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Investigation of the Effect of Plate on Reducing the Scour around Spindle-Shaped Bridge Pier

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ABSTRACT

Objective: The problem of erosion is among the most significant topics in the field of river engineering. Every year, a large number of bridges around the world are destroyed, mainly due to the lack of hydraulic role in their design. Methods of controlling and reducing local scour include the use of roughness, collars, submerged plates and protective piles.

Material and Methods: In the present study, the effect of submerged plates in controlling and reducing scour around the spindle-shaped pier has been investigated. In this research, plates with different angles of 15, 30 and 45 degrees were used in single, two and three rows with different flow rates.

Results and Discussion: The experimental results showed that by installing 45-degree plates with 1, 2 and 3 rows, we see 23.3, 40.5 and 43.8% reduction of scouring compared to the pier without plate. As the number of rows increases, the sediment displacement and accumulation in front of the bridge pier increases, which ultimately reduces scouring. By installing three rows of plates with angles of 15, 30 and 45 degrees to the direction of flow, we see 32.8%, 39.7% and 43.8% reduction of scouring compared to the pier without a plate.

Conclusion: By increasing the angle of the plates along the stream, their effective length increases and thus increases the sediment displacement by them, which results in more sediment being transferred to the front of the base and better scour control. Additionally, the simulation using the Flow-3D mathematical model closely aligns with the physical model, yielding an RMSE of 0.0392.

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1. Introduction

Every year, a large number of bridges are destroyed with the incidence of floods in every river just when they are most needed. One of the most effective causes of these destructions is local scouring around the piers. Demolition of piers due to scouring entails heavy economic and side losses (Landers, 1992). So far, several researchers have studied the problem of scouring, which have not yet been able to provide a single solution to calculate the depth of scouring due to the complexity and multiplicity of factors governing the phenomenon. Factors such as the shape of the channel, the characteristics of the stream, the shape of the pier and the angle of its establishment relative to the flow and the characteristics of the sediments are all factors that contribute to the complexity of the scouring of bridge foundations (Dongel and Melville, 1994). It should be noted that the final scour depth created in the vicinity of the bridge pier is equal to the sum of the erosion depths due to local, general scouring and narrowing of the flow width (Sadeqlu and Hamidi, 2022). The processes of water movement and sediment transport in the rivers due to changes in the bed and sides, create a wide variety of shapes according to the lithology and topography of each area in the plan. The piers disturb the normal flow of the river, and the resulting turbulence erodes the sediment around the foundation. The erosion hole created around the pier depends on its shape and geometric characteristics. In addition, the type of river bed constituents as well as the hydraulic conditions of the stream, such as the occurrence of flood conditions and the passage of dunes, affect the depth of the erosion hole (Dongel and Melville, 1994). The issue of scouring around the bridge pier has occupied the minds of researchers for many years. As local scouring around the bridge pier is considered one of the most important factors in its destruction. This problem exists all over the world and has the potential to cause tragic and humane consequences. Estimates indicate that 60% of bridge failures are due to scouring and hydraulic factors (Landers, 1992).

Therefore, recognizing the phenomenon of scouring and applying the necessary measures to reduce scouring and control it is very important. Among the studies that have been done on protective structures to control and reduce the scour depth around the bridge piers, the following can be mentioned.

Hosseini et al. (2011) investigated the use of submerged plates to control the scour around the rectangular bridge piers with round angles. In this research, the effect of submerged plates to reduce the scour of rectangular piers with round angles was investigated. Experiments were performed on piers with angles of 0, 5 and 10 degrees to the flow direction and submerged plates with different arrangements. The results showed that by increasing the angle of the pier to the direction of the flow, the effect of submerged plates to reduce the scour is reduced. The maximum scour reduction for the pier with 0, 5 and 10 degrees with submerged plates with a height of 5.2 cm above the river bed and an angle of 30 degrees to the flow direction was about 57.45, 76.39 and 78.27 percent, respectively.

Mahmoudi and Heydarpour (2016) investigated the effect of protective piles in controlling and reducing the scour around cylindrical piers. In this research, a laboratory flume with a length of 8 meters, a width of 0.4 meters and a height of 0.6 meters made of plexiglass with a thickness of 2 cm was used in the hydraulic laboratory of the water engineering department of Isfahan University of Technology. In this study, all experiments were performed at a water flow rate of 21 liters per second, a depth of 17 centimeters, and a ratio of $V/V_c=0.9$. The water at the bottom of the flume was filled with siliceous non-sticky round-grain sand particles with a geometric standard deviation of 1.2 and a granulation with an average diameter of 1.4 mm to a height of 12 cm. In this study, a fixed number of 5 protective piles were used in a triangular arrangement. Most of the parameters of the arrangement of the piles were considered fixed and only by changing the two main parameters, the apex angle and the horizontal distance, the piles are distinguished from each other. The arrangements tested at two angles of 30 and 45 degrees and the horizontal distance of the piles from each other, 0.7, 1 and 1.3 times the diameter of the pier, have been tested and compared on the pier with a diameter of 3 cm. The results of the tests showed that the efficiency of the piles increases by reducing the vertex angle or reducing the horizontal distance of the piles.

Ghasemi and Soltani-Gerdfaramarzi (2017) simulated the scour of the bridge pier using Flow-3D software. In this research, hydraulic parameters including velocity, fluid depth, Froude number, etc. were investigated. The results showed that the maximum scour depth at the flow rate of 5, 10, 19 and 30 liters per second is equal to 0, 1.3, 2.4 and 3.6 cm. It was also observed that most scouring is occurred at upstream and less scouring is occurred at downstream.

Wang et al. (2019) investigated the scour protection of cylindrical piers using collars in the physical model. In this study, sediment particles with an average diameter of 0.324 mm were used. Experiments without collars and with collars at different depths and diameters were performed. The results showed that using the collar reduces scouring but as the height of the collar increases, the protective effect decreases. Also, the scour decreases with increasing collar diameter. Namaee et al. (2019) investigated the scouring of the bridge support in frozen conditions in a physical model. The experiments were performed on four pier diameters of a circular bridge with three sediment particles of 0.47, 0.5 and 0.57 mm. The results showed that smaller piers have less scouring. Also, the maximum scour rate has decreased with increasing the diameter of sediment particles on the floor. Moussa et al. (2018) investigated the effect of blockage and scouring on bridges with multi-vent piers in physical and mathematical models. The presence of blockages such as garbage and industrial waste increases the depth of scour around the bridge pier and even causes the failure of the bridge. In this research, software (SSIIM) with the k-e turbulence model was used. The results showed that the depth of local scouring with impermeable blockages depends on the Froude number and the dimensions of the barrier. It was found that the depth of local scouring of the impermeable blockage in front of a bridge pier depended on the Froude number and the dimensions of the barrier. His results showed that there is enough similarity between both numerical and statistical simulations with the physical model. Chen et al. (2018) investigated the effect of collars on bridge scour. The experiments were performed using a collar with a width of 1.25 times the pier width of the bridge and a depth of 0.25 times the pier width of the bridge. Their results showed that the collar at a depth of 0.25 of the pier width of the bridge was more effective in reducing the scour depth. Laboratory tests and numerical studies show that in experiments with the collar, the downstream flow and horseshoe vortex are greatly reduced compared to cases where there is no collar. Also, the maximum energy of turbulent movement is reduced.

Nohani and Ebrahimi (2019) conducted a laboratory experiment on the effect of using the collar and submerged plates together on the reduction of scour depth of cylindrical bridge piers. In this research, with laboratory modeling, the effect of using collar and submerged plates together on the reduction of scour depth of cylindrical piers was investigated. The results showed that the submerged plates by affecting the flow lines and the collar by protecting the pier against downward vortices and horseshoe vortices are suitable tools to reduce scour depth in cylindrical piers.

Niknam et al. (2022) conducted a laboratory experiment on the effect of piles in reducing the scour around spindle-shaped bridge piers. In this research, the effect of protective piles in controlling and reducing the scour around the spindle-shaped piers was investigated. The result of the experiment showed that by installing 5 piles at an angle of 30 degrees and with a relative distance of 0.5=(L/D), there was a 20% reduction in scour compared to the spindle-shaped pier without any pile. The scour reduction was due to the transfer of sediments around the pile towards the pier and accumulation of sediments in the middle of the piles and front of the spindle-shaped piers. Another reason for the scour reduction was the change in the flow regime and the reduction of the velocity and vortex in front of the spindle-shaped pier.

Despite the fact that researches have been done on protecting the cylindrical bridge pier using plates, no research has been done on using plates to protect the spindle-shaped piers. Therefore, this research is done by adding the plate in front of the spindle-shaped pier and by changing the angle and number of rows in order to reduce the formation of vortices and turbulent flows and by using laboratory model and mathematical model.

2. Materials and Methods

2.1. Experimental Procedure

For this laboratory study, a rectangular-section flume with a width and height of 0.5 and 0.6 m made of Plexiglas in the Islamic Azad University of Ahvaz was used (Figure 1). The length of the straight section at the beginning and end of the flume is 4.5 and 2.5 meters, respectively. The inlet path of the flume was considered straight to create a uniform flow. Also, the floor is made of sheet metal with a thickness of 3 mm and the walls are made of Plexiglas with a thickness of 10 mm and a length of 4.5 meters, which also reduces the effect of wall roughness, and hydraulic phenomena are visible in the reservoir. The output path is also direct and its floor is made of a metal sheet with a thickness of 3 mm and its wall is made of plexiglas with a thickness of 10 mm with a length of 2.5 meters).

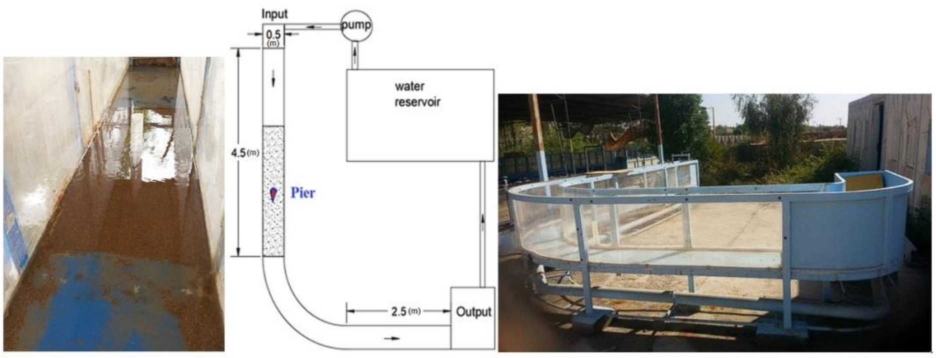

Figure 1- View of the laboratory flume and its plan

After the flume reservoir, a sliding valve has been used to adjust the input flow of the flume. A 90-degree triangular overflow has been installed to measure the inlet flow. A mesh has been used after the initial overflow to prevent waves from entering the channel (Figure 2).

Figure 2- Triangular inlet and outlet overflows with 90-degree vertices, at the beginning and end of the flume.

An 11 kw centrifugal pump with suction pipe diameter and 6-inch flow was used to circulate the water in the laboratory flume according to the desired flow rate. The suction height of the pump is approximately 2 meters and its draft height is about 6 meters and the maximum flow rate can be transferred by the pump is 60 lit/sec.

To maximize scouring, all experiments were performed under clear water conditions. Based on this condition, the relationship V/Vc < 1 holds, where V represents the average flow velocity and Vc denotes the critical velocity at which particle sediment motion begins. (Chiew, 1992).

To calculate Vc the condition of the flume was considered without the bridge pier and the plate. By keeping the flow depth constant and by increasing the flow rate, the flow velocity accelerated. The process of accelerating the flow was continued until the movement of sediment particles started. The flow velocity that caused the movement threshold of sediment particles was considered as critical velocity, which is equal to Vc =0.125 (m/s).

In all the experiments, the flow was uniform and subcritical. The spindle bridge piers will be made of Plexiglas. According to Donat (1995) and Link et al. (2019) studies, the maximum pier diameter of the bridge should be between 10-20% of the flume width. According to the research of Olivto et al. (2002) in order to prevent the effects of roughness, the flow depth should be considered more than 20 mm. The schematic of the spindle bridge pier with the plate has been shown in Figure3.

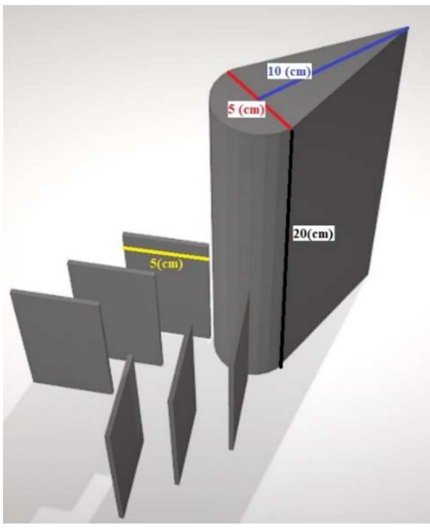

Figure 3- Schematic of a spindle-shaped bridge pier with plates

The diameter of the bridge pier was 5 cm and its height was considered to be 20 cm to prevent immersion.

2.2. Bed materials

Sediment particles made of non-cohesive natural sand with a specified diameter and uniform grading were considered as a bed on the floor of the flume. To establish the condition of particle uniformity, there should be $\sigma_g = \sqrt{\frac{d_{84}}{d_{50}}} < 1.3$, where σ_g indicates the geometric standard deviation. The more uniform the particle size distribution, the larger the scouring dimensions (Ettema et al., 1991). If there is a change in uniformity, the scouring results will change. Other researchers can do research in this area.

Regarding the size of sediments, different criteria have been mentioned. According to the research conducted by Dongel and Melville (1994), for the size of sediments not to affect the depth of scour and to prevent the formation of bed form, the condition $\frac{L_a}{d_{50}} > 25$ should be considered, where L_a is the length of the support (dimension perpendicular to the flow) and d_{50} represents the average diameter of sediment particles (Dongel and Melville, 1994). To establish the condition of particle uniformity, there is $\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} < 1.3$, where σ_g indicates the standard deviation of sediments (Melville, 1992). According to Raudkivi (1988), the average particle diameter should be greater than 0.7 mm to prevent ripple formation. Therefore, sediment particles of non-cohesive natural sand with an average diameter of 1.37 mm, geometric standard deviation of $\sigma_g = 1.13$ and a density of 2.65 were selected. The diagram of sediment particles grading by the sieving method is shown in Figure 4.

2.3. Thickness of bed materials

Chiew and Melville (1999) have stated that the maximum scouring at 2.4 D, which in this study is 12 cm, was selected as 20 cm for more certainty.

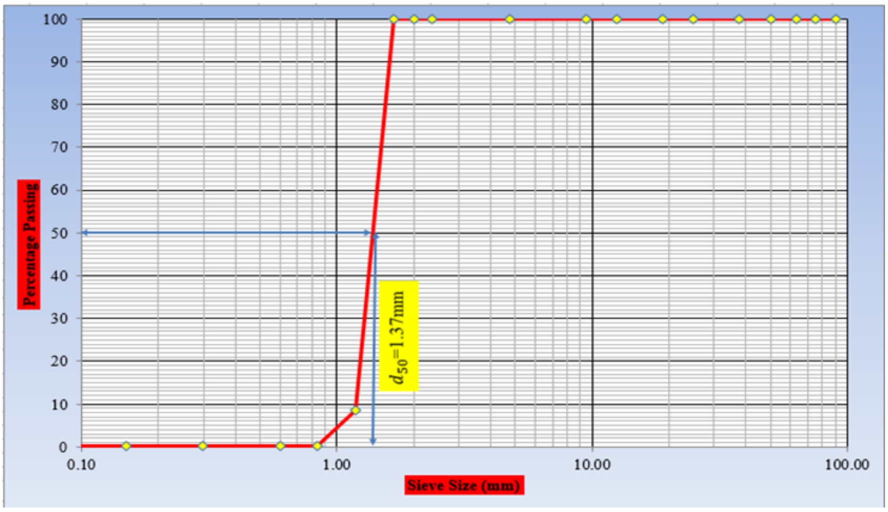

Figure 4- grain size distribution

2.4. Dimensional analysis

Factors related to channel geometry: channel width (B), longitudinal slope of the flume (S)Characteristics of flow hydraulic conditions: upstream flow rate (U), flow depth (y) and gravity acceleration (g).

Sediment specifications: average sediment diameter (d50), sediment density (s), sediment scour depth (ds)

Fluid specifications: specific gravity (ρ) and dynamic viscosity (μ)

Therefore, it can be written:

$$f(S_0.B.\theta.D,S,U,y.g.d_{50}.d_s,\rho,\mu) = 0 \quad (1)$$

D: Pier diameter

If the three variables of flow depth (y), flow velocity (U) and specific gravity of fluid (ρ) are selected as iterative factors, we can write based on Buckingham's dimensional analysis that:

$$f\left(S_0.\frac{B}{Y}.\delta.\theta.\frac{d_{50}}{Y}.\frac{\rho_s}{\rho}.\frac{d_s}{Y}.\frac{\mu}{\rho uy},\frac{u^2}{gy}\right) = 0 \quad (2)$$

In this study, the longitudinal slope of the flume is close to zero, the central angle of the arc is constant in all experiments, so they can be ignored. Also, due to the constant size and material, the

type of fluid and the depth of flow, the $\frac{d_{50}}{Y}$ and $\frac{\rho_s}{\rho}$ ratios can be neglected in all experiments. Finally, it can be written that:

$$d_s/D = f(\theta,N,F_r) \quad (3)$$

Figure 5 shows the pier plan of a spindle-shaped bridge with a plate.

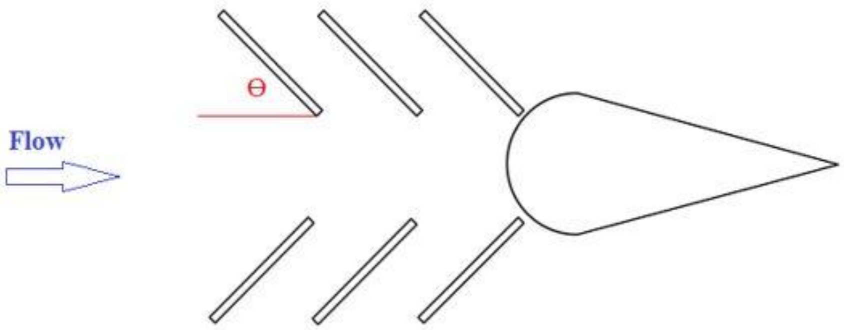

Figure 5- Plan of the spindle-shaped bridge pier with plate

Experiment variables include:
Plate angle (ϴ) (3 variables)
Number of rows of plates (1, 2 and 3 rows) (N) (3 variables)
Flow rate (Fr) (5 variables)

The test variables have been given in Table 1.

Table 1- Test variables

Number of tests	Control tests	(Fr)	Number of rows of plates (N)	Angle of the plates (Θ)
50	5	5 variables	1, 2, 3 rows (3 variables)	15 ,30 and 45 degrees (3 variables)

Experiments include 45 tests with installing plate and 5 control tests without the plate. A total of 50 experiments have been performed.

Laser meters will be used to measure scour depth and sediment topography.

2.5. Duration of the experiments

The duration of the experiment was chosen to be equal to the Ettema (1980) criterion, which is the time when changes in scouring depth over 1hour are less than one millimeter. Figure 6 shows the time development diagram for the control pier (cylindrical pier). According to the diagram in Fig. 6, it can be seen that the changes in scour depth are large at first, but gradually decrease over time. Due to the occurrence of most of the scouring in the first 6 hours of the experiment, this time was considered the same for all experiments. As a result, according to the above criteria and the calculation of the critical speed, considering the flow depth equal to 16 cm and the flow rate of 9 lit/sec, the condition of V/Vc = 0.9 was established in the experiments.

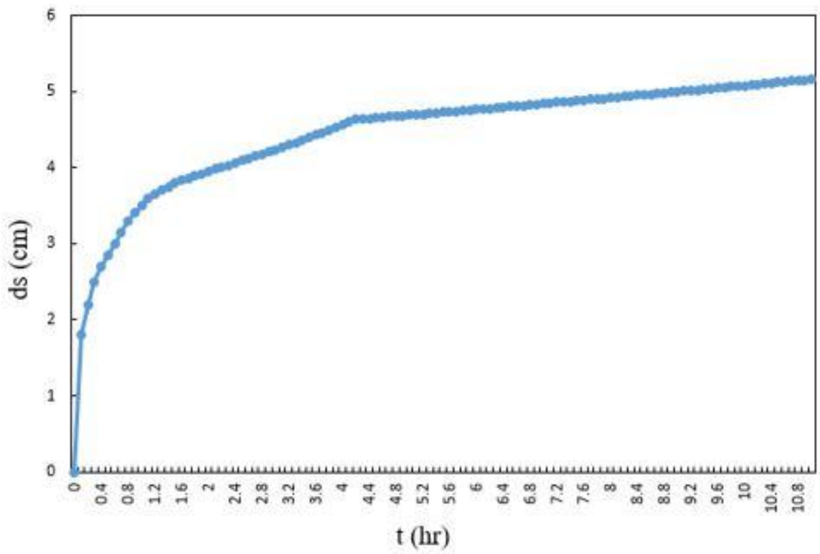

Figure 6- Diagram of time extension of scouring

2.6. Scouring profile mapping tool

For this purpose, a laser meter with an accuracy of 1 mm and 2 bean levels was used, which was marked on a metal frame whose length and width have been marked at intervals of 5 cm and was located at a height of approximately 69.5 cm from the floor. Since there is always the maximum possible velocity in each section in the center line of the flow width, the frame was placed on the channel, and after fixing the width in the center line, by moving the plate on which the laser meter was installed along the flume, with specified longitudinal distances, the height corresponding to these points was determined using the meter in millimeters. The following formula was used to obtain the difference in height of the points.

$$Z = -\left(\frac{Z_s}{10}\right) + \left(\frac{Z_0}{10}\right) \tag{4}$$

Where, Z represents the height of the surface of the scour profile at a specific point in centimeters, Z_s represents the height read by the laser meter in millimeters after the test, and Z_0 represents the initial height read by the laser meter before the test in millimeters.

2.7. FLOW-3D model

It is one of the most powerful models in the field of fluid dynamics, developed and supported by Flow science, Inc. Recently, this model has been widely used in research and industry.

This model is capable of three-dimensional analysis of the flow field and has a very wide range of applications in fluid problems. The governing equations in this model are Navier-Stokes equations and mass survival equations and five different methods are used to solve the turbulence.

This software has the ability to analyze two-dimensional or three-dimensional flow field in volume. This software uses orthogonal three-dimensional elements and has special capabilities in creating a flow barrier.

The Flow-3D model includes many physical patterns, including shallow water, viscosity, cavitation, turbulence, porous media, and more. This model is used in fields such as casting, process engineering, hydraulics, environment, aerospace, marine science, oil, gas, etc.

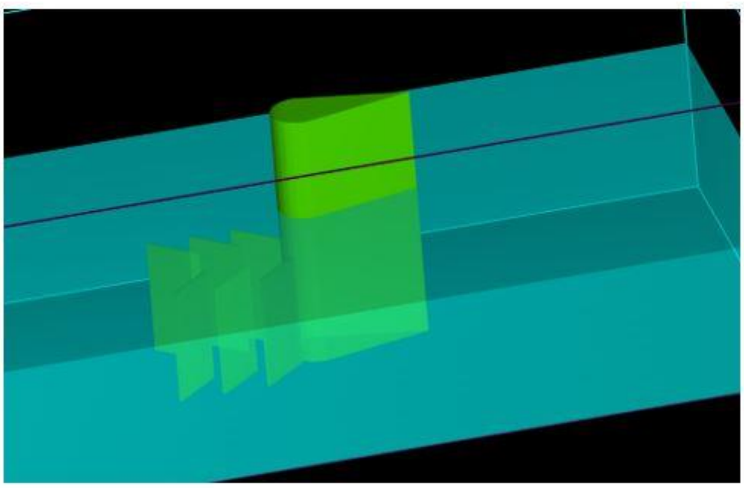

Figure 7- Simulation of a spindle bridge with a plate in a mathematical model

The Wall option was used for the boundary conditions for the side walls and the floor of the flume. The pressure condition for the top boundary was free, for the inlet, the flow was considered constant and for the outlet, the depth was considered constant. By using calibration and checking the correct results, the meshing error was considered to be 0.01 mm for all three xyz axes.

3. Results and Discussion

The results of this study include the evaluation of flow velocity (Froude number), changing the angle of the plates and changing the number of rows of plates on the scour of the spindle-shaped bridge pier, so that the results are divided into 5 sections:

- Investigation of the effect of increasing the flow velocity on the sediment pattern around the unprotected spindle-shaped bridge pier;
- Investigation of the number of rows of plates on the sediment pattern around the spindle-shaped bridge pier;
- Investigation of the effect of plate angle on the sediment pattern around the spindle-shaped bridge pier;
- Investigation of the effect of increasing the Froude number on the sediment pattern around the spindle-shaped bridge pier with plates.
- Simulation of the effect of plates on the scour of the spindle-shaped pier using Flow-3D mathematical model and comparing its results with the results of the physical model.

Figure 8- Pictures of scouring

3.1. The effect of increasing the flow velocity on the sediment pattern around the unprotected spindle-shaped bridge piers

After the experiments, the data needed to analyze the results were collected, which are shown in the following diagrams. In the following, the effect of flow velocity on the sediment pattern around the unprotected spindle-shaped bridge piers has been investigated.

In this section, the control of spindle shaped bridge piers is without protection, in order to compare it with spindle shaped bridge piers with plate protection. In this way, the impact of the plates on reducing or increasing the scour around the spindle-shaped bridge piers can be determined.

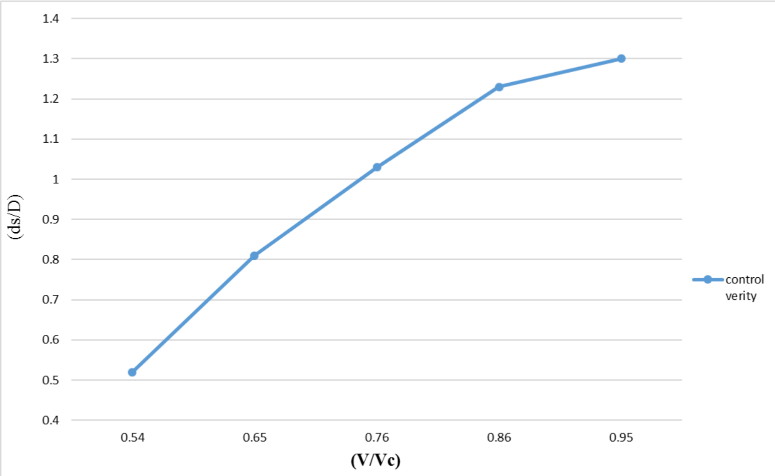

Figure 9- Diagram of the effect of dimensionless flow velocity on the sediment pattern around the unprotected spindle-shaped bridge pier.

In the diagram of Fig. 9, it can be seen that with acceleration of the flow velocity, the amount of scour around the spindle-shaped bridge piers without protection has increased.

With increasing relative velocity (V/Vc) from 0.54 to 0.95, the relative scour rate (ds/D) has increased from 0.52 to 1.3, which indicates a 150% increase in scouring.

3.2. Investigation of the number of rows of plates on the sediment pattern around the spindle-shaped bridge pier

By performing the experiments, the data needed to analyze the results were collected, which have been shown in the following diagrams. In the following, the effect of the number of rows of plates on the sediment pattern around the spindle-shaped bridge pier has been examined. In this research, the plates have been placed in three modes with the number of rows 1, 2 and 3 rows.

Table 2- the effect of the number of rows with 15-degree panels on the scour rate(ds/D)

(V/Vc)	control	1	2	3
0.54	0.52	0.47	0.41	0.32
0.65	0.81	0.69	0.64	0.51
0.76	1.03	0.88	0.81	0.69
0.86	1.23	1.05	0.96	0.85
0.95	1.3	1.16	1.02	0.92

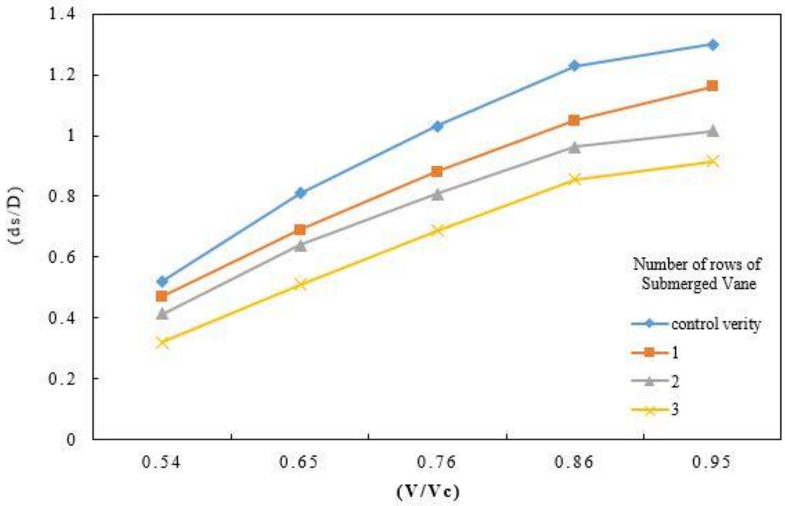

Figure 10-Diagram of the effect of the number of rows of 15-degree plates on the scour rate.

By analyzing the diagram in Fig. 10 and also Table 2, it can be seen that by installing the plate on the spindle shaped bridge pier, the scour rate has decreased. From the results, it can be understood that with the increase in the number of rows of plates, the scour rate has decreased. By installing 15-degree plates and with the number of rows of 1, 2, and 3, we see a 13.1, 21.5, and 32.8 percent reduction respectively in the scour compared to the pier without plates.

Table 3- The effect of the number of rows of 30-degree plates on the scour rate

		(ds/D)		
(V/Vc)	control	1	2	3
0.54	0.52	0.42	0.25	0.23
0.65	0.81	0.66	0.49	0.44
0.76	1.03	0.85	0.69	0.62
0.86	1.23	1.02	0.90	0.80
0.95	1.3	1.08	0.97	0.86

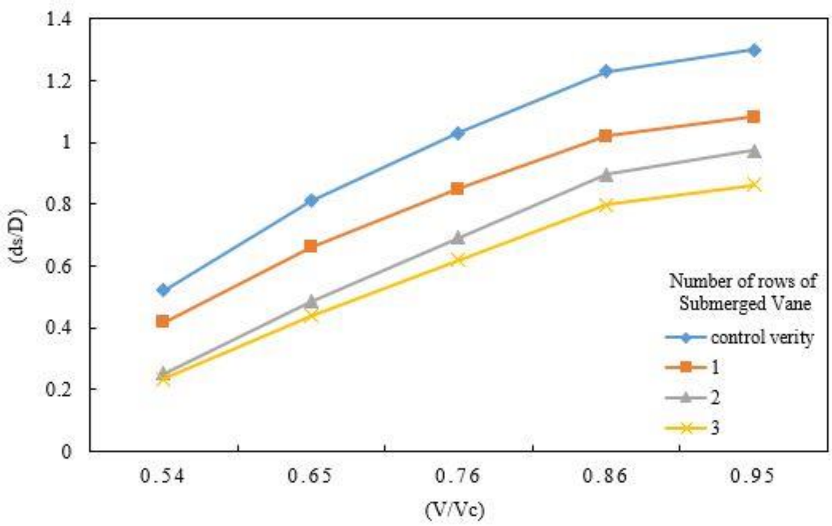

Figure 11- Diagram of the effect of the number of rows of 30-degree plates on the scour rate.

By installing 30-degree plates and with the number of rows of 1, 2 and 3, we see a 17.6, 32.5 and 39.7 percent reduction respectively in the scour, compared to the pier without plates. The amount of scour reduction can be seen in Table 3 and Figure 11. From the results, it can be understood that with the increase in the number of rows of plates, the scour rate has decreased.

Table 4- The effect of the number of rows of 45- degree plates on the scour rate

		(ds/D)		
(V/Vc)	control	1	2	3
0.54	0.52	0.39	0.21	0.20
0.65	0.81	0.62	0.42	0.40
0.76	1.03	0.79	0.61	0.58
0.86	1.23	0.91	0.80	0.74
0.95	1.3	1.04	0.87	0.83

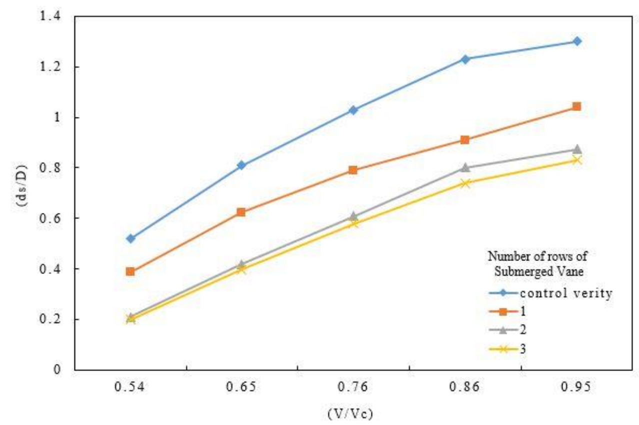

Figure 12- Diagram of the effect of the number of rows of 45-degree plates on the scour rate.

By examining the diagram in Figure 12 and Table 4, it can be seen that with the increase in the number of rows of plates, the scour rate has decreased. By installing 45- degree plates and with the number of rows of 1, 2 and 3, we see a 23.3, 40.5 and 43.8 percent reduction respectively in the scour, compared to the pier without plates.

At the beginning of the experiment, first-generation vortices began to operate at the back of the pier. Due to the collision of the flow with the plates, the scouring process was first observed in the front edge of the first row plates and with the development of the cavity in this area and its movement towards the inside of the plates, the sediment transfer rate was gradually increased. These sediments are moved behind them by vortices created at the edges of the plates, and given the fact that this area is a low pressure area, some sediments are collected in this area and some are transferred downstream by the flow. In the first hour of the experiment, the displaced sediments were collected from the first and second row plates at the end of the second row plates. These sediments were gradually washed away by the flow and transferred to the front of the pier, thus controlling the scouring process in the front of the pier. As the number of rows increases, the sediment displacement and accumulation in front of the bridge pier increase, which ultimately reduces scouring.

3.3. The effect of the angle of the plates on the sediment pattern around the spindle-shaped bridge pier

After performing the experiments, the data needed to analyze the results were collected, which are shown in the following diagrams. In the following, the effect of the angle of the plates with respect to the horizontal axis on the sediment pattern around the spindle-shaped bridge pier has been investigated. In this research, 15-, 30-, and 45-degree angles have been considered for plates with different rows. In this research, the plate is divided into three modes: single-row, double-row and three-row. It should be noted that each row consists of two symmetrical plates installed at different angles.

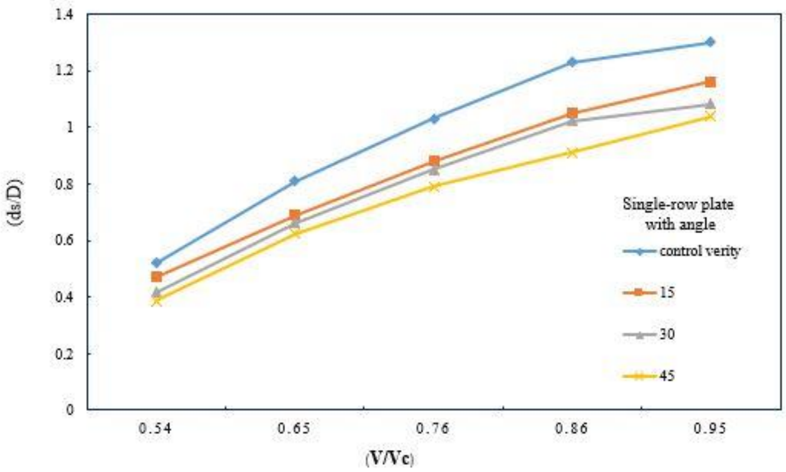

Figure 13- Diagram of the effect of single-row plate's angle on scour rate.

According to the diagram in Fig. 13, it can be well seen that the scour rate has been reduced by installing the plate on the spindle-shaped bridge pier. According to the results, it can be seen that the scour rate has decreased with increasing the angle of the plates relative to the flow direction. By installing a row of plates with an angle of 15, 30 and 45 degrees relative to the direction of flow, we see a 13.1%, 17.6% and 23.3% reduction of scouring compared to the pier without a plate.

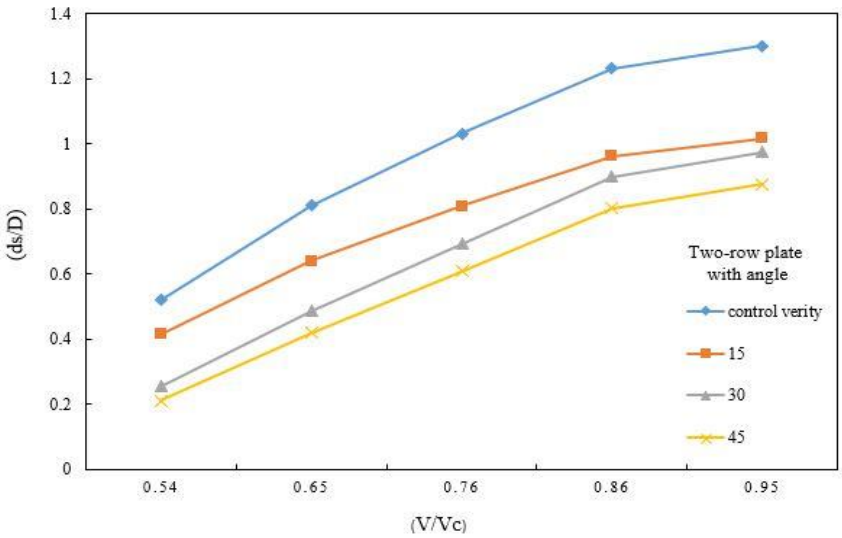

Figure 14- Diagram of the effect of the angle of two-row plates on the scour rate.

According to the diagram in Figure 14, it can be well seen that the scour rate has been reduced by installing the plate on the spindle-shaped bridge pier. From the results, it can be seen that the scour rate has decreased with increasing the angle of the plates relative to the flow direction. By installing two rows of plates with angles of 15, 30 and 45 degrees to the direction of flow, we see 21.5, 32.5 and 40.5% reduction of scouring compared to the pier without plates, respectively.

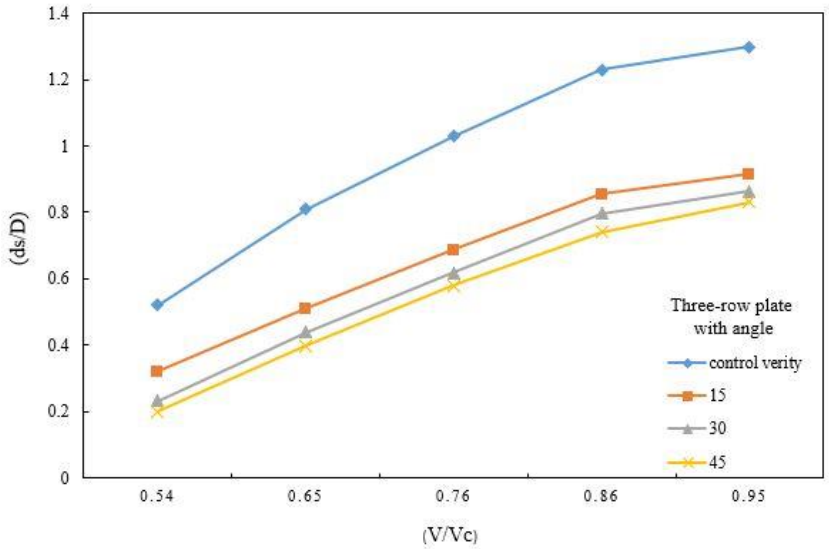

Figure 15- Diagram of the effect of the angle of three-row plates on the scour rate

According to the diagram in Figure 15, it can be well seen that the scour rate has been reduced by installing the plate on the spindle-shaped bridge pier. From the results, it can be found that the scour rate has decreased with increasing the angle of the plates relative to the flow direction. By installing three rows of plates with angles of 15, 30 and 45 degrees to the direction of flow, we see 32.8%, 39.7% and 43.8% reduction of scouring compared to the pier without plate.

By increasing the angle along the flow, the scour rate decreases, because by increasing the angle of the plates along the flow, their effective length increases and thus the sediment displacement by them increases, which results in the transfer of more sediment to the front of the pier and better control of scouring.

3.4. The effect of relative velocity changes on scour rate around the spindle-shaped bridge pier with the presence of plate

In this section, the effect of velocity change on the scour rate has been investigated.

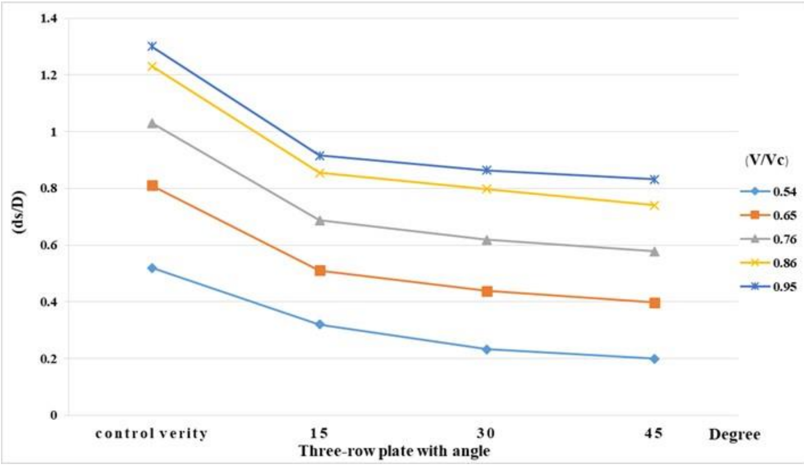

Figure 16- Diagram of the effect of relative velocity on the scour rate

According to the diagram in Figure 16, it can be well seen that by increasing the relative velocity (V/Vc) from 0.54 to 0.95 on average, the scour rate has increased by 207.2%. The water flow after colliding with the aerodynamic pier and creating a downward flow and scouring, which also increases the velocity of the flow has increased the vertical velocity and vertices and increased scour rate.

3.5. Comparison of physical model and simulation results with Flow-3D software

In the following, the results of the physical model and simulation with Flow-3D software will be compared. Because the initial conditions of the simulation are the same as the physical model therefore, the results of the physical model and the Flow-3D mathematical model can be compared.

To calibrate the model, the experiments were performed using observational data and in different modes of roughness coefficient and turbulence models. According to the results obtained from the calibration tests, the least error in the tests was obtained using the Manning roughness coefficient of 0.035 and the Prandtl Mixing Length Mode turbulence model. The error rate in this mode is -1.45%.

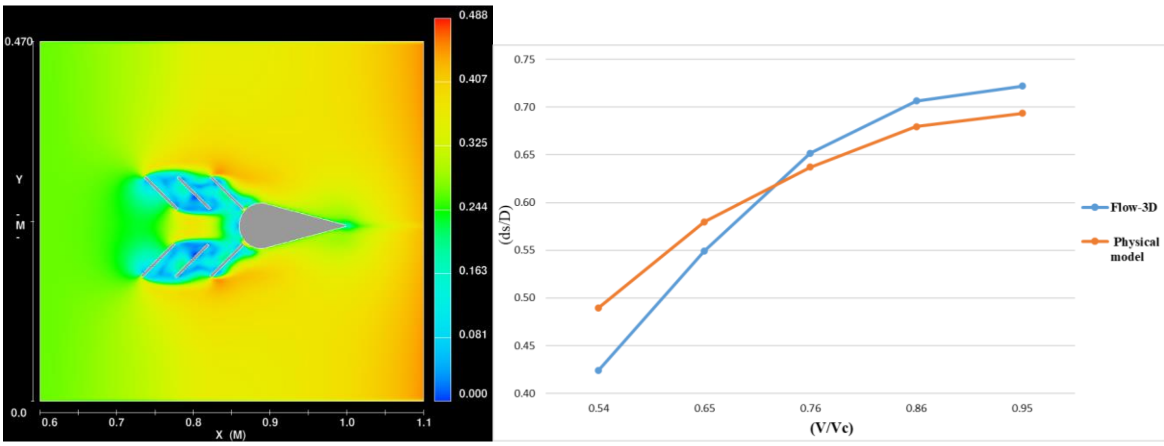

Figure 17- Comparison chart of Flow-3D simulation and physical model with plate.

As shown in Figure 17, Flow-3D simulation results show that the simulation with the Flow-3D mathematical model is close to the physical model, and on average it has only 5.4% error which is acceptable. Also, comparing the simulation results with the physical model shows that by increasing the velocity, the results of simulation with the Flow-3D mathematical model deviate less with the physical model and becomes closer to reality.

3.6. Comparison with other studies

In this section, the results of this research were compared with the work of Mahmoudi and Heydarpour (2016) and Niknam et al. (2022).

The same test conditions were considered for accurate comparison. The results of the experiment are with a three-row plate with an angle of 45 degrees.

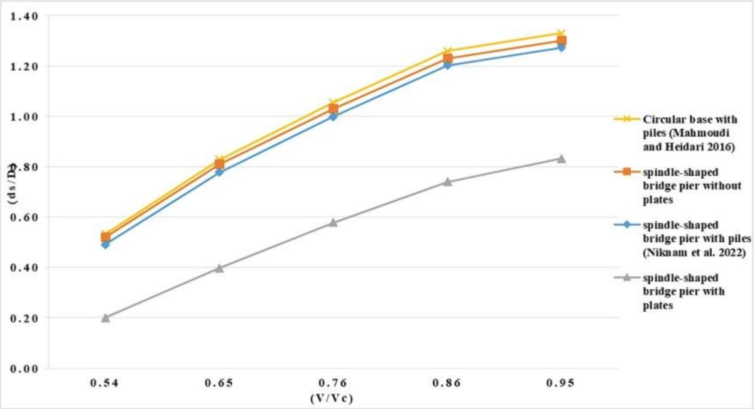

Figure 18- The diagram of comparing with Mahmoudi and Heydarpour's research (2016) and Niknam et al.'s research (2022)

In the diagram of Figure 18, this research is compared with the research of Mahmoudi and Heydari (2016) and the research of Niknam et al. (2022). The results clearly show that the spindle-shaped pier had 1.7% less scour rate than the circular-shaped pier. Also, by installing a three-row submerged plate in front of the spindle-shaped pier, the amount of scour is 82% less than the circular shaped pier with a piles and 72% less than the spindle-shaped pier with piles.

4. Conclusion

The scouring issue is a significant concern in river engineering. Every year, a large number of bridges are destroyed all over the world, which is mainly due to not considering the role of hydraulics in their design. Some of the methods to control and reduce scouring include the use of roughness protrusions, collar, submerged plates and protective piles. In this research, the effect of submerged plates in controlling and reducing the scour around the spindle-shaped pier has been investigated. In this research, plates with different angles of 15, 30, and 45 degrees were used in single, double, and triple rows with different flow rates.

As the number of rows increases, the sediment displacement and accumulation in front of the bridge pier increases, which ultimately reduces scouring. The scour rate decreases by increasing the angle along the flow, because the effective length of the plates increases with increasing the angle of the plates thus, the sediment displacement is increased, which results in more sediment being transferred to the front of the pier and better control of scouring. Increasing the relative velocity (V/Vc) on average increased the scour. The water flow after colliding the spindle-shaped pier and creating a downward flow and scouring, which also increases the vertical velocity has increased the vertical velocity and increased scouring. Flow-3D simulation shows that the simulation with the Flow-3D mathematical model is close to the physical model and has an average error of only 5.4%, which is acceptable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

References

Chen, S.C., Tfawala, S., Wu, T.Y., Chan, H.C., Chou, H.T. 2018. A hooked-collar for bridge piers protection: Flow fields and scour. *Water*, Vol.10, Issue 9, pp. 1251. https://doi.org/10.3390/w10091251.

Chiew, Y.M. 1992. Scour protection at bridge piers. *Journal of Hydraulic Engineering*, 9(112): 1260-1269.

Chiew, Y.M., Melvile, B.W. 1999. Temporal development of local scour at bridge piers. *In North American Water and Environment Congress & Destructive Water*, June 22-28, Anaheim, California, United States.

Donat, M. 1995. *Bioengineering techniques for stream bank restoration:* A review of central European practices. Ministry of Environment, Lands, and Parks and Ministry of Forests, British Columbia. Watershed Restoration Project Report.

Dongel, D.M.S., Melvile, B.W. 1994. Local scour at bridge abutments. Department of Civil Engineering, University of Auckland.

Ettema, R. 1980. *Scour at bridge piers*. PhD. Thesis, The University of Auckland, 216, pp.527. http://hdl.handle.net/2292/5700.

Ettema, R., Melvile, B.W., Barkdoll, B. 1991. *Pier width and local-scour depth.* In North American Water and Environment Congress & Destructive Water (ASCE).

Ghasemi, M., Soltani-Gerdefaramarzi, S. 2017. The Scour Bridge Simulation around a Cylindrical Pier Using FLOW-3D. *Journal of Hydroscience Environmental*, 2(1) 46-54.

Hosseini, S.H., Hosseinzadeh, D.A., Farsadizadeh, D., Arounqi, H., Ghorbani, M.A. 2011. The use of submerged plates in the control of scour around the rectangular-shaped bridge piers with round angles. *Journal of Civil Engineering and Mapping*, 3(45): 301-310 [In Persian].

Landers, M.N. 1992. Bridge scour data management. USGS (U.S. Geological Survey). Staff-Published Research. Proceedings of the Hydraulic Engineering sessions at Water Forum 92. Baltimore, Maryland, August 2–6, Published by American Society of Civil Engineers. pp. 141.

Link, O., Henriquez, S., Ettmer, B. 2019. Physical scale modelling of scour around bridge piers. *Journal of Hydraulic. Research.* 57, 227–237.

Mahmoudi, S.A.H., Heidarpour, M. 2016. Evaluate the performance of the control and reduction of scour protection of bridge piers cylindrical piles. *Journal of Construction Engineering and Management*, 3(1): 7-11.

Melvile, B. 1992. Local scour at bridge abutments. *Journal of Hydraulic Engineering*, 4(118): 615-631.

Moussa, Y.A.M., Nasr-allh, T.H., Abd-elhasseb, A. 2018. Studying the effect of partial blockage on multi-vents bridge pier scour experimentally and numerically. *Ain Shams Engineering Journal*, 4(9): 1439-1450. https://doi.org/10.1016/j.asej.2016.09.010.

Namaee, M.R., Sui, J., Wu, P. 2019. Experimental Study of Local Scour around Side-by-Side Bridge Piers under Ice-Covered Flow Conditions. In Book: The Fluvial Processes and Forms-Dynamics, Delineation and Conservation, https://10.5772/intechopen.86369.

Niknam, A., Heidarnejad, M., Masjedi, A., Bordbar, A. 2021. Laboratory study of the effect of piles in reducing the scour around the spindle-shaped bridge piers. *Water Resources Engineering*, 14(51): 129-145. [In Persian]. https://sid.ir/paper/998849/fa.

Nohani, E, Ebrahimi, S. 2018. Laboratory study of the effect of using collar and submerged plates together to reduce the scour depth of cylindrical-shaped bridge piers. *Iran Water and Soil Research*, 50(2):411-424. [In Persian].

Oliveto, G., Hager, W.H. 2002. Temporal evolution of clear-water pier and abutment scour. *Journal of Hydraulic* Engineering, 128(9): 811-820. https://sid.ir/paper/225687/fa.

Sadeqlu, M., Hamidi, M. 2022. Numerical investigation of the cylindrical bridge pier scour reduction by installing a group of two submerged vanes, *Irrigation and Drainage Structures Engineering Research*, 22(85): 91-114. doi: 10.22092/idser.2022.357739.1502.

Wang, S., Wei, K., Shen, Z., Xiang, Q. 2019. Experimental Investigation of Local Scour Protection for Cylindrical Bridge Piers Using Anti-Scour Collars. *Water*, 11(7), pp. 1515.