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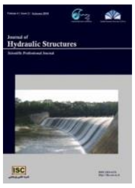

Numerical Study of Scouring pattern around Bridge pier in 180-degree bend Divergent and Convergent Using SSIIM software

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Abstract

Bridges are the most important river structures that are destroyed due to erosion. The change in the shape of the river geometry along the course of the river leads to erosion of the river bed and can also affect scour around the pier. Therefore, in this paper, the effect of the convergence and divergence ratio of 15% in the 180º bend was investigated on the amount of scour around the pier of the circular bridge using the SSIIM numerical model. The results showed that the SSIIM software has a high ability and accuracy in determining the scour pattern in bend channels. The most scour depth appeared in the bend with 15% convergence and it increased by 1.75 and 2.33 times compared to the uniform and divergent bend, respectively. Also, the most sedimentation height occurred in the bend with 15% convergence and it increased by 3.25 and 4.33 times compared to the uniform and divergent bend, respectively.

Keywords: Scour Pattern, Bed Topography, Bridge Pier, Convergence, Divergence.

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1. Introduction

The meandering rivers have always been interesting to hydraulic engineers because of spiral flows, and the flow pattern becomes more complex when the bridge pier is placed in the bend. Several laboratory studies have been investigated in this field, which can be referred to Bozkus and Yildiz [1] that by placing an inclination cylindrical pier in a plane that is parallel to the flow, the scour depth decreases with the increase of the angle of the pier. Ettema et al. [2] stated a direct relationship can be found between the balanced scour depth and the disturbance intensity, so that the scour depth value increased with the decrease of the pier diameter. Zarrati et al. [3] examined the performance of independent and continuous collars in the groups of pier. They concluded that the use of a continuous collar has led to a 50% reduction in local scouring. Emami et al. [4] investigated the scour around the pier in a 180º bend. They observed that with the increase of flow rate, the scour cavity is closer to the outer wall. Masjedi et al. [5] conducted scour tests in a laboratory channel with a 180º bend and placing a rectangular pier with semicircular noses at different positions. They reported that the most scouring occurred at an angle of 60º. Heidarnejad et al. [6] showed the effect of the slots inside the pier on the reduction of the most scour depth by creating slots inside the cylindrical pier and conducting an experiment in a channel with a 180º bend. Vaghefi et al. [7] investigated scouring around circular bridge piers which had two different diameters and varying diversion angles in downstream. They reported that increasing the diversion angle decreased scour depth. Ben Mohammad Khajeh et al. [8] investigated the scour depth and location around an oblique and vertical pier at the apex of a sharp 180º bend, experimentally. Vaghefi et al. [9] studied the scouring around a triplet group of cylindrical piers in two cases perpendicular to the flow and in the direction of the flow with clear water conditions in a 180º bend channel. Rasaei et al. [10] carried out the effect of the pier position on scouring around the pier numerically and experimentally in a 90º converging bend and concluded that the increase in convergence and the change of the pier position in the bend causes an increase in secondary flows and the most depth and volume of the scour cavity in the second half of the bend. Moghanloo et al. [11] investigated a laboratory study of the effect of collar thickness and surface on scour pattern in a 180º bend with an oblong pier. Ben Mohammad Khajeh and Vaghefi [12] studied the effect of abutment on the scour around the oblique pier in 180º bend. They reported that in all cases the most scour depth happened on the upstream side of the exterior abutment. Vaghefi et al. [13] investigated the scour around the pier at the apex of a 180º bend the influence of the presence of an upstream groyne. They found that when a T-shaped groyne was installed on the outer wall, it had a much greater effect on reducing the erosion of the pier, so that the greatest effect was relevant to the placement of the groyne at an angle of 70º on the outer wall. Sedighi et al. [14] studied the effect of oblique double piers on level of bed in clear water conditions. Dehghan et al. [15] carried out the effect of length to width ratio and pier deviation angles on scour pattern in 180º bend. Keshavarz et al. [16] worked the effect of the form and location of the pier on the bed topography in the 180º bend. Sedighi et al. [17] investigated the effect of twin converging bridge piers on the flow pattern in a 180º bend with a rigid bed. Safaripour et al. [18] worked on the effect of the submergence ratio of pair submerged vanes on level of bed changes and temporally evaluated the most scour in a 180º bend with a bridge pier group. Eghbalnik et al. [19] considered the time evolution of level of bed in the presence of two rows of oblique-vertical piers in a 180º bend and presented that the evolution of scour depth decreased over time. Dehghan et al. [20] investigated the effect of increase in the collar width on the decrease of scour around rectangular piers in 180º bend. Vaghefi and Ben Mohammad Khajeh [21] compared the flow pattern around convergent and divergent-vertical pier groups in a sharp 180º bend. In addition, numerous numerical studies have been conducted in this case and some of the studies are mentioned below. Yen et al. [22] by combining the three-dimensional flow model with the scour model, they could simulate the bed changes and the flow pattern around a bridge pier. Ali and Karim [23] simulated the flow around the pier of a cylindrical pier in 3D using FLUENT software, and using the obtained results, presented numerical relationships for the most scour depth around the pier. Salaheldin et al. [24] simulated the divergent flow around the pier using FLUENT software. Elsaeed [25] investigated scour patterns around bridge piers using SSIIM. Nekoufar and Kouhpari [26] studied scour control around the bridge pier by the non-submerged vans using SSIIM software and concluded that this software can be considered a good option for simulating sediment transport and the scouring depth around the bridge pier. Akib et al. [27] modeled the most scour depth around a bridge pier using SSIIM2. Basser et al. [28] simulated scour around a rectangular abutment using SSIIM. Azizi et al. [29] studied the flow around a bridge pier which was surrounded by submerged vanes. Hamidi and Siadatmousavi [30] conducted the flow and scour pattern around the bridge piers using SSIIM numerical model. Asadollahi et al. [31] used the SSIIM numerical model to model the three-dimensional flow and scour pattern around pier groups in the transverse direction. They observed that the most amount of sediment after moving the piers from 60 to 90º and 90 to 120º angle increased by approximately 12% and decreased by 42% respectively. Lahsaei et al. [32] numerically simulated the flow pattern around the divergent pier in the bend with different relative curvature radius. Since many studies in the field of flow pattern and scour in uniform bend in straight and curved paths have been numerically and experimentally investigated, very few numerical studies were conducted on the scour pattern in converging and diverging bends with Cylindrical bridge piers in bends. For this purpose, in this paper, the simulation of scour pattern has been investigated in 180º bend with 15% convergence and divergence ratio with single cylindrical bridge pier at 90º position using SSIIM software. The placement of the bridge pier in a sharp 180-degree bend and in the conditions of convergence and divergence of the bend is one of the innovations of this article. The simultaneous effect of 3 parameters of the radius of curvature, type of bend and gradual narrowing, and widening due to the convergence and divergence of the bend in estimating the scour hole, and determining the maximum points of sedimentation and scouring and bed topographic changes downstream of the pier have been investigated in this article. Also, showing the ability of SSIIM software in such complex calculations due to the mentioned parameters and sediment transport is one of the highlights presented in this article.

2. Material and Methods

2.1. The experimental model

In this paper, the 180º bend channel, Asadollahi et al. [37] was used for the numerical model. The 180º bend channel with a central radius (R_c) equal to 2 times the width of the channel(B) connects a 6.5 m long straight path upstream and a 5.1 m long straight path downstream. Pursuant to the criteria of Leschziner and Rodi [33], it is considered as a sharp bend. The slope of the channel bed is 0.001. The channel is covered by a layer of sand with a thickness of 30 cm with an average diameter of 1.5 mm. The inlet flow rate and flow depth are equal to 70 l/s and 18 cm, respectively. According to the theories of Chiew and Melville [34], the diameter of the pier should not exceed 10% of the channel width, so the circular pier diameter of 5 cm (d) was chosen and placed at 90º section of the bend. The walls of the channel are rigid. All models were carried out in conditions close to the movement threshold with the ratio of average flow velocity to average critical velocity ($U/U_c = 0{,}98$).

2.2. SSIIM model and flow equations

SSIIM is one of the Computational Fluid Dynamics (CFD) programs that analyzed the fluid flow using the Navier-Stokes equations and the *k-ε* turbulence model in a three-dimensional environment. Navier-Stokes equations for incompressible fluids with constant density are defined as equation (1): [35, 36]

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_i} = \frac{1}{\rho_w} \frac{\partial}{\partial x_i}\left(-P\delta_{ij} - \rho\overline{u_i u_j}\right) \tag{1}$$

In equation (1), P is total pressure, x presents distance, U represents velocity in three directions and δ_{ij} is Kronecker delta. In the SSIIM software, the *k-ε* turbulence model is used to calculate the Reynolds stress term, that equation is as follows: [35, 36]

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + P_k - \varepsilon \tag{2}$$

In equation (2), P_k is defined as follows:

$$P_k = \upsilon_T \frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \tag{3}$$

Also, in the above equations, *ε* represents the loss of kinetic energy (*k*) and is defined using equation (4): [35, 36]

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k + C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

Sediment transport is classified into two types: bed load and suspended load. Sediment calculation in the SSIIM model is carried out using the sediment convection-diffusion equation. Therefore, for suspended load, a formula was developed for concentration of sediment near the bed: [35]

$$C_{bed} = 0{,}015 \frac{{D_{50}}^{0{,}3}}{a} \frac{\left[\frac{\tau - \tau_c}{\tau_c}\right]^{1{,}5}}{\left[\frac{(\rho_s - \rho_w)g}{\rho_w \upsilon^2}\right]^{0{,}1}} \tag{5}$$

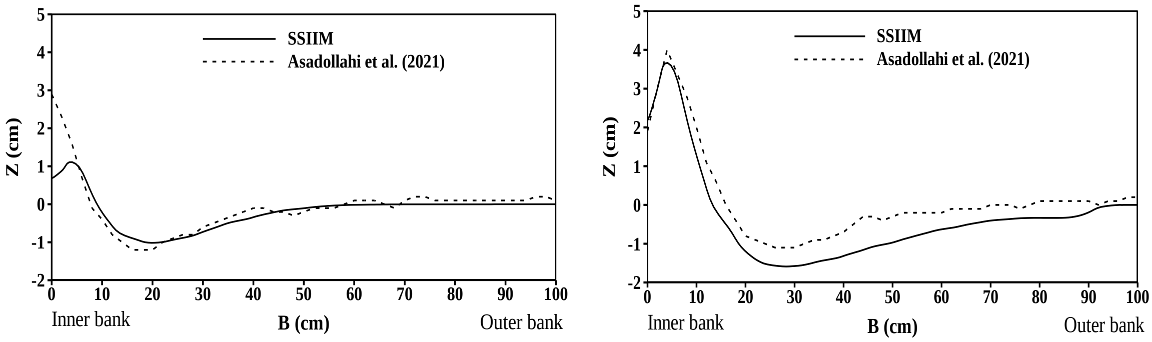
In equation (5), a is the level of the base surface, τ is the bed shear stress, τ_c is the critical bed shear stress for moving sediment particles, ρ_w and ρ_s are the density of water and sediment, υ is the viscosity of water (m2/s), D_{50} is the average size of sediment particles and g is the acceleration of gravity. The SSIIM model for calculating bed load is determined from equation (6): [35, 36]

$$\frac{q_b}{D_{50}{}^{1,5}\sqrt{\frac{(\rho_s-\rho_w)g}{\rho_w}}} = 0{,}053\frac{\left[\frac{\tau-\tau_c}{\tau_c}\right]^{1,5}}{D_{50}{}^{0,3}\left[\frac{(\rho_s-\rho_w)g}{\rho_w \upsilon^2}\right]^{0,1}} \tag{6}$$

The inlet flow, outlet flow, water level and bed/walls are defined as boundary conditions. The inlet flow must be defined at the inlet boundary. At the output boundary, the gradient of all parameters is zero. In addition, the output flow rate should be introduced in the output boundary conditions. At the water surface, the gradient ε and the amount of kinetic energy (k) are assumed to be zero. The mentioned numerical model was implemented for the ($U/U_c = 0{,}72$) and the presented results are in accordance with the mentioned value.

2.3. Validation of the SSIIM model with an experimental model

In this paper, to validate the numerical data from the experimental results of Asadollahi et al. [37] was used in uniform bend without bridge pier. Figure (1) represents the bed changes in cross section for both experimental and numerical models. As presented in Figure (1-a), the bed changes in both models are in good agreement from 5% of the channel width from the interior wall to the end of the bend, while in the experimental model, the most height of sedimentation appears near the interior wall and has increased 3 times compared to the numerical model. In addition, the most scour depth occurred at 20% of the channel width from the interior wall and it has a good match in both models. In Figure (1-b), the scouring pattern was similar in both models. The most sedimentation height in both models has a good match and is equal to 0.04B. Also, the most scour depth in the numerical model has increased compared to the experimental model at the distance of 20% of the channel width from the interior wall to the end of the bend. In Figure (2), the error rates are compared point by point in the SSIIM and experimental models. The bisector line reveals that values in both models were almost equal and mainly concentrated in a 10% error range.



(a) (b)

Figure 1. A comparison between SSIIM and experimental transverse profiles of the bed in a a) 45º b) 80º sections without any pier

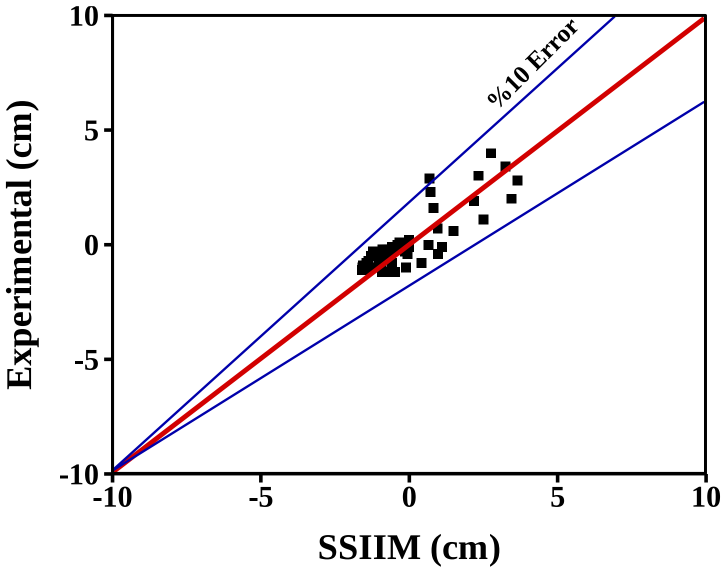
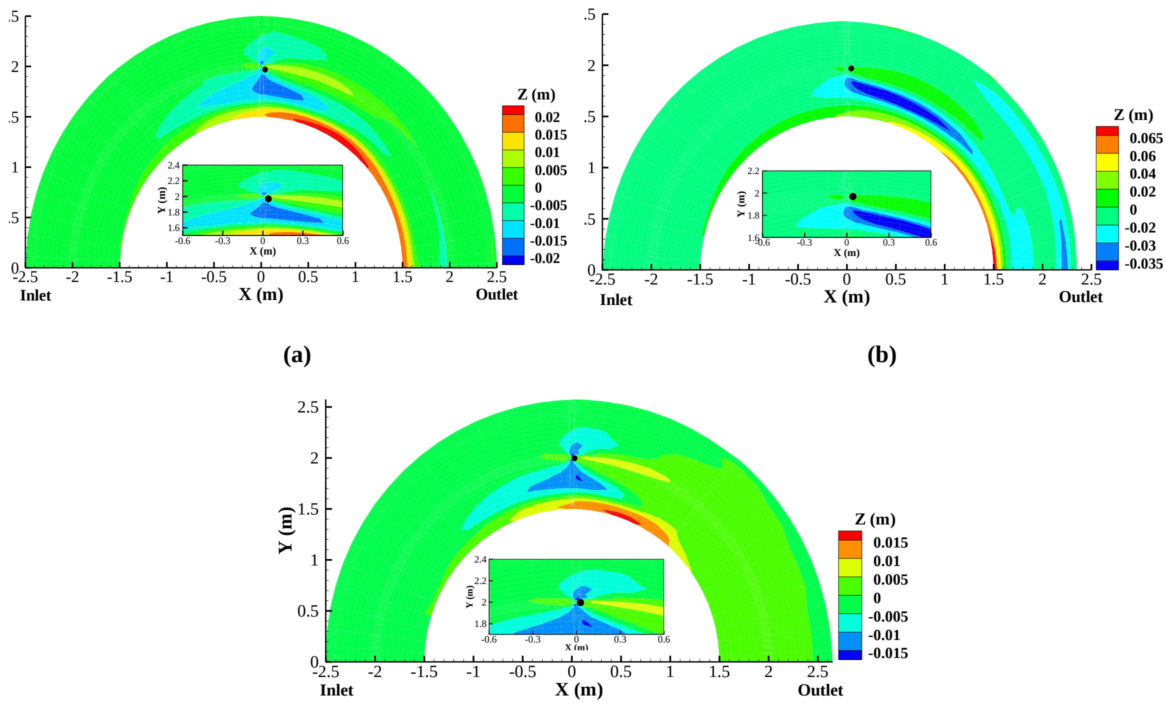


Figure 2. Comparison of level of bed data of SSIIM model and experimental model (Asadollahi et al. (2021)) in two transverse sections 45 and 80° without any pier

3. Results and Discussion

3.1. Bed topography

The changes in the bed topography are shown in Figure (3) with the presence of a single bridge pier at the apex of the uniform, converging and diverging 180º bend. When the bridge pier is placed at the center of the bend, scouring has increased in this area, and the sediments removed from the scour cavity around the pier have been piled up downstream. As a result, the place of accumulation of sediments has moved from the middle of the bend to the downstream of the bend. Also, due to the movement of transverse flows near the bed towards the interior wall, sedimentary stacks have formed in the vicinity of this wall. In this figure, from the beginning of the bend to about 30% of the bend's length (60º angle), the bed topography has not changed significantly in all models. Sediment stacks were observed near the interior wall up to 0.25B, and a scour was formed from approximately 0.25B to 0.4B near the bed. According to Figure (3), in the model with 15% divergence, the sediments have progressed less along the bend and the highest scour depth has occurred in the bend with 15% convergence. In Figure (3-a), the width of the scour cavity is greater at a distance of 0.5B from the interior wall than the outer wall, and its maximum value is 0.02B. In addition, scouring are formed in both the upstream and downstream sides of the pier in a uniform bend. Comparing Figures (3-b and c), it is clear that in the bend model with 15% convergence, the scour cavity tends to the downstream side of the pier, while in the bend model with 15% divergence, this cavity is directed towards the upstream side of the pier. The impact of the flow on the pier upstream creates a down flow, which increases the intensity of the down flow due to the convergence of the bend (Figure 3b), and compared to the case of divergent bend (Figure 3c), the scour value increases.



(c)

Figure 3. bed topography changes with pier placement at the apex of the 180º bend a) uniform, b) 15% convergence and c) 15% divergence

3.2. Scour pattern in longitudinal and transverse sections

Figure (4) shows typical longitudinal profiles at a distance of 5 and 50% of the width of the channel from the interior wall. In Figure (4-a), the process of bed change in all models from 0 to 60º angle from the beginning of the bend is almost the same. Near the interior wall, scouring depth in all three cases of uniform, convergent and divergent bend is almost insignificant and sediments have accumulated in this place due to transverse flows. In addition, the amount of sedimentation increased with the convergence and divergence of the 180º bend by 2.86 times and decreased by 2.1 times compared to the uniform bend, respectively. Therefore, the minimum and maximum height of the sedimentary stack from the angle of 60º to the end of the bend is related to the 180º divergent and convergent bend, respectively, and its value is 0.2d and 1.2d, respectively. According to Figure (4-b), at a distance equivalent to 50% of the width of the channel from the interior wall, the value of scouring depth upstream of the pier in all three cases of uniform, convergent and divergent bends did not have significant changes compared to each other. Therefore, the most scour depth at the location of the pier and in the bend model with 15% convergence was observed and its value is approximately 0.2d. Also, in all models, the scour created upstream of the pier starts at a section of 50º from the beginning of the bend and is connected to the main cavity. The upstream slope of the scour cavity wall is almost the same in all models, while the downstream slope of the scour cavity wall is higher in the bend model with 15% convergence than other models. The cause of this phenomenon is that the return flows in the downstream of the pier are wider and the downward flows are stronger in the downstream of the pier. Figure (5) displays a sample of the transverse profile of the bed in sections of 60, 90 and

120º in a uniform, convergent and divergent bend. In Figure (5-a), scour cavities are formed in the range of 10-50% of the width of the channel from the interior wall. The minimum and maximum scouring depth is in the bend with 15% divergence and convergence, respectively. It should also be noted that the most scour depth in uniform bend is almost the same as divergent bend and is equal to 0.18d. According to Figure (5-b) in all models, the most scour depth occurred at 50% of the width of the channel from the interior wall, and with the convergence of the 180º bend, the scour depth increased compared to the uniform 180º bend. Therefore, the most scour depth occurred upstream of the pier in a model with 15% convergence and is equal to 0.64d. As shown in this figure, the scour depth value at the downstream of the pier to the end of the bend has not changed significantly from each other and it has directed with a lower slope towards the outer wall than the interior wall. According to Figure (5-c), at a distance of 0 to 10% of the width of the channel from the interior wall, the sediments are piled on top of each other, and the largest accumulation of these sediments in this interval occurred in the bend with 15% convergence and its value is 1.2d. Therefore, significant changes have been observed with the convergence of the 180º bend compared to the uniform bend. As it is clear in this figure, in 10 to 80% of the width of the channel from the interior wall, the trend of bed topography changes is different in the bend with 15% convergence compared to other models. In this interval, in the bend model with 15% convergence, two successive scour cavities are formed with values of 0.4d and 0.2d, while in the bend model with 15% divergence, bed changes are not evident in this section. The existence of a favorable pressure gradient in the converging bend compared to the reverse pressure gradient in the diverging bend causes more changes in the topography downstream of the pier in the converging bend. This issue is evident in Figure 4 both in scouring and sedimentation phenomena.

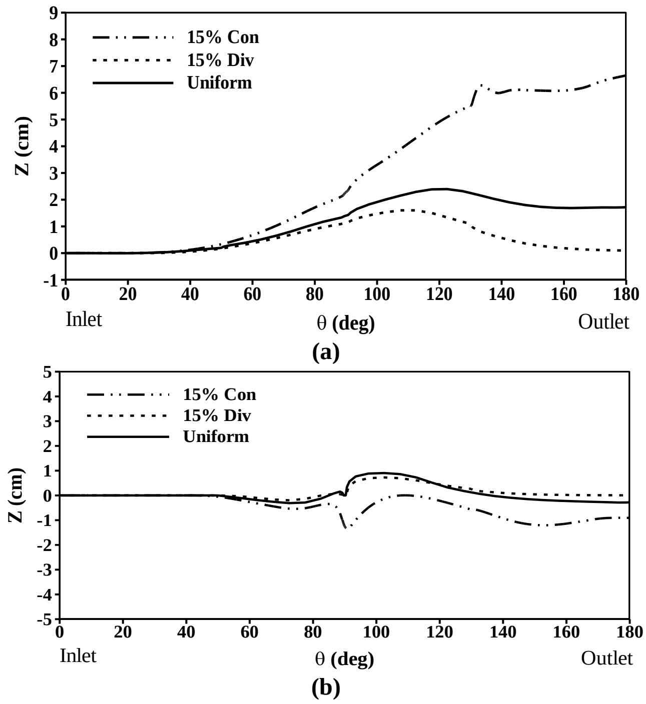


Figure 4. a sample of the longitudinal profile of the bed at the distance of a) 5 and b) 50% of the width of the channel from the interior wall with the pier

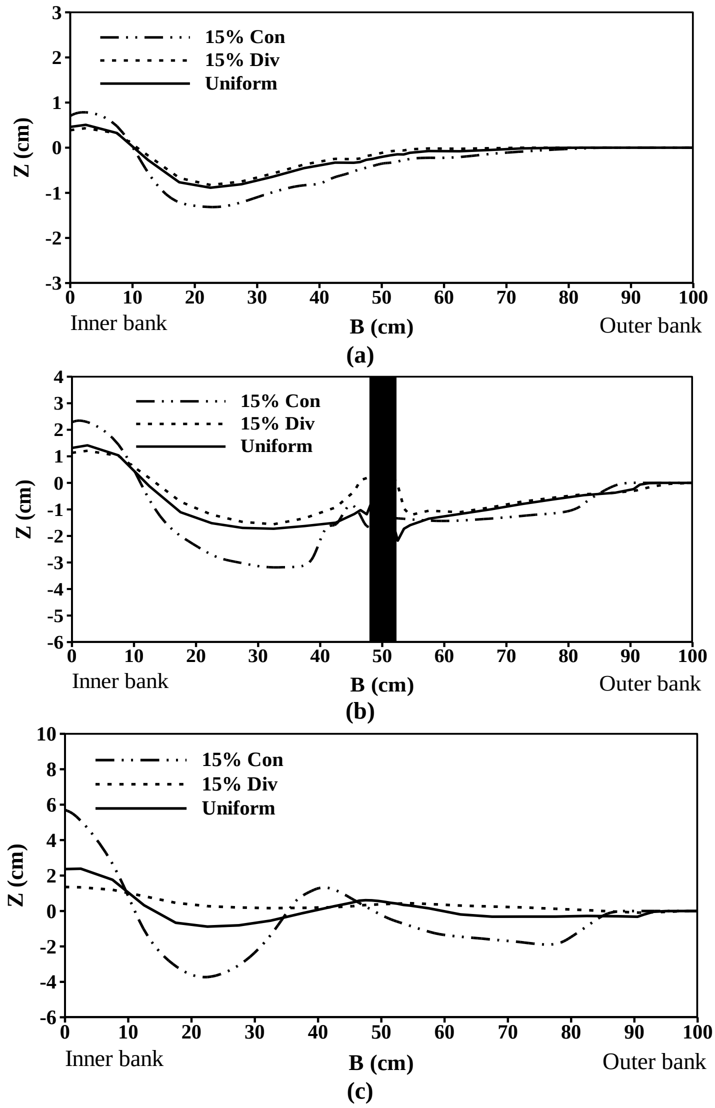


Figure 5. a sample of the transverse profile of the bed in a a) 60, b) 90 and c) 120º sections from the beginning of the pier with the pier.

3.3. The most scour depth and Height of sedimentation

Figure (6) depicts the most scour depth and sedimentation height in a uniform, convergent and divergent 180º bend. In Figure (6-a), the most scour depth has increased with the convergence of the 180º bend compared to the uniform and the divergent bend. The most scour depth occurred in the bend with 15% convergence and increased by 1.75 and 2.33 times compared to the uniform and divergent bend, respectively. Also, the position of the most scour depth occurred between 80 and 120º, which was around the pier. According to Figure (6-b), the most scour depth changes are about 0.3d to 1.3d and occurred downstream of the pier. The highest sedimentation height occurred in the bend with 15% convergence with a value of 1.3d and it increased by 3.25 and 4.33 times compared to the uniform and divergent bend, respectively.

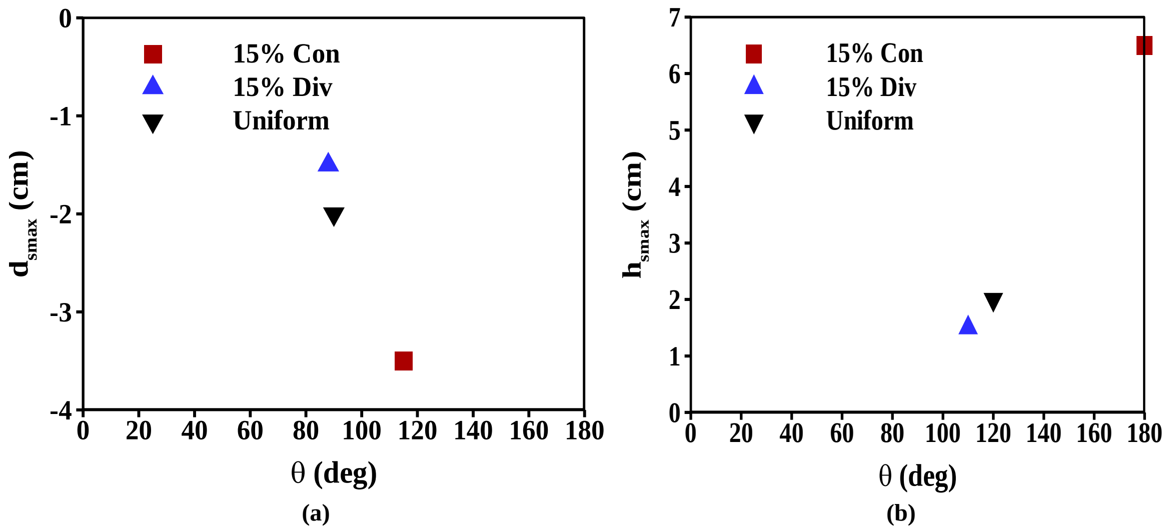


Figure 6. a) the most scour depth b) the most sedimentation height and their position with the pier at the apex of the 180º bend

4. Conclusion

The results of this research are for converging and diverging bends with a convergence and divergence 15% with the placement of a circular pier at a position of 90º from a sharp 180º bend under the influence$(U/U_c = 0{,}72)$. The main aim of this paper is to investigate the scouring of a 180º bend in a uniform case, 15% convergence and 15% divergence with the presence of a cylindrical bridge pier at a 90º position. Validation was investigated using experimental data in a uniform 180º bend without bridge pier. From the present study, the most important results are as follows:

The most scour depth occurred in the bend with 15% convergence with a value of 0.76d and it increased by 1.75 and 2.33 times compared to the uniform and divergent bend, respectively. The minimum scour depth around the pier occurred in a model with 15% divergence and its value was 0.3d. Also, the most sedimentation height has been observed in the interior wall and in the second half of the bend. Therefore, the most sedimentation height in the bend with 15% convergence occurred with a value of 1.3d and increased by 3.25 and 4.33 times compared to the uniform and divergent bend, respectively.

5. Recommendations for future studies

- The placement of group piers in sharp convergent and divergent bend
- Using other forms of pier and comparing with circular pier in sharp convergent and divergent bend
- The installation of protective structures such as a collar or submerged vane to protect the piers located in converging and diverging bends
- The installation of inclined piers or the installation of both piers and abutments in converging and diverging bends and determining the effect of the combined structure on scouring.

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