.

Figures 6(a' to e') shows the average percentage of scour depth reduction for four different Froude numbers and for different positions of the slot to the abutment nose, and figure 6 (a'' to e'') show the dimensionless values of the maximum scour depth. For example, in figure 6(a''), for four different Froude numbers, and the slot positioned on the abutment nose or $\frac{X_s}{L_a} = 0$ and at different heights above the bed, the maximum values of scour depth are presented and in figure 6(a'), the average percentages of scour depth

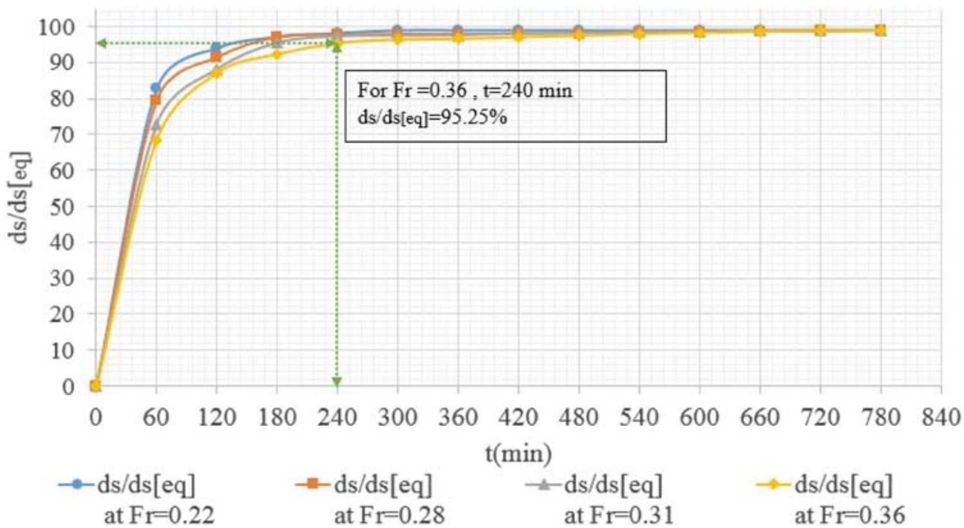


Figure 4. Equilibrium scouring time calculation curve for Fr = 0.36, 0.31, 0.28, and 0.22 in control experiments (scour depth to equilibrium scour depth ratio to time).

reduction in four flow modes are compared for each of the situations.

Figure 6 shows that at all horizontal distances, j = 1,2,3,4,5 among the slots with the same height (i = 6,7,8), the slots S_{81}, S_{82}, S_{83}, S_{84} and S_{85}, which are closer to the bed surface, have better performance. The scour depth reduction percentages are 28.08, 39.68, 53.11, 57.69 and 62.36 compared to the abutment model with no slots, respectively. In the slot models S_{81}, S_{82}, S_{83}, S_{84}, and S_{85}, since they are placed on the bed, a jet flow is created horizontally to move the down flows and horseshoe vortexes (which are considered as important factors responsible for scour formation around the bridge abutment) farther from the structure and, as a result, the effective flow, pressure gradient, and eventually, the depth of scour around the abutment are reduced. In the models S_{61}, S_{71}, S_{62}, S_{72}, S_{63}, S_{73}, S_{64}, S_{74}, S_{65}, S_{75}, which have the same H_s, but are placed farther away from the bed, the scour depth reduction percentages are 18.24, 24.05, 31.01, 34.60, 46.47, 48.21, 51.18, 54.53, 55.83 and 60.06% compared to an abutment model with no slots, respectively. They are less effective compared to the slots located near the bed, however, the percentage of reducing scour depth increases as the slot moves closer to the bed. In slots of twice H_s (from the bed surface to the water surface) (i.e. S_{91}, S_{92}, S_{93}, S_{94} and S_{95}), the scour depth reduction percentages are 42.49, 49.35, 57.65, 61.80 and 65.94%, compared to the abutment model with no slots, respectively. In this group of slot models, in addition to the above-mentioned reasons for the effects of near-bed slots on reducing the scour depth, allowing the flow to pass near the water surface, an effect like shallow flow is created. In this case, the effective flow depth and the pressure gradient are decreased, and as a result, the power of down flow and horseshoe vortex decreases. This results in depth reduction of scour around the abutment. On the other hand, in slots with a height (H_s) equal to the flow depth plus the equilibrium scour depth in a non-slot model (that is, the slot extends below the erodible bed as much as the equilibrium scour depth in a non-slot abutment), the scour depth is less. In this group of slot models, i.e. S_{101}, S_{102}, S_{103}, S_{104} and S_{105}, the scour depth reduction percentages are 50.99, 62.3, 64.02, 67.29 and 71.11%, compared to the model with no slot, respectively. Compared to the similar slots at other positions, they showed better performance. The reason for this phenomenon is that in the cases where the slot height extends from the water surface to the equilibrium scour depth around the non-slot abutment, when the flow collides with the abutment below the erodible bed due to the presence of slot, the flow can pass within the slot, and the power of vortexes around the abutment decreases, while in the abutment with a slot with a height equal to the flow depth or in the slots which are placed above the bed, such mechanism is not observed. The total percentages of scour depth reduction in different positions of slot to the abutment nose in the slot models S_{6j}, S_{7j}, S_{8j}, S_{9j} and S_{10j} are 40.55, 44.29, 48.14, 55.45 and 63.14%, respectively.

It should be noted, though, that the slot can reduce the scour around the bridge abutment, but since the slot eliminates part of the structure, the moment of inertia of the structure decreases slightly and can thus reduce its structural strength.

In general, comparing the results of this part of the study with those of Chiew [10], Kumar *et al* [9], Grimaldi *et al* [12] and Tafrej Norouz *et al* [14] confirms that like bridge pier, the position of the slot to the bed sediment and its dimensions play an important role in reducing scour. Thus, the higher is the slot height, and the closer it is to the bed sediment or below the bed, the greater the impact on reducing scour would be. The difference in the percentage

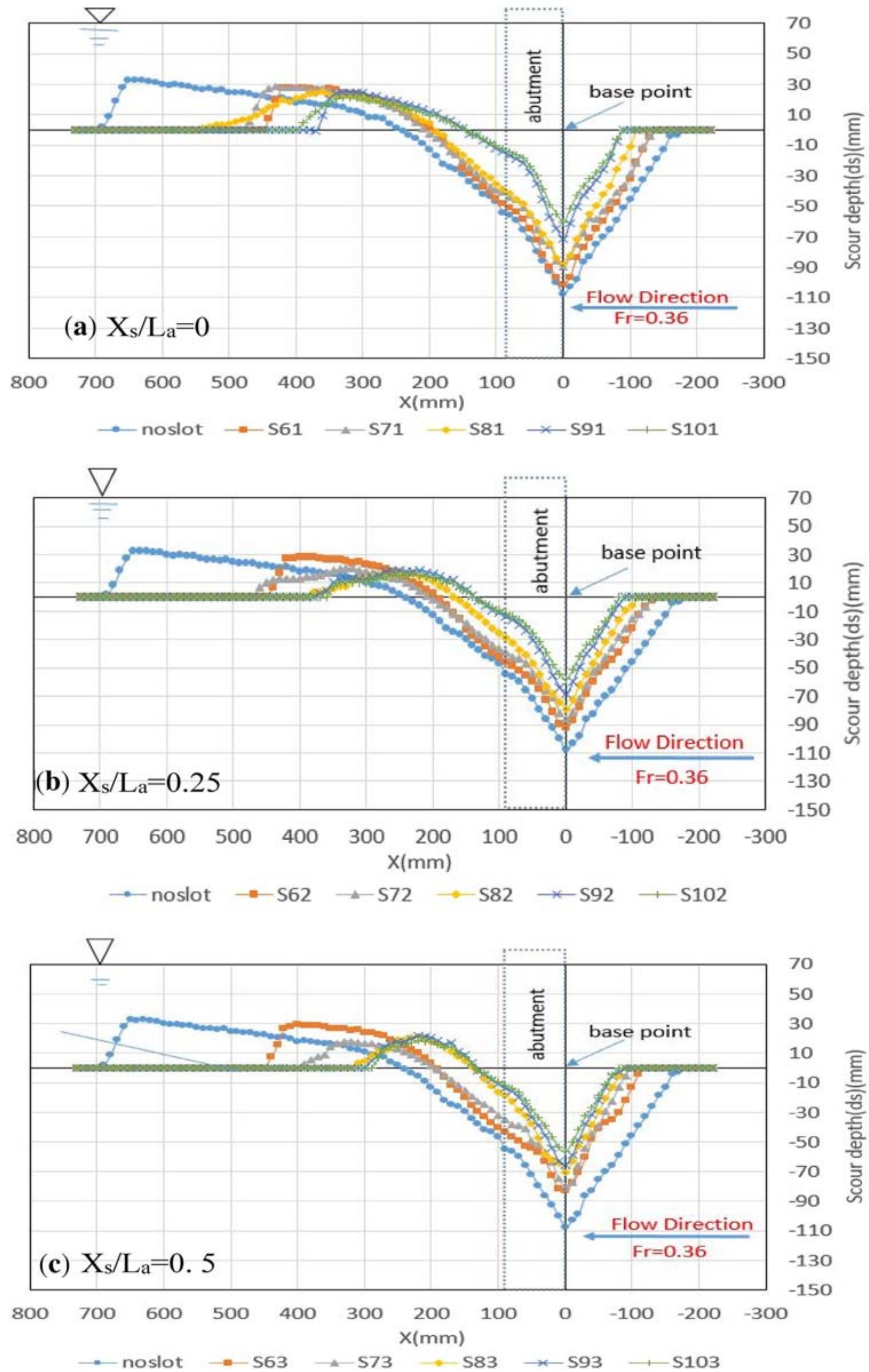
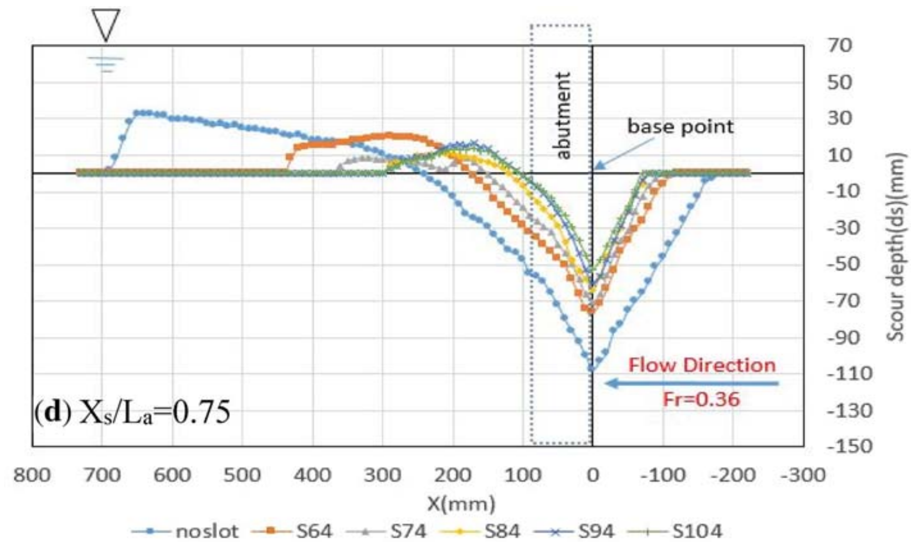


Figure 5. Comparison of the longitudinal profile of the scour around the abutment for Fr= 0.36 and different vertical slot positions.

of scour reduction between different studies as well as this study is related to the size of the sedimentary particles and the different flow conditions used in the experiments.

3.2b *Effect of horizontal slot position on scouring:* In figure 7, the dimensionless scour for all four different Froude numbers and in figure 8, percentages of scour depth



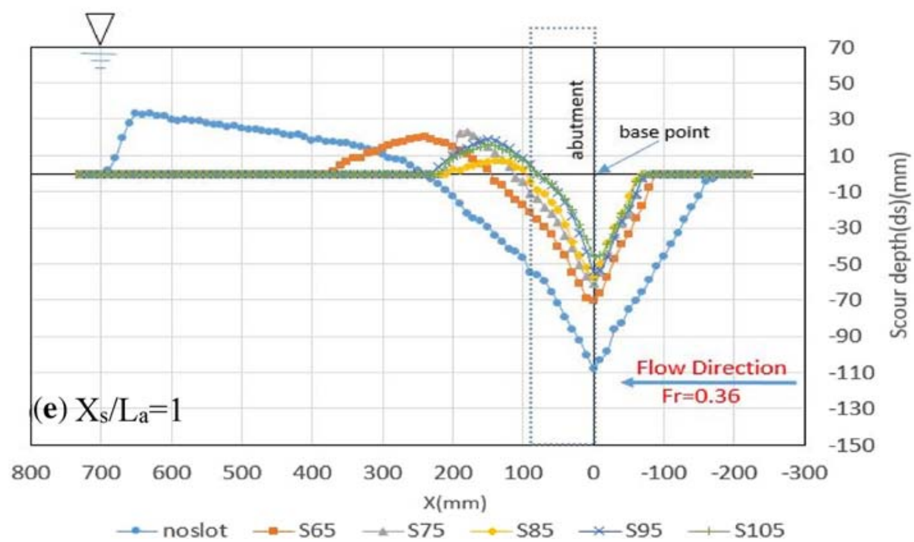


Figure 5. continued

reduction for the average four flows introduced are presented for the five slot horizontal models namely S_{i1}, S_{i2}, S_{i3}, S_{i4} and S_{i5} in five vertical slot positions (i = 6,7,8,9,10).

As shown in figures 7 and 8, it can be concluded that in all slot models, which are at different heights above the bed (i= 6,7,8,9,10), when the slot is moving away from the tip of the abutment nose and closer to the channel wall, its positive performance on reducing scour increases. Thus the average percentages of scour depth reduction at different vertical positions of slot to the bed in the slots S_{i1}, S_{i2}, S_{i3}, S_{i4} and S_{i5}, are 32.28, 43.26, 53.89, 58.50 and 63.19%, respectively. In fact, it can be stated that the slots located near the channel wall weaken the wake vortex in the lower part of the abutment, and in addition, the interference of the flow passing through the slot with the flow passing through the perimeter of the abutment reduces the power of the horseshoes and secondary vortexes, since the slots closer to the channel wall divert the lateral flows and perform more effectively.

4. Limitations and further research

In this research, a rectangular abutment with a vertical wall is considered to study bridge scouring. The sediment particles used were non-cohesive sandstones with a median diameter of 1.37 mm and uniform size distribution (σ_g= 1.13).

All the experiments in this study were performed for uniform sand, under subcritical (Fr <1) and turbulent (R_e> 2000) flow conditions. All the experiments were conducted under clear water conditions. The length of the abutment was selected so that the slot can be placed in the middle of the abutment easily. Thus, the abutment taken into account

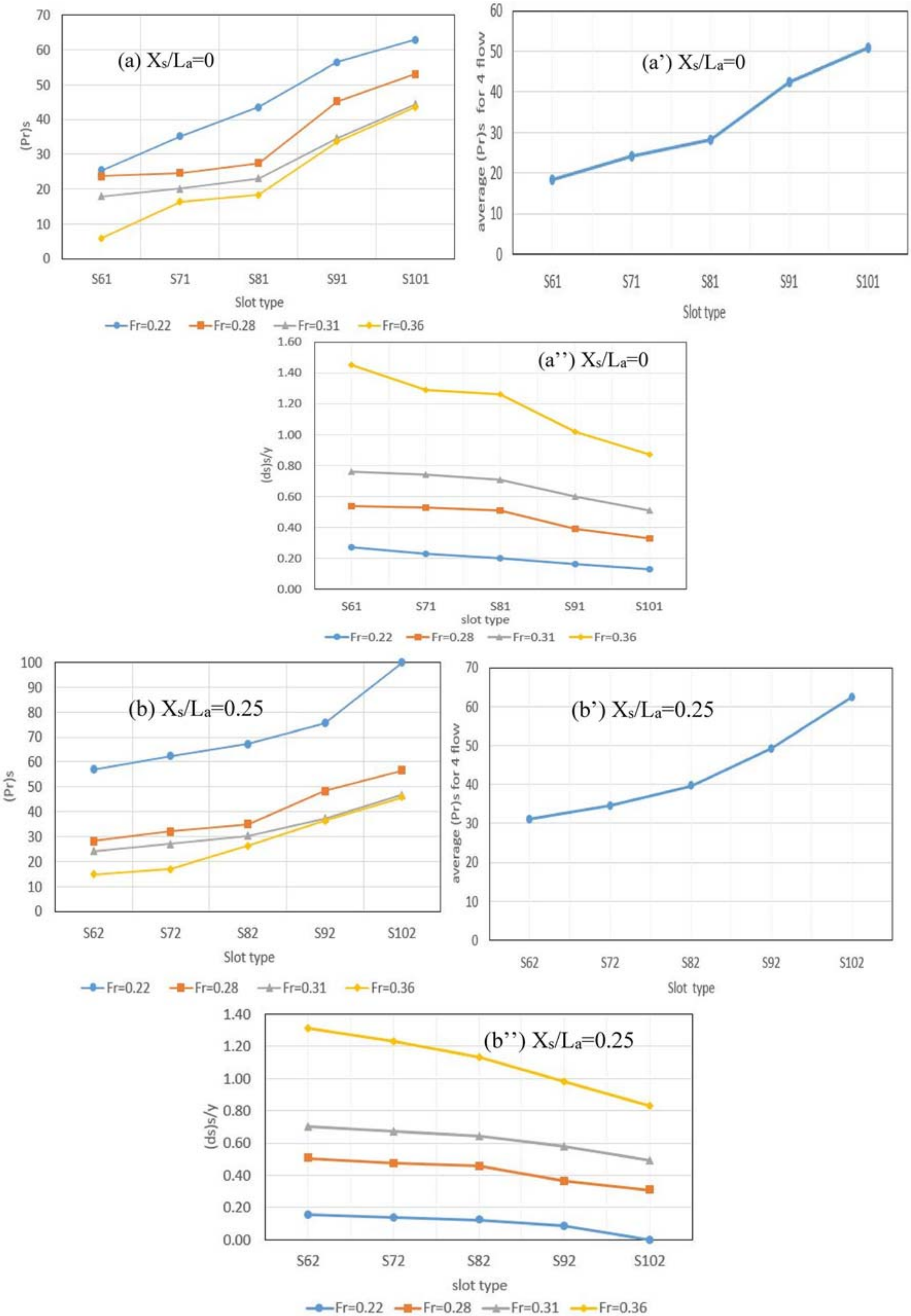


Figure 6. (a-e). Comparison of the percentages of scour depth reduction for different vertical slot positions (a'-e') Average percentage of scour depth reduction for different vertical slot positions (a''-e'') Dimensionless scour depth for different vertical slot positions.

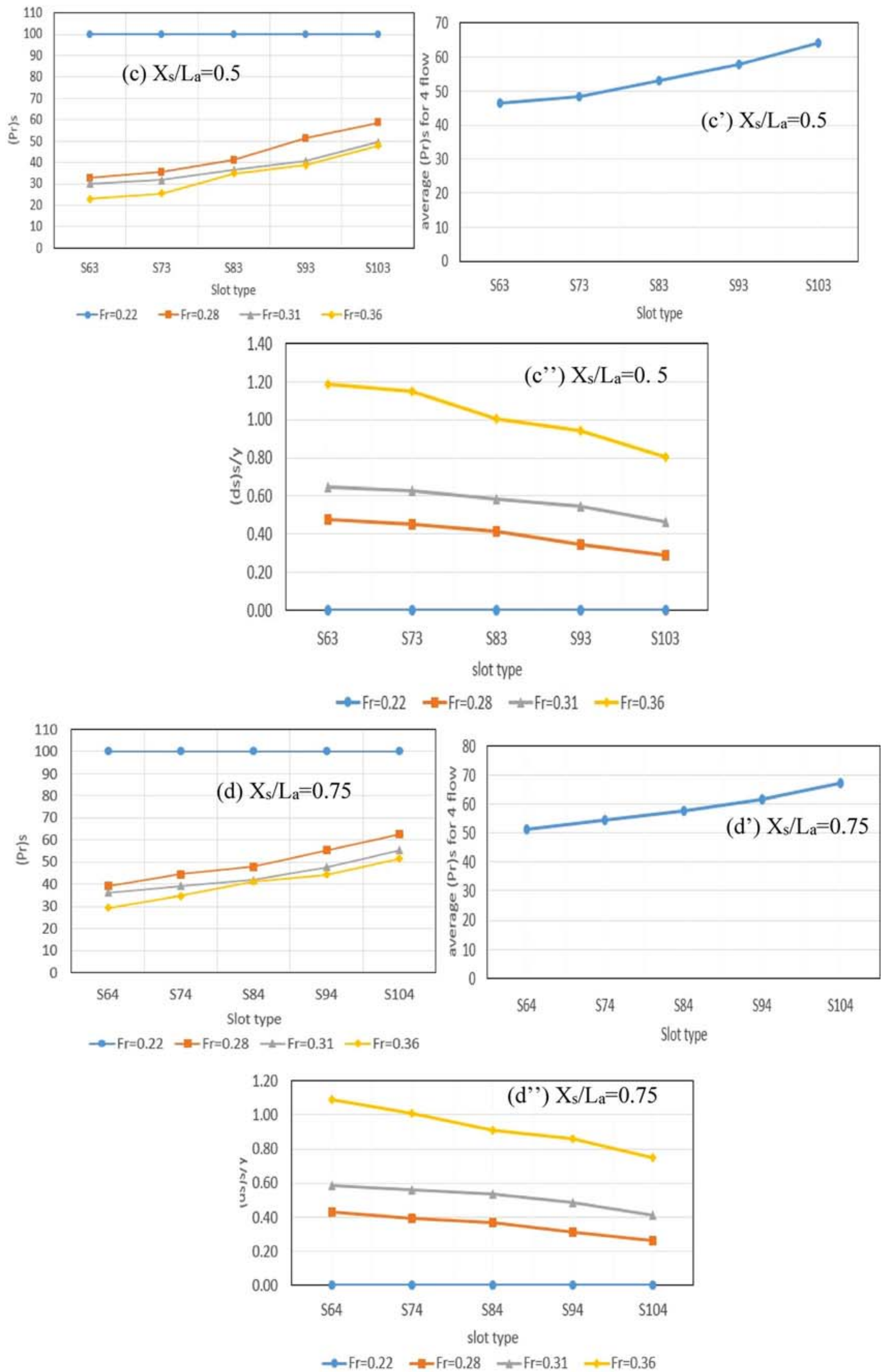


Figure 6. continued

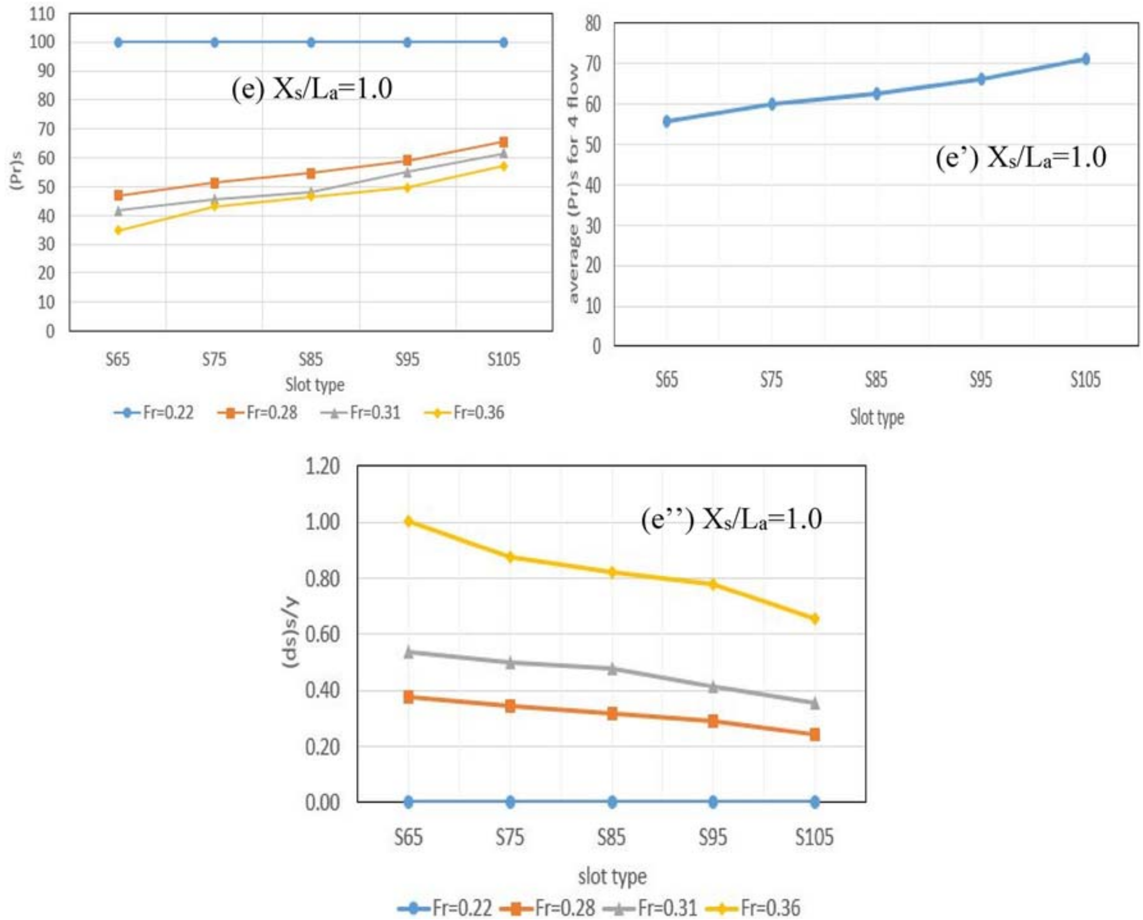


Figure 6. continued

herein was rectangular with square cross sections, 9cm in length and width.

In the reality, the bridge abutments are rectangular (in plan view). The authors found some suggestions in the literatures about the length of the abutment (L_a is the dimension perpendicular to the flow). According to Dongol and Melville (1994), the maximum length of the abutment should be considered between 10% and 20% of the channel width [5]. Therefore, by changing the type and the length of abutment and the slope of the wall, the scouring mechanism can change. Also, as the length of the abutment increases, the amount of scour increases. On the other hand, the obstruction caused by the length of the abutment greatly affects contraction scour. So the effect of the length of the abutment with slot should be studied separately.

To the author's knowledge, there is no clear recommendation on the abutment width (Ba). Thus, in this study, abutment with square cross section was selected. Since the main objective of the research is to investigate the location and dimensions of the slot created in the bridge abutment relative to the bed, thus, the effect of rectangular or square type of abutment was not considered in this research.

The bed sediments in this research are non-cohesive, sandstone particles. A major difference between cohesive and non-cohesive sediments is that non-cohesive sediments erode as single particles, but in cohesive sediments, some fragments of the bed of different sizes may erode abruptly. On the other hand, as the sediments become more cohesive (due to increased inter-particle forces within the sediments), the critical shear stress increases, and as a result, the sediment resistance to erosion increases. Therefore, in order to evaluate the effect of the slots, the overall results obtained in non-cohesive sediments can also be applied to cohesive sediments of the 1.37 mm grain size, but the resulting scour depth will be lower in the case of cohesive sediments. The authors suggest conducting experiments for cohesive sediment to ascertain the reduction scour depth.. Also non-uniformity of bed sediment can influence the performance of slot. In the case of non-uniform sediments, the larger sediment grains cover the smaller ones due to the armoring phenomenon.. That is, sediment particles with coarser grains prevent the erosion of finer sediment particles, thereby reducing the scour depth. It is expected that in case of using the sedimentary particles with larger d_{50},

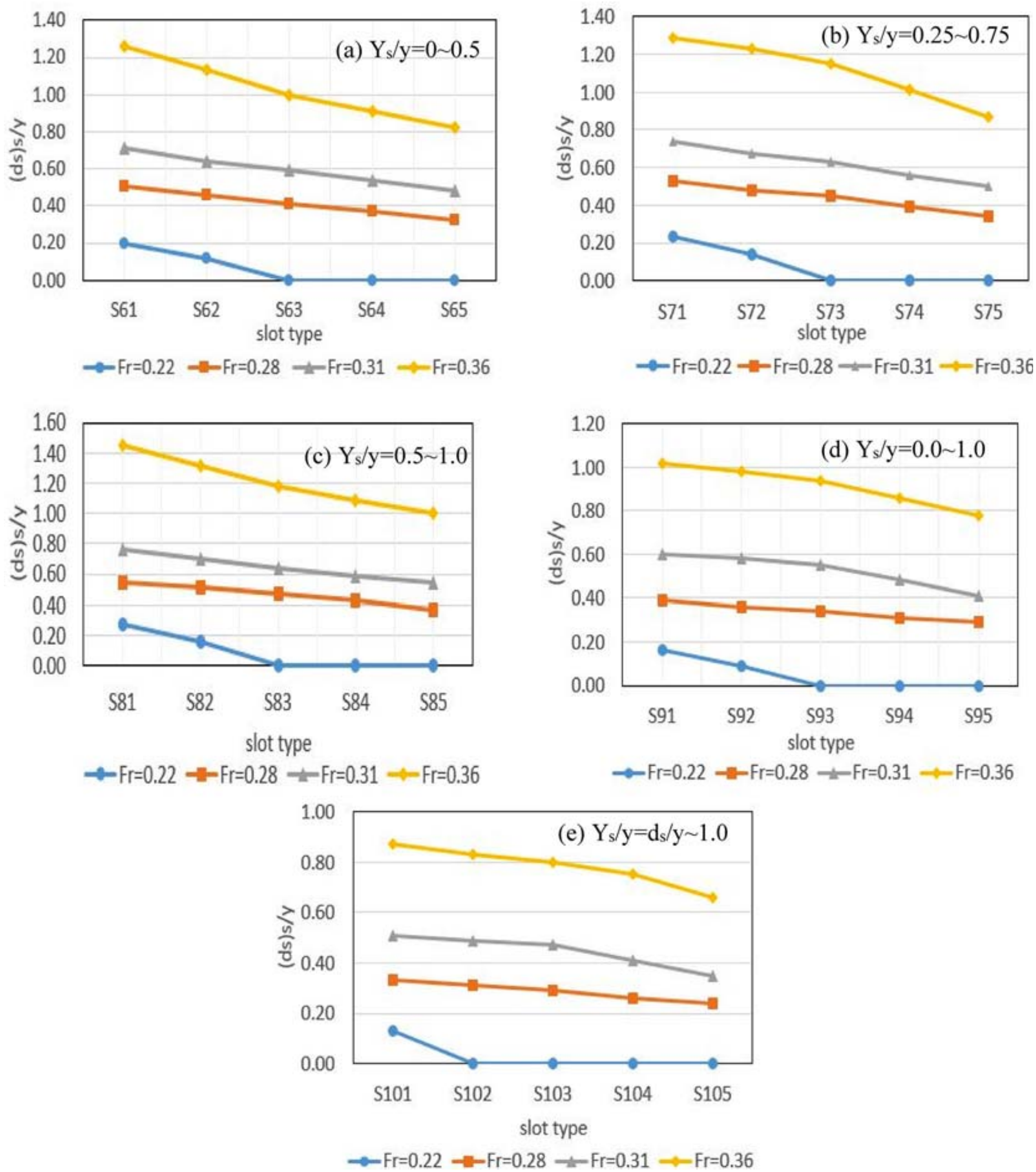


Figure 7. Dimensionless scour depth for different horizontal slot positions.

some areas of the slot are potentially blocked by the particles, decreasing the efficiency of slot use in reducing the scour depth. However, this issue needs further investigation. Therefore, it is suggested to investigate the effect of sediments sizes on scour reduction in abutments with slots for future research.

The results of this study show that although slots can be an effective tool for scour reduction, this hydraulic suggestion can have caused structural weakness in the area close to the foundation with high stress. On the other hand, the slot may lose its positive role over time in the event of multiple floods or the presence of vegetation. These concerns should be considered during field applications of slots.

According to the results, the most effective slot model is attached to the channel wall, and its height starts from the water level and extends below to the bed sediments surface. Compared to other slot models, this model is also the most effective one for other experiments. However, depending on the type of sediments, flow conditions and the type of abutment, the percentage of scour depth reduction varies. The author tried finding the field application of the slot in the bridge abutment, but they could not find any result. It may be due to the weak structural performance of the pier or abutments with slot. Therefore, in applying the results of this research for practical applications, certain operational and structural constraints must be taken into account.

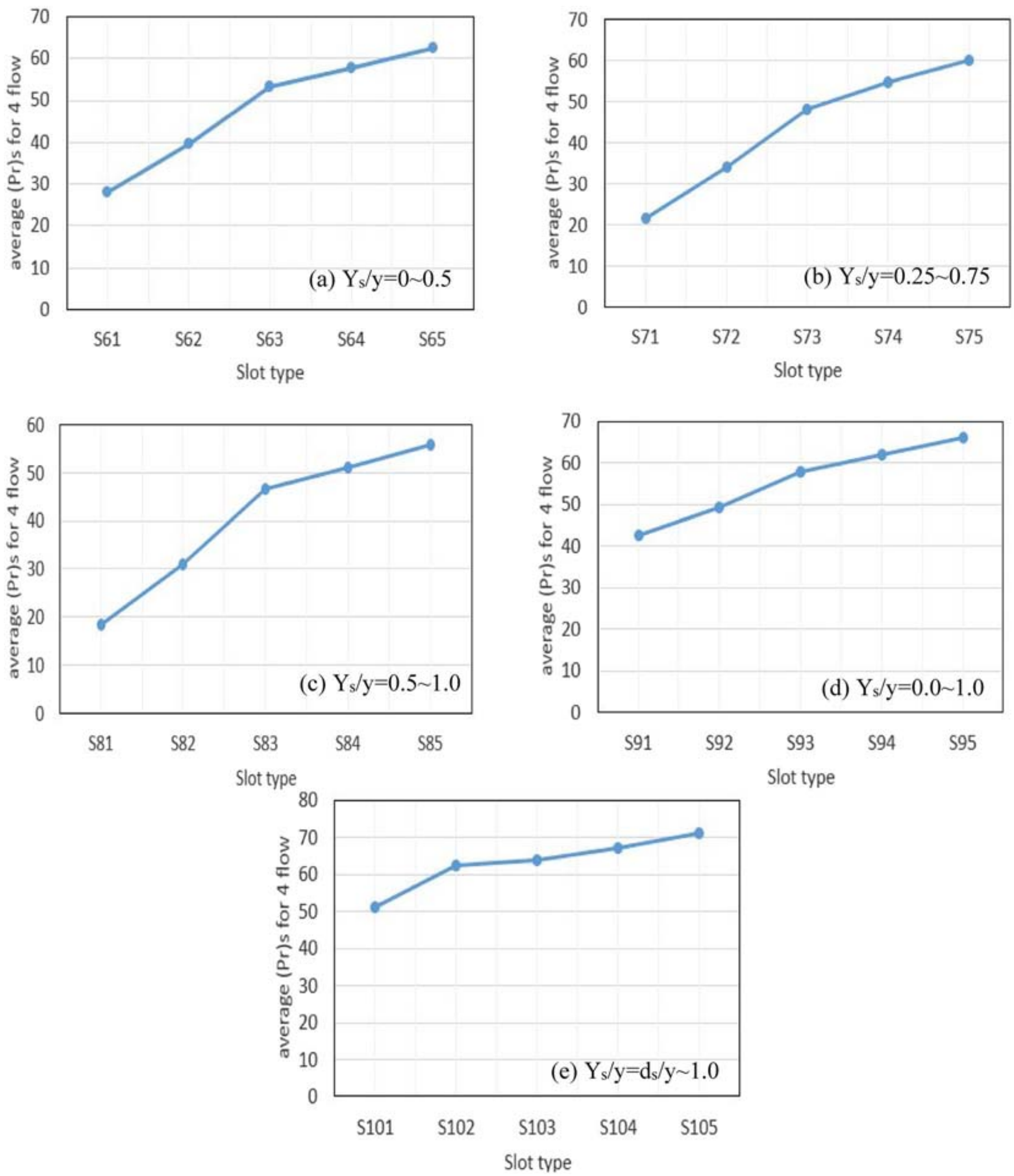


Figure 8. Average percentage of scour depth reduction for different horizontal slot positions.

5. Conclusions

In the present study, the effects of increasing the Froude number as well as 25 different slot models on the pattern of scour around the rectangular bridge abutments with vertical walls were examined using laboratory experiments. For this purpose, the vertical position of the slot relative to the bed and also horizontal position of slot relative to the nose of abutment were varied. Also, the height of the slot and its effect on scour reduction were investigated. The research was conducted on a sandy bed with uniform granulation, and the extent of scour depth and scour hole profile were measured. The results are as follows.

- For the abutments with slots, as the Froude number increases, the effect of using slots on reduction of the scour depth is decreased.
- The results of experiments using the abutment with slot in different models and under different flow conditions showed that the slots closer to the bed or reaching beneath the bed have better performance, and the slots featuring heights equal to the flow depth plus the equilibrium scour depth in a non-slot mode had the best performance.
- On the other hand, concerning the distance of slot from the nose tip or horizontal position of slot in different models, when the slot was positioned away from the

tip of the abutment nose and close to the channel wall, its positive performance increased.

- According to the results of this research, the most effective slot is the S_{105} model, the position of which to the sedimentary bed is $\frac{Y_s}{y} = \frac{d_s}{y} \sim 1$ *and* its position to the nose tip is $\frac{X_s}{L_a} = 1$. However, before using this result for practical cases, the limitations of the experiments should be considered.

List of symbols

$(d_s)_{max}$	the maximum depth of scour hole without using a slot
$(d_s)_{s\,max}$	the maximum depth of scour hole using a slot
ρ	flow density
ρ_s	density of the sediment particles
g	gravity acceleration
L_a	abutment length
d_{50}	median particle diameter
V	average flow velocity
μ	dynamic viscosity
W_s	slot width
B_s	slot depth
H_s	slot height
X_s	the distance of slot from abutment nose tip
B_a	abutment width
Y_s	slot position with respect to the bed
$\emptyset_s$	slot angle with respect to the flow
y	flow depth
B	channel width
t	scour time
t_e	equilibrium time
α	contact angle of the flow with the abutment
Fr	Froude number
Re	Reynolds number
G_s	Relative density of the sediment particles
$(Pr)_s$	percentage of scour depth reduction
σ_g	standard deviation of the sediment
V_c	critical velocity at the threshold of sediment particles movement

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