Submerged Flow Diversion Structure as an Effective Countermeasure to Protect Bridge Piers from Scour

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ABSTRACT

Pier-scour is a common cause of waterway bridges failure. In order to decrease the potential of bridge pier-scour failure, a triangular flow diversion structure hereafter referred as FDS, was optimised in this study, as an effective countermeasure against local scouring. An efficient statistical approach to experimental design, called Taguchi's method, was employed to design the experimental program and reduce the number of experimental tests. This scientific method can be used to find the best values of the controllable factors with a minimum number of tests. According to Taguchi's method, 25 tests were conducted to optimise the dimensions and the installation location of the proposed flow diversion structure. Besides, to compare the experimental results and to assess the effectiveness of FDS, the control and optimum tests were performed. In this study, an advanced technology of 3-D printer was employed to build accurate physical models of the pier and the flow diversion structures. To measure the topography of the scoured bed after each test, a precise 3-D scanner was used. The experiments were conducted in a steady flow and under clear water scour conditions. After achieving equilibrium conditions, the bed profile was measured and the volume of the scour hole determined for each experimental test. The results of these tests revealed the optimum dimensions of the proposed FDS and its best possible place of installation to achieve the maximum reduction in the pier-scour. In the optimum condition, around 40% of the maximum scour depth, and 60% of the scour volume were reduced. This structure can be suggested to be used in the real situation due to its low cost and easy installation procedure.

1. INTRODUCTION

The interactions of three-dimensional flow structures and the bridge pier result in pier-scour, which is a common cause of waterway bridge failures. As reported by Clopper et al. (2007), scour causes 60% of the bridge failures in the United States. Melville & Coleman (2000) concluded that the principal features of the flow structure around a bridge pier are the down-flow and surface roller at the upstream side of the pier, the horseshoe vortex at the base, and the wake vortex at the downstream (Figure 1). These complicated systems of vortices Increase the sediment transport capacity of the flow and carry the bed materials to the downstream. Therefore, changing the complicated flow structures around the pier can be considered as an effective solution to control and reduce the pier-scour.

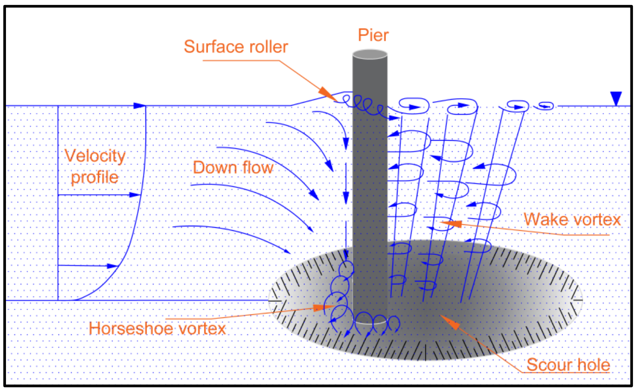

Figure 1- Flow structure around a bridge pier

A few numbers of studies such as Melville & Hadfield (1999), Dey et al. (2006), Grimaldi et al. (2009), Gogus & Dogan (2010), Beg & Beg (2013), and Ranjbar-Zahedani et al. (2017, 2018) have been conducted to introduce or evaluate a flow-altering device as a pier-scour countermeasure. Tafarojnoruz et al. (2010) carried out a broad literature review on flow-altering countermeasures. Based on the shape and performance of these devices, they classified them into four categories, including (1) openings through piers, (2) pier attachments, (3) bed attachments, and (4) other devices as shown in Figure 2.

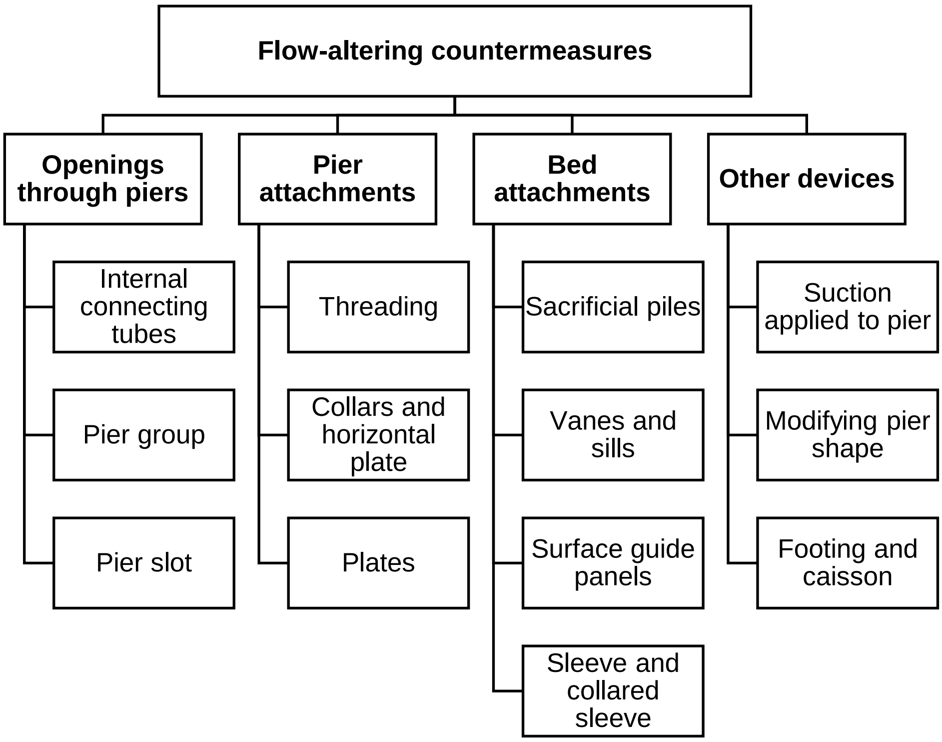

Figure 2- Classification of flow-altering countermeasures against pier-scour, (after Tafarojnoruz et al., 2010)

Each of these categories of countermeasures will be briefly discussed in the following paragraphs.

Opening through pier countermeasures such as internal connecting tubes, pier group or pier slot may reduce the scour depth by allowing a portion of the approach flow to pass through the openings inside a pier or among smaller piers, and consequently decreasing the strength of the down-flow and the horseshoe vortex. However, debris and floating materials during floods may also reduce the efficiency of these methods due to the blocking the slot and tube in the pier or the gaps between the piers as stated by Vittal et al. (1994), Chiew (1992), Tafarojnoruz et al. (2010), Beg & Beg (2013). Additionally, the opening through piers may not be applicable for existing pier because of reducing the strength of the pier structure.

Pier attachments such as the threaded pier, collar and plate should be attached to the pier. These devices may reduce the pier-scour at the beginning of the scour process. However, when the scour-hole develops they cannot protect the pier due to their connection to the pier.

Bed attachments are independent structures that should be installed at the upstream or downstream of the pier. The advantage of this type of pier-scour countermeasures is that it can simply be applied to the existing waterway bridges. The shape, the size, and the installation location affect the performance of these devices. Few studies have been conducted in this category and the proposed structures are included sacrificial piles (Melville & Hadfield 1999), vanes and sills (Odgaard & Wang l987; Lauchlan 1999), surface guide panels (Huang et al. 2005), and sleeve and collared sleeve (Singh et al. 2001, Garg et al. 2008). As recommended by Melville & Hadfield (1999), sacrificial piles can be used as a scour countermeasure when the flow remains aligned and the flow intensity is relatively small. Lauchlan (1999) investigated the use of Iowa vanes for pier scour reduction under live-bed condition. He concluded that although the maximum scour depth reduction was significant in some tests (30% to 50%), no significant trends were evident in the data. A sleeve is a larger diameter cylinder surrounding the pier. Two distinct scour types, including inside and outside of the sleeve may occur. In order to reduce the outside scour, another countermeasure should be applied. Therefore, this device may not be considered as an effective technique.

The fourth category of flow-altering countermeasures includes a suction applied to the pier, modifying pier shape, and footing and caisson. As stated by Tafarojnoruz et al. (2010), suction needs a permanent pumping system, as well as regular monitoring and maintenance. Although the pier shape is an effective factor on the amount of pier-scour, it cannot protect the pier when the scour-hole develops. Besides, this method may not be appropriate for an already existing bridge. Footing and caisson can reduce the scour depth effectively, and they can also be considered economical. However, if the top elevation of this device is located above the original bed level, the scour depth will increase (Tafarojnoruz et al. 2010).

From the above mentioned classified methods, the bed attachment at the upstream of the pier is the focus of this paper. In this study, a flow diversion structure (FDS), previously introduced and studied by Keshavarzi et al. (2009) and Ranjbar-Zahedani et al. (2017, 2018), has been optimised as a pier-scour countermeasure. The proposed FDS has a triangular prismatic shape. An experimental program designed to identify the optimum dimensions and the best installation location to achieve the maximum reduction in local scour around a circular pier is presented in this paper.

2. EXPERIMENTAL STUDY

Experiments were conducted in an 8 m long, 450 mm wide, and 280 mm deep rectangular Plexiglas-sided flume with a longitudinal slope of 0.06%. The discharge was supplied from a tank with a circulating pump system and measured using a turbine insertion flow-meter with an accuracy of 0.5%. This flume was also equipped with a downstream flap gate to regulate the water depth.

2.1 Selecting Model Dimensions

The pier diameter (D) was carefully chosen to minimize any contraction effect on the depth of scour. According to Melville & Coleman (2000), to minimize the contraction effect, the flume width should be at least ten times greater than the pier diameter. In this study using a 40 mm pier diameter satisfies the above criterion.

Based on Melville & Coleman (2000), the maximum possible local scour depth for an aligned circular pier equals to 2.4D (where D is the diameter of the pier). As discussed by Ettema (1976), the ratio of the pier width to the grain size should be more than 50 to avoid the grain size effects on the scour depth. To satisfy these two criteria, 120 mm thick uniformly graded non-cohesive sand with a median grain size (d_{50}) of 0.78 mm was used.

To avoid the water depth effects on the local scour depth, Melville & Coleman (2000) stated that the pier diameter to the water depth ratio should be less than 0.7. Therefore, the water depth used in the experiments was set to 100 mm to satisfy this requirement. Besides, they stated that under clear-water scour conditions, the local scour depth in uniform sediment increases almost linearly with flow intensity to a maximum at the threshold velocity. According to selected water depth (y=100 mm) and median sediment size (d_{50}=0.78 mm), the critical mean flow velocity was obtained to be equal to 0.327 m/s. Subsequently, the mean flow velocity was considered 0.32 m/s around the threshold condition. Therefore, in this study, the flow intensity was equal to 0.98.

2.2 Flow Diversion Structure

The flow diversion structures, employed in this study have a triangular prism shape with the dimensions smaller than the pier. Figure 3 shows the pier and the flow diversion structure schematically.

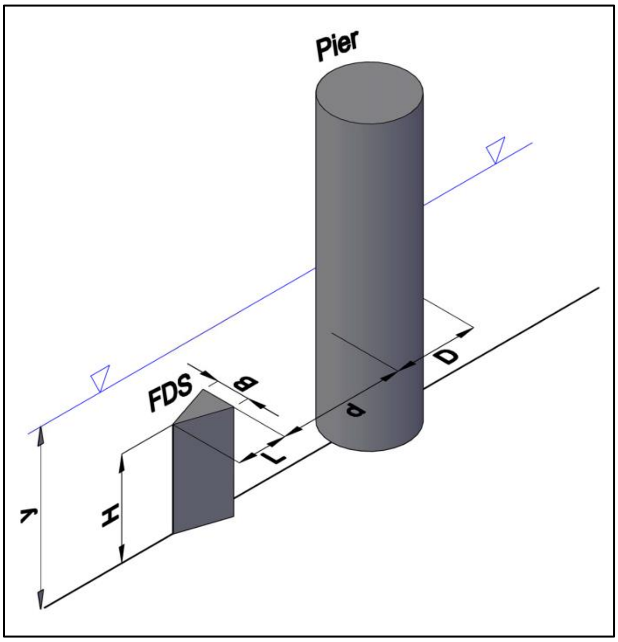

Figure 3- Schematic diagram of the pier and the flow diversion structure (FDS)

In order to optimize the dimensions of FDS (i.e., lateral base: B, longitudinal base: L, and height: H) and its installation location (i.e., the clear distance between the pier and FDS: d) for achieving the maximum reduction of pier-scour, different levels were considered for each parameter. As this structure should be smaller than the pier, hence, five levels were considered for B/D and L/D from 0.2 to 1 with 0.2 increments. Similarly, five levels of H/y were tested (i.e., H/y=0.25, 0.5, 0.75, 1 and 1.25), so that in the first four levels were a fully submerged structure and the last one was an unsubmerged structure. With the intention of selecting the levels for d/D the results of some previous studies conducted by the authors were used. Ranjbar-Zahedani et al. (2017, 2018) indicated that the optimum d/D for unsubmerged FDS with B/D=0.2, and L/D=0.5 was around 1.5D. Keshavarzi et al. (2017, 2018) showed that the minimum local scour occurred around the rear pier, when the clear distance between two in-line piers was in the ranges of 1 to 2 times of the pier diameter. As a result and for attaining further evidence, five levels were considered for d/D from 0.5 to 2.5 (i.e. d/D = 0.5, 1, 1.5, 2 and 2.5).

Table 1 indicates all the variables and their levels, which have been considered in this study. It should be noted that sediments properties, hydraulic characteristics, and pier geometry which were chosen carefully and described earlier, kept constant in all tests.

Table 1: Variables and their levels

Variables	Levels of the variables					Number of levels
B/D	0.2	0.4	0.6	0.8	1	5
L/D	0.2	0.4	0.6	0.8	1	5
H/y	0.25	0.50	0.75	1	1.25	5
d/D	0.5	1	1.5	2	2.5	5

Referring to Table 1, for the full factorial design of this experiment 625 (5×5×5×5=625) runs should be conducted. This numbers of trials are time-consuming and not feasible. Therefore, according to a practical method of experimental design, called Taguchi's method; the experimental tests have been designed and presented in the next section.

2.3 Design of Experimental Tests based on Taguchi's Method

Taguchi’s method is a statistical approach, which can be used for designing the experiments. Taguchi’s method employs a special set of tables called orthogonal arrays, which represent the smallest number of tests and are used for the most common design of experiments. These standard arrays can give the full information of all variables that affect the performance factor. The selection of orthogonal array is based on the number of independent variables and the number of levels for each independent variable. The basic principles of this technique have been explained in the literature (e.g. Bagchi 1993; Roy 2010; Mori 2011).

In this study, the number of independent variables is four; and five levels have been considered for each of them as summarised in Table 1. Based on Taguchi’s method, 25 tests were conducted to find the optimum value for each variable. Beyond of that the control and optimum tests were conducted, and consequently, 27 tests completed for this research. The configurations of the required tests are presented in Table 2.

Table 2: Experimental design based on Taguchi’s method

No	B(mm)	L (mm)	H (mm)	d (mm)
1	8	8	25	20
2	8	40	100	60
3	8	32	50	100
4	8	24	125	40
5	8	16	75	80
6	16	40	75	40
7	16	16	50	60
8	16	24	100	20
9	16	8	125	100
10	16	32	25	80
11	24	16	25	40
12	24	32	125	60
13	24	8	100	80
14	24	24	75	100
15	24	40	50	20
16	32	24	50	80
17	32	32	100	40
18	32	40	25	100
19	32	8	75	60
20	32	16	125	20
21	40	16	100	100
22	40	40	125	80
23	40	24	25	60
24	40	32	75	20
25	40	8	50	40
26	Control test (single pier without flow diversion structure)			
27	Optimum test			

2.4 Experimental Setup and Procedure

The first step of the test was to install the pier and the flow diversion structure at the centre line of the flume along the longitudinal direction carefully. After that, the bed materials were placed and levelled in the sand recess. Then the flume was filled with water from downstream in such a manner that ensured the sand bed was not disturbed. As the depth of water reached the target depth of 0.1 m, the flow rate was gradually increased up to the design rate of 14.4 L/s. The tailgate of the flume was used to maintain the required depth of flow. At the conclusion of the test (after 24 hours), the flow was stopped, and all water drained from the flume. Measurements of the final bed topography were undertaken. The experimental tests were repeated for the all different configurations, listed in Table 2.

In this study, the recent technology of 3D printer was employed to create the physical models of the pier and the flow diversion structures accurately. Additionally, a 3D scanner was utilised for measuring the final bed topography precisely.

3. RESULTS AND DISCUSSION

According to Taguchi's method, 25 tests were conducted to optimize the dimensions and the installation location of the flow diversion structure as a new pier-scour countermeasure. The duration of each experiment was 24 hours, because no sediment movement was noticed after that duration. After achieving equilibrium condition, the 3-D model of bed profile was captured using a 3-D scanner, and the maximum scour depth and the volume of the scour-hole were extracted for each experimental test.

3.1 Main-Effect Analysis of Maximum Scour Depth

The output responses from the experimental tests were the maximum scour depth around the pier and the volume of the scour-hole. The average value of each factor at each level was calculated by dividing the sum of all response factors involving this variable at this level by the number of tests at this factor level. The results for factor level average of the maximum pier-scour depth are illustrated in Table 3. Furthermore, the main-effect plots are depicted in Figure 4.

Table 3: Factor level average for the maximum pier-scour depth

Level	B/D	L/D	H/y	d/D
1	69.24	67.41	58.73	69.51
2	61.47	65.57	63.34	62.35
3	64.43	59.51	67.24	62.42
4	62.81	68.46	68.23	64.55
5	67.35	64.36	67.76	66.48
Rank	**3**	**2**	**1**	**4**

Referring to Table 3 and Figure 4, the height of FDS has the most influence on the effectiveness of FDS for reducing the maximum pier-scour depth. Moreover, it can be inferred that the sequence of the impact of all the other factors on the maximum pier-scour depth reduction can be expressed as L/D>B/D>d/D, as given in Table 3. The best level of each factor should be chosen where the least scour depth has occurred. The results of this study reveal that the best level for the width and the length of FDS are equal to 40% and 60% of the pier diameter, respectively. The trend of clear distance between the pier and the FDS showed when this factor was in the range of $1D \le d \le 1.5D$, the maximum reduction of the scour depth was achieved. Accordingly, it can be concluded that the best installation location for the FDS is at the upstream of the pier with the clear distance equal to 1-1.5D. As illustrated in Figure 4, the optimum level for the height of FDS is equal to 25% of water depth and by increasing this factor the effectiveness of this structure may reduce.

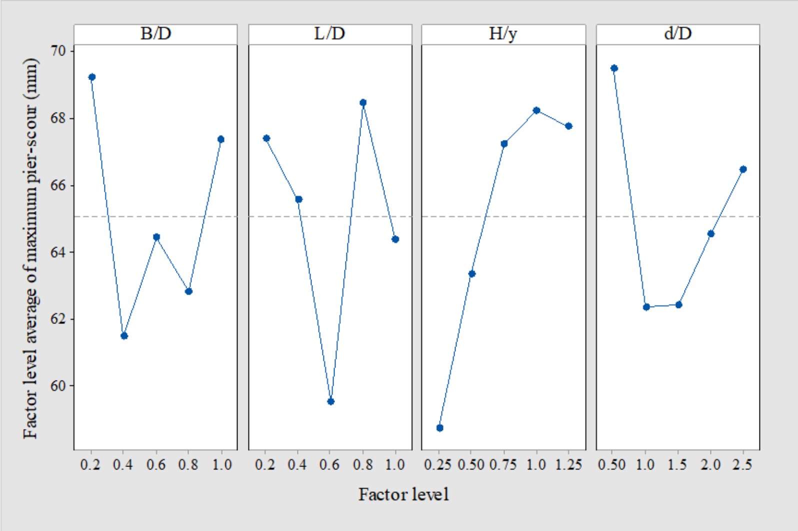

Figure 4- Main-effect plots of the maximum pier-scour depth

3.2 Main-Effect Analysis of Scour Volume

The results for the factor level average of the scour volume are illustrated in Table 4, while the main-effect plots depicted in Figure 5. As indicated in Table 4, the width of the FDS is placed in the first rank for reducing the scour volume. Other factors including the height and length of the FDS and the clear distance between the pier and FDS are in the next ranks, respectively. Although the comparison of the results presented in Tables 3 and 4 show different ranks of each factor, Figures 4 and 5 give the same optimum level for each factor. Hence, the best dimensions of FDS to achieve the maximum reduction of the score-hole volume are equal to B=0.4D, L=0.6D, and H=0.25y. Besides, this structure should be installed at the upstream of the pier with the clear distance between 1 to 1.5D.

Table 4: Factor level average for the scour volume

Level	B/D	L/D	H/y	d/D
1	2660066	2992784	2116873	3135107
2	2335777	2820164	2719425	2566339
3	2554733	2332576	3022166	2511187
4	2810348	2963333	2920328	2718076
5	3423962	2676028	3006093	2854176
Rank	**1**	**3**	**2**	**4**

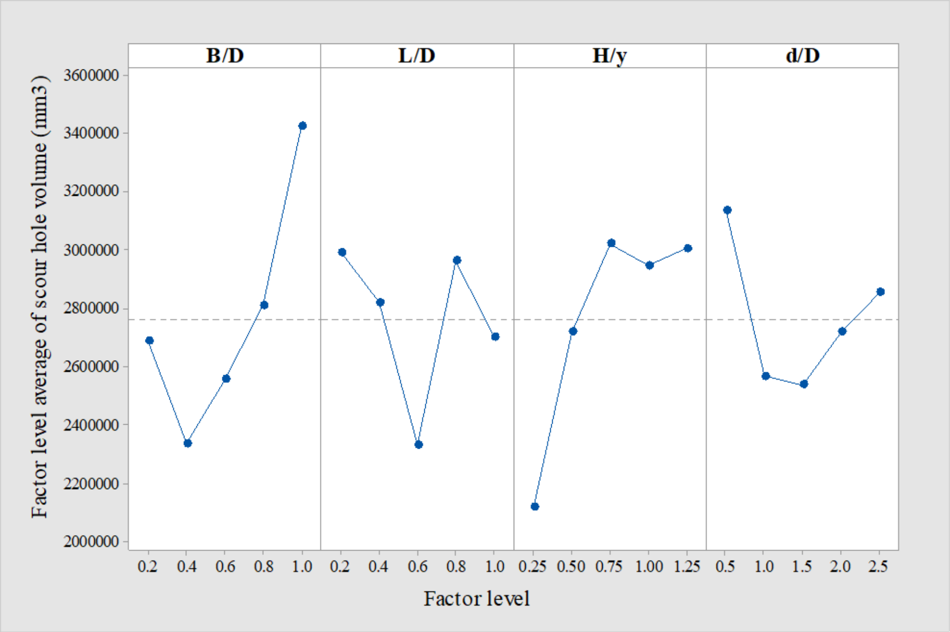

Figure 5- Main-effect plots of the scour volume

3.3 Confirmation Test

Based on Taguchi's design approach a confirmation test should be run under the optimum conditions to verify the experimental results. In this study, a confirmation test was conducted by utilizing the best levels of the factors (i.e., B=0.4D, L=0.6D, H=0.25y, and d=1.5D). Figures 6(a) and 6(b) illustrate the 3-D models of the scour of control and optimum tests, respectively. In this study optimised FDS was implemented and the maximum scour depth and the volume of scour were measured. These measured values were the minimum of the local scour depth and the volume of the scour among all the conducted tests. With comparison the control and the optimum test, it can be concluded that the FDS can reduce the maximum scour depth and the volume of the scour by 40% and 60%, respectively. Regarding the benefits of FDS, it can be stated that this structure is much smaller than the pier and can simply be applied even at the upstream of existing bridge piers. In addition, the height of this structure is very short, and there is no concern regarding the blockage of debris and other floating materials by FDS.

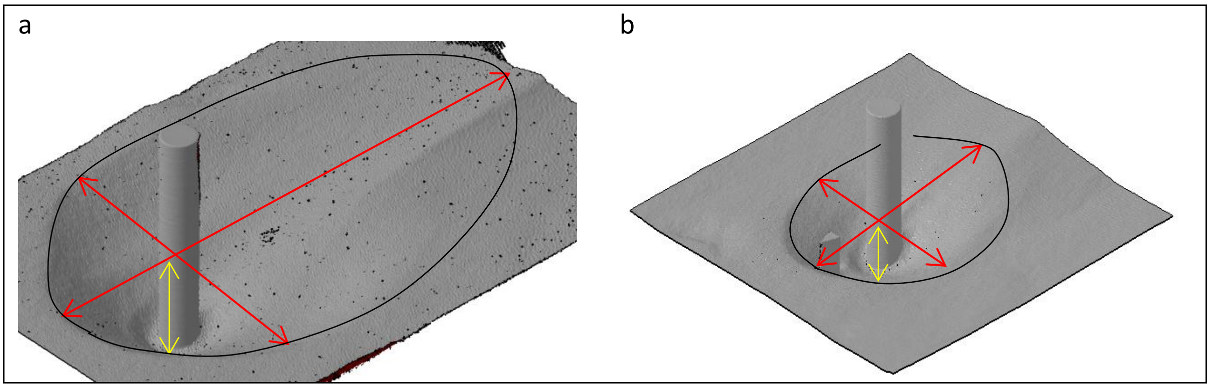

Figure 6- 3-D models of the pier-scour a) single pier; b) pier with the optimum FDS

4. CONCLUSIONS

In this study, the efficient countermeasure against pier-scour named triangular flow diversion structure (FDS), previously studied by Ranjbar-Zahedani et al. (2017, 2018) has been optimised. Taguchi's method which is a statistical approach for design of experiments was applied to find the optimum size and the best place for installing FDS to achieve the maximum reduction of the pier-scour. A modern 3-D printer was used to make the physical models, and a precise 3-D scanner was exploited to measure the final bed topography. The outcomes clearly demonstrate that the best width, length, and height of FDS are equals to 0.4D, 0.6D, and 0.25y, respectively. Furthermore, the best clear distance between FDS and the pier is approximately between 1 and 1.5 times of the pier diameter. In the optimum situation, the scour depth and the volume of the scour hole around the pier reduced by 40% and 60%, respectively. Debris and floating materials will not be blocked by submerged FDS due to its entirely submergence and short height. The optimum triangular FDS can be applied for both new and existing bridge piers to control and reduce the local scour around them.

5. REFERENCES

- Bagchi, T.P. 1993, *Taguchi methods explained: Practical steps to robust design*, Prentice-Hall of India Private Limited, New Delhi, India.
- Beg, M. & Beg, S. 2013, 'Scour reduction around bridge piers: A review', *International Journal of Engineering Inventions*, vol. 2, no. 7, pp. 7-15.
- Chiew, Y.-M. 1992, 'Scour protection at bridge piers', *Journal of Hydraulic Engineering*, vol. 118, no. 9, pp. 1260-9.
- Clopper, P., Lagasse, P. & Zevenbergen, L. 2007, 'Bridge pier scour countermeasures', *World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat*, pp. 1-13.
- Dey, S., Sumer, B.M. & Fredsøe, J. 2006, 'Control of scour at vertical circular piles under waves and current', *Journal of Hydraulic Engineering*, vol. 132, no. 3, pp. 270-9.
- Ettema, R. 1976, 'Influence of bed material gradation on local scour', M.Eng thesis, Department of Civil Engineerin, University of Auckland.
- Garg, V., Setia, B. & Verma, D. 2008, 'Prevention of scour by combination of scour protection devices around bridge piers', *Proc. River Flow*, pp. 1637-43.
- Gogus, M. & Dogan, A.E. 2010, 'Effects of Collars on Scour Reduction at Bridge Abutments', *Scour and Erosion*, pp. 997-1007.
- Grimaldi, C., Gaudio, R., Calomino, F. & Cardoso, A.H. 2009, 'Control of scour at bridge piers by a downstream bed sill', *Journal of Hydraulic Engineering*, vol. 135, no. 1, pp. 13-21.
- Huang, C., Tang, C. & Kuo, T. 2005, 'Use of surface guide panels as pier scour countermeasures', *International Journal of Sediment Research*, vol. 20, no. 2, p. 117.
- Keshavarzi, A., Shrestha, C.K., Melville, B., Khabbaz, H., Ranjbar-Zahedani, M. & Ball, J. 2018, 'Estimation of maximum scour depths at upstream of front and rear piers for two in-line circular columns', *Environmental Fluid Mechanics*, vol. 18, no. 2, pp. 537-50.
- Keshavarzi, A., Shrestha, C.K., Zahedani, M.R., Ball, J. & Khabbaz, H. 2017, 'Experimental study of flow structure around two in-line bridge piers', *Proceedings of the Institution of Civil Engineers-Water Management*, Thomas Telford Ltd, pp. 1-17.
- Keshavarzi, A., Sistani, B., & Ranjbar-Zahedani, M. 2009, 'Evaluation of the effect of flow diversion structure on local scour around cylindrical piers', *Proceedings of the 8th International Conference of Civil Engineering*, Shiraz, Iran (in Farsi).
- Lauchlan, C.S. 1999, 'Pier scour countermeasures', ResearchSpace@ Auckland.
- Melville, B.W. & Coleman, S.E. 2000, *Bridge scour*, Water Resources Publication, LLC, Colorado, USA.
- Melville, B.W. & Hadfield, A.C. 1999, 'Use of sacrificial piles as pier scour countermeasures', *Journal of Hydraulic Engineering*, vol. 125, no. 11, pp. 1221-4.
- Mori, T. 2011, *Taguchi methods: benefits, impacts, mathematics, statistics, and applications*, New York, NY : ASME Press, c2011., USA.
- Odgaard, A.J. & Wang, Y. 1987, 'Scour prevention at bridge piers', *Hydraulic Engineering*, ASCE, pp. 523-7.
- Ranjbar-Zahedani, M., Keshavarzi, A. & Khabbaz, H. 2017, 'Control of local scour at vicinity of bridge piers using flow diversion structure', *Proceedings of the 37th IAHR World Congress*, Kuala Lumpur, Malaysia.

- Ranjbar-Zahedani, M., Keshavarzi, A., Khabbaz, H. & Ball, J. 2018, 'Protecting bridge pier against local scour using flow diversion structure', *Proceedings of the Institution of Civil Engineers-Water Management*, Thomas Telford Ltd, pp. 1-26.
- Roy, R.K. 2010, *A primer on the Taguchi method*, Second edn, Society of Manufacturing Engineers, Dearborn, Michigan, USA.
- Singh, C., Setia, B. & Verma, D. 2001, 'Collar-sleeve combination as a scour protection device around a circular pier', *PROCEEDINGS OF THE CONGRESS-INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH*, pp. 202-9.
- Tafarojnoruz, A., Gaudio, R. & Dey, S. 2010, 'Flow-altering countermeasures against scour at bridge piers: a review', *Journal of Hydraulic Research*, vol. 48, no. 4, pp. 441-52.
- Vittal, N., Kothyari, U. & Haghighat, M. 1994, 'Clear-water scour around bridge pier group', *Journal of Hydraulic Engineering*, vol. 120, no. 11, pp. 1309-18.