CFD simulation of local scouring around airfoil-shaped bridge piers with and without collar

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Abstract. In this paper, the effectiveness of airfoil-shaped pier with and without a collar on local scour depth reduction is numerically investigated utilizing FLOW-3D model. The results show that on a constant $T^* = VT/D$ (V : velocity, T : time, D : pier width), increasing the width of the ballet of pier would result on the reduction of maximum scour depth and it would mitigate the scouring depth behind the piers. Also, because of lack of uplift vortices in using airfoil-shaped pier, there would be no scouring behind the piers. Utilizing collar on the airfoil-shaped pier would result in a reduction of maximum scouring depth in front of the pier as well and the uplift vortices behind the pier would reduce. Investigation of orientation discipline of the airfoil-shaped pier on flow route shows that the pier which is reversely placed in the flow direction (the keen part in front), will cause the horseshoe vortex to weaken and make the scouring to start from downstream. However, scouring caused by horseshoe vortex in front of the airfoil-shaped pier is strongly more than scouring caused by wake vortex in the rear of the pier.

Keywords. Airfoil-shaped pier; local scouring; horseshoe vortex; FLOW-3D.

1. Introduction

Scouring is an important phenomenon which plays a key role in almost all river engineering applications and is the most probable reason for the failure of river structures [1]. This phenomenon occurs, because of the eroding power of water which erodes and transfers the bed particles around the obstructing structures. The obstacle which is placed in flow route will change the flow pattern around [2]. The significance of scour investigation must be highlighted when the depth of scouring approaches the foundation of the structure and causing the menaces to the stability of it [3]. Knowing the flow pattern around the piers with geometric shapes can significantly reduce the damages and collapse of bridge piers. Horseshoe and uplift vortices play a major role in scouring hole creation around bridge piers [4]. Figure 1 shows creation mechanism of horseshoe and uplift vortices due to the collision of flow with the bridge pier.

One of the main methods for control and reduction of scouring in bridge piers is changing the flow pattern and increasing the resistance of bed grains. In such methods (flow pattern changing), downward flow strength and horseshoe vortex which are the main reasons for reduced scouring [5]. In this category, these methods could be named: preparing slots in the pier, reforming the geometric

form of the pier, utilizing some extra instruments such as cables, collars, vanes, etc. and utilizing some bed connected instruments such as submerged vanes, protecting piles and governing plates [6] and [7]. Impact of the piers shape on local scouring rate has been investigated by many researchers [4, 8–12]. Existing literature reveals that the obstruction shape can strongly affect the flow pattern around it. For example, the strength of the downward flow, horseshoe vortex and the wake vortex around the square piers are greater than circular piers. There are few studies on the field of local scour around non-circular piers. The keen nose and round-nosed pier reduces the bed shear stress value more than a circular pier does [13]. In this paper, the impact of simultaneous use of airfoil-shaped pier and collar and their orientation in the flow path on scouring reduction around the pier is investigated numerically. If the results are good, the submerged part of the existing piers (circular in common) can easily reshape to airfoil-shaped piers to mitigate the local scouring potential. This is why the airfoil-shape is selected to get investigated in this paper.

2. Dimensional analysis

Several factors affect the scour rate around bridge piers from which the most important factors are: flow depth (Y), flow velocity (V), critical velocity (V_c), pier diameter (D), pier length (L), gravitational acceleration (g), fluid density

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Figure 1. Local scouring and creation of horseshoe vortices around bridge pier.

(ρ_w), fluid kinematic viscosity (ν), sediment particles density (ρ_s), sediment size (d_s) and experiment duration (T). Generally, one can say:

$$f_1(d_s, Y, D, L, V, V_c, g, \rho_s, \rho_w, \nu, T) = 0 \quad (1)$$

Utilizing Buckingham's theorem in dimensional analysis, the Eq. (1) can be written as the following dimensionless function:

$$f_2\left(\frac{d_s}{D}, \frac{Y}{D}, \frac{L}{D}, \frac{V}{V_c}, \frac{V.T}{D}, \frac{d_s}{D}, \frac{\nu}{VD}, \frac{\rho_s}{\rho_w}, \frac{gy}{V^2}\right) = 0 \quad (2)$$

Given that ρ_w , ρ_w , d_s , D and y are constant in all models, the parameters ν/VD , gy/V^2 and V/V_c which are indicating viscosity force effects, inverse Froude number and flow intensity, respectively and are constant in this study which are equal to 70175, 0.179 and 0.9, respectively. So their effects could be neglected and finally Eq. (2) may be simplified as:

$$f_3\left(\frac{d_s}{D}, \frac{VT}{D}, \frac{L}{D}\right) = 0 \quad (3)$$

In which d_s/D is the dimensionless depth of scouring, $T^* = VT/D$ is dimensionless time and L/D is the proportion of length to the diameter of airfoil-shaped pier (figure 2).

3. Methods and materials

3.1 Governing equations

FLOW-3D model solves the Reynolds averaged Navier-Stokes equations utilizing the volume of fluid method on a meshed domain to analyze a three dimensional flow. These equations in Cartesian coordinates (X, Y, Z) are as follows:

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u A_x)}{\partial x} + \frac{\partial(\rho v A_y)}{\partial y} + \frac{\partial(\rho w A_z)}{\partial z} = R_{SOR} \quad (4)$$

$$\frac{\partial u}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z} \right) = - \frac{1}{\rho} \frac{\partial P}{\partial x} + G_x + f_x \quad (5)$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z} \right) = - \frac{1}{\rho} \frac{\partial P}{\partial y} + G_y + f_y \quad (6)$$

$$\begin{aligned} \frac{\partial w}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right) \\ = - \frac{1}{\rho} \frac{\partial P}{\partial z} + G_z + f_z \end{aligned} \quad (7)$$

In which (u, v, w) are velocity components, (A_x, A_y, A_z) are area fractions related to the flow, (G_x, G_y, G_z) are mass acceleration and (f_x, f_y, f_z) are viscosity acceleration in (x, y, z) directions, ρ is fluid viscosity, R_{SOR} is source term, V_F is volume fraction and P is pressure.

3.2 Numerical model

A turbulence model is needed for additional modeling of nonlinear Reynolds stress term. For this purpose, the *RNG*¹ $k-\epsilon$ turbulence model is used in this study to simulate mean flow characteristics of turbulent flow. Although there are several accurate turbulence models (e.g., *DNS*, *LES*, and hybrid models), the *RNG* $k-\epsilon$ could match successfully with a large number of meshes. It has been utilized successfully in similar numerical studies in which the local scouring is simulated around a pier [14–16] and success in previous studies [17–20]. The *RNG* $k-\epsilon$ turbulence model equations are referenced to Yakhot *et al* studies [21].

FLOW-3D[®] uses the volume of fluid (VOF) method for free surface modeling. In this method the following equation is considered as well:

$$\begin{aligned} \frac{\partial F}{\partial t} + \frac{1}{V_f} \left[\frac{\partial}{\partial x} (F u A_x) + \frac{\partial}{\partial y} (F v A_y) + \dots \right. \\ \left. + \frac{\partial}{\partial z} (F w A_z) \right] = 0 \end{aligned} \quad (8)$$

Where F is the fraction function, $F = 0$ when a cell is empty and when the cell is full $F = 1$. Zahabi *et al* defined a robust way of assigning boundary condition, including assigning wall boundary condition, pressure difference boundary condition and velocity inlet boundary condition which is used in the current study [22].

3.3 Sedimentation scour model

Sediment scour model investigation uses two concentration fields including suspended sediments and bed sediments. Production of suspended sediments in flow is due

¹Re-Normalization Group

Figure 2. Geometric specifications of pier models in this study.

to the effect of local pressure gradient changes. The input flow may contain the suspended particles or they may appear due to the bed erosion. Bed sediments are not easily displaced since they are limited by neighbouring particles. Bed sediments can move when they are changed as suspended particles at the fluid bottom boundary. Suspended load can be changed into bed load when deposition velocity is more than bed erosion velocity [23]. A part of control volume occupied by solid sediment particles is defined by (f_s) and the rest is defined by (f_L) such that: $f_s + f_L = 1$.

Assuming two phase flow of sediment and fluid and according to the momentum equation in continuous part of the fluid equation (9) is achieved. Also, Eq. (10) for the non-continuous phase of sediment particles and Eq. (11) for sediment convection (subtraction of Eq. (9) from Eq. (10)) are presented.

$$\frac{\partial \bar{u}}{\partial t} + \bar{u} \cdot \nabla \bar{u} = -\frac{1}{\bar{\rho}} \nabla P + F \quad (9)$$

$$\frac{\partial u_s}{\partial t} + \bar{u} \cdot \nabla u_s = -\frac{1}{\rho_s} \nabla P + F - \frac{K}{f_s \rho_s} u_r \quad (10)$$

$$\frac{\partial u_{drift}}{\partial t} + \bar{u} \cdot \nabla u_{drift} = \left(\frac{1}{\bar{\rho}} - \frac{1}{\rho_s} \right) \nabla P - \dots - \frac{K}{f_s \rho_s} u_r \quad (11)$$

In these equations u_s is sediment particles velocity, $\bar{u} = (1 - f_s)u + f_s u_s$ is fluids mean volume velocity, F is gravitational forces, K is drag coefficient between sediment and fluid, P is pressure force, $u_r = u_s - u$ is relative velocity of sediment and fluid and $u_{drift} = u_s - \bar{u}$ is buoyancy velocity of sediment particles.

3.4 Specifications of the airfoil-shaped pier model and computational grid

In simulations, in order to investigate the impact of the airfoil-shaped pier on the rate of scouring reduction, different relative lengths are used (L/D) in which L is the length of the pier along the flow and D is pier diameter. In this study simulation results in $L/D = 2.85$ are validated using experimental results of Hasanpoor *et al* [24] which are performed in the hydraulic laboratory of water department of Tabriz university and in a 9 m length, 25 cm width and 50 cm depth flume with bed slope of 0.0022. Evaluations are performed using $L/D = 3, 4, 5$. Table 1 shows models characteristics and the hydraulic conditions of current research.

In general, piers are classified as narrow, wide or intermediate depending on the value of y/D (proportion of flow depth to the pier diameter). Narrow piers are the most commonly studied group, for which y/D is greater than 1.4. For narrow piers, maximum scour depth occurs at the upstream face of the pier [3]. As flow depth increases, its influence on scour depth increases, and the influence of pier size on scour depth decreases, until a limiting point ($y/D = 1.4$). After y/D exceeds 1.4, flow depth no longer influences the scour depth and it becomes constant. Based on the studies of Chiew [25], if $y/D > 3$ the flow depth would not affect the scour depth. In order to scour depth not to be affected by flow depth, $y/D = 8$ is used in this study. Considering that local scouring in clear water conditions should be investigated in this research, $V/V_c < 1$ should be exploited [26]. According to the relationship provided by Melville [27], it is possible to calculate the critical velocity using the shear velocity, which depends on the mean size of the bed grains. In this research critical velocity was evaluated to be equal to 0.25 m/s. Also, because a major part of scour was happening at first two hours of simulation, this duration was considered same for all simulations.

Table 1. Geometric specifications and governing hydraulic conditions in this study.

Models	D (cm)	L (cm)	L/D	V (m/s)	V_c (m/s)	y (cm)	Fr
1	2	5.7	2.85	0.225	0.25	16	0.179
2	2	6	3	0.225	0.25	16	0.179
3	2	8	4	0.225	0.25	16	0.179
4	2	10	5	0.225	0.25	16	0.179

Table 2. Mesh sensitivity analysis.

Test No.	Internal mesh (cm)	External mesh (cm)	Total number of cells	Max Aspect ratio	$T^* = VT/D$ L/D = 2.85 in FLOW-3D	$T^* = VT/D - L/D = 2.85$ in Experimental result
N1	2.6	1.4	1184857	1.84	1.127	1.614
N2	2.4	1.2	1415609	1.66	1.264	1.614
N3	2.2	0.9	1909657	1.48	1.525	1.614

Figure 3. View of the meshed model in FLOW-3D.

In order to simulate the flow domain in three dimensions (x , y , z) numerically, it is possible to use both harmonic and non-harmonic meshes in FLOW-3D. The nested mesh would lead to a good modeling of vortices and also it matches the experimental data. According to the performed sensitivity mesh analysis, (table 2) and comparison of scouring progress with time for numerical simulation and experimental results, three different mesh sizes were used at a distances close to the computational grid. It should be noted that in the presence of nested mesh, the internal and external mesh should not have a large difference in size. Empirically and in order to reduce errors, it is recommended that the ratio of two meshes should set to be about 2. Also, at intersections of two meshes, it should be considered that the mesh size should have a gradual change.

The dimension of the larger mesh is 2.2 centimetres with a count of 627654. Smaller mesh size is 0.9 centimetres with a count of 1282003. In general, 1909657 mesh elements were utilized to model the channel (figure 3).

Figure 4. Boundary conditions of FLOW-3D model.

In order to apply the boundary conditions, the *Symmetric* boundary condition was applied to the top boundary, the *Specified Velocity* boundary condition was applied as flow input and the *Outflow* boundary condition was applied to the downstream boundary. The *outflow* B.C. is applied to prevent the effects of the outside conditions of the solution network [28]. Also, the *Wall* boundary condition was defined for walls and channel bed which act as virtual frictionless walls [29]. Table 3 and figure 4 show application of boundary conditions to the airfoil-shaped pier model.

3.5 Characteristics of bed sediment grains

The mean diameter of the sediment particles should be such that the maximum amount of scour depth could be created; for this purpose, Melville [27] has stated that we should have $D/d_{50} > 25$ (D : the diameter of the pier, d_{50} : the average size of the sediment particles). Also, Lee and Sturm [30] stated that the minimum amount of D/d_{50} should be 25. Torabi and Shafieefar used similar ratio in their experiments [31]. In this research the piers diameter was selected to be $D = 20$ mm and the mean grain size was set as $d_{50} = 0.56$ mm (figure 5); so $G_S = 2.6$ and $D/d_{50} = 35.7$ were evaluated. Figure 5 shows the soil gradation graph for the bed sediments.

Table 3. Applied boundary conditions.

Software	Upstream boundary	Downstream boundary	Free surface boundary	Floor boundary	Lateral boundaries
FLOW-3D	Specified Pressure	Outflow	Symmetry	Wall	Wall

Figure 5. Soil gradation graph for the bed sediment grains.

4. Results and discussion

4.1 Verification of numerical results using experimental data

To validate and compare the results and determine the error limits between the data obtained from FLOW-3D with experimental results, Eq. (12) was exploited:

$$e = \frac{((d_s/D)_N - (d_s/D)_E)}{(d_s/D)_N} \times 100 \quad (12)$$

In which e is relative error, $(d_s/D)_N$ is the dimensionless depth of scouring in numerical solution and $(d_s/D)_E$ is the dimensionless form of the measured scouring depth in hydraulic laboratory. In this research simulation results in $L/D = 2.85$ were validated using experimental results of Hasanpoor *et al* [24]. Figure 6 and table 4 show the scouring progress with time and relative error percentages for the results of both experiments and simulations of the mentioned model.

Regarding figure 6 and numerical and experimental results of the airfoil-shaped pier model with $L/D = 2.85$, it can be seen that the maximum difference is 6.38%. However, there is pretty good accordance between numerical

Table 4. Relative error percentages of scouring progress with time for numerical simulation and experiments of aerofoil-shaped pier, $L/D = 2.85$.

$T^* = VT/D$	Experimental Data	FLOW-3D Data	Error (%)
	ds/D	ds/D	
3085.71	0/508	0/483	-5.18
4285.71	0/738	0/699	-5.61
20228/6	1.440	1.353	-6.38
23142/9	1.494	1.436	-4.06
33771/4	1.614	1.525	-5.81
37200.5	1.602	1.568	-2.18
54514.3	1.636	1.594	-2.83
81428.6	1.682	1.658	-1.47
95657.1	1.699	1.687	-0.70
107829	1.716	1.686	-1.79

and experimental results and it is reliable to extend the numerical simulations.

4.2 Comparison of scour progress with time for cylindrical and airfoil-shaped piers

Figure 7 shows the variations of scour progress with time for cylindrical and airfoil-shaped piers. It can be seen that the scouring hole depth increment at the first stage of simulations is too much and almost after 22 minutes from start ($T^* = 15480$) the process of scour hole depth progress is reduced.

Also, the comparison of the two piers shows that in airfoil-shaped pier and at a constant T^* (constant scour progress time), the scour amount and the scour depth progress are less than that of cylindrical pier. Also utilizing airfoil-shaped pier with $L/D = 2.85$ results in decreasing the maximum depth of scouring up to 15.78% compared to cylindrical pier.

4.3 Impact of length of airfoil-shaped pier on local scouring beneath the pier

Figure 8 shows scour hole progress with time for airfoil-shaped piers with various lengths.

Figure 6. Comparison of scouring progress with time for the numerical computation and experiments for aerofoil shaped pier, $L/D = 2.85$.

Figure 7. Comparison of scour hole progress with time for cylindrical and airfoil-shaped piers, $L/D = 2.85$.

It can be seen that rate of scour hole depth increment is very high at the beginning of simulations for all piers but after about 30 minutes ($T^* = 20468$) there is a considerable decrement in the rate of scour hole depth increment. Also, at a constant T^* , increasing the length of airfoil, causes a decrement in maximum depth of scour hole. Considering the sedimentation pattern around the piers, one can conclude that increasing the length of airfoil along the flow, results on controlling the scour behind the pier. Also, hole dimensions in airfoil-shaped pier with $L/D = 5$ is less than other models with less L/D ratios. It is evident that there is no scouring at the rear of piers because no wake vortices exist.

Figure 9 shows the percentage of maximum scour depth decrement in airfoil-shaped piers compared to cylindrical pier. It is seen that the maximum scouring depth decrease with increment of airfoil length and the pier with $L/D = 5$, shows the maximum decrement.

4.4 Impact of utilizing collar in airfoil-shaped pier

Karimaei and Zarrati [32] showed that the best results and efficiency of collar is when its width is twice the piers

diameter and it is installed at bed elevation. So in this research the collar is modelled at bed elevation and its width set to be twice the piers diameter. Figure 10 shows the scouring simulation process and the scour hole progress with time for airfoil-shaped pier with $L/D = 5$ with and without collar. It is seen that utilizing collar in airfoil-shaped pier has reduced the maximum scour depth in front of pier. Also utilizing collar in airfoil-shaped pier has fully controlled the wake vortices and almost there is no scouring behind the pier. Considering figure 10, it is seen that the presence of collar results on postponing the scour start time and this increases the balance time of scouring. The results of this study are in good agreement with results of Alabi [33].

Figure 11 shows scour hole progress with time in airfoil-shaped pier with various lengths of airfoils along with collar. It is seen that in presence of collar in airfoil-shaped piers, the scour process does not start until the minute 70 ($T^* = 46194$). This time would become more with increment of the airfoil length. Also, increasing the length of airfoil with collar has decreased the scour more than other models. It must be noted that increasing the length of airfoil with collar has resulted in increment of scouring balance time.

Figure 8. Comparison of scour hole progress with time for airfoil-shaped pier models with various lengths.

4.5 Impact of airfoil-shaped pier orientation in the flow direction

Figure 12 shows the scour hole progress for the airfoil-shaped pier with $L/D = 5$ (which showed less scour depth in previous sections in this research) placed in the flow direction and vice versa. It is seen that the airfoil-shaped pier which is placed opposite to the flow direction, (keen

nose in the front) weakens the horseshoe vortices. In this case, as a result, maximum depth of scour in front of pier compared to the normal state is decreased. Also because of presence of wide nose at the rear of pier and existence of wake vortices, scouring is started from the behind. However, scouring caused by horseshoe vortices in front of the airfoil-shaped pier, is much more than that of wake vortices. Finally, it can be concluded that to control the

Figure 9. Percentage of maximum scour depth decrement in airfoil-shaped piers compared to cylindrical pier.

scouring around bridge pier, that shape must be selected which can control and weaken the horseshoe vortices. In this research airfoil-shaped pier and placing it opposite to the flow direction showed the least local scouring.

Figure 13 shows the velocity pattern around airfoil-shaped pier and a cylindrical pier. It is seen that the velocity decreases because the flow collides the pier and because of the presence of horseshoe vortices the sediment particles start to move and transfer to the downstream. The important difference between the velocity patterns of cylindrical and airfoil-shaped piers is at the rear of piers. At the rear of airfoil-shaped pier (wide nose in the front) the negative velocity region (wake vortices region) is very small and sometimes the wake vortices do not appear at all. Comparing the velocity patterns of airfoil-shaped pier in flow

Figure 11. Scour hole progress with time in aerofoil-shaped pier with collar and various lengths of airfoils.

direction and opposite to the flow direction shows that the flow velocity is distributed at a wider region. Also, the velocity direction changes slightly, the horseshoe vortices are very weak and the scouring is less than that when the pier is along the flow. It should be noted that the negative velocity region at the rear is more than that for the pier is positioned along the flow.

Figure 14 shows the scour hole progress for the airfoil-shaped pier with $L/D = 5$ in the flow direction and vice versa with collar. It is seen that placement of airfoil-shaped pier opposite to the flow direction and with a collar would accelerate the scouring start time. But after a while, the wake vortices appear at the rear and as a result, produce scouring in the mentioned place. But scouring amount in

Figure 10. Comparison of scour profile and scour hole progress with time for aerofoil-shaped pier with and without collar.

Figure 12. Comparison of scour hole progress for airfoil-shaped pier in flow direction and opposite to the flow direction.

Figure 13. The velocity pattern around piers A: airfoil-shaped (along the flow direction), B: airfoil-shaped (opposite to the flow direction) and C: circular pier.

Figure 14. Comparison of scour hole progress for aerofoil shaped pier in flow direction and vice versa with collar.

front of the pier is more than rear in airfoil-shaped pier because of the presence of horseshoe vortices.

5. Summary and conclusions

Despite previous studies, investigation of the impact of bridge piers shape on scour control still needs more and extensive studies. In this research, the effect of utilizing airfoil-shaped pier on reducing the local scour has been investigated and the following results are achieved:

- The values and percentage of relative error of scour progress with time for airfoil-shaped pier with $L/D = 2.85$ and it can be seen that the maximum difference between the numerical and experimental results is 6.3%. So it can be concluded that there is a good agreement between numerical results and experimental data.
- In constant, values of T^* increasing the length of airfoil has decreased the maximum scour depth.
- The hole dimensions at the airfoil-shaped pier with $L/D = 5$ is less than other models because of more length of the airfoil. Also, due to lack of wake vortices, a few scouring occurs at the rear. With increasing the length of pier, the rate of maximum scour depth decrement increases and the pier with $L/D = 5$ has the most decrement (18.69%).
- Utilizing collar in airfoil-shaped pier reduces the maximum depth of scour hole in front of it. Also, the presence of collar at the rear of the airfoil-shaped

pier has fully controlled the wake vortices and no scouring is seen at the rear. It should be noted that the existence of collar causes the scouring to start with delay and this increases the balance time of scouring.

- It is seen that placement of airfoil in the flow path controls the scour depth at the rear.
- Investigation of the airfoil-shaped piers positioning style in the flow path showed that the pier which is placed opposite to the flow (keen nose in front) weakens the horseshoe vortices and as a result, the maximum scour depth reduces in front of the pier compared to the cylindrical pier. The placement of wide nose of the airfoil in rear and existence of wake vortices, scouring starts from the rear. But however, scouring in front of the airfoil-shaped pier is more than scouring at the behind of pier because of the presence of horseshoe vortices.
- Placement of airfoil-shaped pier with collar opposite to the flow direction accelerates the scouring process. However, after a while, this results in more reduction of scour depth. Finally, it is seen that to control scouring around bridge piers, the shape must be selected so as it can control and weaken the horseshoe vortices. Based on the results of this paper, the airfoil-shaped pier with collar and opposite to the flow placement (keen nose in front) shows the best performance in scouring reduction.

List of symbols

d_s	sediment size (m)
D	pier diameter (m)
L	pier length (m)
Y	flow depth (m)
T	experiment duration (s)
T^*	constant scour progress time (—)
V	flow velocity (m/s)
V_c	critical velocity (m/s)
g	gravitational acceleration (m/s^2)
ν	fluid kinematic viscosity (m^2/s)
ρ_w	fluid density (kg/m^3)
ρ_s	sediment particles density (kg/m^3)

References

- [1] Ben Mohammad Khajeh S, Vaghefi M and Mahmoudi A 2017 The scour pattern around an inclined cylindrical pier in a sharp 180-degree bend: an experimental study. *Int. J. River Basin Manag.* 15(2): 207–218
- [2] Ettema R, Constantinescu G and Melville B 2011 Evaluating of bridge scour research: Pier Scour Processes and Prediction. *Contractor's Final Report for NCHRP Project*. 01: 24–27
- [3] Copp Howard D 1988 *Scour at Bridge piers*. Washington D.C. Washington State Department of Transportation
- [4] Breusers N H C and Raudkivi A 1991 *Scouring. 2th Hydraulic Structures Design Manual*. Balkema, Rotterdam, Netherlands
- [5] Tafarojnoruz A, Gaudio R and Dey S 2010 Flow altering countermeasures against scour at bridge piers: a review. *J. Hydrol. Res.* 48(4): 441–452
- [6] Kumcu S Y, Kokpinar M A and Gogus M 2014 Scour protection around vertical-wall bridge abutments with collars. *KSCE J. Civ. Eng.* 18(6): 1884–1895
- [7] Mazumder M H and Barbhuiya A K 2014 Live-bed scour experiments with 45° wing-wall abutments. *Sadhana* 39(5): 1165–1183
- [8] Bauri K P and Sarkar A 2016 Flow and scour around vertical submerged structures. *Sādhanā* 41(9): 1039–1053
- [9] Dey S 1997 Local scour at piers, part 1: A review of development of research. *Int. J. Sediment Res.* 12(2): 23–44
- [10] Ismael A, Gunal M and Hussein H 2014 Use of Downstream-Facing Airfoil-Shaped Bridge Piers to Reduce Local Scour. *Int. J. Civ. Eng. and Tech.* 5(11). 44–56
- [11] Melville B W and Coleman S E 2000 *Bridge scour*. Highlands Ranch, Colorado. Water Resources Publications, LLC
- [12] Vaghefi M, Ghodsian M and Salimi S 2016 The effect of circular bridge piers with different inclination angles toward downstream on scour. *Sadhana* 41(1): 75–86
- [13] Guemou B, Seddini A and Ghenim A 2013 Numerical Investigations of the Bridge Pier Shape Influence on the Bed Shear Stress. *Electronic Journal of Geotechnical Engineering (EJGE)*, 18: 5685–5698
- [14] Abdelaziz S, Bui M D and Rutschmann P 2011 Numerical investigation of flow and sediment transport around a circular bridge pier. In: *Proc. 34th World Cong. Int. Assoc. Hydro-Environment Res. and Eng.* Engineers Australia. p. 3296
- [15] Ghasemi M and Soltani Gerdefaramarzi S 2017 The Scour Bridge Simulation around a Cylindrical Pier Using FLOW-3D. *J. Hydrosiences and Environ.* 1(2): 46–54
- [16] Wei G, Brethour J M, Gruenzner M and Burnham J 2014 The Sediment Scour Model in FLOW-3D. *Technical note FSI-14-TN-99 Flow Science*
- [17] Choufu L, Abbasi S, Pourshahbaz H, Taghvaei P and Tfwala S 2019 Investigation of flow, erosion, and sedimentation pattern around varied groynes under different hydraulic and geometric conditions: A numerical study. *Water* 11(2): 235
- [18] Daneshfaraz R, Ghaderi A and Ghahremanzadeh A 2015 An analysis of flowing pattern around T-shaped Spur Dike at 90° Arc, based on Fluent and Flow-3D Models. *International Bulletin of Water Resources and Development* 3(3): 1–9
- [19] Daneshfaraz R and Ghaderi A 2017 Numerical Investigation of Inverse Curvature Ogee Spillway. *Civil Engineering Journal* 3(11): 1146–1156
- [20] Daneshfaraz R, Joudi A R, Ghahramanzadeh A and Ghaderi A 2016. Investigation of flow pressure distribution over a stepped spillway. *Advances and Applications in Fluid Mechanics* 19(4): 811
- [21] Yakhot V, Orszag S A, Thangam S, Gatski T B and Speziale C G 1992 Development of turbulence models for shear flows by a double expansion technique. *Physics of Fluids A: Fluid Dynamics* 4(7): 1510–1520
- [22] Zahabi H, Torabi M, Alamati E, Bahiraei M and Goodarzi M 2018 Effects of geometry and hydraulic characteristics of shallow reservoirs on sediment entrapment. *Water* 10(12): 1725
- [23] Shamohamadi B and Mehboudi A 2016 Analyzing parameters influencing scour bed in confluence channels using Flow3D numerical model. *Civ. Eng. J.* 2(10): 529–537
- [24] Hasanpour N, Hosseinzadeh Dalir A and Arvanaghi H 2012 Investigation of Local Scour around Airfoil-shaped Pier with Collar. *Sci. Soil and Water* 23(3): 221–234. (in Persian)
- [25] Chiew Y M 1995 Mechanics of riprap failure at bridge piers. *ASCE J. Hydrol. Res.* 121(9): 635–643
- [26] Najafzadeh M, Barani G A and Kermani M R H 2013 Abutment scour in clear-water and live-bed conditions by GMDH network. *Water Sci. and Technol.*, 67(5): 1121–1128
- [27] Melville B W 1997 Pier and abutment scour: integrated approach. *ASCE J. Hydrol. Res.* 123(2): 125–136
- [28] Daneshfaraz R, Ghahramanzadeh A, Ghaderi A, Joudi A R and Abraham J 2016 Investigation of the Effect of Edge Shape on Characteristics of Flow under Vertical Gates. *Journal-American Water Works Association* 108(8): 425–432
- [29] Daneshfaraz R, Minaei O, Abraham J, Dadashi S and Ghaderi A 2019 3-D Numerical simulation of water flow over a broad-crested weir with openings. *ISH Journal of Hydraulic Engineering* 1–9
- [30] Lee S O and Sturm T W 2009 Effect of sediment size scaling on physical modeling of bridge pier scour. *ASCE J. Hydrol. Res.* 135(10): 793–802
- [31] Torabi M A and Shafieefar M 2015 An experimental investigation on the stability of foundation of composite vertical breakwaters. *Journal of Marine Science and Application* 14(2): 175–182

- [32] Karimae Tabarestaai M and Zarrati A R 2012 Effect of collar on time development and extent of scour hole around cylindrical bridge. *Int. J. Eng.* 25(1): 11–16
- [33] Alabi P D 2006 *Time development of local scour at a bridge pier fitted with a collar*. Master Degree Thesis. University of Saskatchewan. CA