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Using a Curved Bed Sill as a Scour Countermeasure around a Complex Bridge Pier

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Keywords:

Scour; Scour countermeasure; Bridge pier; Bed sill; Complex pier.

Highlights:

- *A curved bed sill was used as a scour countermeasure around the complex bridge pier.*
- *Experimental investigation of scour depth around complex bridge pier.*
- *The investigation included three different locations and elevations of the curved bed sill.*

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Abstract: Bridges are constructed to facilitate transport between riverbanks. These bridges are supported by piers of varying geometric shapes that differ from one bridge to another. The interaction between these piers and the flowing water generates different types of vortices, forming a scour hole around the piers. This local scour around the foundation of bridge piers is a major cause of bridge failure. This study experimentally investigated using a curved bed sill as a clear water scour countermeasure at a complex bridge pier. The investigation included three locations of the curved bed (at the upstream edge of the piles cap, 5cm, and 10cm toward the downstream), three elevations of the curved bed sill, and four elevations of the piles cap ranging from 0% to 75% of the pile cap thickness covered by bed materials. The results indicated that using a curved bed sill can reduce the scour depth in all cases with the relative piles cap elevations to its thickness up to 50%. Among those in this study, the most effective location was at the upstream edge of the pile cap, and its effectiveness increased directly with its elevation. This case recorded a scour depth reduction of up to 41%. Placement curved bed sill at the upstream edge of the piles cap can serve as an efficient scour countermeasure around the complex piers that will be constructed in the future and for existing piers, as it does not interfere with the pier foundation location.

استخدام عتبة القعر المنحنية لتقليل النحر حول دعامة الجسر المركبة

إسراء هاشم صالح، نشوان كمال الدين العمري
قسم هندسة السدود والموارد المائية / كلية الهندسة / جامعة الموصل/ الموصل – العراق.

الخلاصة

تم إنشاء الجسور لتسهيل النقل بين ضفاف الأنهار، وتُحمل هذه الجسور على دعامات ذات أشكال هندسية مختلفة تختلف من جسر لآخر، وتتولد العديد من الدوامات المائية قرب دعامات الجسور، وذلك نتيجةً لتقاطعها مع جريان المياه، إذ يُعد النحر الموضعي حول أسس الدعامات هو السبب الرئيس لفشل الجسور، وفي هذا البحث، تم التحري مختبرياً عن استخدام عتبة القعر المنحنية لتقليل النحر حول الدعامة المركبة في ظرف جريان الماء الصافي، وتضمنت الدراسة التحري عن ثلاثة مواقع مختلفة لعتبة القعر المنحنية (عند بداية غطاء الركائز و٥ سم و١٠ سم باتجاه مؤخر الدعامة المركبة)، وثلاثة ارتفاعات مختلفة للعتبة، فضلاً عن أربعة ارتفاعات مختلفة لغطاء الركائز تتراوح بين ٠٪ إلى ٧٥٪ من سمك الغطاء المغطى بمواد القعر، وأشارت النتائج إلى أن استخدام عتبة القعر المنحنية يمكن أن يقلل من عمق النحر في جميع الحالات ولاسيما عندما يكون ارتفاع غطاء الركائز نسبةً الى سمكه لغاية ٥٠٪، وكان الموقع الأكثر فاعلية لعتبة القعر في هذه الدراسة هو حافة مقدم غطاء الركائز، وان فعالية عتبة القعر بهذا الموقع تزداد بشكل مباشر مع زيادة ارتفاعها، وسجلت هذه الحالة انخفاضًا في عمق النحر بنسبة تصل إلى ٤١٪، ومن الممكن استخدام عتبة القعر المنحنية عند حافة مقدم غطاء الركائز لتقليل النحر حول دعامات الجسور المركبة التي سيتم بناؤها في المستقبل، وكذلك لدعامات الجسور المقامة حالياً لأنها لا تتعارض مع موقع أساس الدعامات.

الكلمات الدالة: النحر، تقليل النحر، دعامة الجسر، عتبة القعر، دعامة مركبة.

1.INTRODUCTION

Bridges are crucial in road transport networks as they shorten transportation distances, thus saving time [1]. These bridges are mostly supported on piers with various geometric shapes, such as single and complex piers. Constriction of the bridge piers on the bottom of the rivers and waterways intersects the flowing water, changing the flow direction and generating vortexes. These vortexes remove the bed materials surrounding the piers, forming a scour hole around the piers [2, 3]. The scour may be simply defined as the reduction in the normal bed level due to erosion of the bed materials [4]. In general, when scouring occurs in the water stream bed around hydraulic structures, it can reduce the sand cover of the foundation and affect its stability [5, 6]. In the case of the complex bridge piers, the scouring process around complex bridge piers is complicated due to the interaction between the three main components of the complex piers: piles, piles cap, and columns [7]. Moreno et al. [8] investigated the influence of column width (D_C) and piles cap elevation (Z) on the scour using two models of complex piers with rectangular columns. The results for both models were analyzed, and it was noted that the equilibrium scour depth directly depends on (Z), where Z is the piles cap elevation. It was observed that the model of (D_C/D_{PC}) = 0.4 recorded less scour depth than the model of (D_C/D_{PC}) = 0.55, where Dc is the width of the column, and D_{PC} is the width of the piles cap. Yang et al. [9] conducted experimental work on the complex piers to investigate two models of skewed complex bridge piers with different piles cap elevations on the scour depth. The results showed that increasing the skew angle between complex bridge piers and the flow direction significantly increased the scour depth. The width of the column facing the flow significantly increased with even a slight skew angle, i.e., in the case of a skew pier, the width and length of the pier are important factors that impact the scour depth. Additionally, the researchers noted that the piles cap elevation significantly affected the scour depth. Based on the numerical and physical tests, Martinez et al. [10] reported an integrated procedure to estimate the potential scour around two of three South American towers for the Jakau Canal bridge. Many researchers have attempted to reduce the scour depth around bridge piers using different structures, such as submerged vanes, as a countermeasure of the scour [11], collars around the piers [12, 13], openings through the piers [14], bed sills [7], and other structures. The bed sill could be used as a way to reduce scour depth around bridge piers. Tafarojnoruz et al. [11] used a rectangular bed sill and Wang et al. [15] used a submerged weir to reduce the scour depth around bridge piers. Wang et al. [15] recorded about a 54% reduction in the scour depth when placing a submerged weir at the downstream end of the circular pier. In addition to that, Keshavarzi et al. [13] investigated the scour pattern around an arch-shaped bed sill with a circular bridge pier. Concerning a complex bridge pier, Varaki et al. [7] managed to reduce the scour depth by up to 40% when using a bed sill at the upstream edge and by about 10% when using a bed sill at the downstream edge of the pier. The current study aims to experimentally examine the effect of using a curved bed sill as a scour countermeasure around a complex bridge pier. The study considers different positions and elevations of the curved bed sill and different elevations of the piles' cap, which can be partially covered or uncovered by bed materials.

2.METHODOLOGY

2.1.Dimensional Analysis

In the case of using a curved bed sill as a scour countermeasure around a complex bridge pier, the scour depth (ds) is influenced by many factors, including:

- Flow property represented by Water discharge (Q), flow velocity (V), flow depth (y), and gravity acceleration (g).

- The water properties are represented by mass density (ρ) and dynamic viscosity of the water (μ).
- The bed materials parameters are represented by the mass density of the bed material (ρ_s), median diameter of the sediment particles (d_{50}), standard deviation of sediment particles (σ_g), and critical velocity of the particles' inception motion (V_C).
- The geometric parameters of the channel and the model are represented by the channel bed width (W); column width (Dc) and length (Lc); piles cap's width (D_{PC}), length (L_{PC}), thickness (T_{PC}), and elevation above the initial bed level (Z); pile diameter (d_P); and distance between the piles (S_P). It also includes curved bed sill elevation above the initial bed level (Z_S) and placement from the beginning of the pier cap(X).

In this study, because of a little variation in the laboratory temperature, one type of bed material was used as a movable bed, and the experiment running time (T) was fixed at three hours for all experiments. This time was chosen based on what was concluded and determined by Alsaidi et al. [14], who noted that a percentage of approximately 96.82% of the depth of scour occurs at three hours of operation time, compared to the depth of scour that occurs after six hours. The water properties (ρ and μ) and bed materials parameters (d_{50}, σ_g, and ρ_s) were ignored in the analyses. The scour depth can be described as presented below in Eq. (1):

$$d_S = f_1(g, y, Q, V, W, V_C, L_C, D_C, L_{PC}, D_{PC}, T_{PC}, Z, d_P, S_P, X, Z_s) \quad (1)$$

Applying Π – theory yields the dimensionless parameters as follows:

$$\frac{d_s}{D_{pc}} = f_2\left(\frac{V}{V_c}, \frac{V}{\sqrt{gy}}, \frac{Q}{Dpc5/2\sqrt{g}}, \frac{w}{D_{pc}}, \frac{Z}{T_{pc}}, \frac{Lc}{L_{pc}}, \frac{Dc}{D_{pc}}, \frac{dp}{S_p}, \frac{X}{Tpc}, \frac{Zs}{T_{pc}}\right) \quad (2)$$

The complex pier's dimensions remained constant for all experiments, and a clear water condition with a flow intensity (V/Vc = 0.9) was consistently maintained. Furthermore, the values of the channel bed width (W), water discharge (Q), and flow depth (y) remained constant, resulting in a constant value of Fr $\left(\frac{V}{\sqrt{gy}}\right)$. Therefore, Eq. (2) can be simplified to:

$$\frac{ds}{Dpc} = f_3(Z_r, X_r, Z_{sr}) \quad (3)$$

where $Z_r = Z/T_{PC}$, $X_r = X/T_{PC}$, and $Z_{sr} = Z_s/T_{PC}$.

2.2. Experimental Setup

The experiments were conducted in the hydraulics laboratory that belongs to the Dams and Water Resources Engineering Department at the University of Mosul. An open rectangular concrete channel with a length of (19.1) m, width of (1.50) m, and depth of (0.7) m was used to accomplish the experimental work. Figure 1 shows the scheme of the experimental channel. A 7-meter section of the channel was filled with movable bed materials to be the working section. The working section included one meter at the beginning, and its end was covered by fine gravel to reduce the local scour due to entering the flow into the working section. The rest of the working section (5 meters long) was filled with a 20 cm thick layer of uniform sand with d_{50} of 0.82 mm and σ_g of 1.3.

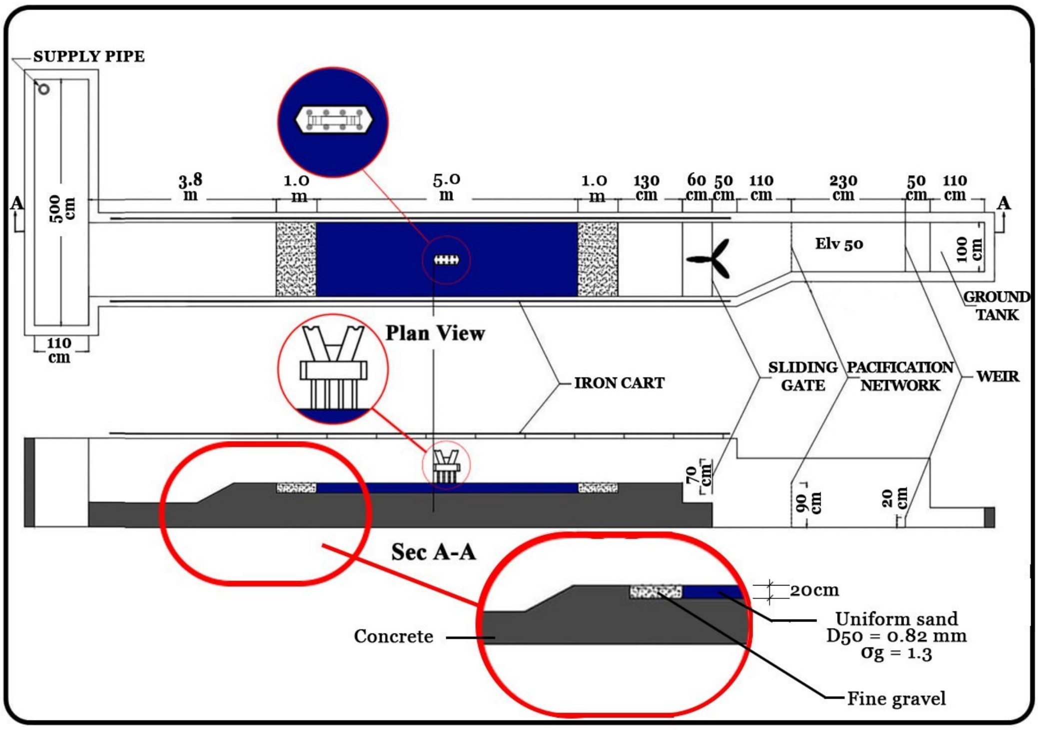
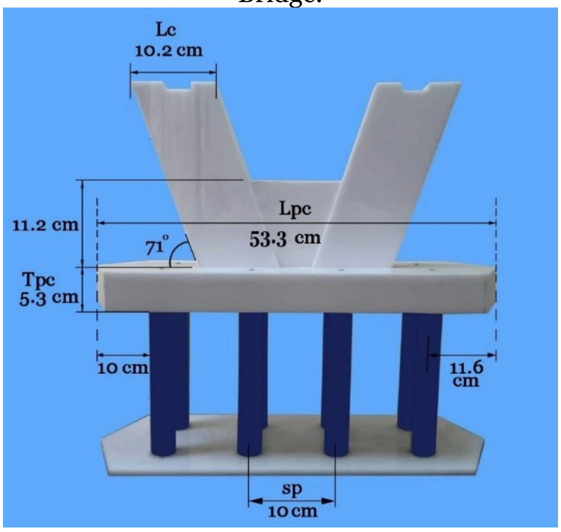


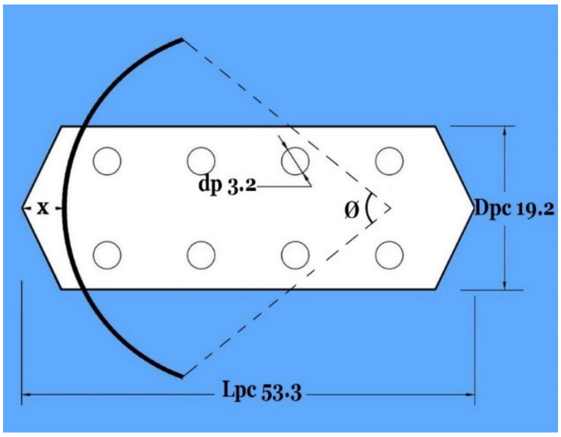
Fig. 1 Scheme of the Experimental Channel.

The sluice gate at the end of the channel was used to maintain the experiments' flow condition (a certain flow depth for a certain water discharge). Water discharge was measured using a sharp-crested weir installed at the end of the channel, previously calibrated by [16] A Gate valve was installed at the main feeding pipe to control water discharge. The water was supplied using a pump with a maximum discharge of 95 l/sec. The flow system is based on the water circulation system, where the water is pumped to the channel and then returned to a ground tank below the pump through conveyor channels in a closed water system. A model of the complex pier with a geometric shape close to the shape of the complex piers of the fourth bridge in Mosul City, as shown in Fig. 2, was fabricated from smooth surface plastic and used in this study. A model of a complex pier consisted of eight cylindrical piles with d_P of 3.2 cm arranged in two rows, a rectangular piles cap with pointed ends, and two inclined rectangular columns with an angle of 71°. A piles cap length (L_{PC}) was 53.3 cm, width (D_{PC}) was 19.2 cm, and thickness (T_{PC}) was 5.3 cm. The rectangular columns' width (perpendicular to the flow) (D_C) was 4.2 cm, and the length (parallel to the flow) (L_C) was 10.2 cm. A piece 11.2 cm high was installed between two columns to connect them. Figure 3 (a) shows the complex pier model specification.

Fig. 2 The Complex Pier of the Fourth Mosul Bridge.



(a)



(b)

Fig. 3 (a) The Complex Pier Model; (b) Location of the Bed Sill.

The complex pier model was installed at the beginning of the second half of the working section. Each experiment was started with a flattening bed by leveling the sand bed before starting the experiment. A constant flow depth of 15 cm was considered for all the experiments. The experiments were conducted under clear water flow conditions with flow intensity (V/V_C) = 0.9. The threshold velocity value was determined using Melville and Sutherland's equation Melville and Sutherland [17]. A set of experiments with four elevations of piles cap (Z_r) (0%, 25%, 50%, and 75%) and without curved bed sill were conducted at the beginning for a comparative purpose. After that, a curved bed sill, which was 140° sector from a 42 cm diameter circle, was installed in different locations and elevations to investigate its effect as a scour countermeasure. Three-bed sill locations were considered in the study. The locations were at the beginning of the piles cap (X_r = 0%), 5 cm, and 10 cm toward the downstream (X_r = 94.3% and 188.7%, respectively) (Fig. 3 (b)). For each location, three levels (Z_{Sr}) of the curved bed sill were also considered, i.e., -24.5, 0, and 24.5 %. Maximum scour depth was measured during the experiment running time (3 hours) using a point gauge with accompaniment with a micro camera to clarify the vision underwater. After that, the water was drained slowly, and the bed topography around the model was meshed and measured manually using a point gauge with an accuracy of 0.1 mm.

3.RESULTS AND DISCUSSION

Bed sills can be used as a countermeasure of the local scour at a complex bridge pier [7]. This study investigated the effect of a curved bed sill on local scour around the complex bridge pier. Three locations of the curved bed sill (X_r) were considered in the study (X_r = 0% (at the upstream edge of the pile's cap), 94.34%, and 188.7% towards the downstream). For each location, three elevations (Z_{Sr}) of the curved bed sill were also considered (Z_{Sr} =-24.5%, 0%, and

24.5% relative to the normal bed level). Four piles cap (Z_r) elevations were chosen for the complex pier (Z_r = 0%, 25%, 50%, and 75%) and tested for all these locations and elevations. The local scour depth around the complex bridge pier using different locations and elevations of the curved bed sill was compared with that without using a curved bed sill.

3.1. The Effect of the Curved Bed Sill Location on the Local Scour Around Complex Piers

To demonstrate the effect of the curved bed sill location on the scour depth on local scour around the complex pier, three locations were investigated (as mentioned before). These locations were determined based on the shape of the scour hole generated throughout the testing complex pier without using the bed sill. The distance of X = 0 cm was at the upstream edge of the pile's cap (X_r = 0%), and the distance of X = 10 cm (X_r = 188.7% %) represented the approximate location of the maximum scour depth, located at the first pile location. The other location with X =5 cm (X_r = 94.34%) represented the intermediate distance between the two other locations. Figure 4 presents the longitudinal section of the bed topography of the experiment with Z_r = 50%, which demonstrates the location of the maximum scour depth location without using a bed sill.

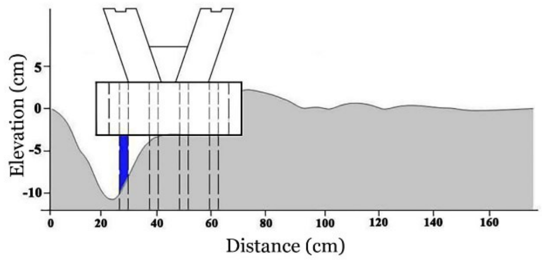
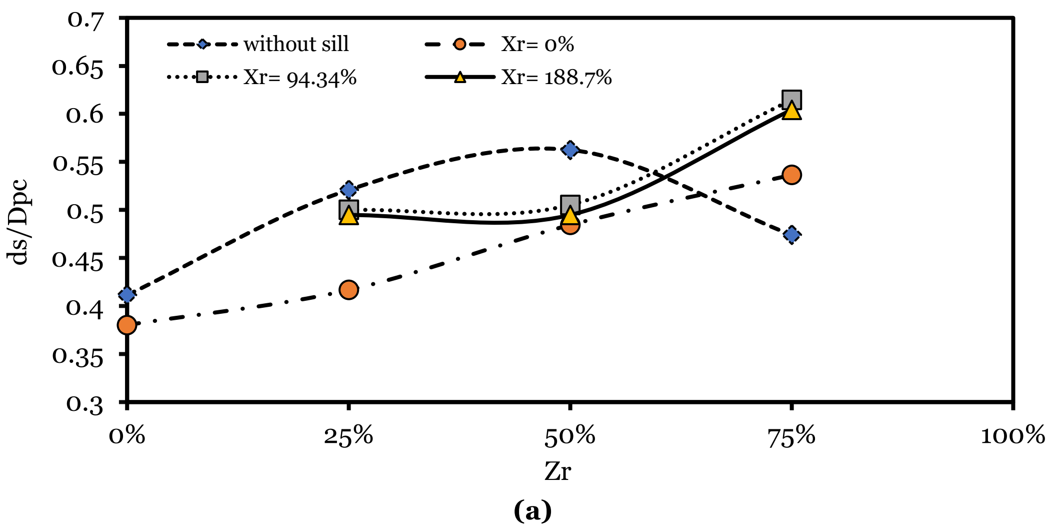
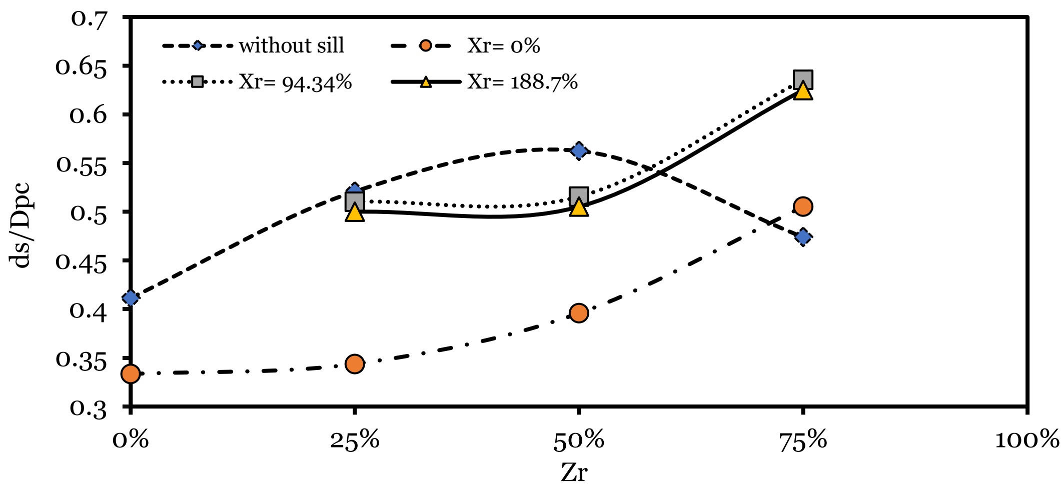


Fig. 4 Longitudinal Section of the Bed Topography of the Experiment without Using Bed Sill in Case of Z_r = 50%.

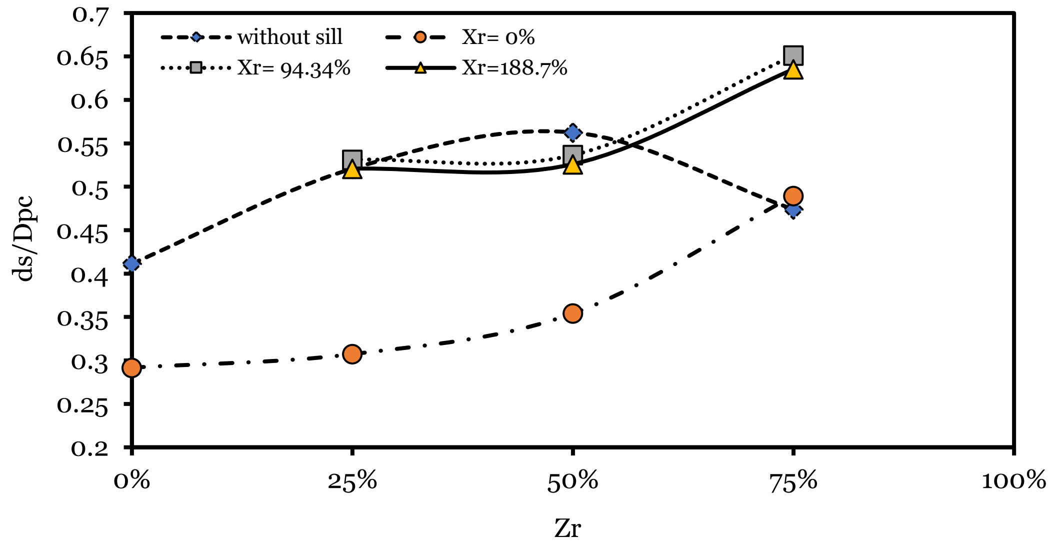
Figure 5 shows the maximum local scour depth around the complex pier relative to the cap width (ds/D_{PC}) for different bed sill locations X_r = (0, 94.34, and 188.7) %, and cap elevations ratio Z_r = (0, 25, 50, and 75) % for curved bed sill elevation Z_{sr} = (-24.5, 0, and 24.5)%. The maximum local scour depth around the complex pier without using a bed sill was also drawn in the figure for comparison purposes. Figure 5 shows that the location of the curved bed sill at a distance X_r = 0% recorded the best results of scour depth reduction compared with the other locations, followed by the distance X_r = 188.7% and the distance X_r = 94.34%. Using the curved bed sill upstream of the piles cap edge (X_r = 0%) reduced the effect of the pointed head of the piles cap on the scour depth by reducing the vortices effect. In addition, using the curved bed sill reduced the impact of water, which was in the direction of the flow, from flowing directly under the piles' cap. Flowing water under the piles' cap increased the depth of the scour due to increased shear stress under the piles cap and transporting bed materials from the scour hole. Regarding the curved bed sill location at X_r = 94.34% and 188.7%, both locations reduced the maximum scour depth, however, less than that recorded in the case of X_r = 0%. In the case of X_r = 188.7%, the bed sill reduced transporting bed materials outside the scour hole because it was located almost at the center of the scour hole. Thus, it reduced the maximum scour depth compared to the absence of a curved bed sill. It also reduced the maximum scour depth compared to that in the case of X_r = 94.34% because it reduced the impact of the first two piles on the scour by covering them as it was directly in front of the piles. It was also noted placing the curved bed sill at X_r = 0%, a new minor local scour hole was generated upstream of the bed sill location, as shown in Fig. 6. The new minor local scour hole insignificantly affected the scour depth around the complex pier as it was out of the pier location, and it was much less than that around the complex pier (at the original scour location).



(a)

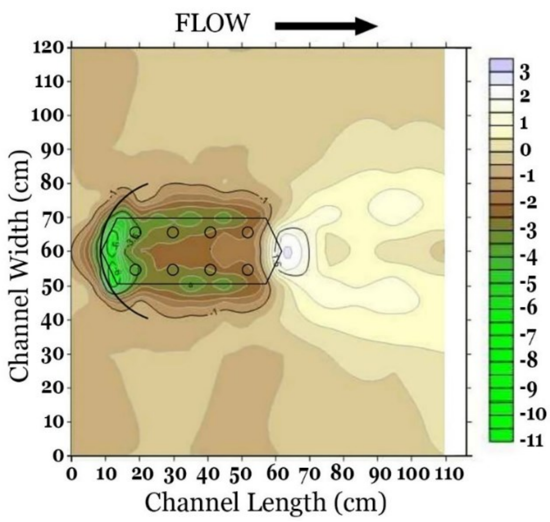


(b)



(c)

Fig. 5 Relative Local Scour Depth for different Bed Sill Locations and Piles Cap Elevations with (a) Z_{sr} = -24.5%, (b) Z_{sr} = 0%, and (c) Z_{sr}= 24.5%.



(a) **(b)**

Fig. 6 Local Scour in Front of the Curved Bed (X_r = 0% and Z_{sr} = 24.5%).

Coefficients of the scour depth reduction (Ks) and scour hole volume reduction (Kv) were calculated using Eqs. (4) and (5) to compare different cases.

$$K_S\ \% = \frac{ds/Dpc - (ds/Dpc)\ S}{ds/Dpc} \times 100 \qquad (4)$$

$$K_V\% = \frac{V - Vs}{V} \times 100 \qquad (5)$$

where ds/D_{pc} and $(ds/D_{pc})s$ are the ratios of maximum scour depth to piles cap thickness with and without using a curved bed sill, respectively, for the same flow condition. V and Vs are the volumes of the scour hole in cm^3 with and without using a curved bed sill, respectively, for the same flow condition. The positive values for coefficients (K_S and K_V) mean a reduction in the scour depth and scour hole volume around the complex pier, and vice versa for negative values. The K_S and K_V values for different cases are presented in Tables 1-3.

Table 1 Coefficient of the Scour Depth and Scour Hole Volume Reductions in the Case of Z_{sr} = -24.5% and for Different Locations of the Curved Bed Sill.

Items	Z_r= 0%	Z_r= 25%	Z_r= 50%	Z_r= 75%
		Xr= 0%		
K_S	7.6%	20%	13.88%	-13.2%
K_V	-12.1%	20.35%	33.8%	-4.34%
		Xr = 94.34%		
K_S	-	4%	10.2%	-29.7%
K_V	-	5.9%	8.2%	-44.83%
		Xr= 188.7%		
K_S	-	6%	12.03%	-27.47%
K_V	-	3.2%	5.64%	-70.95%

Table 2 Coefficient of the Scour Depth and Scour Hole Volume Reductions in the Case of Z_{sr} = 0% and for Different Locations of the Curved Bed Sill.

Items	Zr= 0%	Zr= 25%	Zr= 50%	Zr= 75%
		Xr= 0%		
KS	18.98%	34%	29.63%	-6.6%
KV	-7.31%	23.41%	34.74%	4.663%
		Xr= 94.34%		
KS	-	2%	8.33%	-34.06%
KV	-	-3.02%	4.63	-76%
		Xr= 188.7%		
KS	-	4%	10.18%	-31.86%
KV	-	-6.7%	-6.23%	-78.27%

Table 3 Coefficient of the Scour Depth and Scour Hole Volume Reductions in the case of Z_{sr}= 24.5% and for different Locations of the Curved Bed Sill.

Items	Zr= 0%	Zr= 25%	Zr= 50%	Zr= 75%
		Xr = 0%		
KS	29.11%	41%	37.04%	-3.29%
KV	-1.53%	25.736%	37.82%	6.85%
		Xr= 94.34%		
KS	-	-2%	4.63%	-37.36%
KV	-	-4.81%	-6.1%	-83.97%
		Xr= 188.7%		
KS	-	0%	6.48%	-34.06%
KV	-	-10.87%	-9.74%	-83.1%

where (dsb/Dpc) is the ratio of scour depth formed in front of the bed sill. From Fig. 5 and the above tables, it can be noted that placing the curved bed sill changed the scour pattern of the complex pier. Without a curved bed sill, maximum scour depth increased as the visible part of the piles' cap increased to Z_r = 50%. Beyond this value, the maximum scour started to decrease because the effect of the thickness of the piles' cap decreased when the distance between the top of the cap and the normal bed level increased [18]. However, when using a curved bed sill, the scour depth continued to increase with the visible part of the piles' cap. Generally, the values of Ks recorded a reduction in the scour depth in cases of $Z_r \le 50\%$, and the effectiveness of using the curved bed increased with Z_r up to 50%. However, it recorded a negative effect in the case of Z_r = 75%. The maximum scour reduction (Ks) was 41% in the case of X_r = 0%, Z_r = 25%, and Z_{sr} = 24.5%. Regarding Kv values, as presented in Tables 1-3, the effectiveness of using a curved bed sill decreased as moving the curved bed sill toward the downstream edge of the piles cap. For example, Kv values in the case of Z_r = 25% and Z_{Sr} = -24.5% were 20.35%, 5.9%, and 3.2% for X_r = 0%, 94.34%, and 188.7%, respectively. Varaki et al. [7] reported that placing the bed sill at the upstream edge of the piles cap of the complex pier was better than in an intermediate location between the upstream and downstream edge of the piles cap.

3.2.The Effect of the Curved Bed Sill Elevation on the Local Scour Around Complex Piers

To illustrate the effect of different curved bed sill elevations on the scour depth, three curved bed sill elevations were investigated, i.e., Z_{sr} = -24.5%, 0%, and 24.5%, for each location in the present study. Figure 7 (a) illustrates the relative maximum scour depth (d_s/D_{pc}) for different curved bed sill elevations (Z_{Sr} = -24.5%, 0%, and 24.5%), different piles cap elevations (Z_{Sr}), and X_r= 0%. From Fig. 7 (a) and Tables 1-3, all bed sill elevations recorded scour depth reduction when the (Z_r) was up to 50%, and the performance of the curved bed sill at this location (X_r = 0%) increased with Z_{Sr} within the elevation limits of the study. The curved bed sill at the upstream edge of the piles cap (X_r = 0%) decreased the impact of hitting the water with the piles cap, reducing creating vortices that can affect the scouring process. The effectiveness of this bed sill increased with its elevation. Based on the present findings from this case, the curved bed sill at an elevation of Z_{sr} = 24.5% performed better than other elevations.

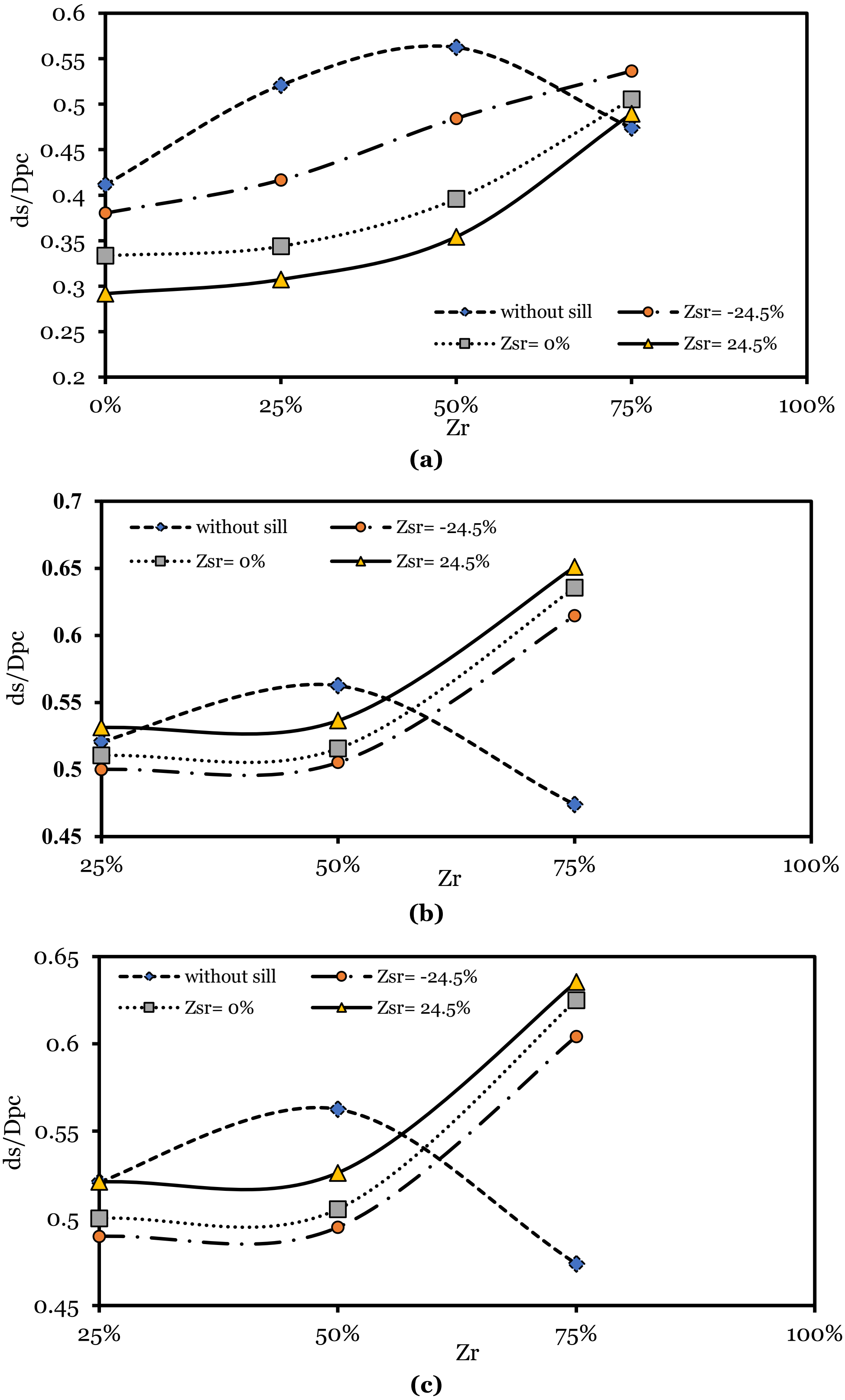


Fig. 7 Relative Local Scour Depth for Different Curved Bed Sill Elevations and Piles Cap Elevations: (a) $X_r = 0\%$, (b) $X_r = 94.34\%$, and (c) $X_r = 188.7\%$.

Figures 7 (b) and (c) illustrate the relative maximum scour depth (d_s/D_{pc}) for different curved bed sill elevations (Z_{Sr}= -24.5%, 0%, and 24.5%), different piles cap elevations (Z_{Sr}), and X_r = 94.34%, and 188.7%. Figures 7 (b) and (c) and Tables 1-3 clearly show a reduction in the scour depth for almost all cases, with Z_r up to 50% when the curved bed sill was placed under the piles cap, X_r = 94.34%, and 188.7%. However, it provided scour reduction but less than that for the case at X_r = 0%. For these two cases, the performance of the curved bed sill increased as its elevation decreased. In two specific locations (X_r = 94.34% and 188.7%), the curved bed sill is an effective scour countermeasure as it prevents the bed materials from moving out of the scour hole. However, its performance reduced as its elevation increased because it became a minor source of vortices generation along with complex pier components (piles, piles cap, and columns). The best-recorded reduction in the scour depth (highest Ks value) in these two cases was in the complex pier with Z_r = 50%, followed by the case of Z_r = 25% with Z_{Sr}= -24.5% and 0%. However, it recorded a negative effect in cases of Z_r = 75%. In addition, using the curved bed sill in the case with Z_{Sr} = 24.5% insignificantly affected the scour depth. The experiments with Z_r= 0% and the curved bed sill under the piles' cap were not conducted as the bed sill at these locations significantly affects the scour depth, which mainly occurs due to the piles cap leading edge; in this case, it is submerged under the bed. Regarding Kv values, as presented in Tables 1-3, the effectiveness of using a curved bed sill increased with the elevation of the bed sill in the case of X_r 0%. As mentioned before, this behavior is due to placing the curved bed sill at this location reduces the effect of the pointed piles cap and thus reduces the power of the generating vortices. The positive effect of the curved bed sill on the reduction of the generating vortices increased with its elevation.

4.CONCLUSIONS

The effect of a curved bed sill (a sector of a 42 cm in diameter circle with a 140°) on local scour at a complex bridge pier was investigated in the present study. The study included an investigation of three elevations and locations of the curved bed sill and four elevations of the piles cap. The experiments were conducted under clear water conditions (V/V_c = 0.9) and a constant water depth of 15 cm. The obtained results from this study showed the following:

- Using a curved bed sill directly affected the scour depth. When studying the impact of the bed sill location on the maximum local scour depth around the complex pier, it was found that the bed sill yielded positive results in reducing the maximum scour depth around the complex pier with the models of Z_r from 0% to 50%.
- Among the different locations in this study, the curved bed sill location at a distance X_r of 0% showed the best location performance. Placing the curved bed sill at the upstream edge of the piles cap (X_r = 0%) reduced generating the vortices due to the pointed head of the piles cap. In addition, it reduced the impact of water, in the direction of the flow, from flowing directly under the piles cap, thus reducing the bed shear stress and scour depth.
- Regarding the other locations of the curved bed sill (X_r = 94.34% and 188.7%), the curved bed sill reduced the transport of the bed materials out of the scour hole as it was in the scour hole. Both locations showed scour depth reduction; however, the percentage of scour reduction was less than that of placing a curved bed sill at X_r = 0%.
- The effectiveness of the curved bed sill increased with its elevation in the case of the X_r = 0%, as it helped to reduce the impact of hitting the water with the piles cap. However, in the cases of the other two locations, it became a minor source of vortices generation along with complex pier components. Therefore, its performance decreased as its elevation increased.

Other curve lengths of the curved bed sill should be evaluated as a scour countermeasure at a complex bridge pier and necessary to be considered in future work.

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NOMENCLATURE

ds	Maximum scour depth, cm
d_{50}	Median diameter of the sediment particles, mm
D_C	Column width, cm
d_P	Pile diameter, cm
D_{PC}	Piles cap width, cm
g	Gravity acceleration, m/s^2
L_C	Column length, cm
L_{PC}	Piles cap length, cm
Q	Water discharge, l/s
S_P	Distance between the piles, cm
T_{PC}	Piles cap width thickness, cm
V	Flow velocity, m/s
V_C	Critical velocity of the particle inception motion, m/s
W	Channel bed width, m
X	placement from the beginning of the pier cap, cm.
y	Flow depth, m
Z	Initial bed level, cm
Z_s	curved bed sill elevation above the initial bed level, cm
Greek symbols	
ρ	mass density of the water, kg/m^3
μ	dynamic viscosity of the water, kg/(m s)
ρ_s	Mass density of the bed material, kg/m^3
σ_g	standard deviation of sediment particles

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