Experimental Study of Inclined Bridge Pier Scouring

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ABSTRACT

The bridges are one of important structures in any country. The failure of bridges occurs due to many factors including design flaws and manufacturing construction errors. Among all imperfections scouring around the pier is the most detrimental. So, the estimation of local scouring around a bridge pier is of fundamental importance for the safe design of bridges. Although numerous researches have been done on local scouring around a single bridge pier. The present study investigates the effect of angle of inclination of dual bridge pier configuration on local scouring around bridge piers. Principally rectangular shaped dual bridge piers were installed in sand bed of laboratory flume at angle of inclination of 0°,7°,12°,15° and 19° with vertical respectively. Three different flow rates 9, 14 and 18L/sec were considered during each trial. The duration of each trial was kept around 2 hours. The scour depth was measured separately around both piers with the help of point gauge under clear water condition. The value of scour depth around upstream pier was larger as compared to downstream pier because of the lower strength of horseshoe vortices around downstream pier. From the experimental results, it can be concluded that there is an inverse relationship between the angle of inclination and scour depth, an increase in the angle of inclination leads to decrease in scour depth around both piers. The value of scour depth was maximum when piers were at 0° and minimum at 19°. It was also found that scour depth increases with the increase in flow rate.

Keywords: Bridge Pier, Inclined Bridge Piers, Local Scouring, Flow Rate.

1. INTRODUCTION

Scouring is a process in which removal of sediments such as sand and gravel occurs from abutments and piers of bridges. Karimi, *et al.* [1] stated that bridge piers and abutments existing across the river decrease the cross section of water flow. When the swiftly flowing water strike these piers and supports the streamlines of flowing water are diverted towards river bed floor and create horseshoe, swirling and rising vortices. These vortices are main cause of local scouring around bridge piers. This local scour results in the exposure of foundation, which leads towards bridge failure. Many researchers have studied the scouring process theoretically and experimentally using different shapes of piers and many parameters affecting this phenomenon. According to Briaud *et al.* [2], more than 1000 bridge failure reported in the United States and 60% of these failures were due to local scouring. Shirole and Holt [3] studied and demonstrated 283 bridge failures, most of these failures were due to phenomena of scouring. Bozkus *et al.* [4] found that scouring around inclined pier was smaller as compared to vertical piers. The scour rate was higher in early stage of experiment while it decreases with the passage of time and scour depth at upstream side of pier was larger as compared to downstream side.

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Heidarnejad *et. al.* [5] investigated that slots can be used to reduce the pier scouring in 180-degree river bend. This study indicated that application of slots for reduction of scour depth decreases with the increase in the proportion of the average flow velocity to threshold velocity of sediments movement. Kumar et. al. [6] explained that scour depth and its temporal variation is also dependent on the variation of foundation and pier geometry. In the study compound piers were used, and it was indicated that by changing the elevation of top surface of foundation the scour depth is also changed. The maximum scour depth is reduced when the top surface of the well is below the general level of river bed in comparison to the maximum scour depth caused by the pier alone.

Debnath and Chaudhuri [7] stated that maximum equilibrium scour depth in clay beds is similar to that of sand, while increase in the clay fraction for clay–sand mixed beds reduced maximum equilibrium scour depth. Guo *et al.* [8] found that scouring around pier is also dependent on time. The scour depth increases as time increases until equilibrium state is achieved while shape of longitudinal profile does not change with respect to time.

Kitsikoudis *et al.* [9] stated that the scour depth is reduced with increase in pile inclination. Reduction in scour depth is about 50% whereas scour volume decreases 73% when pile inclination is 42. Zhao and Cheng [10] investigated experimental and numerical study of local scour around a submerged vertical circular cylinder. It was indicated that scour depth is reduced with reduction in height of cylinder. The result of numerical model was 10-20% smaller than those measured in experiments.

Vaghefi *et al.* [11] presented an experimental study of circular bridge pier with different angles of inclination, with an increase in the angle of inclination the scour depth is reduced. Mohammed *et al.* [12] stated that local scour depth around the pier is reduced by usage of collar, current deflector and sacrificial pile and upstream piers. Hamidi and Siadatmousavi [13] presented numerical model to check the scouring pattern around pier. The results showed that there was consistency in scouring pattern near each pile, and the deep scouring pattern was established between two piers after some time.

Guan *et. al.* [14] investigated that horseshoe vertices are formed in front of pier that develop scouring pattern and size of these vortices increases with increasing scour depth. Moussa [15] investigated scouring around pier by applying CCHE-2D and HEC-RAS 5 1-D models to Aswan and El Minia bridges and concluded that scouring at Aswan Bridge is higher due to big dimensions of piers than El-Minia bridge. It was found that scouring is smallest at sharp nosed piers at normal flow to the pier.

Karimi *et al.* [1] presented experimental study to examine scour depth by using cylindrical piers with different inclination angles and concluded that the scour depth was maximum at inclination angle 0° and minimum at 15° while the size and depth of scoured hole decreased with increasing angle of inclination. Murtaza *et al.* [16] investigated experimentally that scour depth was minimum around octagonal pier and maximum around square shape pier while in case of circular and oval faced scour depth was intermediate as compared to square and octagonal bridge pier. Elnikhely [17] stated that the reduction in scour depth was 80% by using perforated pile for angle 45° while the scour reduction for perforated pile was 47% at angle 90°.Scour depth at 0° around perforated pile was greater than at 90° and 45°. Ghani and Ali [18] presented numerical model to investigate flow variables around piers. It was observed that with increase in discharge the turbulence at downstream side of pier was also increased. Amir *et. al.* [19] Stated that vegetation was proved best tool for reduction of scouring. There was 39% reduction in scour depth in case of vegetated banks as compared to unvegetated banks at a flow rate of 0.04 m^3/sec.

Failure of bridges during the flood leads to disorder in transportation systems and may cause loss of life and properties. Therefore, scouring consideration in the design of bridges is an important issue. So, it is necessary to calculate the scour depth at bridge pier to control and reduce the bridge failure. Although a lot of research have been done for estimation of scour depth around pier but there is need to investigate the techniques for scour reduction around bridge pier.

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From the previous studies it can be seen that one of important technique for scour reduction is by providing inclined bridge pier. Single inclined bridge pier has been used in previous research to investigate the effect of inclination on scour depth. In present study two inclined rectangular piers (upstream pier and downstream pier) with different angle of inclination and varying flow rates, are used simultaneously to investigate the variation in scouring pattern around both piers under clear water condition to check their reliability for safe design of future bridges.

2. MATERIALS AND METHOD

To study the local scouring around inclined bridge piers the experiments were conducted in laboratory flume. Laboratory flume was 20m long, 1m wide and 0.75m deep open channel. The whole channel was made of concrete, but the walls of the channel were made of glass. Water was released into the channel through the pipe by a pump that carries water in an overhead tank from an underground storage. The flow was controlled with a valve installed ahead of the channel as shown in Fig. 1(a-b). In the initial stage of the experiment, water was pumped in a channel at a very slow rate to avoid disturbance in bed material. A plastic sheet was used to make flow uniform up to a 5m length of the channel. The flow velocity was measured with a velocity sensor, and flow depth was measured with point gauges. Yanmaz and Kose [20] investigated that if standard deviation δ_g <1.30 then sand will be uniform. The sand used in this study was uniformly graded, having D_{50} = 0.28, specific gravity 2.79. Geometric standard deviation (δ_g) = 1.21 was used as bed material up to a 10m length of the channel. The sand bed was perfectly horizontal with a thickness of 30.48 cm. Before starting each trial of the experiment, the bed was properly levelled. Configuration of wooden made dual rectangular pier were tested at five different inclination angles of 0⁰, 7⁰, 12⁰, 15⁰ and 19⁰ with vertical as shown in Fig. 2(a-b). The scouring pattern of both piers was measured around upstream face, downstream face, left face, right face, upstream diagonal face and downstream diagonal face respectively as shown in Fig. 3. Maximum duration of each trial was 2 hours. Chiew and Melville [21] stated that 80% of equilibrium scour depth was achieved after 10% of equilibrium time. The flow rate was measured with compound rectangular-

trapezoidal sharp-crested weir as shown in Fig. 4. Three different flow rates 9, 14, and 18 L/s were used in experiments.
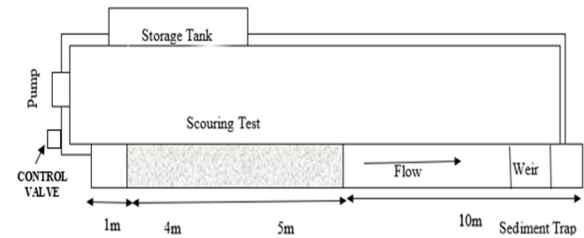

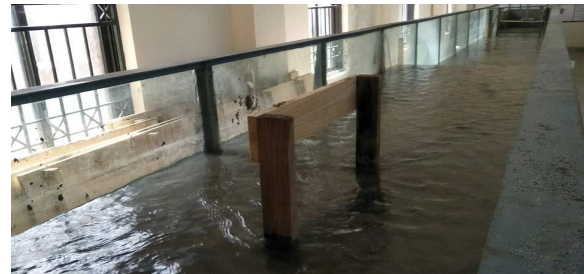Fig. 1(a): Top View of Laboratory Flume

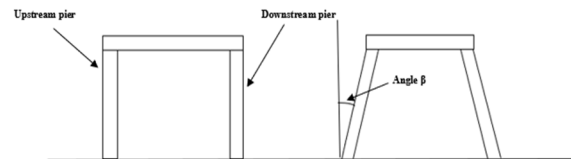Fig. 1(b): Two Rectangular Piers Layout

Fig. 2(a): Two Rectangular Piers Layout
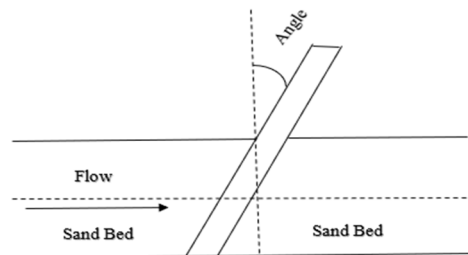

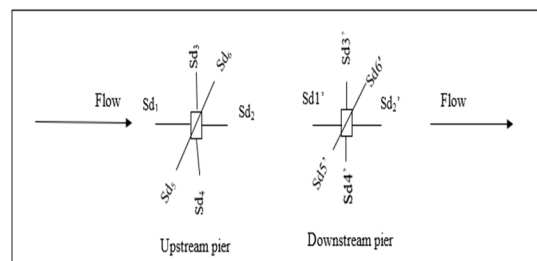
Fig. 2(b): Inclined Rectangular Pier Position Inside Flume

Fig. 3: Pattern Scour Measurement around two Rectangular Piers

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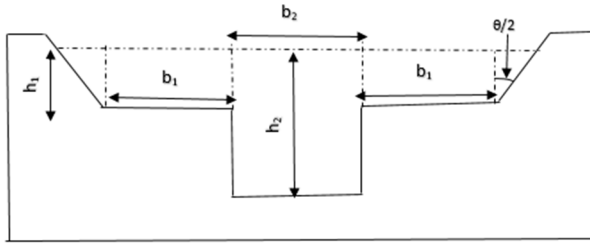
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Fig. 4: Compound Rectangular-Trapezoidal Sharp-Crested Weir

The desired flow rate used in experiments was adjusted by varying over the weir. The values of discharges were calculated by Equation (1) of Compound rectangular-trapezoidal sharp-crested weir [22].The discharge values are shown in Table 1.

$$Q = \frac{2}{3}C_{rd2}\sqrt{2g}b_2h_2^{\frac{3}{2}} + \frac{2}{3}C_{rd1}\sqrt{2g}(2b_1)h_1^{\frac{3}{2}}$$
$$+ \frac{8}{15}C_{td}\sqrt{2g}\tan\left(\frac{\theta}{2}\right)h_{1e}^{\frac{5}{2}} \qquad (1)$$

where b is weir length, g is gravitational acceleration, C_{rd} is discharge coefficient of the rectangular sharp-crested weir, C_{td} is discharge coefficient for triangular sharp-crested weir, h is water head on the weir crest h_e is effective head z, θ wis notch angle

$$C_{rd} = \frac{0.611 + 2.23\left(\frac{B}{b}-1\right)^{0.7}}{1+3.8\left(\frac{B}{b}-1\right)^{0.7}} + \frac{0.075 + 0.011\left(\frac{B}{b}-1\right)^{1.46}}{1+4.8\left(\frac{B}{b}-1\right)^{1.46}}\frac{h}{p} \qquad (2)$$

The discharge coefficient C_{rd} values would depend on the channel width B, weir length b, head on the crest h and weir height P.

$$h_e = h + K_h \qquad (3)$$

where K_h is correction head. The K_h is measured in mm. Correction head factor accounts for viscous forces and surface tension effects.

$$K_h = 3.9058 - 3.8580\theta + 1.19400\theta^2, \qquad (4a)$$
$$C_{td} = 0.6085 - 0.05250\theta + 0.02135\theta^2 \qquad (4b)$$

3. RESULTS AND DISCUSSION

All the experiments were performed at three different flow rates 9, 14, and 18 L/sec. The scouring pattern *was measured at Upstream & Downstream pier separately during each trial. The results of scouring pattern of upstream & downstream pier are shown in Tables 2-3 respectively. The maximum scour depth is

Table 1: Discharge Calculation													
Compound Rectangular -Trapezoidal Sharp-Crested weir													
No.	Width B (mm)	b₁ (mm)	b₂ (mm)	h₁ (mm)	h₂ (mm)	P (mm)	K_h	h_{1e}	θ/2	Crd₁	Crd₂	C_{td}	Qₜ (L/s)
1.	960	257	96	18	113	55	0.82232	18.8223	0.7289	0.6133	0.6097	0.5631	9
2.	960	257	96	34	129	55	0.82232	34.8223	0.7289	0.6137	0.6092	0.5631	14
3.	960	257	96	44	139	55	0.82232	44.8223	0.7289	0.6137	0.6092	0.5631	18

Table 2: Maximum Scour Depth around Upstream Pier (P1) at different inclinations and flow rates								
Upstream Pier	Angle (β)	Q (L/sec)	Sd1 (cm)	Sd2 (cm)	Sd3 (cm)	Sd4 (cm)	Sd5 (cm)	Sd6 (cm)
P1		9	7.2	4.6	6.9	6.3	6.9	5.5
P1	0	14	9	5.5	8.2	8.4	7.7	7.1
P1		18	10.4	6	9.6	9.1	8.9	7.8
P1		9	5.9	3.2	5.2	5	5.6	4
P1	7	14	8.1	4.5	7.2	7	7.1	6.5
P1		18	8.8	5	8.1	8	8	7
P1		9	5	1.9	4.7	4.5	4.9	3.4
P1	12	14	7	3.5	6.6	6.3	6.4	5.7
P1		18	7.6	4	7	6.9	7.3	6
P1		9	4.3	1.4	3.8	3.6	4	2.8
P1	15	14	6.4	2.9	5.7	5.6	5.3	4.8
P1		18	6.8	3.3	6	6.1	6.5	4.5
P1		9	3.1	0.3	2.9	2.5	2.9	1.5
P1	19	14	3.9	0.8	3.5	3.6	3.5	3.4
P1		18	5	2	4.9	5	4.8	3.6
Note: β is inclination angle; Q is flow rate & Sd₁, Sd₂, Sd₃, Sd₄, Sd₅, Sd₆ are scour depth values around Upstream Pier (P1).								

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Table 3: Maximum Scour Depth around Downstream Pier (P2) at different inclinations and flow rates								
Downstream Pier	Angle (β)	Q (L/sec)	Sd1' (cm)	Sd2' (cm)	Sd3' (cm)	Sd4' (cm)	Sd5' (cm)	Sd6' (cm)
P2		9	4.3	0.9	3.1	2.9	3.9	1.4
P2	0	14	5.6	1.1	4	4.3	4.9	3.7
P2		18	5.9	1.7	4.6	4.9	5.4	4.3
P2		9	3.1	0	1.7	1.9	2.4	0.9
P2	7	14	4.2	0.5	3.5	3.4	4	2.8
P2		18	5.2	0.8	4	4.1	4.7	2.6
P2		9	2.3	0	1.4	1.5	1.8	0.5
P2	12	14	3.6	0	2.9	2.7	3.3	1.9
P2		18	4.5	0	3.6	3.4	4	1.8
P2		9	1.8	0	1	1.1	1.4	0
P2	15	14	3.1	0	2.4	2.1	2.6	1.2
P2		18	3.3	0	2.7	2.9	2.8	0
P2		9	0.6	0	0.2	0	0.3	0.5
P2	19	14	1.1	0	1.2	1.1	1.7	0.4
P2		18	1.8	0	1.2	1.7	1.4	0
Note: β is inclination angle; Q is flow rate & Sd1', Sd2', Sd3', Sd4', Sd5', Sd6' are scour depth values around Downstream Pier (P2)								

increased with increase in flowrate. With increase in inclination angle the scour depth is decreased. It can be seen from Tables 2-3 that the values of maximum scour around all sides of both piers are maximum when pier was at 0° inclination with a flow rate of 18L/sec while minimum when pier was inclined at 19° with a flow rate of 9L/sec. The scour depth value is negligible at downstream side of downstream pier (P2).

3.1 Relation between Angle of Inclination, Flow Rate and Scouring Pattern

Fig. 5(a-c) shows the variation of longitudinal scour profile by varying inclination angle at a flow rate of 9, 14 and 18 L/sec respectively of the upstream pier (P1). The Upstream side and downstream side of Pier (P1) shows that the scouring is maximum at an inclination angle of 0° with 18L/sec. As the angle of inclination is increased to 7° the scouring is reduced. From the experimental results it is observed that the longitudinal scouring goes on decreasing as the angle of inclination increases further and becomes minimum when the angle of inclination is 19° (with vertical) with 9L/sec. The main reason for this is when pier is at 0° with vertical, the strong horseshoe vortices are created which causes maximum scouring at upstream side of pier. When angle of inclination is increased, the strength of horseshoe vortices becomes weak which decrease the scouring. The scouring at downstream

side is lesser than upstream side due to transportation of erosive material and weaker horse-shoe vortices.
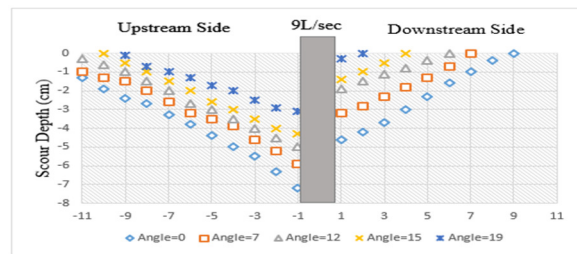

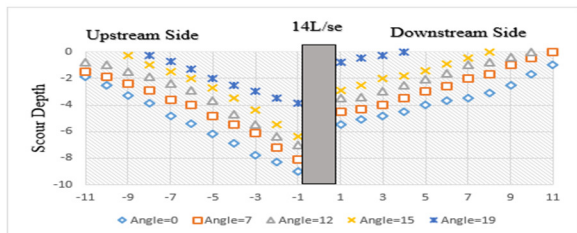Fig 5(a): Longitudinal Scour Profile of Upstream Pier at 9L/Sec.

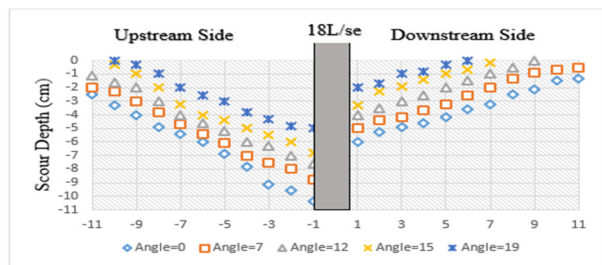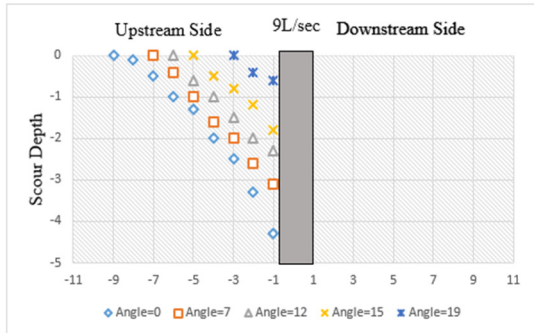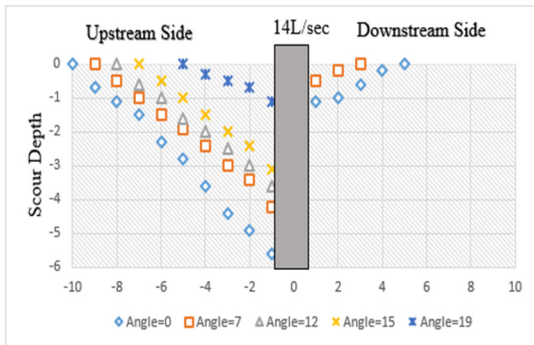Fig 5(b): Longitudinal Scour Profile of Upstream Pier at 14L/Sec.

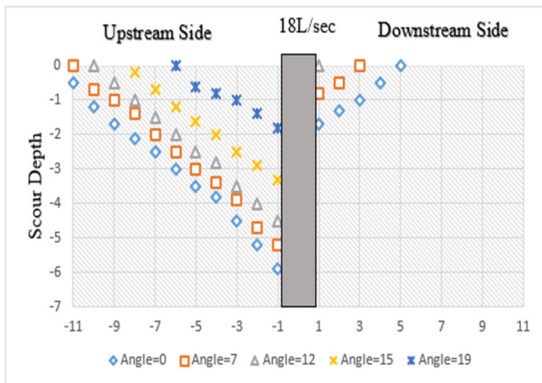Fig 5(c): Longitudinal Scour Profile of Upstream Pier at 18L/Sec.

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Fig. 6(a-c) show the variation of scouring pattern by varying inclination angle around downstream pier (P2) at a flow rate of 9, 14 and 18L/sec respectively. From experiments it is observed that the scour depth at the upstream side is maximum at 0° with flow rate 18L/sec and minimum at 19° with flow rate 9L/sec. Whereas, the scouring at the downstream side is negligible because of the weak horseshoe vortices and also the transportation of erosive material cause aggradation at the downstream side.

Fig. 6(a): Longitudinal Scour Profile of Upstream Pier at 9L/Sec.

Fig. 6(b): Longitudinal Scour Profile of Upstream Pier at 14L/Sec.

Fig. 6(c): Longitudinal Scour Profile of Upstream Pier at 18L/Sec.

3.2 Variation of Scour Hole Pattern Around Upstream Pier with Angle of Inclination

Fig. 7 represents the variation of the 3D-scouring pattern generated by using Surfer (16) around upstream pier (P₁) with inclination angle 0°, 7°, 12°, 15° and 19° at flow rate 9, 14, and 18L/sec respectively. The flow is along x-axis. The maximum scour depth and scour hole is generated when the pier is at 0°, with an increase in the angle of inclination the scour depth and scour hole is reduced.

Fig. 7(a-c) shows the scouring pattern around upstream pier (P₁) at angle of inclination 0° and flow rate 9, 14, and 18 L/sec respectively. These geometries represent that scour depth & scour area were maximum at 0° with flow rate 18L/sec. At downstream of the pier, the deposition has occurred with lesser scouring is lesser as compared to upstream side.
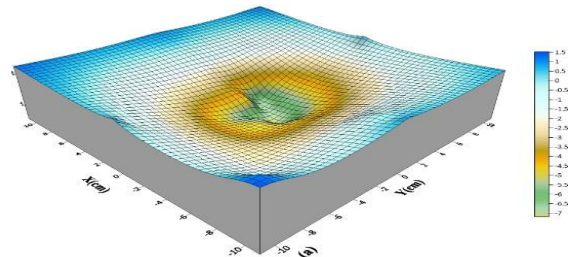
Fig. 7(a): The Scour and Deposition Pattern around Pier (P₁) at angle 0⁰ and flowrate 9L/Sec.
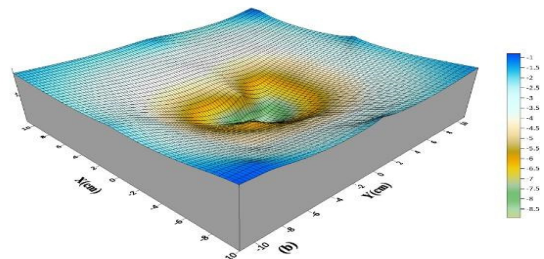
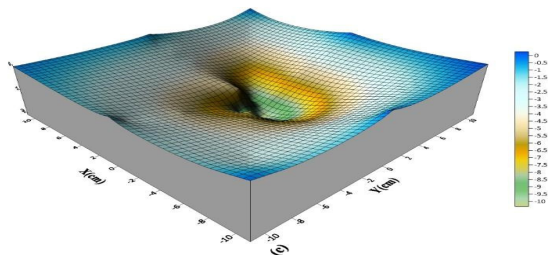Fig. 7(b): The Scour and Deposition Pattern around Pier (P₁) at angle 0⁰ and flowrate 14L/Sec.

Fig. 7(c): The Scour and Deposition Pattern around Pier (P₁) at angle 0⁰ and flowrate 18L/Sec. The green area denotes maximum pattern.

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Fig. 7(d-f) shows the scouring pattern variation at 7° and flow rates 9, 14, and 18 L/sec respectively. The scour area and depth were greater in the case of 7° with flow rate 18L/sec while the scour depth was smaller in case of 7° with flow rate of 9L/sec respectively.
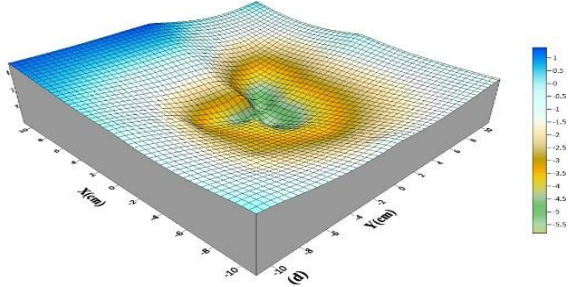

Fig. 7(d): The Scour and Deposition Pattern around Pier (P$_1$) at angle 7^{0}and flowrate 9 L/Sec.
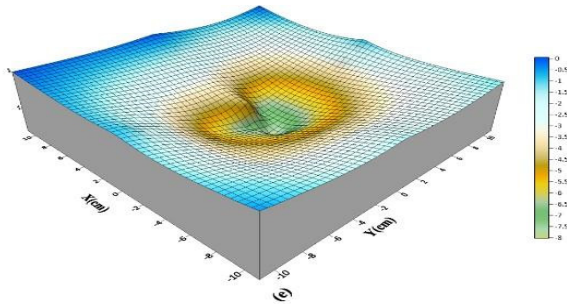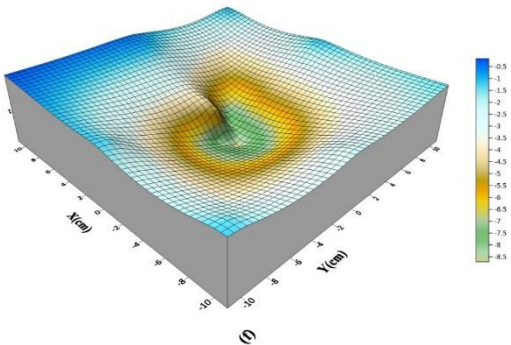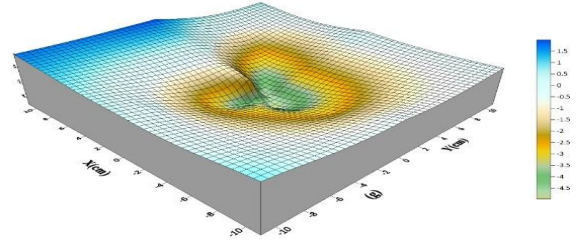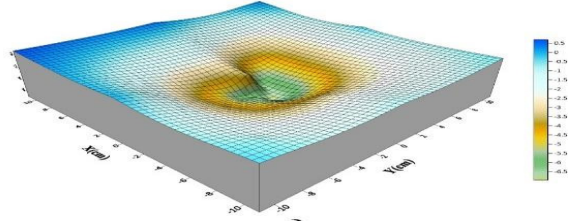

Fig. 7(e): The Scour and Deposition Pattern around Pier (P$_1$) at angle 7^{0}and flowrate 14 L/Sec.
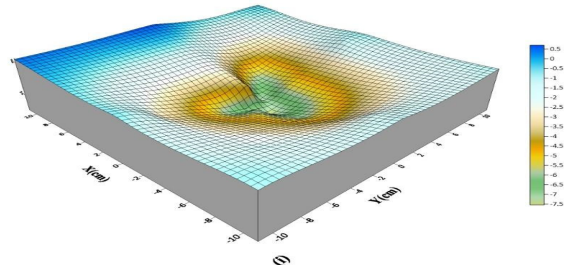

Fig. 7(f): The Scour and Deposition Pattern around Pier (P$_1$) at angle 7^{0}and flowrate 18 L/Sec.
The green area denotes maximum Scouring Pattern

The Fig. 7(g-i)) represent the scour pattern variation at 12° and flow rate 9, 14, and 18 L/sec respectively. These figures show the scour depth and scour area is decreased further as angle of inclination is increased to 12°. While the scour depth and scour area are increased with increase in flow rate.

Fig. 7(g): The Scour and Deposition Pattern around Pier (P$_1$) at angle 12^{0}and flowrate 9 L/Sec.

Fig. 7(h): The Scour and Deposition Pattern around Pier (P$_1$) at angle 12^{0}and flowrate 14 L/Sec.

Fig. 7(i): The Scour and Deposition Pattern around Pier (P$_1$) at angle 12^{0}and flowrate 18 L/Sec.
The green area denotes maximum Scouring Pattern

Fig. 7(j-o) represent scour pattern at angle of inclination 15˚and 19˚ and flow rate 9,14, and 18 L/sec respectively. These figures show scour area and depth around pier is reduced as angle of inclination is increased to 15˚. It becomes minimum at an angle of inclination 19˚.
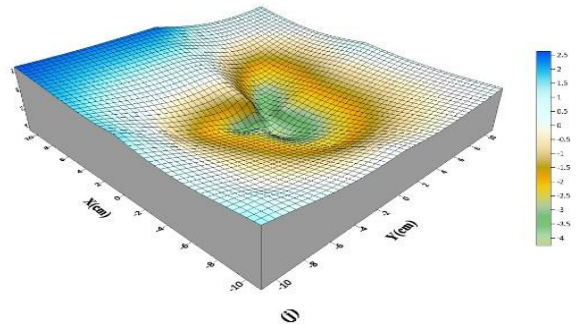

Fig. 7(j): The Scour and Deposition Pattern around Pier (P$_1$) at angle 15^0 and flowrate 9 L/Sec.
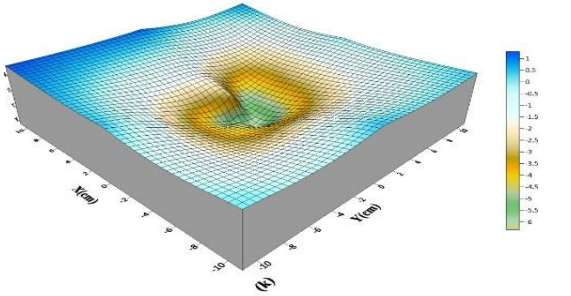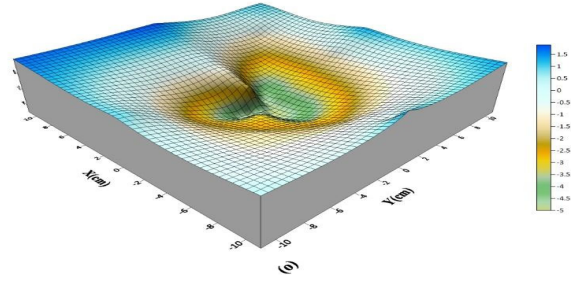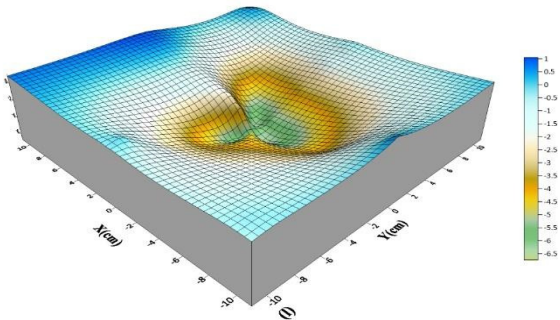
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Fig. 7(k): The Scour and Deposition Pattern around Pier (P$_1$) at angle 15^0 and flowrate 14 L/Sec.

Fig. 7(l): The Scour and Deposition Pattern around Pier (P$_1$) at angle 15^0 and flowrate 18 L/Sec. The green area denotes maximum scouring pattern
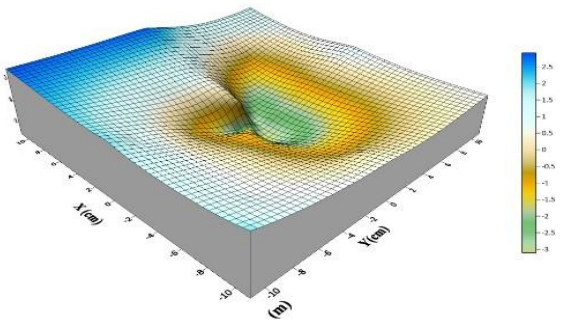

Fig. 7(m): The Scour and Deposition Pattern around Pier (P$_1$) at angle 19^0 and flowrate 9 L/Sec.
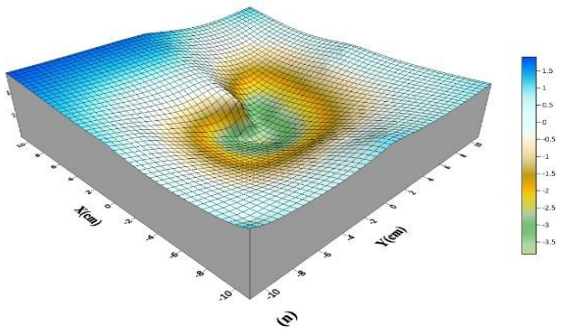

Fig. 7(n): The Scour and Deposition Pattern around Pier (P$_1$) at angle 19^0 and flowrate 14 L/Sec.

Fig. 7(o): The Scour and Deposition Pattern around Pier (P$_1$) at angle 19^0 and flowrate 18 L/Sec. The green area denotes maximum Scouring Pattern

3.3 Variation of Scour Hole Pattern Around Downstream Pier with Angle of Inclination

Fig. 8 represents the variation of scouring pattern around downstream pier at angle of inclination $0°,7°,12°,15°$ and $19°$ and flow rate 9,14, and 18 L/sec respectively. The scour area and depth are greater in case of $0°$ as shown in Fig. 8(a-c) while it decreases as angle of inclination is increased to $7°$ and $12°$ as shown in Fig. 8(d-i). The scour area and depth become minimum at angle of inclination $19°$ as shown in Fig. 8(m-o). In case of downstream pier deposition occurred at downstream side of pier(P$_2$) because the scouring material form (P$_1$) is transported to downstream side of pier (P$_2$).
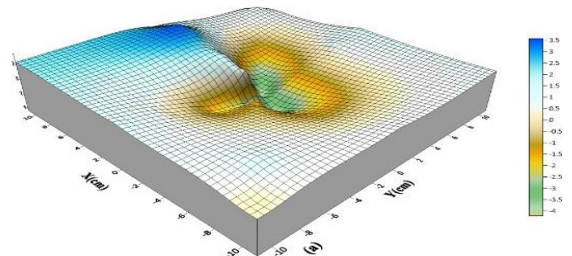

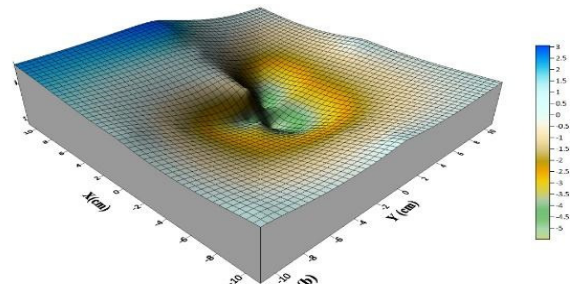Fig. 8(a): The Scour and Deposition Pattern around Pier (P$_2$) at angle 0^0 and flowrate 9L/Sec.

Fig. 8(b): The Scour and Deposition Pattern around Pier (P$_2$) at angle 0^0 and flowrate 14L/Sec.

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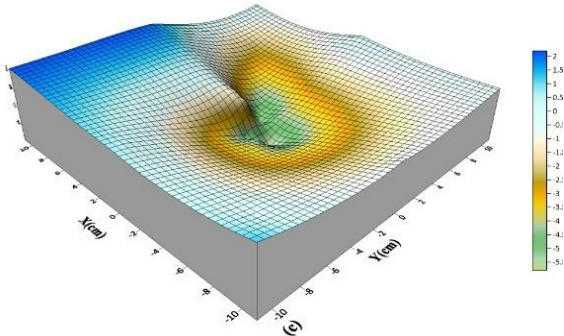
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Fig. 8(c): The Scour and Deposition Pattern around Pier (P$_2$) at angle 0^0 and flowrate 18L/Sec. The green area denotes maximum scouring pattern.
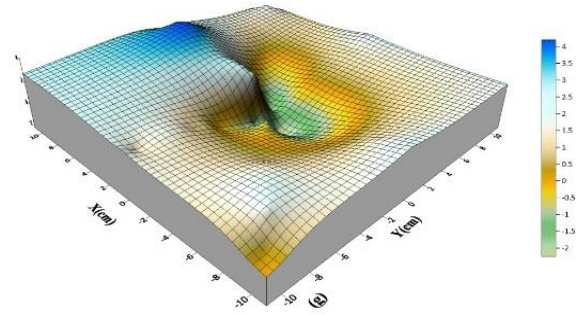

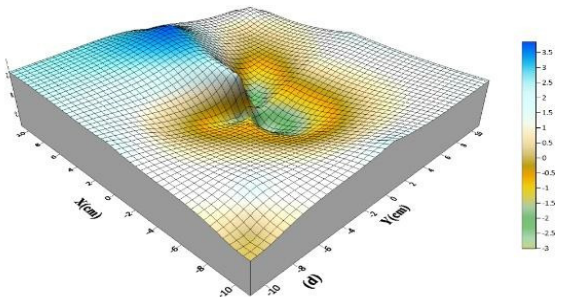Fig. 8(g): The Scour and Deposition Pattern around Pier (P$_2$) at angle 12^0 and flowrate 9L/Sec.

Fig. 8(d): The Scour and Deposition Pattern around Pier (P$_2$) at angle 7^0 and flowrate 9L/Sec.
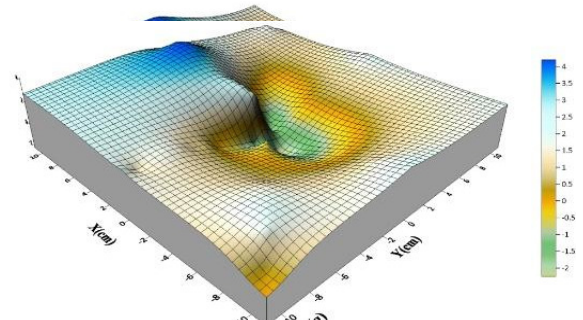

Fig. 8(h): The Scour and Deposition Pattern around Pier (P$_2$) at angle 12^0 and flowrate 14L/Sec.
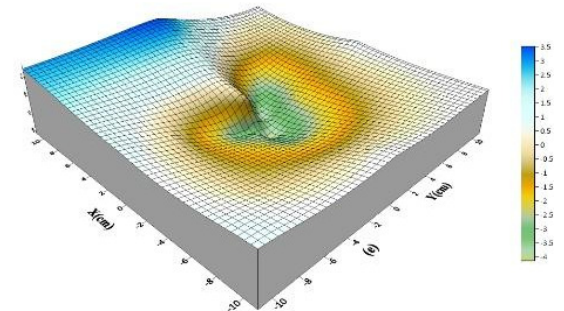

Fig. 8(e): The Scour and Deposition Pattern around Pier (P$_2$) at angle 7^0 and flowrate 14L/Sec.
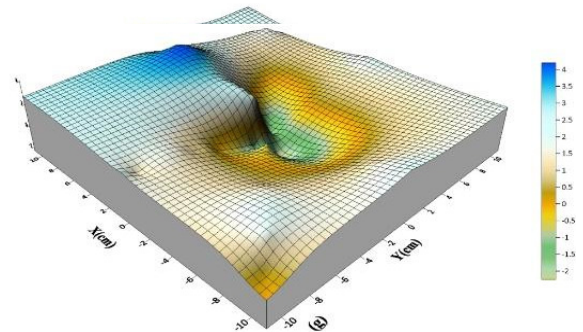

Fig. 8(i): The Scour and Deposition Pattern around Pier (P$_2$) at angle 12^0 and flowrate 18L/Sec. The green area denotes maximum Scouring pattern

Fig. 8(f): The Scour and Deposition Pattern around Pier (P$_2$) at angle 7^0 and flowrate 18L/Sec. The green area denotes maximum scouring pattern

Fig. 8(j): The Scour and Deposition Pattern around Pier (P$_2$) at angle 15^0 and flowrate 9L/Sec.

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Fig. 8(k): The Scour and Deposition Pattern around Pier (P$_2$) at angle 15^0 and flowrate 14L/Sec.

Fig. 8(l): The Scour and Deposition Pattern around Pier (P$_2$) at angle 15^0 and flowrate 18L/Sec. The green area denotes maximum scouring pattern
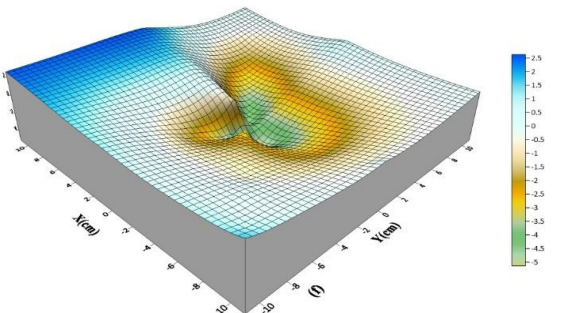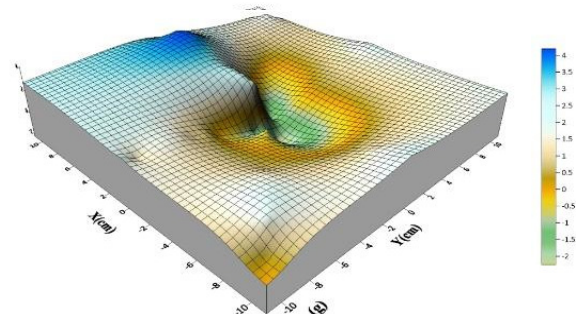

Fig. 8(m): The Scour and Deposition Pattern around Pier (P$_2$) at angle 19^0 and flowrate 9L/Sec.
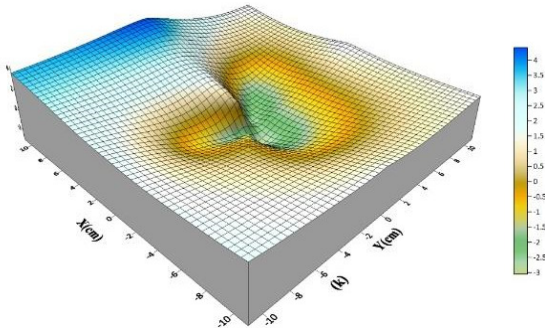

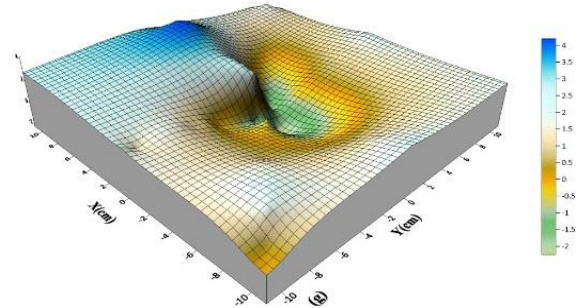Fig. 8(n): The Scour and Deposition Pattern around Pier (P$_2$) at angle 19^0 and flowrate 14L/Sec.

Fig. 8(o): The Scour and Deposition Pattern around Pier (P$_2$) at angle 19^0 and flowrate 18L/Sec. The green area denotes maximum scouring pattern
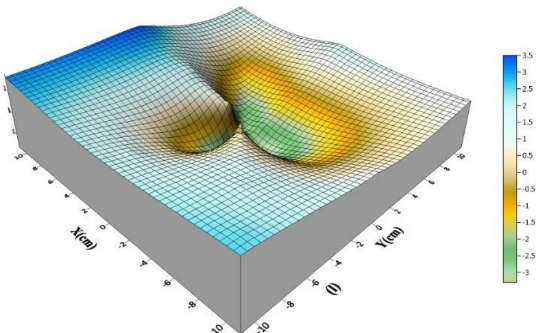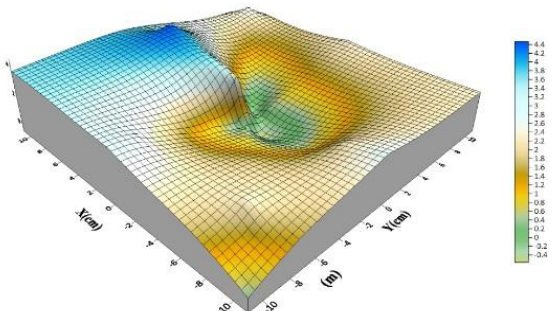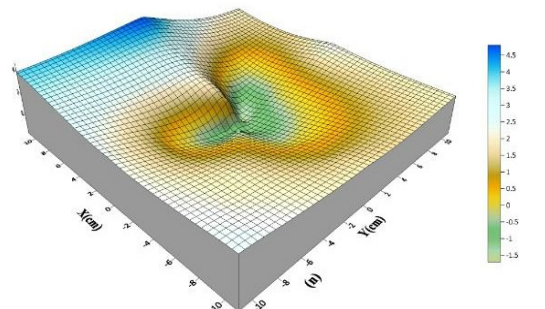
4. CONCLUSIONS

Basic purpose of this study was to investigate the local scouring around pair of inclined bridge piers and comparison between scouring pattern of both piers. Upstream and downstream rectangular bridge piers were used at inclination angle of 0°,7°,12°,15° and 19° with vertical.it is concluded that:

(i)   The scour depth and scour area are reduced with increase in pier inclination, because increasing inclination would weaken the strength of downward horseshoe vortices which reduces the scour depth. The value of scour depth is maximum at 0° while minimum at 19°.

(ii)   There is direct relation between flow rate and scour depth. The scour depth is minimum at 9L/sec while it becomes maximum at 18L/sec.

(iii) The scour depth at downstream side is lesser as compared to upstream side in case of both piers. This is due to weaker strength of horse-shoe vortices at downstream side and area with lower velocity at downstream side is resulted.

(iv)   At downstream side of downstream pier (P$_2$) the value of scour depth is relatively small because of aggradation and transportation of erosive material.

(v)   So, the inclined pier configuration is reliable for reduction of scouring around piers. The value of inclination angle of piers should be adjusted according to structural aspects.

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