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ARTICLE

Effect of Mutual Interference of Bridge Piers on Scouring in Meandering Channel

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ABSTRACT

Local scour is the reduction of original bed level around any hydraulic structure. Bridge failure due to scouring has made researchers study the cause of scouring and predict the scour depth and pattern around bridge piers and foundations. Several investigators have extensively studied local scour around isolated bridge pier, but modern designs of the bridges comprise of wide span and thus group of piers rather than a single pier. The flow and scour pattern around group of piers are different from the case of a single pier due to the interaction effect. The objective of present study is to investigate the effect of mutual interference of bridge piers on local scour experimentally around two piers in non-cohesive bed. Experiments were carried out on model bridge piers of circular cross section in a meandering channel. It was observed that when front and rear piers were placed at an angular displacement of θ = 40° and 80° respectively, maximum depth of scour is maximum. Here θ is the angle the line drawn at the inlet of bend to the line joining the centre of curvature and any point on the outer portion of the bend.

1. Introduction

Scour is a natural phenomenon caused by the erosive action of flowing stream around bridge piers and below foundations. Lots of study have been carried out in the past to estimate the scour characteristics around bridge piers and below foundations in straight reaches of the channels. Many empirical relationships considering many variables have been developed for the design purposes. There is little information available about the scour at bridge pier in curved channel reaches. The main feature of a curved flow is the presence of spiral flow, and lateral sediment transport across the channel bend. Particles at the surface of the flow in the bend tend to move toward the outer wall while at the bed they tend to move toward the inner wall of the channel.

2. Literature Review

The problem of scour around an isolated pier has been

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extensively studied and also documented by several investigators like Melville (1975) [1], Debnath et al. (2010) [2], Garde et al. (1997, 2014) [3,4], Ting et al. (2014) [5] and Ibrahim (2013) [6]. Very less literature is available on scour around bridge piers in curved or meandering channels. Emami et al. (2008) [7] have carried a series of experiments on scour at Cylindrical Bridge Pier in both straight channel and in U-shaped channel having central angle of 180^o. The minimum amount of scour depth (d_s) at each discharge occurred at straight channel. The amount of scour depth increases when pier is located in the bend, as compared to that in a straight channel. The maximum amount of scour depth for each discharge occurs for pier at section 60°of the bend. Masjedi et al. (2010) [8] have carried out an experimental work on effects of bridge pier position in a 180 degrees flume bend on scour hole depth. An oblong model pier of width 60 mm and length 180 mm was used for the study in seven different positions of 0, 30, 60, 90, 120, 150 and 180 degrees under three different flow conditions. The results of this study showed that, while oblong pier is placed in the bend, the maximum scouring depth occurs in position of 60^o. The maximum scour depth at the beginning of bend is minimum and then increases gradually to reach its maximum value at 60^o position. Elsaeed et al. (2015) [9] have carried out field measurements on bridge pier scour valuation in meandering channels, to predict and evaluate the effect of releasing high/extreme flow discharges on scour at 13 bridge piers of 3 bridges located at Kafr El-Zayat City in Egypt using field data, empirical equations and a 2-D model. The results they found are as follows: The maximum scour depth was directly proportional to discharge. The increase of the scour hole around the piers of the first bridge was higher than the increase of the scour hole around the piers of the second and third bridges. The scour around the bridge piers calculated by the scour bend equation gave higher scour values than both general scour (Neil's equation) and contraction scour. Contraction scour results gave the lowest scour values when compared to the other types of scours. Ajeel S. et al. (2016) [10] have carried out an experimental and numerical comparative study of the flow patterns in a strongly-curved 60º open channel bend. The transverse velocity profiles in the sharp bends showed that the maximum velocity occurs near the inner wall up to almost the end of the bend. The maximum velocity is transferred to the channel axis 3 between 50° and 60° cross sections and then it occurs in the outer wall of the channel in the cross sections after the bend. Matooq and Mahmood (2017, 2018) [11,12] carried out extensive laboratory work to measure the local scour and its extent around bridge piers centrally located in an 180o open channel bend. The pier was 8 located from 0^o to 180^o locations with the interval of 30^o (at 0^o, 30^o, 60^o, 90^o, 120^o, 150^o and 180^o). The results show that the maximum depth of scour and the maximum extents (i.e., length and width) of scour hole, and maximum modification factor due to bend have occurred when the pier is located at sector 90^o of the bend. Also, with the same context of straight reach, the scour increases with an increase in the size of the pier for the same flow conditions.

Dimensional analysis

Since,

$$d_s = f\,(v, \rho, x, w, \theta, d_{50}, \mu, g, D_1, D_2) \tag{1}$$

where, d_s = Scour/ deposition, v = Fluid velocity, ρ = Fluid density, x = transverse spacing, w = width of channel, θ = Angular displacement, d_{50} = Sediment size, μ = Dynamic viscosity, g = Acceleration due to gravity, D_1= Diameter of front pier, D_2 = Diameter of rear pier

Total no. of variables, n = 11. Taking ρ, v, w as repeating variables, m = 3. Therefore total no. of

Π terms = 11–3 = 8, Using Bukingham's Π theorem method:

$$\pi_1 = f\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)$$

Therefore,

$$d_s/w = f\,\{x/w,\ d_{50}/w,\ \theta,\ v/\sqrt{(gw)},\ \rho v w/\mu,\ D_1/w\ ,\ D_2/w\} \tag{2}$$

Since only one size of sediment was used, only one flow rate was used, the diameters of both piers were invariant hence most of the dimensionless parameters are dropped.

Thus, scour or deposition may be written as

$$d_s/w = f\{x/w,\ \theta\} \tag{3}$$

This equation forms the basis for the data analysis of scour/deposition around bridge piers in the meandering channels.

3. Experimental Program

Extensive data on scour/deposition around bridge piers have been collected in an open horizontal rectangular sinuous (meandering/curved) channel (0.35 m wide and 0.43 m deep) made up of 0.5 mm thick tin sheet, The schematic diagram and photographic view of the experimental setup are shown in Figures 1 and 2.

The experimental channel consisted of 2.88 m long upstream and 2.11 m long downstream straight reaches. In between the upstream and the downstream reaches four sinuous bends having central angle as 80° each were provided in series. Each bend has rectangular cross section with 0.35 m width, 0.43 m height and with 0.705 m radius of curvature at center line. A straight transition of 0.05

m is provided between each bends. Uniform size of sand with size d_{50} as 0.27 mm (Figure 3) was used to prepare the test bed. For taking observations a flow rate of Q = 3.5×10^{-3} m^3/s was used constantly. Water is allowed to pass in the experimental channel at a constant rate from a re-circulating water supply system. After steady state condition is reached, the observations for measuring the scour around bridge pier have been started. The experimental data were mainly concentrated for the 2nd bend of meandering channel as shown in Figures 4, 5 and 6.

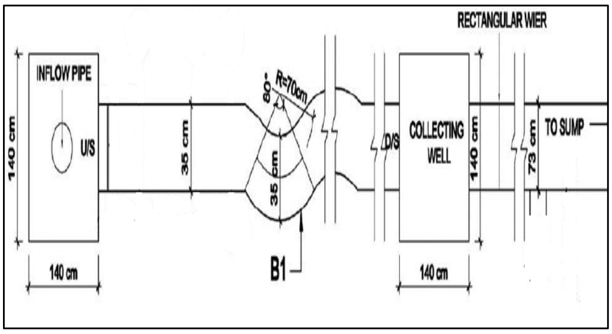

Figure 1. Schematic diagram of the Experimental-Setup

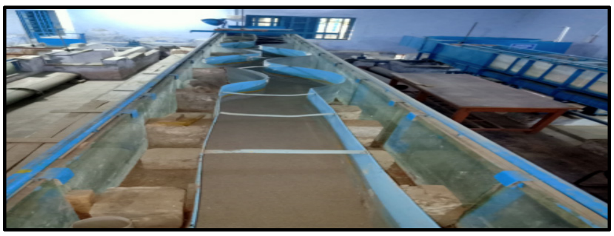

Figure 2. Photogrammetric view of the Experimental-Setup

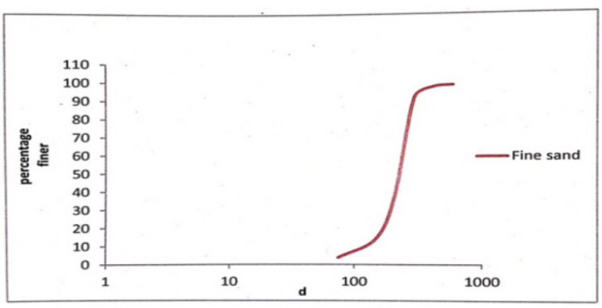

Figure 3. Particle size Distribution Curve

Experimental data were collected in the vicinity of two piers placed at different positions. To collect the data at each pier location of 2nd Bend of meander channel, different transverse sections (u1, u2, u3 (tip), center, d1, d2, d3 & d4) as shown in Figure 7 were taken to cover the whole surrounding of pier and scour extent.

Figure 4. Showing the pier positions for 3rd Run in Bend – 2

Figure 5. Showing the pier positions for 4th Run in Bend – 2

Figure 6. Showing the pier positions for 5th Run in Bend – 2

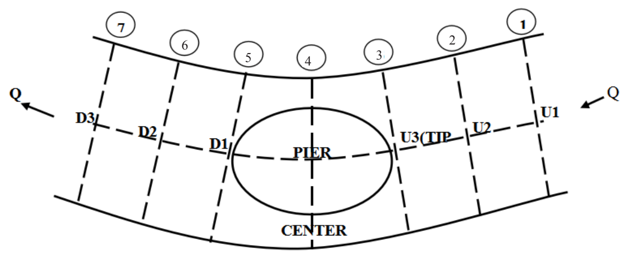

Figure 7. Position of Pier in Bend - 2 and various Sections under consideration

The whole above mentioned procedures were conducted for flow rate of Q = 3.5×10^{-3} m^3/s total of five run were done with two piers placed at some distance apart. For every run one pier position is fixed at 80° of the 2nd bend stated as rear pier at downstream side Another pier which we state as front pier was positioned in upstream side at different location of 2nd Bend in every run. Position of front pier for first run is at straight reach of the channel then changing its position from 0° of 2nd Bend for 2nd run then increasing by 20° up to 60° of 2nd bend for successively runs. The pier position for each run is shown in Figure 8.

The data collected for scour/deposition is mentioned in Table 1.

4. Data Analysis, Result and Discussions

The data collected in the laboratory for scour around bridge pier for two discharge value $Q = 3.5 \times 10^{-3}$ m^3/s for two piers (i.e. front pier and rear pier) to see the interference effect of piers have been plotted for one sediment size. The results and discussions are presented below:

Figures 9 and 10 show the variation of scour depth along transverse direction of front pier at straight and different angular displacements (θ = 0° & 40°) for a discharge of $Q = 3.5\times10^{-3}$ m^3/s. The various colour lines show the scour variations along six transverse sections; such as centre line, u/s section-1(u2), u/s section-2 (u3) i.e. tip of the pier, d/s section-1 (d1), d/s section-2 (d2) and d/s section-3 (d3) (Figures 9 and 10). It is clear from these plots that for x/w = 0 to 0.2 there is deposition at θ = 0°; then scouring increases from x/w = 0.2 to 0.4. The scouring being maximum at all cross section from x/w = 0.4 to 0.6. After that from x/w = 0.6 to 0.8 there is less scour and finally at x/w = 0.8 to x =1 inner bank there is also some amount of scour. However, the trend of variation of scour and deposition is not same

Table 1. Data of Scour around both the Piers of 2nd Run

FRONT PIER					REAR PIER				
LOCATION- 0 DEGREE					LOCATION 80 DEGREE				
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u1**	**x/w**	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u1**
0	60	60.46	0.46	0.01314	0	60	60.46	0.46	0.01314
0.5	60	59.44	–0.56	–0.01600	0.5	60	58.85	–1.15	–0.03286
1	60	59.49	–0.51	–0.01457	1	60	59.13	–0.87	–0.02486
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u1**	**x/w**	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u2**
0	60	60.89	0.89	0.02543	0	60	60.32	0.32	0.00914
0.34	60	59.18	–0.82	–0.02343	0.34	60	58.5	–1.5	–0.04286
0.5	60	58.06	–1.94	–0.05543	0.5	60	57.75	–2.25	–0.06429
0.65	60	58.83	–1.17	–0.03343	0.65	60	59.58	–0.42	–0.01200
1	60	59.42	–0.58	–0.01657	1	60	59.11	–0.89	–0.02543
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u3**	**x/w**	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at u3**
0	60	61.2	1.2	0.03429	0	60	59.89	–0.11	–0.00314
0.25	60	60.24	0.24	0.00686	0.25	60	58.63	–1.37	–0.03914
0.34	60	58.62	–1.38	–0.03943	0.34	60	56.98	–3.02	–0.08629
0.5	60	57.1	–2.9	–0.08286	0.5	60	56.23	–3.77	–0.10771
0.65	60	58.26	–1.74	–0.04971	0.65	60	58.05	–1.95	–0.05571
0.74	60	59.3	–0.7	–0.02000	0.74	60	59.85	–0.15	–0.00429
1	60	59.39	–0.61	–0.01743	1	60	59.13	–0.87	–0.02486

x/w	Initial B.L.	Final B.L.	Scour ds (cm)	(ds/w) at Centre	x/w	Initial B.L.	Final B.L.	Scour ds (cm)	(ds/w) at Centre
0	60	60.84	0.84	0.02400	0	60	60.23	0.23	0.00657
0.25	60	58.82	–1.18	–0.03371	0.25	60	59.08	–0.92	–0.02629
0.34	60	57.32	–2.68	–0.07657	0.34	60	56.9	–3.1	–0.08857
0.4	60	56.45	–3.55	–0.10143	0.4	60	56.25	–3.75	–0.10714
0.6	60	57	–3	–0.08571	0.6	60	55.92	–4.08	–0.11657
0.65	60	58.03	–1.97	–0.05629	0.65	60	57	–3	–0.08571
0.74	60	58.5	–1.5	–0.04286	0.74	60	59.02	–0.98	–0.02800
1	60	59.01	–0.99	–0.02829	1	60	58.93	–1.07	–0.03057
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at d1**	**x/w**	**bed level**	**final B.L.**	**Scour ds (cm)**	**(ds/w) at d1**
0	60	61.21	1.21	0.03457	0	60	59.64	–0.36	–0.01029
0.25	60	58.89	–1.11	–0.03171	0.25	60	58.52	–1.48	–0.04229
0.34	60	57.93	–2.07	–0.05914	0.34	60	57.95	–2.05	–0.05857
0.5	60	57.29	–2.71	–0.07743	0.5	60	57.8	–2.2	–0.06286
0.65	60	58.91	–1.09	–0.03114	0.65	60	58.84	–1.16	–0.03314
0.74	60	59.23	–0.77	–0.02200	0.74	60	60.46	0.46	0.01314
1	60	59.67	–0.33	–0.00943	1	60	60.12	0.12	0.00343
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at d2**	**x/w**	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at d2**
0	60	60.87	0.87	0.02486	0	60	59.45	–0.55	–0.01571
0.25	60	59.02	–0.98	–0.02800	0.25	60	58.6	–1.4	–0.04000
0.34	60	58.61	–1.39	–0.03971	0.34	60	58.78	–1.22	–0.03486
0.5	60	58.54	–1.46	–0.04171	0.5	60	58.19	–1.81	–0.05171
0.65	60	58.67	–1.33	–0.03800	0.65	60	59.2	–0.8	–0.02286
0.74	60	58.54	–1.46	–0.04171	0.74	60	60.92	0.92	0.02629
1	60	59.98	–0.02	–0.00057	1	60	61.14	1.14	0.03257
x/w	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at d3**	**x/w**	**Initial B.L.**	**Final B.L.**	**Scour ds (cm)**	**(ds/w) at d3**
0	60	60.69	0.69	0.01971	0	60	59.41	–0.59	–0.01686
0.34	60	59.28	–0.72	–0.02057	0.34	60	58.85	–1.15	–0.03286
0.5	60	58.36	–1.64	–0.04686	0.5	60	58.3	–1.7	–0.04857
0.65	60	59.03	–0.97	–0.02771	0.65	60	58.77	–1.23	–0.03514
1	60	59.75	–0.25	–0.00714	1	60	59.63	–0.37	–0.01057

for different angular displacements θ.

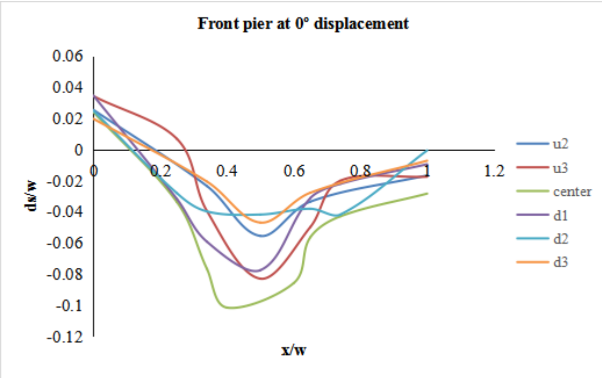

Figure 8. Variation of Scour along different sections of front pier when placed at 0°

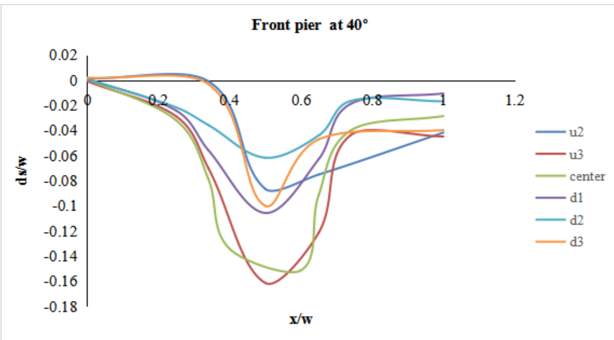

Figure 9. Variation of Scour along different sections of front pier when placed at 40°

It is clear from the graphs that the scour depends on angular displacement (θ). As front pier position (θ) increases from 0° to 60° on outer bank (x/w = 0) of bend deposition reduces and at θ = 60° there is scouring. It is also found that at inner bank of bend, this phenomenon is just reverse. The variation of scour/deposition along inner bank (x/w = 1) of bend is that there is scour at θ = 0° and scour reduces as θ = 20°, as θ (40°, 60°) increases scour reduces and there is deposition at θ = 60°. The variation of scour/deposition along outer bank is there is deposition at θ = 0° and deposition reduces at θ = 20°, as θ (40°, 60°) values increases the deposition reduces and scouring increases at outer bank. The value of maximum scour occurs at the tip of the front pier for all different angular displacements.

Figures 11 and 12 show the variation of scour depth along transverse direction of rear pier at θ = 80° for different front pier positions (straight and θ = 0°, 20°, 40°, 60°) for a discharge of Q = 3.5×10^{-3} m^3/s. The various color lines shows the scour various along six transverse sections; such as centre line, u/s section-1(u2), u/s section-2 (u3) i.e. tip of the pier, d/s section-1 (d1), d/s section-2 (d2) and d/s section-3 (d3). It is clear from these plots that for x/w from 0 to 0.2, outer bank there is scour at rear pier for front pier placed at θ = 0°; then this scour increases from x/w = 0.2 to 0.6.

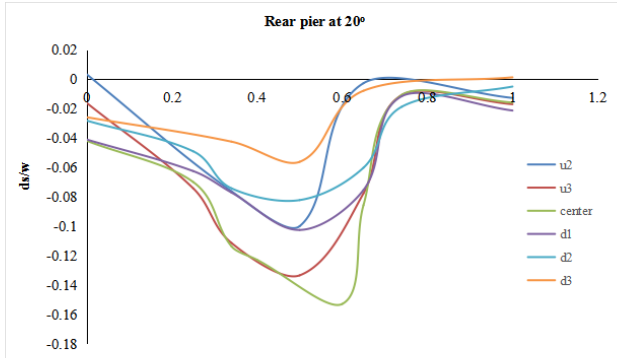

Figure 10. Variation of Scour along different sections of rear pier when front pier placed at 20°

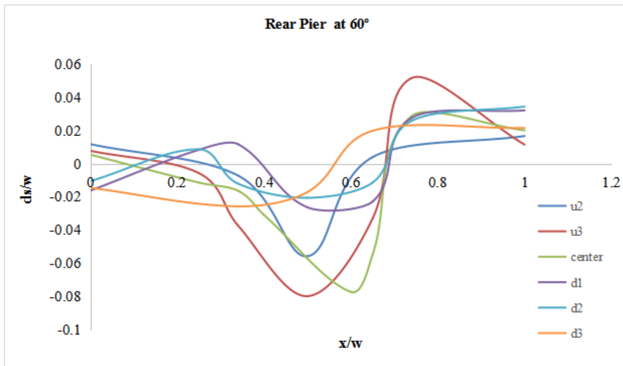

Figure 11. Variation of Scour along different sections of rear pier when front pier placed at 60°

The scouring being maximum at all cross section from x/w = 0.4 to 0.6. After that at x/w = 0.8 to x =1 inner bank there is deposition. However, the trend of variation of scour and deposition is same for different angular displacements (θ). It is clear from the graphs that as the front pier position is changed (θ increased from 0° to 60°) the scour at inner bank (x/w = 1) of rear pier (θ = 80°) the deposition value increases. It is also found that at inner bank of bend, this phenomenon is just reverse. As the front pier positions is changed (θ increases from 0° to 60°) the scour at outer bank (x/w = 0) of rear pier the scour value increases. The value of maximum scour occurs at the tip of the rear pier at all the cross sections in all different angular displacements. As the value of θ of front pier increases the value scour at rear pier increases, maximum when front pier at θ = 40° and again at θ = 60° the value again decreases which is due to increase in interference effect of both piers.

Figure 12 shows the variation of scour depth along straight and different angular displacements (θ = 0°, 20°, 30°, 40° & 60°) for different transverse direction of front pier at same discharge. At every cross section (u2, u3, centre, d1, d2, d3) the variation of scour at front pier as the value of θ increases the value of scour increases from 0° to 40° and attains a maximum value at θ = 40°. Also at θ = 60°, the scour decreases which is due to increase in interference effect of rear pier. As the flow approaches towards the pier, it is obstructed by the pier geometry, reducing the area of flow section and hence increasing the local velocity and bed shear. This causes the scouring of the bed materials from the bed. As the flow further approaches more nearer to pier, more and more flow is obstructed, thereby increasing the velocity of flow and bed shear at the side of the pier and more scouring occurs near the vicinity of the pier. Similar condition occurs at all sections of the downstream side.

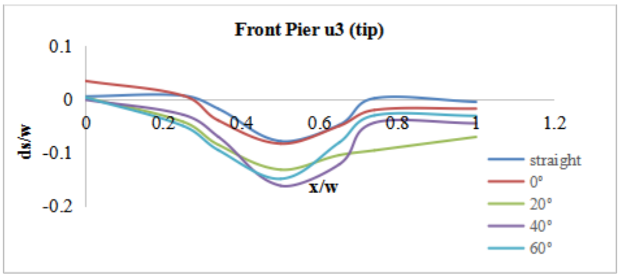

Figure 12. Variation of Scour of front pier for different Angular Displacement at u3 (tip) section

Figure 13 shows the variation of scour depth at rear pier at θ = 80° due to change in front pier position at different angular displacements for various cross sections. At every cross section (u2, u3, centre, d1, d2, d3) the variation of scour at rear pier increases as front pier θ increases from 0° to 20°, then again scour value reduces from 20° to 40° for almost all the sections and again decrease from θ = 40° to 60°. Maximum scour is at tip of rear pier due to front pier being at 40°. This decrease at 40° and 60° is due to interference effect as front pier and rear pier are getting close to each other.

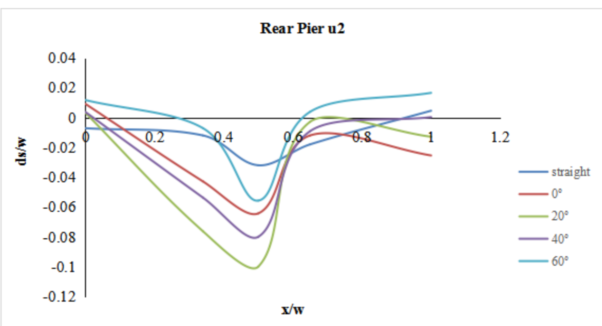

Figure 13. Variation of Scour of rear pier for different Angular Displacement of front pier at u2 section

Figure 14 shows the variation of scour at different straight and angular Displacement (θ = 0°, 20°, 40°, 60°) for different cross section along the longitudinal centre line. From graph it is clear that at every angular displacement (0°, 20°, 40°, 60°) the maximum scour is at cross section U3 (tip of front pier). The variation along longitudinal centre line at different sections at different angular displacement is that as θ increase from 0° to 20° up to 40° the scour value increases and then there is a decrease at θ = 60°.

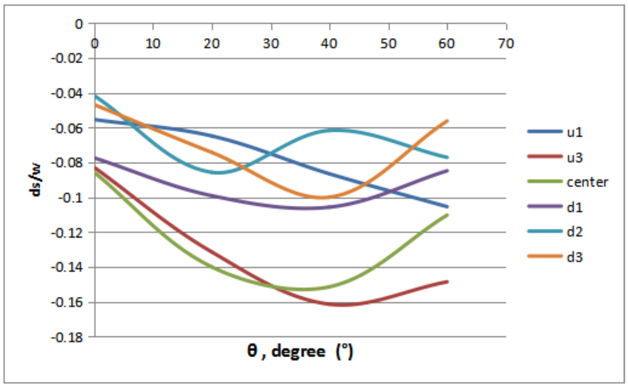

Figure 14. Variation of Scour along different Angular Displacement and different sections for front pier along longitudinal centerline

Figure 15 compares the variation of maximum scour at different angular displacements between front pier and rear pier. From the graph it is clear that maximum scour value at θ = 0° for front pier is less than rear pier. At θ = 20° maximum scour value for both piers is almost same. As θ increases from 20° to 40° maximum scour value for front pier is more than the maximum scour value of rear pier and difference goes on increasing pier maximum at θ = 60°. The maximum scour value for front pier being at 40° and maximum scour value for rear pier when front pier is at 40°.

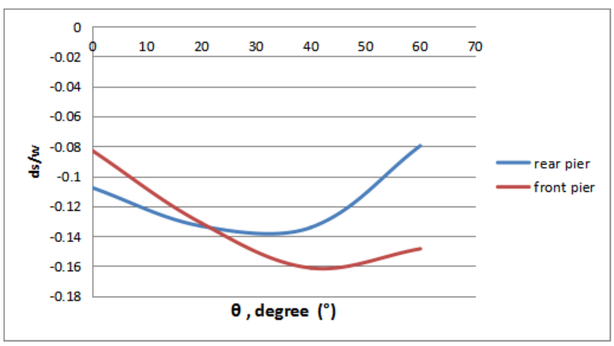

Figure 15. Comparison between maximum scour between rear pier and front pier at different angular displacements

Figure 16 shows the variation of scour of front pier at inner bank (x/w = 1) for different angular displacements that is as the value of θ is increasing from 0° to 20° the scour value at different sections at inner bank is increased up to θ = 20°. Then further increase of θ from 20° to 60° the scour value at for all the sections at inner bank decreases. This variation is due to the meandering effect of the channel. At inner bank of front pier there is score and as θ increases from 0° to 20° there is an increase in scour. Then further increase in θ from 20° to 60° depositions occurs.

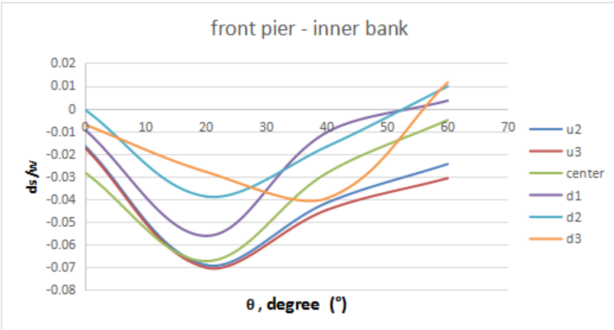

Figure 16. Variation of Scour along different Angular Displacement and different sections for front pier at inner bank

Figure 17 compares the amount of scour between rear pier and front pier when front pier placed at different angular displacements (θ) for different sections. In almost all the sections at when front pier placed θ = 0° the front pier scour is less than the rear pier scour and difference is not much. However, when θ = 20° the scour for both front and rear pier is almost same for all the cross sections. When θ is at θ = 40° the scour is more at front pier than at rear pier. On further increase of θ at 60°, the scour is more at front pier than at rear pier and difference is also increased between the two.

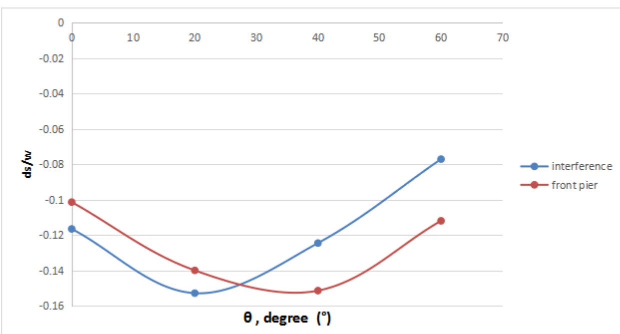

Figure 17. Comparison between scour of rear and front pier at different angular displacements at center section at 40°.

Figure 18 shows the variation of longitudinal length of scour hole of rear pier when front pier is placed at different angular displacements (θ). As the angular displacement of front pier (θ) is increased the longitudinal length of scour hole of rear pier increase for θ = 0° to 20° then there is slight decrease in length at θ = 40° and again there is increase in length of scour hole at θ = 60°. As front pier at θ = 60° and rear pier gets close and there is over lap of their individual scour hole making it a large scour hole.

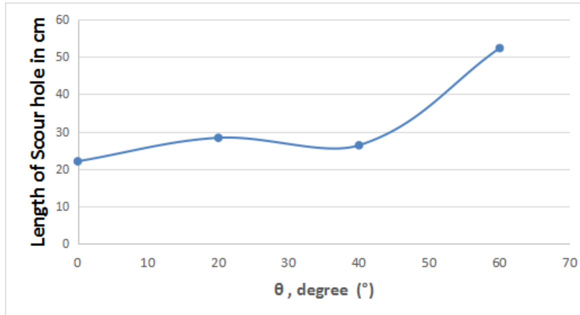

Figure 18. Variation of longitudinal length of scour hole of rear pier due to change in angular displacement of front pier

5. Conclusions

Following conclusions have been drawn from the present study:

1) The maximum scour occurs at tip of the pier for both front and rear piers for any angular displacement of front pier (θ). Here θ is the angle the line drawn at the inlet of any bend to the line joining the centre of curvature and any point on the outer portion of the bend. The maximum scour being for both front and rear pier is at tip of both piers when front pier placed at 40°.

2) As the θ of front pier is increasing from 0° to 60° the amount of scour is also increasing for both the piers but the rate of increase is more in front pier than rear pier which increases the difference in scour values of both piers much more at θ = 60°.

3) As the θ of front pier is increasing from 0° to 60° the length of scour is also increasing for both the piers as both piers are coming close and at last at front pier θ = 60° getting overlapped. Ultimately having maximum length of scour when front pier is at θ = 60°.

4) At inner bank of front pier there is score and as θ increases from 0° to 20° there is increase in scour. Then further increase in θ from 20° to 60° depositions occurs. At outer bank of front pier at θ = 0° there is deposition and as θ is increasing scour is increasing up to θ = 40° then again from θ = 40° to 60° there is slight deposition. This variation is due to the meandering effect of the channel and interference effect

5) At inner bank of rear pier for different θ of front pier, For some sections (u2, u3 and centre) as θ of front pier is increasing from 0° to 20° there is decrease in scouring

and then from 20° to 60° there is increase in depositions. However, for other sections (d1, d2 and d3) it is completely opposite. At outer rear pier for different θ of front pier the phenomena of scour/ deposition is reverse of inner bank.

6) The effect of interference is more as front pier and rear pier are placed closer and as θ increases. For this when front pier at θ = 40° and rear pier at θ = 60° then maximum scour occurs and when front pier at θ = 60° and rear pier at 80° maximum length of score occurs.

7) When front pier is at θ = 60° and rear pier θ = 80° then scour for rear pier is very less compared to when front pier is at θ = 40° which is because of shielding mechanism due to increase in interference effect of piers.

8) From the above it can be concluded that the worst pier position condition in meandering channel when rear pier at 80° is placing front pier at front pier at θ = 40° as scour depth is maximum at both the piers.

9) The effect of interference of bridge piers in meandering channel along is a function of distance between the piers along with the position of piers at different angular displacements.

Author Contributions

The work presented in this manuscript is purely based on the M. Tech. dissertation of second author under the supervision of first author. The work is basically comprises with the rigorous experimentation work followed by plotting of graphs and analysis of results. The third author contributed in the preparation of the figures/tables etc. and also checked the draft. The main author supervised other two authors to prepare the text in the guide lines given by editor.

Conflict of Interest

There is no conflict of interest among the authors.

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