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Investigation of scour around the dual bridge piers under unsteady flow conditions using experimental model

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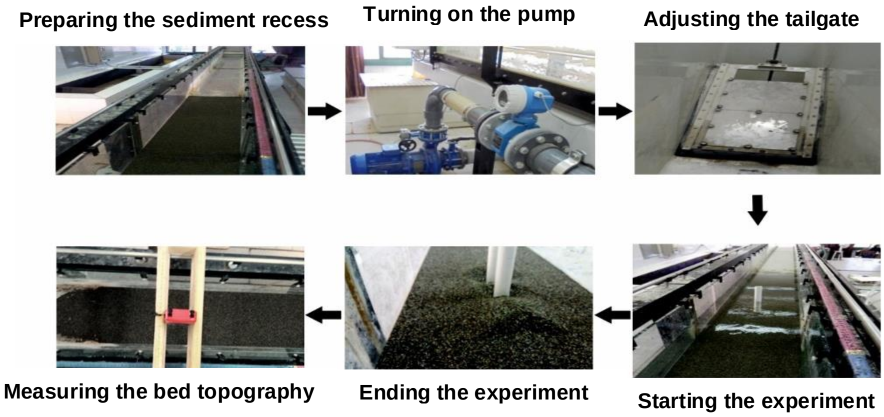
GRAPHICAL ABSTRACT



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ABSTRACT

The local scour around the bridge piers is the main cause of their destruction. Based on this, extensive studies have been done to understand this phenomenon. Most of these studies have been done under steady flow conditions. This is while the flow in the river is unsteady. Therefore, the experiments of this research were carried out under unsteady flow conditions. The purpose of this research is to investigate the scour around the dual bridge piers at different distances of the piers from each other in a uniform flow as well as unsteady flow using symmetric hydrographs. The hydrographs used in the experiments are stepped hydrographs in 5 steps. The experiments were conducted under clear water conditions and U/U_C=0.95. In all experiments, the diameter of the bridge pier (D) was constant and equal to 2.5 cm. The center-to-center distance between the dual bridge piers (S) was selected as 2D, 3D, 4D and 5D. In the unsteady flow, with increasing relative distance between the dual bridge piers, the maximum dimensionless scour depth of the first and second piers was increased and its maximum was measured at a relative distance of S/D=5 (in the range of relative distances studied in the research). But in the uniform flow, the maximum dimensionless scour depth of the first and second pier was observed at S/D=3 and S/D=4, respectively. Also, at a constant distance between the piers, increasing the peak and base flow of the hydrographs step-by-step, increased the maximum dimensionless scour depth of the first pier of dual bridge piers with an increasing rate. However, increasing the peak and base flow of the hydrographs step-by-step, increased the maximum dimensionless scour depth of the second pier with a decreasing and increasing rate, respectively.

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1. Introduction

Bridges are among the most important and most used river structures that have been used for a long time. Destruction and damage to bridges, which often occur during flood, will cause communication paths interruption, financial losses and even mortality. Also, the interruption of communication paths disrupts helping flooded areas and has social consequences. The scour of the bridges piers is the biggest reason for the bridges break down in the United States. Over the past 93 years, more than 1,000 bridges out of 600,000

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bridges built in the United States have been destroyed, 60 % of which were due to scour (Sumer and Fredsoe. 2002). Between 1985 and 1987, 90 bridges were destroyed in New York, Pennsylvania, Virginia, and East Virginia due to the destruction of the bridge piers (Melville and Coleman. 2010). Therefore, it is very important to know the phenomenon, predict its amount, and apply necessary countermeasures to control and reduce scour. Fig. 1, shows the flow pattern around bridge pier.

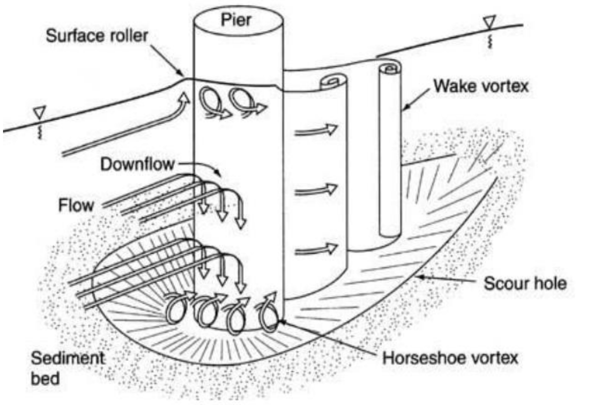

Fig. 1. Flow pattern around bridge pier (Hamill. 1999)**.**

When the flow hits the bridge pier, due to the pressure reduction from the free flow surface to the bed, downflow is created, and this downflow collides with the main flow and creates a horseshoe vortex (EL-Ghorab. 2013). On the other hand, the separation of the flow from the bridge pier leads to the formation of vortices whose axes are perpendicular to the river bed. These vortices which are called wake vortices, suck the particles of the bed upward like the tornado, and expose them to the flow. In this way, it helps carrying the materials segregated from the front side and around the pier to the lower side, while an independent scour hole is created in the downstream of the pier (Chiew. 1992). For economic and geotechnical reasons, the pier group is used to design the bridge piers (Bateni et al. 2018). The scour process around the pier group is different from that in the single pier. The mechanisms that affect the scour around the piers group include reinforcement, the effect of protection or shelter, the effect of the current vortex and the effect of the compression of the horseshoe vortices (Hannah, 1978). In the dual bridge piers perpendicular to the flow path, there will be only the effect of the compression of the horseshoe vortices. Salamatian et al. (2014) investigated the local scour in a cylindrical single pier under flood hydrograph. The results showed that the scour depth has been increased during the rising limb of the hydrograph while it had slight changes along the recession limb of the hydrograph. Additionally, at hydrograph peak (peak flow), maximum scour depth has been occurred. Karimaei Tabarestani and Zarati (2014) studied the effect of flood peak flow occurrence time on scour around the bridge pier. The results of the experiments showed that despite the difference in the temporal evolution of the scour depth around the pier for hydrographs with the same duration and different peak flow occurrence time, the final scour depth is the same. Also, for hydrographs with two different peak flows and the same duration, the peak flow occurrence time affects the temporal evolution of the scour depth, but it has a little impact on the final scour depth. Also, the study of the direction of the temporal evolution curve of the scour depth shows that, due to collapse of the walls when the flood peak flow lowers, the scour depth decreases somewhat after passing through the first peak flow. The largest decrease was found to be about 5% of the pier width. Assuming the flood hydrograph in a stepped form, Chang et al. (2004) presented a method for calculating scour depth changes based on stepped hydrograph model in unsteady flow. Their experiments showed that the effect of the peak flow hydrograph on the final scour depth is more than that of the hydrograph duration. Also, when the flow velocity increases to reach the peak flow, the scour depth is strongly changed, but in the recession branch of the hydrograph, changes in scour rates are negligible. Lai et al. (2009) studied the effect of hydrograph on the scour depth around the bridge pier. Analyzing the time variation of scour depth under different ascending hydrographs, they presented a relation for estimating the maximum scour depth around the bridge pier. Lu et al. (2011) proposed a quasi-experimental model to predict the time variation of scour depth at the bridge piers whose foundations are exposed to current due to scouring. They used three types of hydrographs with the same peak flow, but different peak flow occurrence time. The simulation results of their proposed model showed good agreement with experimental results. Briaud et al. (2001) conducted a research on the effects of flood with higher peak velocity, and then, flood with lower peak velocity on the scour depth of the bridge pier. The results showed that if the scour depth caused by the first flood is greater than that of the second flood, the second flood has no effect on the scour depth development. Otherwise, the time variation of the scour depth caused by the second flood must also be taken into account. Oliveto and Hagger (2002) examined the shape of the bridge pier scour hole in non-uniform sediments and unsteady flow. Dividing the hydrograph into steps with steady flow, they used estimation relations of scour depth in the steady flow and provided a computational method for estimating the scour depth in unsteady flow conditions. Lu et al. (2008) carried out a series of field observations on the Si-Lo Bridge in the Shui river (the longest river in Taiwan) and collected the scour depth data. Separating each section of scour, they proposed a method for simulating the time variation of the total scour depth under unsteady flow. The collected field data, which are the sum of general and local scour, are used to evaluate the efficiency of the model. Comparison of observational local scour depths data with computational values (scour depth calculated using several conventional formulas based on flood peak flow) showed that most of these relations estimate the scour depth more than actual value. Kothyari et al. (1992) conducted an experimental study to calculate the time variation of scour depth at the front of a bridge pier in steady and unsteady conditions. The results showed that the stepped hydrograph model yields acceptable results. Ataie-Ashtiani and Beheshti (2006) examined the scour depth in the piers group; and in the adjacent dual bridge piers with ratios of S/D=1, 2, 4, 5, 6 (S= the distance between the piers, D= pier diameter), they concluded that increasing the distance between two piers leads to reduction of the scour depth, but in general, the two adjacent piers, with different S/D, have a higher scour compared to the single pier. Nazariha (1996) investigated the maximum scour depth in the 2, 3, 4, and 6 pier groups. He evaluated the effect of different angles of piers locations compared to each other and the distance between them. In the group of adjacent dual piers, and in the ratios of S/D=1, 3, 5, and 7, the results showed that for ratios of S/D>4, the scour depth would be independent of the S/D ratio. He also provided the following relation for estimating the scour depth of the front pier:

$$\frac{D_{sf}}{D_s}=1.9\left(\frac{S}{D}\right)-0.1 \quad (1)$$

Hannah (1978) studied the scour depth in the dual bridge piers, steady flow, and clear water conditions. The results showed that when the piers are exactly adjacent, S/D=1 (S= the distance between the piers, D= pier diameter), the scour depth at the front pier is equal to the scour depth in the single pier. However, with increasing distance, the effect of the reinforcing factor on the first pier is observed; this factor reaches its maximum at S/D=2.5, and at S/D=11, the scour depth at the front pier is equal to its value in the single pier.According to the studies conducted, the purpose of this study was to investigate the scour around the dual bridge piers at different distances of the piers from each other in a uniform flow as well as unsteady flow using symmetric hydrographs with changes in peak and base flows.

2. Materials and methods

The experiments were carried out in a laboratory flume with a length of 10 m and a width of 30 cm located in the Hydraulic Laboratory of the Faculty of Agriculture, University of Birjand. The bridge piers were placed in a sediment recess with a length of 2.2 m and a depth of 15 cm (Fig. 2).

The distance between the beginning of the sediment recess and the beginning of the flume was considered to be 3.9 m. This distance causes a fully developed flow on the sediment recess. Also, the distance between the end of the sediment recess and the end of the flume was determined to be 3.9 m. This distance causes the water surface profile on the sediment recess to be uniform and not affected by the tailgate. The flow rate was adjusted using an inlet valve and measured by using electromagnetic flowmeter. Several flow relaxers were installed at the beginning of the flume to reduce flow turbulence. The experiments were carried out under clear water conditions and at U/U_C=0.95 (U= flow velocity and U_C= velocity of incipient motion of sediment particles). Clear water scour occurs when there is no transfer of sediment from the flow approaching the scour hole ($U<U_C$). On the

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other hand, live bed scour occurs when the scour hole is continuously fed by the sediment from approaching flow ($U>U_C$) (Sadeghi et al. 2018). In order to eliminate the effect of the canal walls on local scour, according to Chiew and Melville (1987), the pier diameter should not be greater than 10 % of the canal width (B/D>10). According to Raudkivi and Ettema (1983), the ratio of the distance between center of the pier and the flume wall to the pier diameter should be greater than 6.25. In these experiments, a cylindrical pier model of PVC material with a constant diameter of 2.5 cm was used. In this research, the center to center distance of the two piers (S) was selected as 2D, 3D, 4D, and 5D. Sand sediments with uniform grains were used. The diameter of the sediment should be selected in such a way that the bed form is not observed. Therefore, the average diameter of sediments should be larger than 0.7 mm. Also, in order to remove the effect of the size of the sediments on the scour depth, D/d_{50}>20-25, in which, D is the pier diameter and d_{50} is the average diameter of the sediment particles (Raudkivi and Ettema, 1998). Therefore, the sand sediment was selected with an average diameter of 1 mm. The sediment uniformity criterion is based on the geometric standard deviation, σ_g. Sediments are considered uniform if σ_g<1.27 (Dey and Barbhuiya, 2005). In this study, σ_g was obtained to be equal to 1.27, which indicates the uniformity of sediments. σ_g is defined based on the following relationship:

$$\sigma_g = \sqrt{\frac{D_{84.1}}{D_{15.9}}} \tag{2}$$

The experiment of incipient motion of sediment particles was performed for four flow rates of 8, 12, 16 and 20 L/sec. The purpose of this experiment is to obtain the depth of the incipient motion in a specific flow rate. For this purpose, sediment recess (without the presence of piers) was completely flattened and the tailgate was completely pulled upward. Then, the flume was slowly filled up by the flow of water and the desired flow rate was adjusted. After setting the flow rate, the tailgate was slowly pulled downward. This process was continued until the general motion of sediments was observed in sediment recess. The purpose of this research is to conduct experiments in clear water conditions and U/U_C=0.95. In this study, for the flow rates of 8, 12, 16, and 20 L/sec, the depth of incipient motion of sediment particles were observed in flow depth of 10.4, 14.6, 19.1, and 23.4 cm, respectively.

Also, the flow depths for conducting experiments were selected to be 10.9, 15.4, 20.1, and 24.6 cm, respectively. According to Chiew (1995), if y/D>3 (y flow depth and D pier diameter), the flow depth does not affect the scour depth. Cylindrical piers were installed in the center of the sediment recess. Then the surface of the sediments was completely flattened. In order to prevent undesirable scour due to low flow depth, the flume was filled with a low-rate pipe and then the flow rate and desired depth were adjusted. The duration of all hydrographs was fixed and equal to 10 hours. Experiments were carried out at different distances of the dual bridge piers for uniform flow and symmetric hydrographs with changes in peak and base flows. The hydrographs used in the experiments are stepped hydrographs and in 5 steps. In these hydrographs, Q_p represents the peak flow, Q_b represents the base flow and T_b represents the total test time (Fig. 3). After the completion of the experiments, topography of the bed was also taken. Laser meter with accuracy of ± 1 mm was used to measure bed topography. The results of the experiments (a total of 36 experiments) are included in the Table 1.

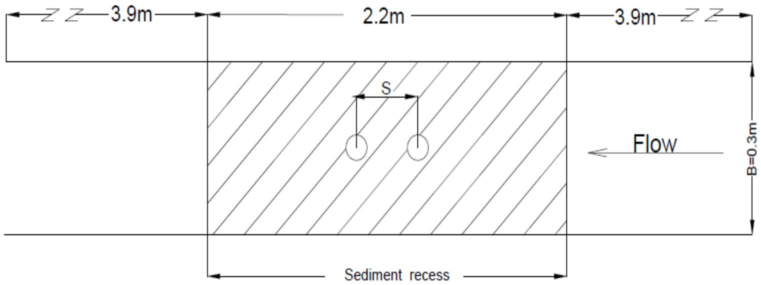

Fig. 2. Plan of laboratory flume.

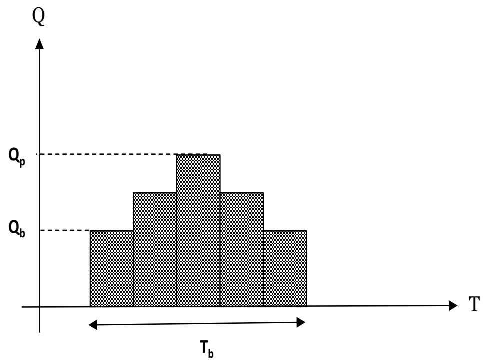

Fig. 3. Scheme of stepped hydrographs used in the research.

3. Results and discussion

3.1. Investigation of maximum dimensionless scour depth of the first pier at different distances of the dual bridge piers in uniform flow

In Fig. 4, maximum dimensionless scour depth of the first pier of the dual bridge piers is shown at different distances of piers from each other in uniform flow. As shown in Fig. 4, in the uniform flow, the maximum dimensionless scour depth of the first pier of the dual bridge piers is observed at S/D=3. For example, in a uniform flow of 16 L/sec, the maximum dimensionless scour depth of the first pier at S/D=2, 3, 4, and 5 was measured to be 1.24, 1.4, 1.36, and 1.28, respectively. Also, at a constant distance between the piers, the maximum scour depth was increased by increasing the flow rate. For example, in the dual bridge piers with S/D=2, at uniform flows of 8, 12, 16 and 20 L/sec, the maximum dimensionless scour depth of the first pier was measured to be 0.84, 1.08, 1.24, and 1.36, respectively. Also, as shown in this Fig., the maximum dimensionless scour depth of the first pier of the dual bridge piers is greater than the maximum dimensionless scour depth of the single pier. This is due to the reinforcing factor of the horseshoe vortices in the dual bridge piers (Hannah, 1978). These results are consistent with the results of Ataie-Ashtiani and Beheshti (2006).

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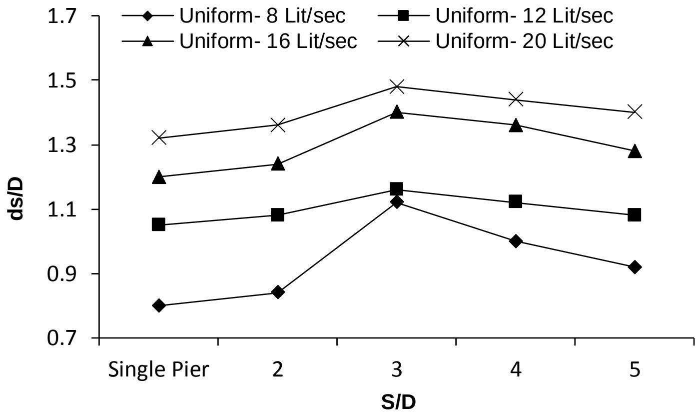

Fig. 4. Maximum dimensionless scour depth of the first pier of the dual bridge piers at different distances of piers from each other in uniform flow.

Table 1. Experimental data.

Experiment number	Flow depth (y), cm	Base flow (Q_b), L/sec	Peak flow (Q_p), L/sec	S/D	First pier scour depth, cm	Second pier scour depth, cm
1	10.7	8	8	2	2.1	0.6
2	15.6	12	12	2	2.7	0.9
3	20.2	16	16	2	3.1	1
4	24	20	20	2	3.4	1.7
5	10.7	8	8	3	2.8	1.4
6	15.6	12	12	3	2.9	1.5
7	20.2	16	16	3	3.5	1.7
8	24	20	20	3	3.7	1.9
9	10.7	8	8	4	2.5	1.5
10	15.6	12	12	4	2.8	1.6
11	20.2	16	16	4	3.4	1.7
12	24	20	20	4	3.6	2
13	10.7	8	8	5	2.3	1.4
14	15.6	12	12	5	2.7	1.5
15	20.2	16	16	5	3.2	1.6
16	24	20	20	5	3.5	1.9
17	24	20	8	2	2.7	1.1
18	20.1	16	8	2	2.3	1
19	15.6	12	8	2	2.1	0.6
20	24	20	8	3	2.8	1.2
21	20.2	16	8	3	2.3	1
22	15.6	12	8	3	2.1	0.7
23	24	20	8	4	2.9	1.5
24	20.2	16	8	4	2.4	1.6
25	15.6	12	8	4	2.2	1.7
26	24	20	8	5	2.9	1.4
27	20.2	16	8	5	2.6	1.3
28	15.6	12	8	5	2.5	1.1
29	24	20	12	2	2.9	1.2
30	24	20	16	2	3.1	1.3
31	24	20	12	3	2.9	1.3
32	24	20	16	3	3.2	1.5
33	24	20	12	4	3	1.3
34	24	20	16	4	3.2	1.5
35	24	20	12	5	3	1.5
36	24	20	16	5	3.2	1.7

3.2. Impact of peak flow on maximum dimensionless scour depth of the first pier of the dual bridge piers

In this section, the base flow of hydrographs was constant (8 L/sec) and peak flow of hydrographs have been increased step-by-step. Peak flow of hydrographs was increased step-by-step from 8 to 12, 16 and 20 L/sec. Fig. 5, shows maximum dimensionless scour depth of the first pier of the dual bridge piers at different distances of the piers from each other. In a certain hydrograph, with the increase in the relative distance between the piers, the maximum dimensionless scour depth of the first pier of the dual bridge piers has been increased. Maximum dimensionless scour depth was observed at S/D=5 (in the range of relative distances studied in the research). For example, in a hydrograph with a base flow of 8 and a peak flow of 12 L/sec (8(Q_b)-12 (Q_p)), the maximum dimensionless scour depth of the first pier of the dual bridge piers in different S/D of 2, 3, 4, and 5 was 0.84, 0.84, 0.88, and 1, respectively. While in the uniform flow, the maximum dimensionless scour depth of the first pier of the dual bridge piers is observed at S/D=3. For example, in a uniform flow of 8 L/sec, the maximum dimensionless scour depth of the first pier of the dual bridge piers at S/D=2, 3, 4, and 5 was measured to be 0.84, 1.12, 1, and 0.95, respectively. It is also shown in this Fig., at a constant distance, with stepwise increase in peak flow of hydrographs, the maximum dimensionless scour depth of the first pier of the dual bridge piers has been increased with an increasing rate, which is consistent with the results of the Guney and Bor Turkben (2015). For example, in the dual bridge piers with S/D=5, at peak flows of 12, 16 and 20 L/sec, the maximum dimensionless scour depth of the first pier was 1, 1.04, and 1.16, respectively.

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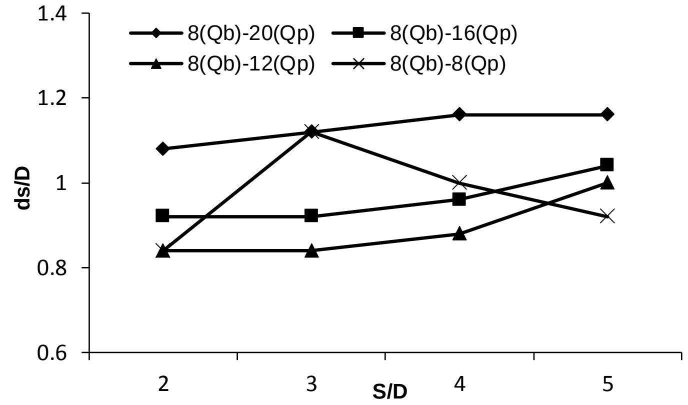

Fig. 5. Maximum dimensionless scour depth of the first pier of the dual bridge piers at different distances of the piers from each other with changes in the peak flow of hydrographs.

3.3. Impact of base flow on the maximum dimensionless scour depth of the first pier of the dual bridge piers

In this section, the peak flow of hydrographs is constant (20 L/sec) and the base flow of hydrographs has been increased step-by-step. The base flow of hydrographs has been increased step-by-step from 8 to 12, 16 and 20 L/sec. Fig. 6 shows the impact of base flow on the maximum dimensionless scour depth of the first pier of the dual bridge piers at different relative distances of the piers. As shown in Fig. 6, in a certain hydrograph, with the increase in the relative distance between the piers, the maximum dimensionless scour depth of the first pier of the dual bridge piers has been slightly increased. Maximum dimensionless scour depth was equally observed at S/D=4 and 5. For example, in a hydrograph with a base flow of 8 and a peak flow of 20 L/sec ($8(Q_b)$-$20(Q_p)$), the maximum dimensionless scour depth of the first pier of the dual bridge piers in different S/D of 2, 3, 4, and 5 was 1.08, 1.12, 1.16, and 1.16, respectively. While in the uniform flow, the maximum dimensionless scour depth of the first pier of the dual bridge piers is observed at S/D=3. For example, in a uniform flow of 20 L/sec, the maximum dimensionless scour depth of the first pier of the dual bridge piers at S/D=2, 3, 4, and 5 was measured to be 1.36, 1.48, 1.44, and 1.4, respectively. It is also shown in this Fig., at a constant distance, with stepwise increase in base flow of hydrographs, the maximum dimensionless scour depth of the first pier of the dual bridge piers has been increased with an increasing rate. For example, in the dual bridge piers with S/D=3, at peak flows of 8, 12 and 16 L/sec, the maximum dimensionless scour depth of the first pier was 1.12, 1.16, and 1.28, respectively.

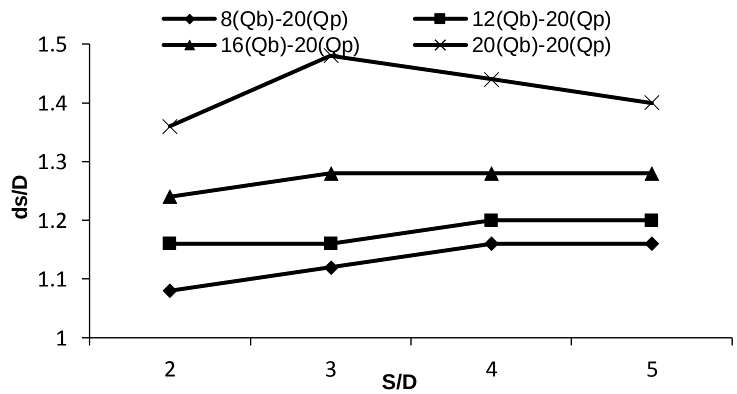

Fig. 6. Maximum dimensionless scour depth of the first pier of the dual bridge piers at different distances of the piers from each other with changes in the base flow of hydrographs.

3.4. Investigation of maximum dimensionless scour depth of the second pier of the dual bridge piers in uniform flow

Fig. 7 shows the maximum dimensionless scour depth of the second pier of the dual bridge piers at different relative distances of the piers in uniform flow. As shown in Fig. 7, in uniform flow, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been observed in S/D=4. For example, in a uniform flow of 12 L/sec, the maximum dimensionless scour depth of the second pier of the dual bridge piers at S/D=2, 3, 4, and 5 was measured to be 0.36, 0.6, 0.64, and 0.6, respectively. It is also shown in this Fig., at a constant distance between the piers, with increase in flow rate, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been increased. For example, in the dual bridge piers with S/D=2, at uniform flows of 8, 12, 16, and 20 L/Sec, the maximum dimensionless scour depth of the second pier was 0.24, 0.36, 0.4, and 0.68, respectively.

3.5. Impact of peak flow on the maximum dimensionless scour depth of the second pier of the dual bridge piers

In this section, the base flow of hydrographs is constant (8 L/sec) and the peak flow of hydrographs has been increased step-by-step. The peak flow of hydrographs has been increased step-by-step from 8 to 12, 16 and 20 L/sec. Fig. 8, shows the impact of peak flow on the maximum dimensionless scour depth of the second pier of the dual bridge piers at different relative distances of the piers. As shown in Fig. 8, in a certain hydrograph, with the increase in the relative distance between the piers, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been increased. Maximum dimensionless scour depth was observed at S/D=5 (in the range of relative distances studied in the research). For example, in a hydrograph with a base flow of 8 and a peak flow of 12 L/sec ($8(Q_b)$-$12(Q_p)$), the maximum dimensionless scour depth of the second pier of the dual bridge piers in different S/D of 2, 3, 4, and 5 was 0.24, 0.28, 0.36, and 0.44, respectively. While in the uniform flow, the maximum dimensionless scour depth of the second pier of the dual bridge piers is observed at S/D=4. For example, in a uniform flow of 8 L/sec, the maximum dimensionless scour depth of the second pier of the dual bridge piers at S/D=2, 3, 4, and 5 was measured to be 0.24, 0.56, 0.6, and 0.56, respectively. It is also shown in this Fig. that at a constant distance, with stepwise increase in peak flow of hydrographs, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been increased with a decreasing rate. For example, in the dual bridge piers with S/D=3, at peak flows of 12, 16 and 20 L/sec, the maximum dimensionless scour depth of the second pier was 0.28, 0.4, and 0.48, respectively.

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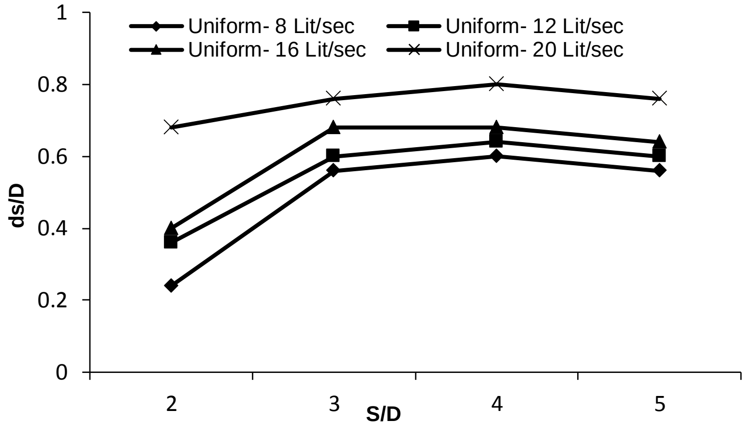

Fig. 7. Maximum dimensionless scour depth of the second pier of the dual bridge piers at different relative distances of the piers in uniform flow.

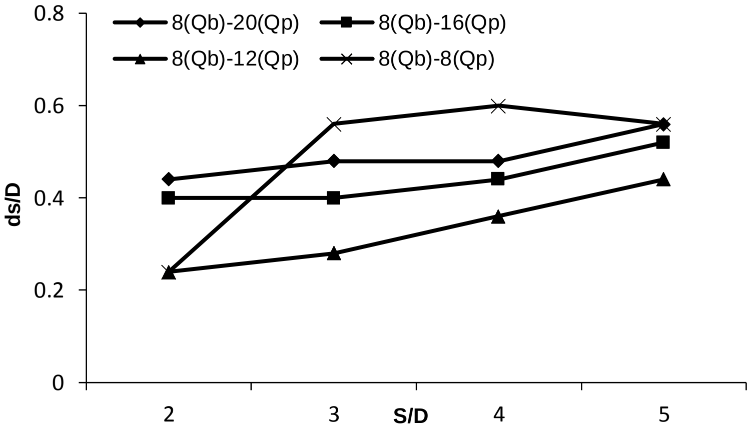

Fig. 8. Maximum dimensionless scour depth of the second pier of the dual bridge piers at different relative distances of the piers from each other with changes in the peak flow of hydrographs.

3.5. Impact of base flow on the maximum dimensionless scour depth of the second pier of the dual bridge piers

In this section, the peak flow of hydrographs is constant (20 L/sec) and the base flow of hydrographs has been increased step-by-step. The base flow of hydrographs has been increased step-by-step from 8 to 12, 16 and 20 L/sec. Fig. 9 shows the impact of base flow on the maximum dimensionless scour depth of the second pier of the dual bridge piers at different relative distances of the piers. As shown in fig. 9, in a certain hydrograph, with the increase in the relative distance between the piers, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been slightly increased. Maximum dimensionless scour depth was observed at S/D=5 (in the range of relative distances studied in the research). For example, in a hydrograph with a base flow of 8 and a peak flow of 20 L/sec (8(Q_b)-20 (Q_p)), the maximum dimensionless scour depth of the second pier of the dual bridge piers in different S/D of 2, 3, 4, and 5 was 0.44, 0.48, 0.48, and 0.56, respectively. While in the uniform flow, the maximum dimensionless scour depth of the second pier of the dual bridge piers is observed at S/D=4. For example, in a uniform flow of 20 L/sec, the maximum dimensionless scour depth of the second pier of the dual bridge piers at S/D=2, 3, 4, and 5 was measured to be 0.68, 0.76, 0.8, and 0.76, respectively.

It is also shown in this Fig., at a constant distance, with stepwise increase in base flow of hydrographs, the maximum dimensionless scour depth of the second pier of the dual bridge piers has been increased with an increasing rate. For example, in the dual bridge piers with S/D=3, at base flows of 8, 12 and 16 L/sec, the maximum dimensionless scour depth of the second pier was 0.48, 0.52, and 0.6, respectively.

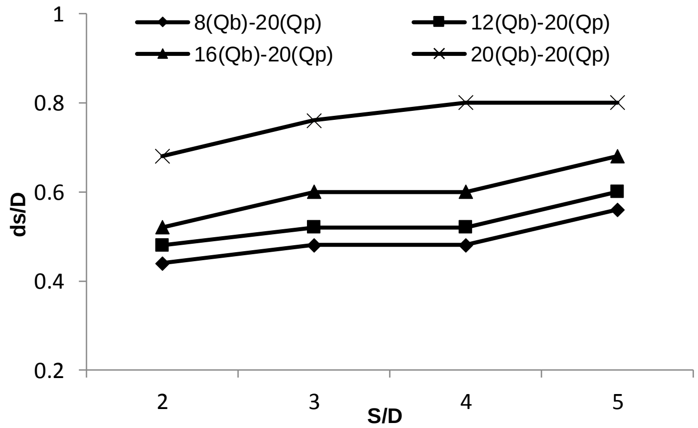

Fig. 9. Maximum dimensionless scour depth of the second pier of the dual bridge piers at different distances of the piers from each other with changes in the base flow of hydrographs.

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4. Conclusions

In this research, local scour around the dual bridge piers at different distances of piers from each other in a uniform flow and unsteady flow using symmetric hydrographs with changes in peak and base flows were studied. The results showed that in the unsteady flow, increasing the relative distance between the dual bridge piers results in increased maximum dimensionless scour depth of the first and second piers and its maximum was measured at a relative distance of S/D=5 (in the range of relative distances studied in the research). But in the uniform flow, the maximum dimensionless scour depth of the first and second piers was observed at S/D=3 and S/D=4, respectively. Also, at a constant distance between the piers, with step-by-step increase in the peak and base flows of hydrographs, the maximum dimensionless scour depth of the first pier has been increased with an increasing rate. While, with step-by-step increase in the peak and base flows of hydrographs, the maximum dimensionless scour depth of the first and second piers has been increased with decreasing and increasing rates, respectively.

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