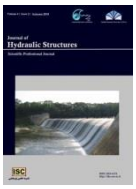
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Laboratory study of scouring around the roughened pile groups in the presence of material harvesting pits and at different Froude numbers

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Abstract

Harvesting the river materials can cause negative effects on the river and can intensify scouring around the bridge piers. This study investigates local scouring around roughened pile groups with gravel for Froude numbers of 0.1, 0.25 and 0.5 with the presence of harvesting pits. It was found that applying roughness reduced the scour depth by 4.8 cm (73%). Due to increasing pile stability because of reducing local scouring, results show that the application of roughness to the surface of piers is a suitable, straightforward, cost-effective, and easy-to-apply method to reduce scouring. In addition, the maximum scour depth both up. and downstream of the harvesting pit occurred upstream of the initial piers. Comparison of scour areas shows that scour expansion in the transverse direction was greater than in the longitudinal direction and the amount of expansion increases when Froude number has been increased. Also, the extent of scouring around the initial piers was greater than the extent of scouring around the other piers. The maximum scour depth was 15 cm in front of the first pier and corresponded to simple piers and flow with a Froude number of 0.5.

Keywords: Local Scouring, Bridge Pile Groups, Harvesting River Materials, Roughened Pile Groups.

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1. Introduction

Expansion of human societies and the increased demand for harvested river materials has caused adverse effects on the hydraulic, morphological, and biological characteristics of rivers. Improper extraction of materials like sand and gravel from riverbeds have caused pits in rivers and has intensified scouring around the bridge piers. Therefore, of special concern in hydraulic sediment engineering are the effects of river material removal on scour processes around bridge foundations. Rivers which were scoured from mining river materials (Figure 1). The present study investigates the scour around the pile groups in the presence of a harvesting pit. The current effort is intended to aid designers as they attempt to reduce local scouring.



(a) **(b)**

Figure 1. Photo of the scouring around bridge piers because of harvesting of river materials in IRAN. (a) Talar Bridge and (b) Save Bridge.

Statistical studies in recent decades have shown that scouring around bridge piers is one of the important contributing causes of bridge failure and the phenomenon has caused extensive financial losses (Bozkuş et al., [1]). Most studies have been performed with a focus on single piers. With increasing populations and transportation traffic, the necessity of building wide bridges has increased which in turn requires the employment of pile groups (instead of single piers). Zhao and Sheppard [2] showed that the maximum scouring depth in pile groups occurs at the first piers. According to the research done by Ataei-Ashtiani and Beheshti [3], the use of the pile group increases scouring around the pile group compared to the use of single piers. Liang et al. [4] conducted a laboratory study of scouring around a single pier, two piers next to each other, and a three-in-three pile group. They presented an empirical relationship to calculate depth of scour.Solaimani et al. [5] investigated the effect of distance and arrangement of the piers on the depth, length, and volume of scouring around the pile groups and concluded that increasing the distance between piers, in addition to increasing the depth of scour, increased the area and the volume of scouring. Vaghefi et al. [6] performed a study using an excrementally flume with a 180° bend to investigate the effect of vertical triangular piers on bed topographical changes. They installed the piers that were oriented parallel and perpendicular to the flow. The piers were positioned at various stream wise locations in the bend (at 0, 60, 90 and 120 degrees into the bend of the flume) and observed that the maximum scouring depth occurs at piers arranged perpendicular to the flow and located 90 degrees into the bend. Malik and Setia [7] studied the scouring around bridge pile groups. They included three models of piers (piers positioned next to each other, one after the other, and with a triangular arrangement). They found that for piers arranged in a row, when the distance between the piers exceeds 16 times the diameter of the piers, the behavior of the piers is independent from each other and consequently each pier

behaves as a single pier. Yang et al. [8] investigated the scouring around the pile groups with different arrangements with the aim of evaluating the effect of the dimensionless ratio of distance of the pier diameter and Froude number. They observed that as the dimensionless ratio increased, the scour equilibrium depth decreased and the H_e/D ratio (H_e: scour depth at equilibrium, D: pier diameter) increased as the Froude number increased.

Unfortunately, there is little research on the harvesting of river materials and its effect on scouring near bridge piers. QI Mei-lan [9] investigated the effects of sand mining from a riverbed on the strength of the bridge structure and the scouring around the piers. Rezaie et al. [10] in a laboratory study, added clay and cationic polyacrylamide to sediment and succeeded in reducing the scour depth around a single pier by 46.78%. Daneshfaraz et al. [11] performed a laboratory study to investigate the effect of harvesting on the scour at single bridge piers positioned either upstream or downstream from the harvesting pit. They found that the effect of a material harvesting pit on the scouring from an upstream bridge pier is greater than the scouring at the downstream bridge pier. In another study Daneshfaraz et al. [12] investigated the maximum depth and length of pits created by the harvesting of riverine materials and concluded that the static angle of the material in water has a large effect on the increase of length and depth of the pit. In addition, the ratio of the pit height to flow depth can reduce the length and depth of the pit scour. Majedi Asl et al. [13] investigated scouring around pile groups reinforced with cables in the presence of a river material harvesting pit. They concluded that the mining of river material from upstream of the bridge pile groups reduces the maximum depth of scouring around the piers. River materials harvested from downstream of the bridge pile groups increases the maximum scour depth. Majedi Asl et al. [14] investigated the effect of sand mining pits on scouring around bridge pile groups for different flow characteristics and bed particle parameters. They observed that the increase of Froude number and the presence of a pit hole increases the equilibrium time. Also, they presented a regression equation to estimate the scour depth.

Daneshfaraz et al. [15] investigated experimentally the scour around the roughened pile groups in the presence of aggregate extraction pits, using different discharges. The results obtained by the rough surface models showed that as the discharge was increased, the local scour was increased too; at the same time, the bed profile was posed at the low level. Daneshfaraz et al. [16] investigated the flow pattern and local scouring around bridge pile groups due to the operation of clear water conditions through non-cohesive sediments. Pile groups were positioned upstream and downstream of a sand mining pit. The results of this numerical simulation showed that using hydrodynamic piers reduced the scour depth upstream of all piers and the material harvesting pit. The flow patterns around the pile groups showed that the presence of hydrodynamic piers in the upstream pile group leads to a decrease in the maximum flow velocity, whereas, when such piers were positioned in the downstream pile group, the velocity increases. Daneshfaraz et al. [17] has investigated the scouring around the roughened bridge pile groups in the presence of material harvesting pit in several hydraulic conditions. The results of this section showed that the using of gravel on the surface of the piers reduced the rate of scouring and increased the equilibrium time. The results of evaluating of the scour area around the piers showed that the scour area increased with increasing Froude number and decreased with increasing flow discharge.

A review of previous studies shows that local scouring studies around pile groups in the presence of material harvesting pit are rare. Therefore, this study has a goal of investigating the local scouring around the upstream and downstream piers of the pit resulting from material harvesting. The present study utilizes the concept of a pile group instead of single piers with different Froude numbers. The two models of piers are a simple pier model and a gravel-

roughened pier. The innovation of this study, which distinguishes it from other studies, is that the use of gravel roughness on the pier surface can affect scour and can be used as a solution to reduce this phenomenon.

2. Materials and methods

2.1. Laboratory setup

In order to investigate the effect of pier surface roughness and different hydraulic conditions on scouring around the cylindrical pile groups, a physical model was created in a laboratory located on Iran and University of Maragheh. The model included a flume that was 13 meters in length, 1.2 meters in width, and 0.8 meters in height. The flume had a metal frame and its body was made of Plexiglas. The inlet of the flume was covered by an anti-turbulent net to make the flow uniform. In the middle of the flume, a sedimentary bed with dimensions of 4.26 m in length, 1.2 m in width, and 0.226 m in height was surrounded by two false floors at the beginning and end of the bed. An oval pit with dimensions of 1.01 x 0.8 m^2 was dug up in the middle of the sediment bed (Figure 2).

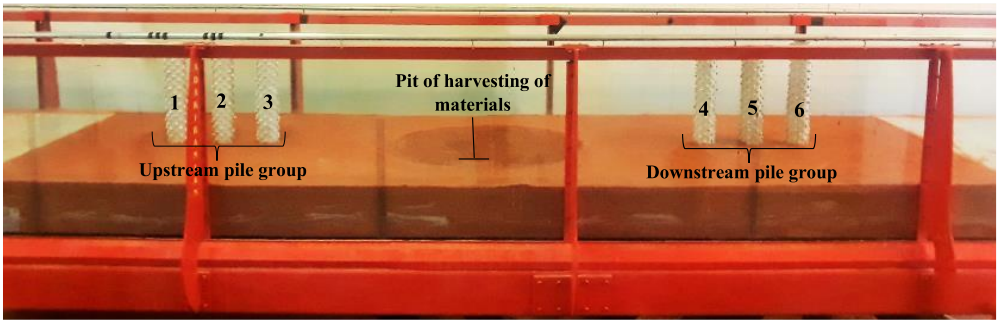


Figure 2. Schematic of the laboratory flume with details of bed and relevant dimensions.

To eliminate the effect of sediment size on scour depth, the dimensionless ratio of pier diameter to average particle size must be greater than 25 (Melville [18]). Also, to prevent the formation of ripples in the sedimentary bed, the average size of the particles should exceed 0.7 mm (Raudkivi and Ettema [19]). Sand particles with an average size of 0.86 mm and geometric standard deviation $\sigma_g = \sqrt{d_{84}/d_{16}} = 1.32 < 1.4$ were used (Dey et al. [20]). Figure 3 has been prepared to illustrate the gradation diagram of bed sediment particles.

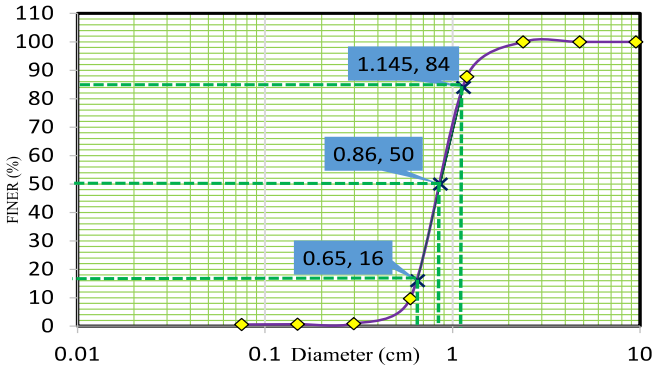


Figure 3. Gradation diagram of bed sediment particles.

To eliminate the effect of flume wall on local scouring, the pier diameter should be less than 10% of the flume width (Chiew and Melville [21]). Also, according to the recommendations of Ataei-Ashtiani and Beheshti [3] if the dimensionless ratio of the distance between the piers to the diameter of the piers is between 0.15 and 2, the behavior of the piers will be the same as the pile groups. If this ratio is less than 0.15, the behavior of each pier will be the similar to the behavior of a large, singular pier. Thus, in order to create a physical model of the piers, three 9-cm diameter PVC pipes positioned at a distance of 12 cm were used upstream and downstream of the harvesting pit. The position of the pit and the piers are shown in figure 4.

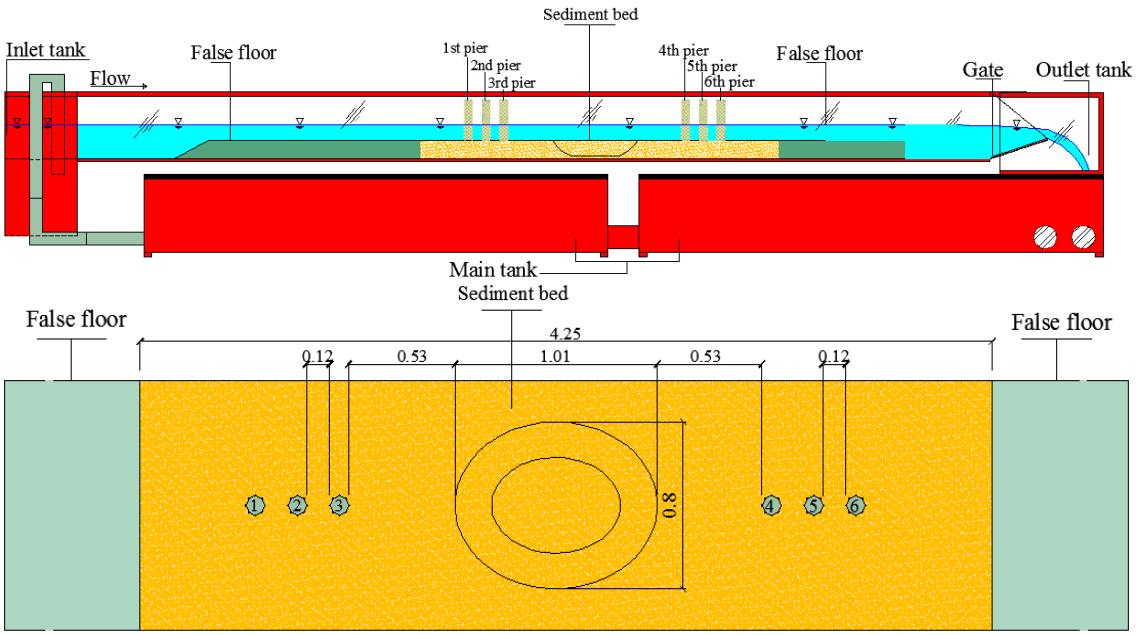


Figure 4. Schematic of the laboratory flume with details of bed and relevant dimensions.

The used roughness was prepared using gravel with an average size of 1 cm. The gravel was adhered to the body of cylindrical piers and were spaced 4 cm apart. The relevant hydraulic conditions are summarized in Table 1.

Table 1. Experiments hydraulic conditions

Pier Model	d_0 (cm)	Q (L/s)	Fr	d_{50} (mm)	D (cm)
Simple	6.3	30	0.5	0.86	9
	10.6	30	0.25	0.86	9
	18.5	30	0.1	0.86	9
Roughened	6.3	30	0.5	0.86	9
	10.6	30	0.25	0.86	9
	18.5	30	0.1	0.86	9

In the above table, d_0 is the initial flow depth, Q is the flow discharge, Fr is the Froude number, d_{50} is the average size of the sediment particles, and D is the pier diameter. In all tests, the flow discharge was 30 liters per second. Three values of Froude numbers were employed. The values were 0.1, 0.25 and 0.5. The required data in this study includes the scouring depth

exactly in front and back of the piers and also the length of the scouring hole around the piers at 30, 60, and 120 minutes intervals during the experiments. After finishing the experiments, the flow in the flume was stopped and was drained slowly through the end gate. These data were gathered using a 3D laser scanner with a measurement accuracy of ±1 mm.

2.2. Dimensional analysis

Scouring around the pile groups in the presence of a harvesting pit is a complex phenomenon that requires sufficient knowledge of the factors affecting it. The effective parameters related to flow, sediment, flume, pier, scour hole and the material harvesting pit are related to each other using the Buckingham π method and the following equation was extracted:

$$F = f\left(V, d_0, g, \rho, \nu, B, \rho_s, d_{50}, \sigma_g, D, K_r, t_e, t, L_{sx}, L_{sy}, d_s, l_p, b_p\right) \quad (1)$$

In the above equation (Eq. 1), V is the upstream flow velocity, d_o is the initial flow depth, g is gravitational acceleration, ρ is fluid density, ν is fluid kinematic viscosity, B is the flume width, ρ_s is the density of the sediment, d_{50} is the average particle size, σ_g is the deviation of particle size, D is the pier diameter, K_r indicates the pier surface roughness, t_e represents scour equilibrium time, t is time, L_{sx} is width of the scour hole, L_{sy} is the length of scour hole, d_s is the scour depth, l_p is the length of the harvesting pit and b_p is the width of the material harvesting pit. Dividing by ρ, V, and d_o, dimensionless parameters can be expressed as follows.

$$\Pi = f\left(\frac{D}{d_0}, \frac{V}{\sqrt{g.d_0}}, \frac{\upsilon}{V.d_0}, \frac{B}{d_0}, \frac{\rho_s}{\rho} = G_s, \frac{d_{50}}{d_0}, \sigma_g, \frac{K_r}{d_0}, \frac{V.t_e}{d_0}, \frac{V.t}{d_0}, \frac{L_{sx}}{d_0}, \frac{L_{sy}}{d_0}, \frac{d_s}{d_0}, \frac{l_p}{d_0}, \frac{b_p}{d_0}\right) \quad (2)$$

To simplify Eq. (2), further consolidation of variables leads to:

$$\Pi = f(Fr, \frac{Vd_0}{\upsilon}, G_s, \frac{d_{50}}{d_0}, \frac{K_r}{d_0}, \sigma_g, \frac{t}{t_e}, \frac{L_{sx}}{L_{sy}}, \frac{d_s}{D}, \frac{B}{d_0}, \frac{l_p}{b_p}) \quad (3)$$

According to Franzetti et al. [22] If $R_e \geq 7000$, kinematic viscosity will not affect local scouring. According to the Table 1, the Reynolds number for all experiments are more than 7000. These very high values mean that the dimensionless parameter $\frac{Vd_0}{\upsilon}$ can be ignored. According to Melville and Chiew [23] if $\frac{B}{D} = \frac{1.2}{0.09} \geq 10$, the effect of flume walls on depth of local scour can also be ignored. Therefore, the dimensionless parameter $\frac{B}{d_0}$ was omitted. Furthermore, due to the uniform distribution of sediment particles, sediment size and material were same in all experiments. Since $\frac{D}{d_{50}} = \frac{0.09}{0.00086} \geq 25$, the effect of sediment on scour depth can also be ignored and dimensionless parameters $\frac{d_{50}}{d_0}$, σ_g and G_s can be omitted (Melville and Chiew [23], El-Ghorab [24]). Therefore, the relative dimensionless depth can be represented as follows:

$$\frac{d_s}{D} = f(Fr, \frac{K_r}{d_0}, \frac{t}{t_e}, \frac{L_{sx}}{L_{sy}}, \frac{l_p}{b_p}) \quad (4)$$

3. Results and discussion

In this section, the effect of roughness on scouring depth and scouring area adjacent to pile groups will be presented. The results will be shown for both simple and roughened models. The flow condition for Froude numbers of 0.1 and 0.25 was clear water and for a Froude number of 0.5, the flow resulted in a live bed. Accordingly, for Fr = 0.5, the scour depth, scour area, and changes in the material harvesting pit exceeded that of other Froude numbers.

3.1 Equilibrium time

The scouring around bridge piers are a complex phenomenon that occurs as a result of the interaction of strong three-dimensional flow around the piers and the erodible sedimentary bed. The presence of a pier in the flow path changes the path and changes the elevation of the moving bed. The intensity and depth of scouring will depend on the characteristics of the flow, the sediment particles of the bed, the geometry and the way the pier is installed.

After the flow starts and the flow velocity reaches critical velocity, scouring begins. It is the eroded particles from in front and sides of the piers transferred to the downstream of the pier. This phenomenon increases with the increase in flow velocity, which leads to an increase in the sediment carrying capacity of the flow. In addition, at the beginning of scouring, due to the high shear stress in front of piers, scouring occurred faster, and with the passage of time and the reduction of shear stress, the intensity of this phenomenon decreases. For non-uniform sediment particles, larger particles are less at risk of erosion and thus create a protective layer in the scour hole, which after some time prevents the scouring of finer particles (Mohammadi,[25]).

Immediately after the flow establishment in the flume, vortices formed around the piers and scouring began around the pile groups. After the scouring hole appeared around the bridge piers and the sediment particles around the piers moved downstream, the strength and volume of the vortices gradually decreased and the scouring speed decreased too. At the end of the experiments, the sediment transport and the size of the scour hole around the piers reached such a point that the vortices were not able to transfer sediment downstream and the sediment moved only inside the scour hole. This stage, also known as the equilibrium time, signaled the end of the experiment. According to this, the experiments has stopped when the scouring around the piers had ceased.

Figure 5 illustrates the evaluation of scouring equilibrium time. According to this figure equilibrium time is increased after applying roughness on the surface of piers because gravel roughness provides little turbulence around themselves which increases movement duration of erosion and sedimentation phenomenon. Also, it can be seen that although scouring equilibrium time decreased with increasing Froude number, scour depth increased due to increasing flow turbulence and sediment transition capacity.

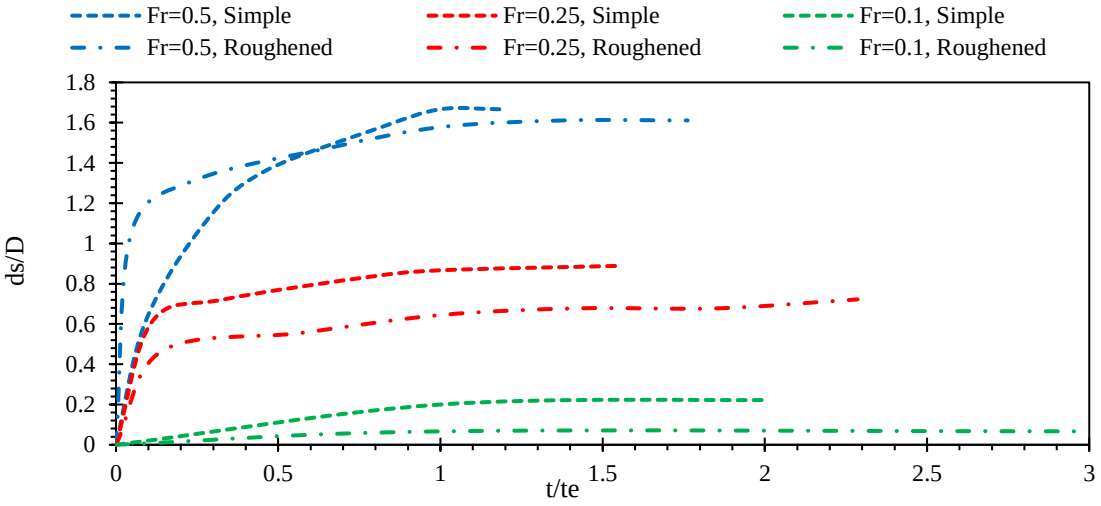


Figure 5. Equilibrium time for different Froude numbers

3.2. Effect of roughness of pier surfaces on scour depth around the pile groups at different Froude numbers

The results for scour depth behind and in front of the bridge piers at the end of the equilibrium time for both simple and roughened models are presented in figure 6. As seen in the figure, after the roughness is applied to the pier surfaces, the scour depths for the upstream piers are different from the scour depths at downstream pier locations. Also, for all piers (both upstream and downstream), the maximum scouring depth occurred in front of the initial piers. The sheltering effects that the upstream piers have on the downstream locations are evident. The maximum scour depth in the group of upstream piers is equal to 10.4 cm (pier number 1) in the simple model with a Froude number of 0.5. In the group of downstream piers, the corresponding value is equal to 8 cm and belongs to pier number 4 in the roughened model with a Froude number of 0.25.

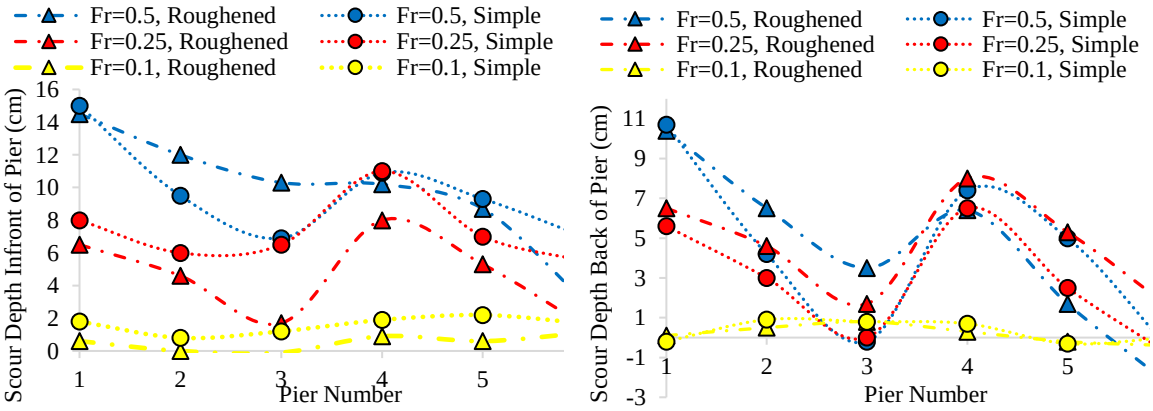


Figure 6. Comparison of equilibrium scour depths around the pile groups in front of and behind the piers for simple and rough pier model for different Froude numbers.

For Froude numbers of 0.25 and 0.1, roughness on the surface of the piers reduces the scouring depth in front of all piers. Roughness around the piers acts as a guard for the bed sediment particles and prevents further scouring of the bed. Also, the roughness of the gravel at the surface of the bridge piers creates tiny vortices which distort the main vortices around the piers. If the strength of these vortices becomes sufficient to overcome the main vortices resulting from the collision of the flow with the piers or to neutralize some of it, the local scour around the piers is lessened. But if the strength of the small vortices resulting from the roughness is not sufficient to overcome the strength of the main vortices, the scouring is not reduced. In fact, this situation can cause more turbulence and consequently intensify scouring.

For a Froude number of 0.5, it was observed that with added roughness, the scour depth decreases for all piers downstream of the harvesting pit. For the upstream piers, the scouring depth has decreased in front of and behind the first pier. On the other hand, for the 2nd and 3rd piers, the scouring depth has increased. The reason for this is the alignment of the vortices created by the gravel roughness with the main vortices resulting from the collision of the flow with the piers.

The extent of changes in scour depth from application of roughness for all experiments is presented in Table 2. In this table, positive numbers indicate a decrease in scour depth and negative numbers represent an increase in scour depth after applying roughness on the surface of the piers. According to Table 2, the maximum reduction in scour depth after applying roughness elements was 4.8 cm. This scour depth reduction occurred with a Froude number of 0.25 and was located upstream of pier number 3.

Vital data on scouring around the pile groups include the maximum scouring depth around the piers 1 and 4. The initial piers are the first barriers to water flow and the scour depths around these piers is often greater than at other piers. After applying roughness on the surface of the piers, we observed a decrease in scouring in front of most of the piers. According to the Table 2 it is observed that the application of roughness at the surfaces of the piers is a desirable, cost-effective and easy-to-implement method to reduce scour around the bridge pile groups.

Table 2. Scour depth changes after applying roughness on the surface of the piers

Data position	***Fr***	***1st pier***		***2nd pier***		***3rd pier***		***4th pier***		***5th pier***		***6th pier***	
		Value (cm)	*Rate (%)*	*Value (cm)*	*Rate (%)*	*Value (cm)*	*Rate (%)*	*Value (cm)*	*Rate (%)*	*Value (cm)*	*Rate (%)*	*Value (cm)*	***Rate (%)***
In front of piers	0.5	0.5	3.33	-2.5	26	-3.4	-49	-0.3	-3	0.6	6	3.9	**55**
	0.25	1.5	18.75	1.4	23	**4.8**	**73**	3	27	1.7	24	3.9	**70**
	0.1	1.2	66.67	0.8	100	1.3	108	1	52	1.6	72	0.6	**35**
Back of piers	0.5	0.3	2.8	-2.3	-54	-3.7	1850	1	13	3.3	66	1.8	**-360**
	0.25	2.9	51	3.9	130	-0.7	100	3.8	57	0.2	8	2.7	**-337**
	0.1	-0.3	150	0.4	44	0	0	0.4	58	-0.1	33	0.4	**100**

3.3. Temporal changes to scour area around the roughened pile groups in the longitudinal direction of flow (y) and transverse direction of flume (x)

Figures 7 and 8 show changes in scour width in both longitudinal (y) and transverse (x) directions around the pile groups during different experiments. The diagrams for Froude numbers of 0.5 and 0.25 are shown, but for a Froude number of 0.1, the area of scour around the piers was so small that the area of scour could not be distinguished by the unevenness of the flow in the bed. Consequently, those results are not shown.

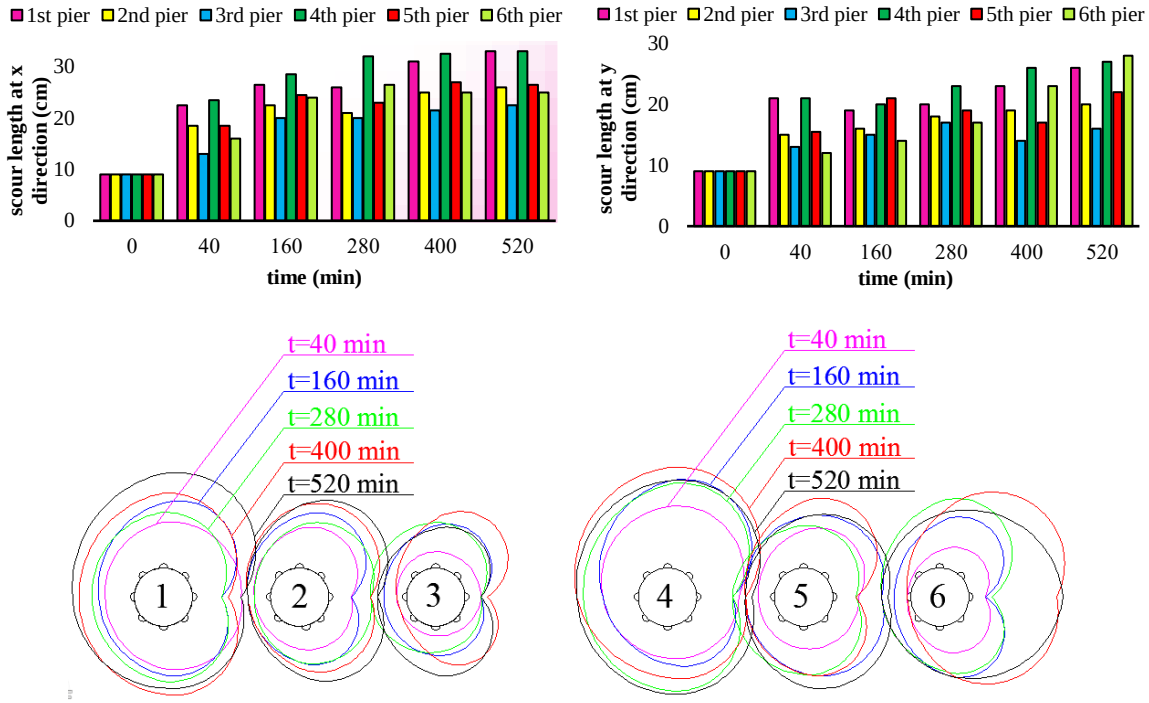


Figure 7. Temporal variations of scour area around the roughened bridge pile groups in the longitudinal (y) and transverse (x) directions for Fr = 0.25.

For a Froude number of 0.25, immediately after the start of the experiment, the scouring area began to increase and the expansion of the scouring area in the transverse direction of the flume was greater than the expansion in the longitudinal direction. The reason for this difference is that in the transverse direction there is only one pier, but in the longitudinal direction there are three piers and this causes sheltering in the longitudinal direction. The width of the scour around pier 1 (the most upstream pier) increased over time and at the end of the experiment reached its maximum size of 33 cm in the transverse direction and 26 cm in the longitudinal direction. The fourth pier also experienced significant scouring and after 520 minutes, its scouring pit extended 33 cm in the transverse direction and 27 cm in the longitudinal direction. The sixth pier had the maximum scour length with a dimension of 28 cm in the longitudinal direction.

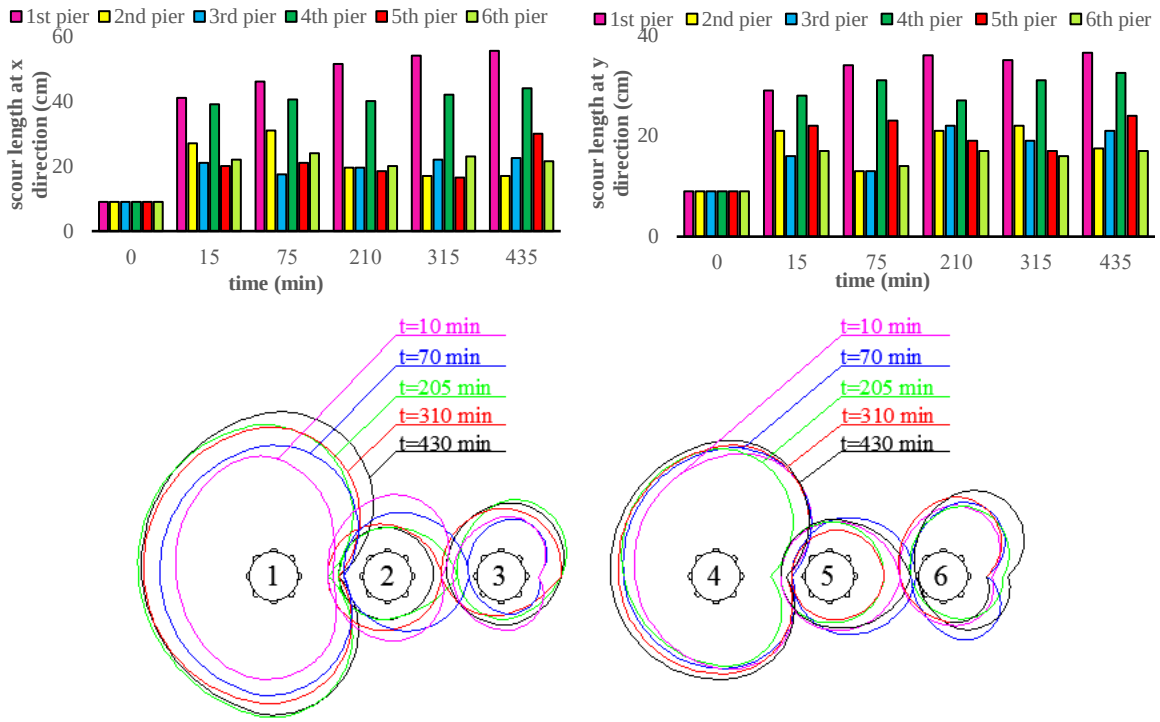


Figure 8. Temporal variations of scour area around the roughened bridge pile groups in the longitudinal (y) and transverse (x) directions for Fr = 0.5.

For a Froude number of 0.5, the maximum scour area, both in the transverse and in the longitudinal direction was at piers 1 and 4. The maximum area of scouring upstream of the pit was related to the first pier with a dimension of 55.5 cm in the transverse direction and 36.5 cm in the longitudinal direction. Downstream of the material harvesting pit, the corresponding maximum pits were at the fourth pier and were 44 cm in the transverse direction and 32.5 cm in the longitudinal direction. For this Froude number, the extent of scouring around the piers was very different and depended on the pier location. For a Froude number 0.25, the differences among the piers was smaller. From these observations, we conclude that the scour expansion in the transverse direction is greater than the longitudinal direction, and this expansion increases with increasing Froude number.

3.4. Variations of the bed plan and material harvesting pit at the end of experiments for different Froude numbers

After the experiments finished, the changes to the harvested pit were drawn using AutoCAD 2014. The results are presented in figure 9. The presence of a bed material harvesting pit provides a place to dispose of the washed sediments that arrive from upstream of the material harvesting pit. These sediments include sediments washed from the general scour of the bed and local scour around the upstream pile group. The sediments are deposited into the excavation pit which transports the pit downstream. In these figures, areas in red signify locations where sedimentation has occurred while erosion is active in the blue areas. These observations confirm the influence of the Froude number on the harvesting. Because the Froude number of 0.1 was the minimum value in the present study, it has a greater flow depth than other Froude numbers at a constant flow discharge, and thus causes less scouring. For this Froude number there change in

the shape of the harvesting pit. However, at a Froude number of 0.25, which is the average value of the Froude number created in this study, the material harvesting pit began to expand in all directions mostly in the downstream direction.

For a Froude number of 0.5, the material harvesting pit underwent many changes; the material harvesting pit has deformed more and has moved downstream more than for the other scenarios. Therefore, we conclude that with increasing the Froude number at a constant flow discharge, not only the extent of scouring around the piers increases, but also the area of the material harvesting pit increases. The reason for this is that with increasing Froude number, the flow velocity increases which causes scouring to increase.

Also, according to figures 9, for a Froude number of 0.25, the extent of scouring around the downstream pile group is greater than the upstream pile group, because the material harvesting pit has changed the flow pattern of the downstream material harvesting pit. For a Froude number of 0.5, the extent of the upstream pile group is more than the downstream pile group. in the explanation is that for this Froude number, the large velocity has caused the sediment bed to try to reconstruct the harvesting pit. The deposition of sediment materials from more upstream locations into the harvesting pit and the removal of other materials from the interior of the harvesting pit conspire together to move the harvesting pit downstream.

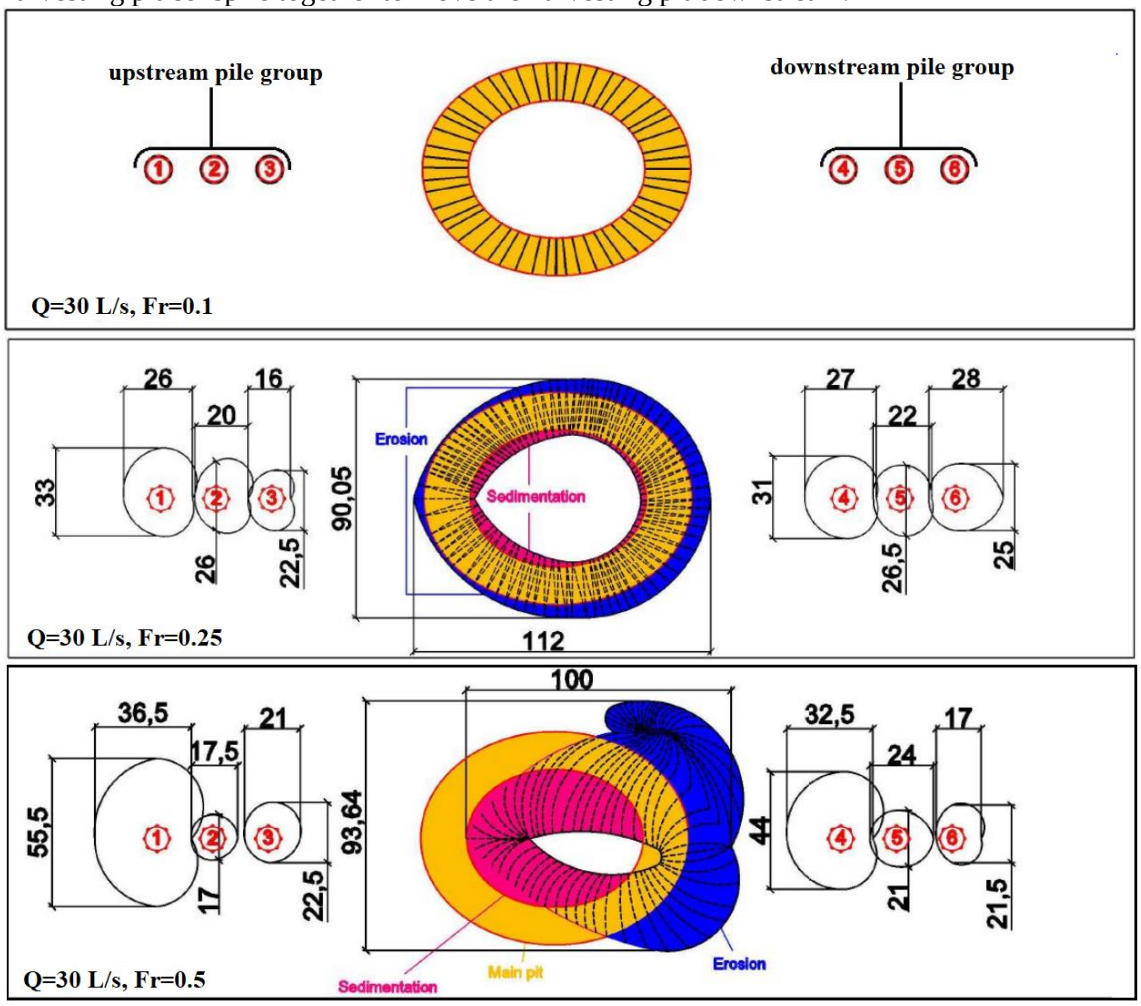


Figure 9. Bed plan at the end of experiments for different Froude numbers.

3.5. Final bed profiles for different Froude numbers

Figure 10 shows the longitudinal profile in a bed at different Froude numbers for the roughened model at the end of the experiments. As can be seen for the Froude number of 0.1, the changes in the longitudinal profiles of the bed are very small and the material harvesting pit has not changed.

According figure 10 and table 3 for a Froude number of 0.1, no scouring has occurred. However, with a Froude number of 0.25, the longitudinal profile of the bed has changed.

For a Froude number of 0.25, the maximum changes that occurred in the upstream bed profile of the excavation pit is related to pier 1 with a scouring depth of 6.5 cm. At downstream it is at pier 4 which also had a scouring depth of 6.5 cm. Upstream of the harvesting pit, in front of the second and third piers, the scour depths were smaller at 4.6 and 1.7 cm, respectively. At the fifth and sixth piers, the scour depths were 3.8 and 0.1 cm, respectively. In addition, the material harvesting pit for a Froude number of 0.25 has undergone many changes due to the accumulation of scouring sediment from the pit (at point a). This area experiences an increase in level and the crown of the material harvest pit (point b) has moved 8 cm.

For a Froude number of 0.5, the changes that occurred in the longitudinal profile of the bed and pit of the material harvesting were greater than for the Froude number of 0.25. At the higher Froude number, upstream of the material harvesting pit the minimum scour level was related to the first pier with a value of 14.5 cm and the second and third piers with values of 12 and 10.3 cm, respectively. Downstream of the material harvesting pit, the pier 4 scouring depth was 10.2 cm while for the fifth and sixth piers, the corresponding values were 8.7 and 3.1 cm.

Table 3: Scouring depth in front of piers (cm)

Fr	Upstream piers			Downstream piers		
0.1	No scour occurs					
0.25	6.5	4.6	1.7	6.5	3.8	0.1
0.5	14.5	12	10.3	10.2	8.7	3.1

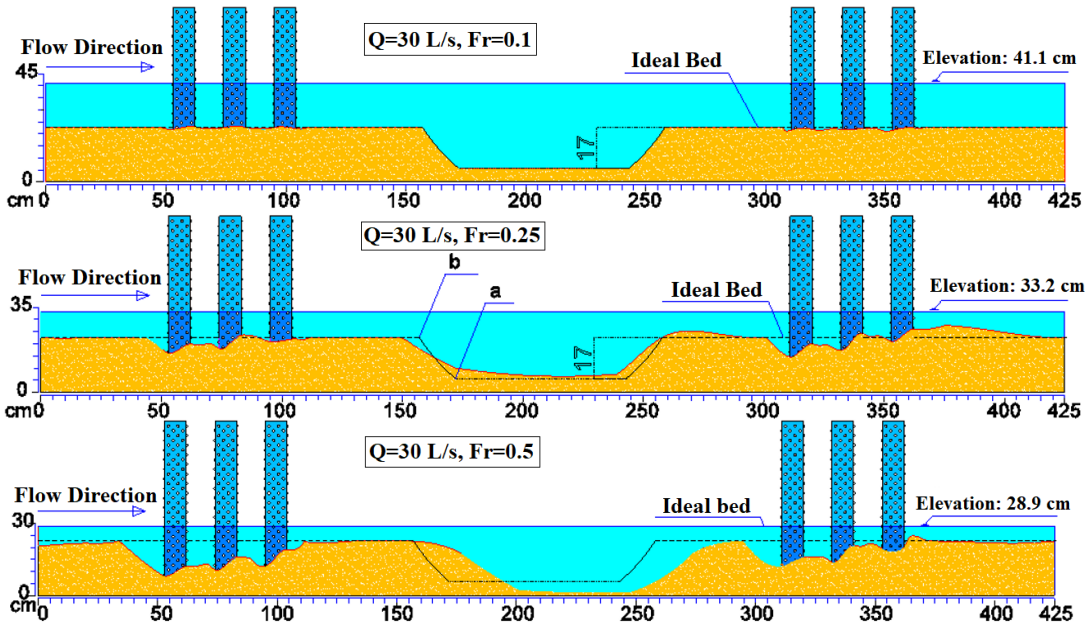


Figure 10. Bed profile at the end of experiments for different Froude numbers.

Comparing the longitudinal profiles of the bed, we conclude that with increasing Froude number, the changes in the longitudinal profile of the bed also increase. When the Froude number equals 0.25, the changes to the longitudinal profile at the downstream end of the pit were greater than in the upstream region. On the other hand, for a Froude number of 0.5, the changes to the bed profile upstream of the pit was higher. When the Froude number is 0.5, the material harvesting pit experiences greater changes than for the Fr = 0.25 case. For the lower Froude number, a large volume of sediment is transferred downstream during scouring. Due to the downstream motion of the material harvesting pit, some of the washed sediments from the bottom of the harvesting pit moved downstream and settled around the downstream pile group. This reduces the scouring around the downstream pile group compared to the upstream pile group.

In all experiments, the scoured sediments resulting from the general scouring of the bed and local scouring around the upstream pile group were deposited into the pit and the scoured sediments from downstream piers have been moved downstream of the flume. The volume of scoured sediment was measured at the end of the experiments and was determined to be 0.06864 m^3 for a Froude number of 0.5, 0.008888 m^3 for a Froude number of 0.25 and negligible for a Froude number of 0.1. These data indicate an increase in the volume of scoured sediments with increasing Froude number.

According to the results presented in the study of Majedi-Asl et al. [13] the maximum reduction of scouring after arming the pile groups was 58%, while in the present study, the application of roughness on the surface of the pile groups reduced the maximum scouring by 4.8 cm (73%). Therefore, the idea presented in this study to reduce scouring, in addition to being a new idea, has a better performance than the study of these researchers.

4. Conclusion

In this study, local scouring around the bridge pile groups in the presence of material harvesting pit and for different Froude numbers has been investigated. The flow conditions encompassed Froude numbers of 0.1, 0.25 and 0.5. In the following for the first time, in order to reduce the scouring around the piers the surface of the bridge piers was roughened by gravels with an average diameter of 1 cm at intervals of 4 cm, and its effect was investigated in different hydraulic conditions with changes in the Froude number. Finally, the results were compared with simple and no added gravel situations. The results of scouring around the pile groups shows that the application of roughness to the surface of the piers is a desirable, cost-effective, and easy-to-implement method to reduce scouring. After applying roughness on the surface of the piers, the maximum reduction of scour depth was related to the Froude number of 0.25 and for the pier number of 3 in the upstream where the decrease in scouring was 73% (4.8 cm). A reduction of 73% in scouring is an important advantage for the method of roughening the surface of bridge piers, because as scouring around the bridge piers reduces the stability of the bridge, so reducing the scour depth around the bridge piers decreases the amount of damage to the bridges and make them more stable.

In all the experiments, the maximum scour depth of the pile groups in both upstream and downstream of the excavation pit occurred in front of the most upstream piers. The maximum scour depth was 10.4 cm in front of the pier number of 1, in the flow with a Froude number of 0.5 and the pier with a simple model.

Comparison of scour areas showed that scour expansion in the transverse direction was greater than the longitudinal direction and this expansion increased with increasing the Froude

number. In addition, on average, the upstream piers experienced the most significant scouring. The results related to the changes in the pit resulting harvesting of river materials at the end of the experiments confirm the changes in the harvested pit in the two Froude numbers of 0.25 and 0.5.

This study shows that the presence of a material harvesting pit provides a hole for deposition of upstream scoured sediments. These sediments include material scoured from the general bed as well as local scour from around the upstream pile group. In addition, the extraction of river materials causes pits and unevenness in the sedimentary bed. Therefore, the sedimentary bed always tries to reconstruct the created unevenness. At Froude number of 0.1, the sediment carrying capacity by the stream was not sufficient to cause a significant change in the material harvesting pit. At landing number of 0.25, the material harvesting pit expanded both longitudinally and transversely, but its changes in the longitudinal direction were greater than the transverse direction. Also, at the Froude number of 0.5, the changes in the longitudinal and transverse directions were so great that the material harvesting pit moved downstream. In all experiments, the scoured sediments resulting from the general scouring of the bed and local scouring around the upstream of bridge pile group were deposited into the pit and the scoured sediments of downstream piers moved to the downstream end of the flume. Measurement of scoured sediment volume in all models indicates an increase in its volume with increasing the Froude number.

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