Studying the Behavior of Increasing the Diameter of Piers under Bridges Subjected to Sloped Drainage

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Abstract. This study centers on analyzing the behavior of individual bridge piers subjected to the dynamic effects of flowing water. The investigation specifically targets the quantification of scour depths and the identification of key parameters that influence scour intensity around bridge-supporting piers. These parameters include pier diameter, variations in flow velocity, discharge rates, water depth, and the Froude number. To explore the influence of these variables, a physical model was constructed to simulate and measure scour depths around piers under controlled conditions. The findings reveal a direct correlation between these factors and the extent of scour in the underlying soil. The primary mechanism driving scour around piers is the formation of various types of vortices namely horseshoe, surface, wake, and local vortices which generate localized hydrodynamic forces. These forces dislodge and transport soil particles from the upstream face of the pier to downstream regions where the vortex-induced forces diminish, thereby causing sediment erosion and scour development.

Keywords: Piers, scouring, bridges, drainage, soil, sloped water flow.

1. INTRODUCTION

Worldwide, numerous bridges and hydraulic structures suffer damage caused by water flow, sometimes resulting in structural failure. This failure typically stems from complete or partial local erosion known as scour around bridge piers. The severity of such damage depends on multiple factors, including the intensity of water flow, water depth, pier geometry, spacing between piers, and the inclination angle of the piers relative to the flow direction. Many critical infrastructures vital to human life, such as bridges supported by piers, are directly exposed to riverine environments. The scour-induced erosion of soil at the base of these piers often leads to significant material losses and imposes substantial economic burdens due to repair and reconstruction costs. Among the primary causes of bridge failure are structural overload and scour. This issue has attracted extensive global research efforts, with numerous studies examining scour under various perspectives and conditions. It is well established that scour around bridge piers represents a principal threat to the stability of bridge foundations [1–5].

The scour phenomenon around bridge piers is of critical importance in infrastructure engineering, as it constitutes a major cause of bridge failure. Key factors contributing to such failures include scour itself, collisions, and structural overload. At bridge sites, scour is typically categorized into three main types: general scour, local scour, and contraction scour [6]. In a laboratory study, Abdul-Nour [7] explored the relationship between scour depth and the spacing between bridge piers, considering variables such as flow velocity, sediment size, and pier geometry. The experimental results demonstrated a clear positive correlation: as pier spacing decreased, scour depth increased. The maximum observed increase in scour depth ranged from 10% to 28% relative to scour depths measured at isolated pier locations under comparable conditions. Hosny [8] carried out an in-depth experimental investigation of in situ scour around cylindrical piers in cohesive soils, employing reconstituted natural clay as the test medium. The study revealed that the equilibrium scour depth in cohesive soils is substantially less than that observed in non-cohesive soils. Furthermore, even a modest clay content of approximately 10% or greater was found to significantly alter the soil's properties and influence the scour behavior.

In a detailed study by Khassaf [9], the local scour phenomenon near the piers of the Kufa Bridge was thoroughly investigated, with particular emphasis on the influence of the spacing between the columns on scour depth. Dimensional analysis was utilized to develop an empirical formula based on the collected measurement data. The scour depths predicted by this formula demonstrated strong agreement with the observed values. The study found no significant reciprocal effect between the spacing ratio and the maximum scour depth at the Kufa Bridge piers. Moreover, it was noted that the middle pier exhibited a greater scour depth than the others. Building on these findings, the study proposed a design methodology for estimating equilibrium scour depths at bridge sites. This approach relies on envelope curves derived from empirical data predominantly sourced from laboratory experiments, which account for wide variations in flow velocity and depth, sediment size and gradation, as well as pier dimensions, shapes, and alignments. The methodology seeks to minimize predicted scour depths by factoring in conditions such as pure, clear water, relatively shallow flow depths, and coarser sediment characteristics [10]. Khwairakpam et al. [11] conducted a series of systematic experiments in a sloped water channel featuring a cylindrical pier to examine the scour process. These experiments varied key parameters, including Froude numbers and flow depths. Observations revealed a significant relationship between the scour number and the overall scour geometry including depth, length, width, area, and volume. The study highlighted the importance of Froude density (FD50) and flow depth (h) as critical factors influencing scour behavior.

In another investigation, Al-Shukur and Obeid [12] explored the effects of pier shape on scour depth across different flow velocities. Their experimental program tested ten distinct pier shapes including circular, rectangular, octagonal, beveled, hexagonal, elliptical, and streamlined profiles with the goal of identifying designs that minimize local scour. The results indicated that rectangular piers experienced the greatest scour depths, whereas streamlined pier designs consistently produced the least scour, suggesting optimal configurations for reducing scour-related risks.

2. MATERIALS AND LABORATORY TESTS

The laboratory flume and its associated equipment are vital components for conducting hydraulic research and experiments. The open channel used in this study is a conventional setup constructed primarily from cast iron, featuring upstream and downstream basins with a wall thickness of 4 mm. The channel's sidewalls are made of 10 mm thick transparent glass, allowing visual observation of flow phenomena. The entire structure spans a length of 18.7 meters, comprising an upper basin measuring 3.7 m in both length and height. The system includes a 3-meter-long basin with a height of 0.77 meters, which is connected to three flow calming filters, complemented by two additional filters serving the same purpose to minimize turbulence. The main channel itself measures 12 meters in length, 0.5 meters in width, and 0.5 meters in height. Furthermore, the flume incorporates an adjustable lower base, whose inclination can be modified using hydraulic supports, enabling precise control of the channel slope as required for various experimental conditions (see Figure 1).

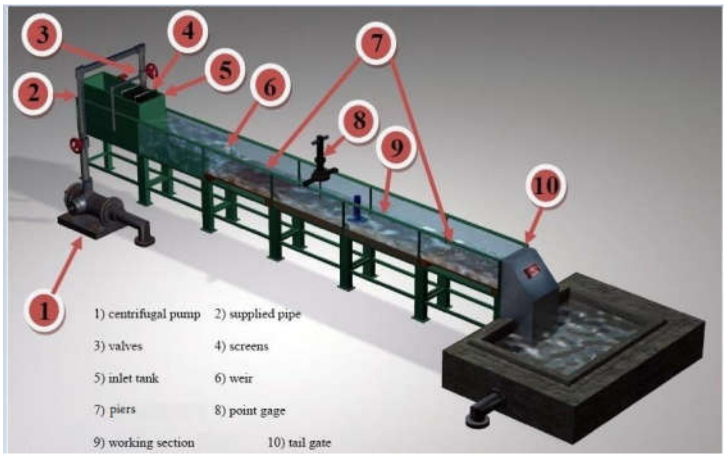

Figure 1. Laboratory channel used in the experiments.

2.1 Laboratory Piers

Three wrought iron piers with circular cross-sections, each corresponding to a distinct model, were fabricated according to precise dimensional specifications and coated with an oil-based paint for protection. Each pier had a uniform thickness of 2 mm and diameters of 25 mm, 32 mm, and 50 mm, respectively. During the experiments, purified liquefied water was applied to the piers at three controlled flow rates: 20 liters per second, 30 liters per second, and 40 liters per second.

2.2 Chemical and physical tests for water and bottom soil

Table 1 presents the results of the chemical analysis conducted on the liquefied water used in the experiments. Additionally, both chemical and physical characterizations of the sediment used in the study were performed. As detailed in Table 2, key parameters such as moisture content, sulfate concentration, gypsum content, and pH levels of the bottom soil were determined. The comprehensive chemical composition of the water is summarized in Table 1.

Table 1. Chemical analysis of water.

pH	TDS, mg/L	Total difficulty, l/mg	Ca^{+2}, mg/L	Mg^{+2}, mg/L	Cl^{-1}, mg/L	SS	Ec
7.83	206	240	52.01	4.79	36.79	41	2.6

Table 2. Physical analysis of sand.

Property	Value	Property	Value
Specific Gravity, Gs	2.65	USCS-soil type	SP
Coefficient of gradation, C_c	0.79	Gypsum	0.7
Coefficient of uniformity, C_u	2.94	SO_3	0.325

2.3 Mechanisms for Carrying out Laboratory Tests

All laboratory experiments were conducted under clear-water conditions with subcritical flow in a horizontal, open channel. The experimental methodology is summarized as follows:

- The sandy soil utilized was first sieved through a No. 4 sieve, with only the fraction passing through retained for testing; coarser particles retained on the sieve were discarded.
- A 10 cm thick layer of the prepared sand, mixed with 22.1% water content, was evenly placed in the 3-meter-long flume basin. A movable gate was then employed to level the sediment bed. The channel bottom was smoothed, and the gate opening was adjusted to a height of 10 cm.
- To avoid premature scour before achieving steady flow conditions and to allow entrapped air to escape from the sand matrix, discharge in the channel was gradually increased while the pump was operational. Subsequently, the sliding gate opening at the downstream end was incrementally raised to reach the desired flow depth.
- After a stabilization period of three hours, maximum scour depths and flow depths around the piers were measured repeatedly.
- Scour depth measurements were taken systematically on a 1×1 cm grid around the pier, extending up to 25 cm from the pier's reference point, to accurately map the scour profile.

3. LABORATORY RESULTS

The observed scour mechanism around the piers was thoroughly examined, accompanied by a detailed analysis of the laboratory findings. The study also explored the influence of key variables on scour depth, including pier diameter, critical flow velocity, water surface elevation, Froude number, and the extent of the scour zone.

3.1 Scour occurrence mechanism

When a solid obstruction such as bridge pier perforations is introduced into a waterway, the flow transitions to a turbulent state. As water impacts the upstream face of the pier, it accumulates momentarily before rapidly diverting around the sides, generating a spiral flow pattern at the pier's leading edge. This flow transformation induces a pressure differential that redirects the water from a primarily horizontal path to a downward vertical movement, leading to the development of vortices. These vortices take on a characteristic horseshoe shape around the pier's base, exerting uplift forces on soil particles that contribute to sediment erosion and scour. This process causes sediment displacement from the upstream to the downstream side of the pier. Additionally, the water collision at the pier's front produces surface eddies commonly referred to as surface rollers that elevate the local water level. As noted by Hirschfeld [13], the height of this raised water level is influenced by both the flow velocity and the pier's geometry. Figure 2 illustrates the dynamics of these surface rollers and the horseshoe vortex formation occurring upstream of the pier.

3.2 The effect of the diameter of the piers on the depth of the scour

Table 3 demonstrates that the scour depth of the underlying soil increases both with the diameter of individual cylindrical piers and with higher runoff drainage rates. This data confirms the adverse impact of larger pier diameters on sediment erosion, highlighting a clear trend where increasing pier size intensifies scour depth around single cylindrical piers.

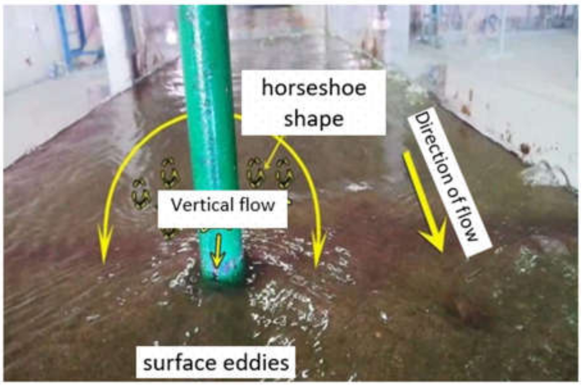

Figure 2. The movement of water at the front of the pier in a horseshoe shape and surface eddies.

Table 3. Laboratory results for scour on single cylindrical piercings.

Pier Dia., D (mm)	Q (m^3/s)	V (m/sec)	V_c (m/sec)	V/Vc	y (m)	Ds (mm)	Ds/y	D/y	Fr
25	0.02	0.143	0.254	0.56	0.28	25.32	0.904	0.893	0.086
25	0.03	0.194	0.258	0.75	0.31	28.11	0.907	0.806	0.111
25	0.04	0.229	0.264	0.87	0.35	34.21	0.977	0.714	0.123
32	0.02	0.143	0.254	0.56	0.28	31.41	1.122	1.143	0.086
32	0.03	0.194	0.258	0.75	0.31	38.57	1.244	1.032	0.111
32	0.04	0.229	0.264	0.87	0.35	46.57	1.331	0.914	0.123
50	0.02	0.143	0.254	0.56	0.28	36.56	1.306	1.786	0.086
50	0.03	0.194	0.258	0.75	0.31	52.41	1.691	1.613	0.111
50	0.04	0.229	0 surface eddies	[illegible]	0.35	63.12	1.803	1.429	0.123

Figure 3 presents the relationship between scour depth and pier diameter for piers measuring 25 mm, 32 mm, and 50 mm in diameter. The data show that a pier with a 50 mm diameter experienced a maximum scour depth of 63.12 mm under a discharge rate of 40 liters per second. In contrast, the smallest pier, with a diameter of 25 mm, exhibited a scour depth of 25.32 mm at a lower discharge rate of 20 liters per second. These results align with the findings of Johnson [14] and Alabi [15], who demonstrated that larger pier diameters correspond to deeper scour and longer development times for scour holes under equivalent shear stress conditions. Moreover, increasing the discharge from 20 to 40 liters per second led to a 35.1% increase in scour depth around the 25 mm pier, from 25.32 mm to 34.21 mm. Similarly, the 50 mm pier exhibited a more pronounced response, with scour depth increasing by 72.6% from 36.56 mm to 63.12 mm. This pattern suggests that doubling both the pier diameter and the discharge approximately doubles the resulting scour depth, highlighting the compounded effect of these parameters on sediment erosion around bridge piers.

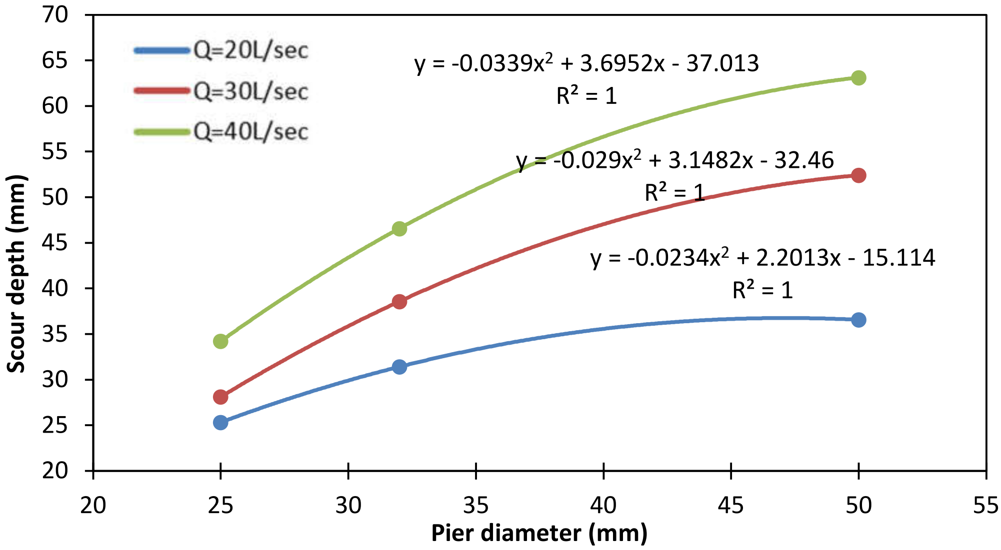

Figure 3. Relationship between scour depth and single cylindrical pier diameter at different discharges.

Figures 4 to 6 illustrate the scour patterns that developed in the central region of the flume around individual cylindrical piers with diameters of 25 mm, 32 mm, and 50 mm, respectively, under three distinct drainage conditions. The analysis of these patterns indicates that the most pronounced scouring consistently occurs at the upstream face of each pier commonly referred to as the leading edge where flow separation and vortex formation are most intense. The extent and depth of scour are influenced by both the diameter of the pier and the discharge rate through the channel, with larger diameters and higher drainage volumes producing more significant sediment displacement.

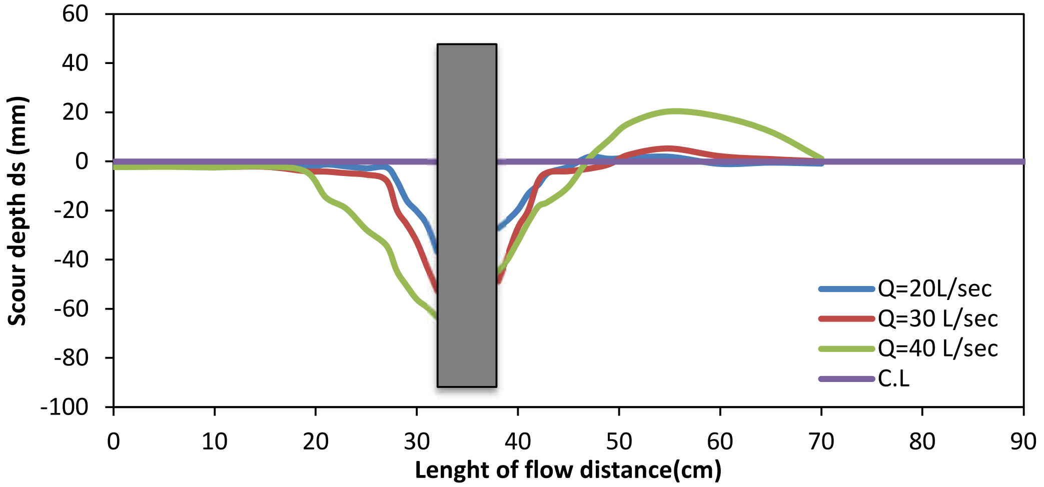

Figure 4. The highest scour value for a pier with a diameter of (50 mm) with drainage of different intensities.

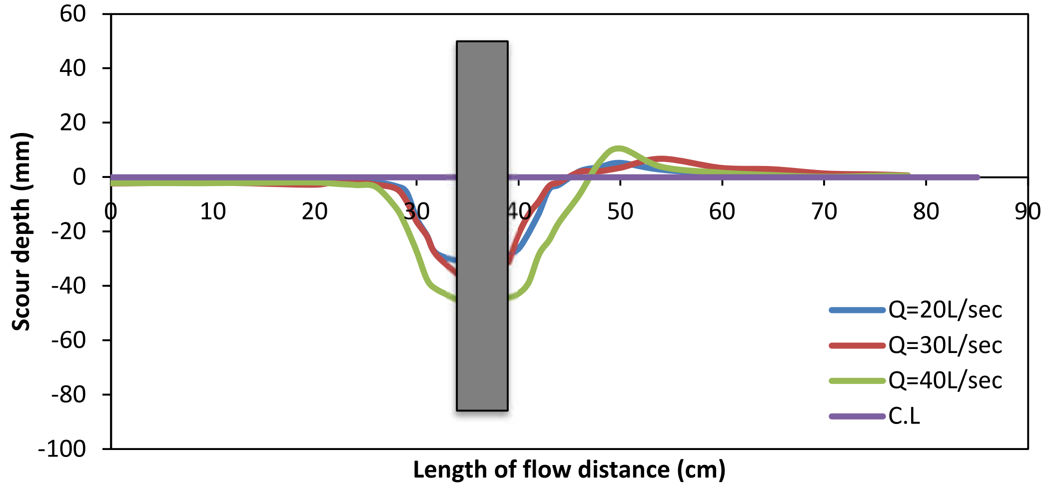

Figure 5. The highest scour value for a pier with a diameter of (32 mm) with different drainage intensities**.**

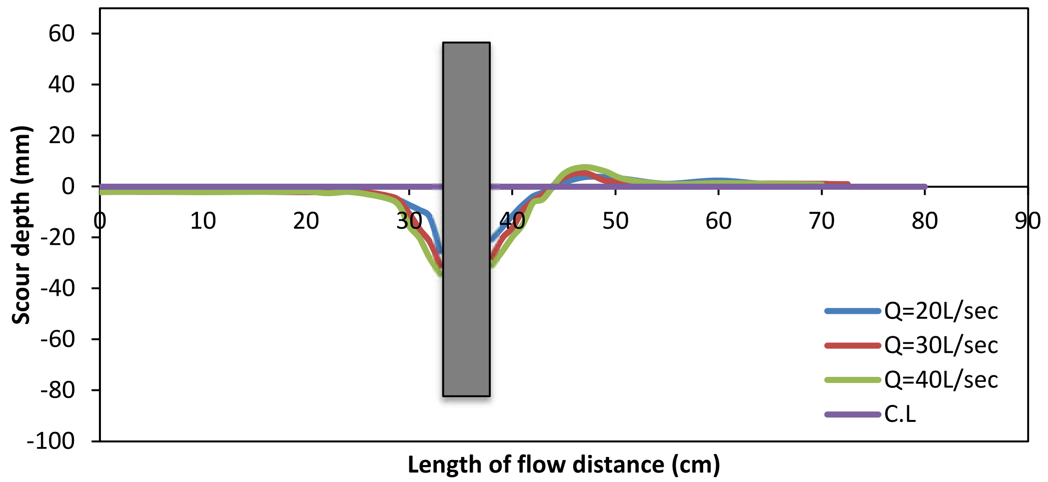

Figure 6: The highest scour value for a pier with a diameter of (23 mm) with different drainage intensities**.**

3.3 Effect of Flow Depth with Scour Amount

An increase in flow depth is positively associated with greater drainage capacity, which in turn intensifies the scouring of soil around bridge piers. Lagasse et al. [16] affirmed a direct proportionality between flow depth and scour depth, indicating that deeper flow conditions can lead to scour depths that are twice or more the initial magnitude. Figure 7 illustrates this relationship by showing how scour depth varies with flow depth for piers of three different diameters. According to the data, the maximum recorded scour depth was 63.12 cm, which occurred near a 50 mm diameter pier under a discharge rate of 40 liters per second, corresponding to a flow depth of 35 cm. In contrast, the minimum scour depth measured at 36.56 cm was observed around the same pier under a reduced discharge rate of 20 liters per second and a flow depth of 28 cm. Similar patterns were observed for smaller pier diameters. For the 32 mm pier, the scour depths ranged from 31.41 cm (minimum) to 46.57 cm (maximum) at a constant flow depth of 35 cm. In the case of the 25 mm pier, scour depths varied between 25.32 cm and 34.21 cm, recorded at a flow depth of 28 cm. These findings reinforce the conclusion that both pier diameter and flow depth play significant roles in controlling the extent of local scouring, with larger diameters and higher drainage rates resulting in more pronounced sediment removal.

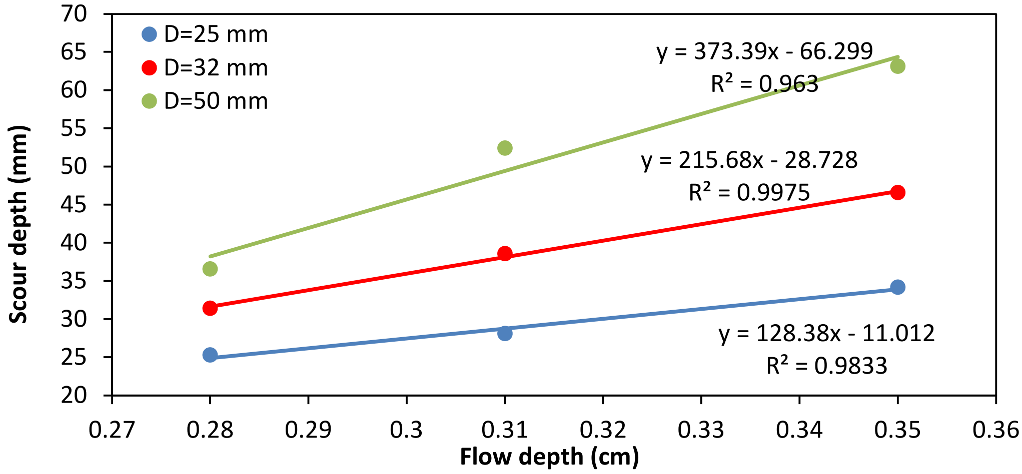

Figure 7. Relationship of scour depth with flow depth for single cylindrical piers.

3.4 Effect of Froude number (Fr)

An analysis of the Froude number from a dimensional standpoint underscores its critical role in characterizing open channel flow behavior. Defined by the expression $Fr = v / \sqrt{(g \cdot y)}$, the Froude number is governed primarily by two parameters: the flow velocity (*v*), which influences the intensity of sediment scouring, and the flow depth (*y*), representing the height of the water column over the channel bed. In this study, it is assumed that both the soil properties and ground acceleration (*g*) remain constant across all experimental flow conditions. Laboratory measurements indicate that the Froude number ranged between 0.0862 and 0.1234 under the tested scenarios. Figure 8 presents the variation in scour depth surrounding cylindrical piers of three different diameters (25 mm, 32 mm, and 50 mm) as a function of the Froude number.

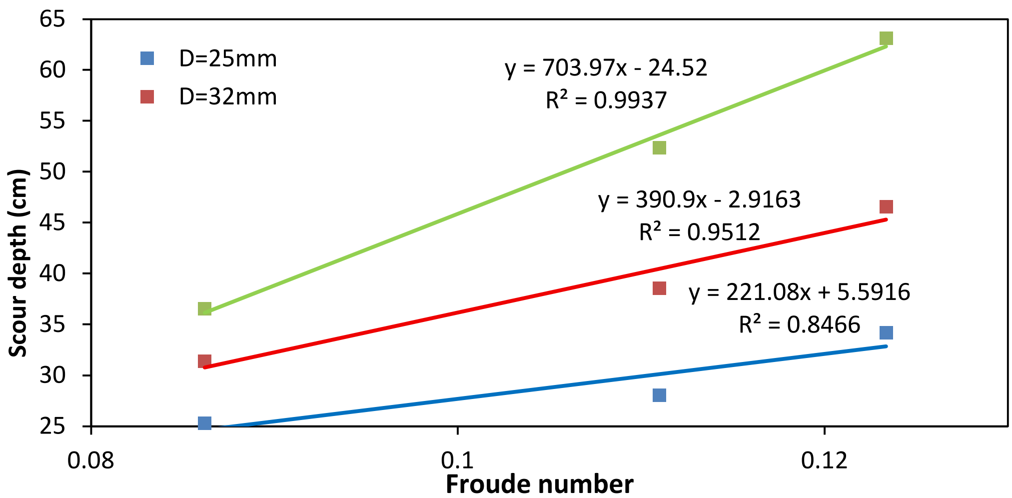

Figure 8. The scour behavior of bottom soil for three individual piercings (25, 32, and 50 mm) with Froude number.

The results show a clear trend: as the Froude number increases, so does the magnitude of scour. Furthermore, the figure illustrates the associated increase in construction or mitigation costs correlated with deeper scour profiles. This trend is consistent across various pier configurations, including isolated (single) piers, groups of consecutive piers, and solid-wall piers with rounded ends, confirming the broader applicability of the observed relationship between the Froude number and scour development.

3.5 The effect of flow speed on scour depth

Breusers et al. [17] identified that local scouring under clear-water conditions occurs when the ratio of flow velocity (V) to critical velocity (Vc) lies within the range of $0.5 \leq V/Vc < 1$. In accordance with this criterion, all experimental scenarios in the present study were carefully designed to maintain the V/Vc ratio within this specified range specifically, greater than 0.5 but less than 1 ensuring clear-water scour conditions throughout the tests. Figure 9 illustrates the relationship between flow velocity and scour depth for cylindrical piers of varying diameters. The results reveal a direct positive correlation: as flow velocity increases, the scour depth beneath the pier also rises. For instance, at a flow velocity of 0.2286 m/s and a pier diameter of 50 mm, the maximum scour depth recorded was 63.12 cm. In contrast, at a lower velocity of 0.1429 m/s, the corresponding scour depth was significantly reduced to 36.56 cm. Piers with diameters of 32 mm and 25 mm also exhibited variations in scour depth across the same two flow velocities. Specifically, the maximum and minimum scour depths were measured as 46.57 cm and 31.41 cm for the 32 mm pier, and 34.21 cm and 25.32 cm for the 25 mm pier, respectively. These findings highlight the sensitivity of scour depth to both pier diameter and flow velocity. A 60% increase in flow speed (from 0.1429 m/s to 0.2286 m/s) led to scour depth increases of 72.65%, 48.26%, and 35.11% for pier diameters of 50 mm, 32 mm, and 25 mm, respectively. Notably, doubling the pier diameter from 25 mm to 50 mm effectively doubles the rate at which scour depth increases with velocity underscoring the nonlinear and compounding influence of structural geometry on scour development.

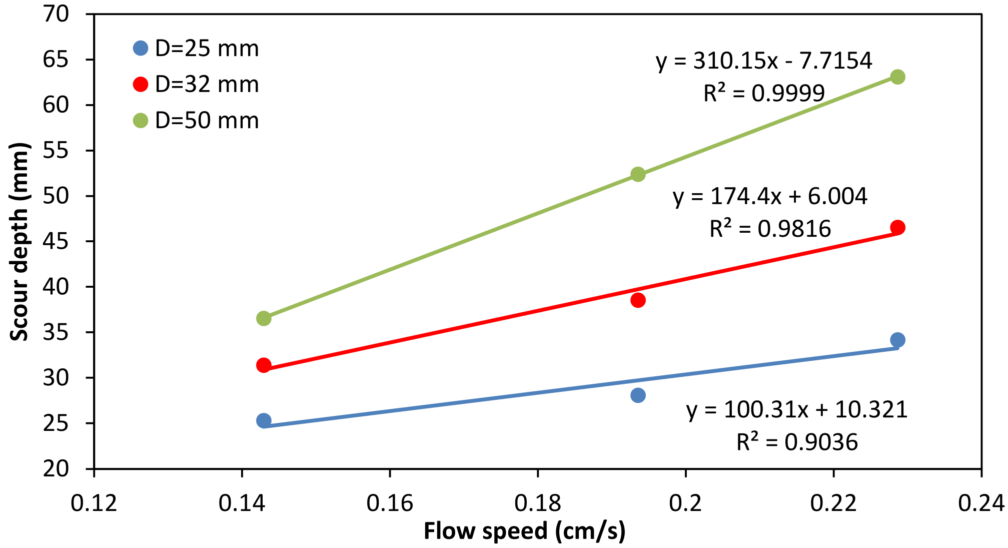

Figure 9. Relationship of scour depth with flow speed for single cylindrical piers.

4. CONCLUSION

There is a clear and direct correlation between the depth of scour beneath a bridge pier and several critical hydraulic and geometric parameters, including pier diameter, flow depth, flow velocity, projected drainage area, and the Froude number. As any of these variables increase, the scour depth tends to rise accordingly. The greatest scour typically occurs at the upstream face (leading edge) and the downstream end (wake region) of the pier. Hydrodynamically, piers with smaller diameters are associated with shallower scour profiles, whereas larger diameters exacerbate sediment removal beneath the structure. This behavior underscores the importance of optimizing pier geometry to balance hydraulic performance with structural and economic constraints. Overall, scour depth exhibits an approximately linear growth in response to increasing values of pier diameter, flow depth, flow intensity, and Froude number.

REFERENCES

[1] Bilal AM, Jebur MM, Zhussupbekov A, Karkush M. Evaluation of in Situ Loading Tests Conducted on Micropiles Used to Enhance the Bearing Capacity of Karbala Sandy Soil. Soil Mechanics and Foundation Engineering. 2025 Mar;62(1):65-72.

[2] Karkush MO, Mohsin AH, Saleh HM, Noman BJ. Numerical analysis of piles group surrounded by grouting under seismic load. In Geotechnical Engineering and Sustainable Construction: Sustainable Geotechnical Engineering 2022 Mar 20 (pp. 379-389). Singapore: Springer Singapore.
[3] Karkush M. Behavior of pile groups subjected to axial static and lateral cyclic loads in contaminated soils. In Geo-China 2016 2016 (pp. 166-174).
[4] Abdulnabi TY, Karkush MO, Safa Y, Mahdi AH. Effect of Embedment Depth on the Load-Settlement Behavior of Precast Pile in Al-Gharraf Oil Field. In International Conference on Geotechnical Engineering-IRAQ 2022 May 17 (pp. 211-221). Singapore: Springer Nature Singapore.
[5] Fattah MY, Karkush MO, Al-Neami MA, Al-Kaabi TY, Hameedi MK, Jebur MM, Fadhil SH, Al-Dahlaki MH. Observations on the Behavior of Continuous Flight Auger Piles in Iraq. In International Conference on Geotechnical Engineering-IRAQ 2022 May 17 (pp. 222-229). Singapore: Springer Nature Singapore.
[6] Cheremisinoff NP, Cheng SL. Hydraulic Mechanics 2 Civil Engineering Practice. Technomic Published Company, Lancaster, Pennsylvania, USA. 1987.
[7] Abdul-Nour M. Scouring depth around multiple M. Sc (Doctoral dissertation, Thesis, Department of Irrigation and Drainage, University of Baghdad), 1990.
[8] Hosny MM. Experimental study of local scour around circular bridge piers in cohesive soils. Colorado State University; 1995.
[9] Khassaf SI. A study of scour around Al-Kufa bridge piers. Kufa Journal of Engineering. 2010;1(2).
[10] Melville BW, Sutherland AJ. Design method for local scour at bridge piers. Journal of Hydraulic Engineering. 1988 Oct;114(10):1210-26.
[11] Khwairakpam P, Ray SS, Das S, Das R, Mazumdar A. Scour hole characteristics around a vertical pier under clear water scour conditions. ARPN Journal of Engineering and Applied Sciences. 2012;7(6):649-54.
[12] Al-Shukur AH, Obeid ZH. Experimental study of bridge pier shape to minimize local scour. International Journal of Civil Engineering and Technology. 2016 Jan;7(1):162-71.
[13] Hirshfield F. The impact of ice conditions on local scour around bridge piers (Doctoral dissertation, University of Northern British Columbia).
[14] Johnson PA. Advancing bridge-pier scour engineering. Journal of Professional Issues in Engineering Education and Practice. 1991 Jan;117(1):48-55.
[15] Alabi PD. Time development of local scour at a bridge pier fitted with a collar (Doctoral dissertation, University of Saskatchewan).
[16] Lagasse PF, Schall JD, Richardson EV. Stream stability at highway structures: Hydraulic Engineering Circular No. 20, 2001.
[17] Breusers HN, Nicollet G, Shen HW. Local scour around cylindrical piers. Journal of hydraulic research. 1977 Jul 1;15(3):211-52.