

Experimental Study Of The Local Scour Around Different Shape Of Piles

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Abstract

This experimental study investigates the local scour phenomena around piles of different cross-sectional shapes—square, circular, and triangular—under controlled hydraulic conditions. The primary goal is to understand how the geometry of piles influences the depth and pattern of scour, which is critical for the stability and design of hydraulic structures. The results reveal that pile shape significantly affects scour characteristics. Triangular piles experience the deepest and most severe scour, with maximum depths reaching up to 5 meters near the pointed apex facing the flow. This is due to the sharp angle accelerating water velocity and creating strong vortices that enhance erosion. Circular piles exhibit a more uniform scour pattern with moderate maximum depths around 2.5 meters. Their rounded shape allows smoother flow around the pile, leading to widespread but less intense scour compared to the triangular piles. Square piles show intermediate scour depths, generally less severe than triangular piles but somewhat comparable to circular ones. The sharp corners of square piles create flow separations and vortices but tend to distribute scour more locally. Across all shapes, the highest scour occurs upstream near the pile front due to the formation of horseshoe vortices and accelerated flow. Downstream scour depths are generally lower because of flow deceleration and sediment deposition. These findings emphasize the importance of considering pile shape in the design of foundations to mitigate scour risks. Understanding scour behavior around different geometries helps engineers develop better scour protection measures and ensure the longevity of hydraulic structures.

Keywords: Pile shape, Scour depth, Dimensional Analysis

NOMENCLATURE			
D_p	Pile diameter	v/v_c	Flow intensity
d_{16}	Sediment size for which 16% of the particles are finer	v_c	Critical flow velocity for sediment entrainment
d_{50}	Median particle size	v^*c	Mean approach velocity at the threshold condition
d_{84}	Sediment Size for which 84% of the Particles are Finer	v	Mean velocity of approach flow
d_s	Maximum scour depth below the bed level	y	Flow depth
F_p	Pile Froude number	σ_g	Geometric standard deviation of sediment size distribution
t	Scouring time		
μ	Dynamic viscosity of fluid		

Introduction

Local scour around hydraulic foundations—such as bridge piers and structural piles in rivers and coastal environments—is considered one of the most critical challenges in

hydraulic and civil engineering. This phenomenon results from the interaction between flowing water and sediment movement near the pile, causing the removal of bed material and exposing the structure to potential instability or even collapse. Several studies have confirmed that local scour is among the primary causes of bridge failures worldwide, especially during floods and high-velocity flow conditions [1].

The scour process is mainly governed by turbulent flow patterns around the pile. When the flow encounters the obstruction, separation occurs at the upstream face, forming horseshoe vortices, while wake vortices develop downstream. These vortical systems exert strong shear stresses on the bed, mobilizing sediment particles and deepening the scour hole. The intensity of scour is controlled by various factors, including flow velocity and depth, sediment characteristics (grain size, density, cohesion), and channel conditions.

Among all influencing parameters, pile geometry plays a fundamental role in shaping the hydrodynamics around the structure. Research shows that piles with sharp corners—such as square or rectangular shapes—produce stronger turbulence and deeper scour holes compared to circular or streamlined piles [8]. Although the scour around circular piles has been widely explored in classical and modern studies [4], the influence of non-cylindrical pile shapes under different hydraulic conditions has received comparatively less attention [2].

In recent years, both experimental and numerical investigations have sought to better understand scour mechanisms around piles of various shapes, develop predictive models, and quantify scour development over time [3]. Experimental studies, in particular, provide accurate measurements of scour depth, scour width, and temporal scour evolution in controlled settings, thereby supporting the development of reliable engineering design criteria [12].

Therefore, studying local scour around piles is not merely of academic interest; it is a vital component of designing safe and sustainable hydraulic structures. Understanding how various factors—especially pile shape—influence scour formation contributes to improving foundation design, reducing maintenance costs, and mitigating risks associated with structural failures [35].

2. EFFECT OF PILE SHAPE ON SCOUR FORMATION

The mechanisms of scouring and the flow patterns around piles are highly complex and have been extensively described in previous research. Scour around a pile results primarily from the interaction between downflow at the upstream face and the formation of a horseshoe vortex at the pile base. Dargahi [11] and Tanaka [15] indicated that the magnitude of local scour is directly related to the size and strength of the vortex system generated around the pile. Additionally, flow separation along the sides of the pile leads to the development of wake vortices, which contribute to sediment removal downstream [10].

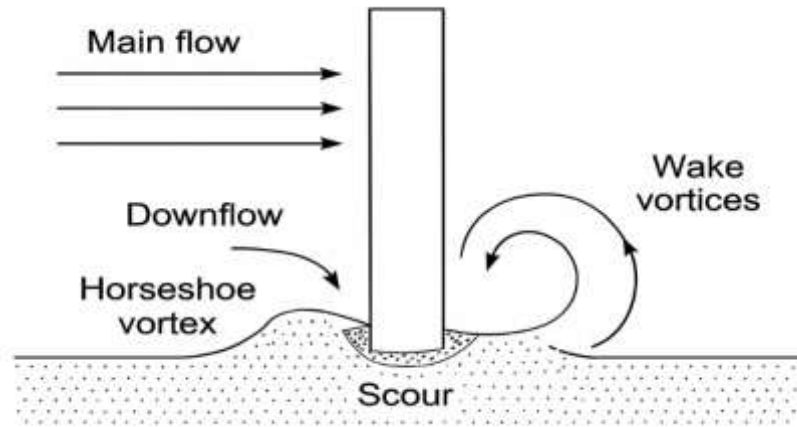
These vortices are initiated by the combination of the approaching main flow and the flow disturbance caused by the obstruction of the pile. The intensity and geometry of these vortices vary significantly depending on the shape of the pile. For example, sharp-edged shapes such as square or triangular piles tend to generate more intense turbulence and deeper scour holes compared to circular or streamlined profiles.

The main objectives of this study are:

To identify the optimal pile shape (triangular, square, or circular) for minimizing scour depth and extent.

To analyze the flow field around each pile geometry and understand the vortex structures responsible for sediment transport.

To provide practical design recommendations for engineers to mitigate local scour in hydraulic and



3. DIMENSIONAL ANALYSIS FOR SCOUR AROUND DIFFERENT PILE SHAPES

Dimensional analysis is a vital step in experimental hydraulics, allowing researchers to identify the key variables that influence a physical phenomenon—in this case, the local scour depth around piles with different geometric shapes. The scour process is affected by multiple parameters related to the flow, fluid properties, sediment characteristics, pile geometry, and channel configuration. In the context of this study, the focus is on assessing how the shape of the pile affects the magnitude of local scour under clear-water conditions.

The depth of scour d_s around a pile can be considered a function of the following variables:

$$d_s = f(y, v, v_c, g, \rho, \mu, d_{50}, \rho_s, \sigma_g, D_p, S, B, t, \text{Shape}) \quad (1)$$

Where:

- d_s : Maximum scour depth below the bed level
- D_p : Pile diameter or pile side dimension
- d_{16} : Sediment size for which 16% of the particles are finer
- d_{50} : Median particle size
- d_{84} : Sediment size for which 84% of the particles are finer
- F_p : Pile Froude number
- t : Scouring time
- μ : Dynamic viscosity of fluid
- v/v_c : Flow intensity
- v_c : Critical flow velocity for sediment entrainment
- v_c^* : Mean approach velocity at the threshold condition
- v : Mean velocity of approach flow
- y : Flow depth
- σ_g : Geometric standard deviation of sediment size distribution
- Shape = geometric cross-sectional profile of the pile (circular, square, triangular, etc.)

Using Buckingham π -theorem, and considering shape as a dimensionless categorical variable, the above relationship can be reduced to:

$$\frac{d_s}{D_p} = f\left(\frac{y}{D_p}, \frac{v_c}{v}, \frac{D_p g}{v^2}, \frac{d_{50}}{D_p}, \sigma_g, \frac{B}{D_p}, \frac{t}{t_e}, \text{Shape}\right) \quad (2)$$

Where:

- $\frac{d_s}{D_p}$ = dimensionless scour depth
- $\frac{y}{D_p}$ = relative flow depth
- $\frac{v_c}{v}$ = flow intensity
- $\frac{D_p g}{v^2}$ = inverse Froude number (pile Froude number)
- $\frac{d_{50}}{D_p}$ = relative sediment size
- σ_g = geometric standard deviation of sediment size
- $\frac{B}{D_p}$ = relative channel width
- $\frac{t}{t_e}$ = dimensionless time (where t_e is the equilibrium time)

To isolate the effect of pile shape, all other parameters are held constant across tests, including sediment characteristics, flow intensity, and pile diameter. Hence, the functional form of the relationship can be simplified for controlled experiments as:

$$\frac{d_s}{D_p} = f(\text{Shape}) \quad (3)$$

This simplified equation emphasizes the influence of pile geometry alone on scour depth. By comparing the results across different shapes (circular, square, triangular), one can identify which geometry induces the least severe scouring, providing useful insights for engineering design

3- Dimensional Analysis for piles

The dimensional analysis technique is very important prior to conducting experiments, as it helps identify the most significant variables that affect the depth of scour, which is the main subject of this study. Therefore, dimensional analysis was performed first, and the experiments were subsequently designed based on its outcomes.

The geometry of scour around a circular pile depends on flow conditions (approach flow depth and velocity), fluid parameters (density and viscosity), sediment properties (grain size, sediment density, and geometric standard deviation), pile characteristics (pile diameter), channel geometry (channel width), time, and pile shape (rectangular, triangular, or circular). Therefore, the scour depth can be expressed as a function of the following parameters:

$$(d_s) = f(y, v, v_c, g, \rho, \mu, d_{50}, \rho_s, \sigma_g, D_p, S, B, t, k) \quad (1)$$

where:

y = flow depth,

v = mean approach flow velocity,

v_c = critical velocity,

g = gravitational acceleration,

ρ = density of the fluid,

μ = dynamic viscosity of the fluid,

d_{50} = median grain size of sediment particles,

ρ_s = density of the sediment,

$\sigma_g = (d_{84}/d_{16})^{0.5}$ = geometric standard deviation of sediment size distribution,

d_{16} = sediment size for which 16% of the particles are finer,

d_{84} = sediment size for which 84% of the particles are finer,

D_p = pile diameter,

S = channel slope,

B = channel width,

t = scouring time,

k = coefficient representing pile shape.

From the above equation, it is evident that σ_g is a dimensionless term. Using dimensional analysis, Equation (1) can be rewritten using Buckingham's π -theorem as:

$$F\left(\frac{d_s}{D_p}, \frac{y}{D_p}, \frac{v_c}{v}, \frac{D_p g}{v^2}, \frac{v D_p \rho}{\mu}, \frac{d_{50}}{D_p}, \frac{v D_p \rho_s}{\mu}, \sigma_g, \frac{S}{D_p}, \frac{B}{D_p}, \frac{t}{t_e}\right) \quad (2)$$

After simplification, and by eliminating the parameters with constant values, the following considerations are applied:

1. When $\sigma_g < 1.5$ for uniform sediment and $D_p/d_{50} > 25$, this ratio can be excluded from the scour formula [19].
2. The channel bed is horizontal and without any inclination.
3. For $B/D_p \geq 10$, side-wall (blockage) effects due to the pile are negligible [20].
4. The pile shape coefficient k is considered constant.
5. At equilibrium conditions, the scour depth is independent of dimensionless time.

With these considerations, Equation (2) reduces to:

$$\frac{d_s}{D_p} = f\left(\frac{y}{D_p}, \frac{v_c}{v}, \frac{D_p g}{v^2}\right) \quad (3)$$

From the simplified equation, the scour depth ratio (d_s/D_p) varies with the flow depth ratio (y/D_p), the flow intensity (v_c/v), and the pile Froude number ($D_p g/v^2$).

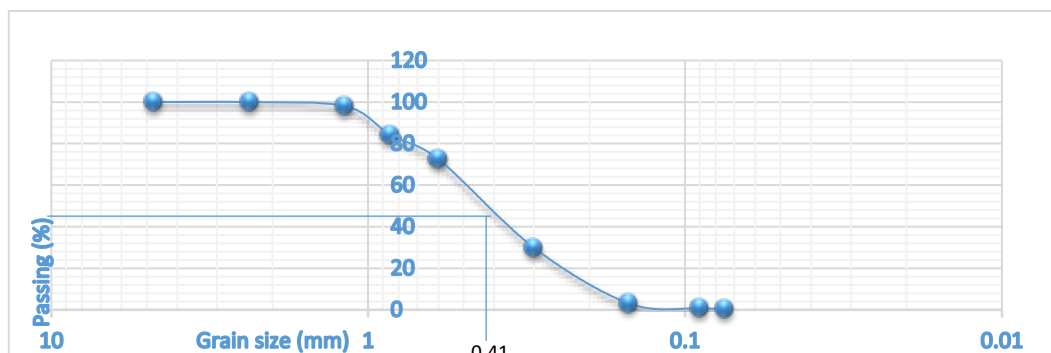
4- EXPERIMENTAL WORK

The main channel consisted of 10 m long and 0.8 m width. with one side glass, A sharp crested full width weir fixed at the upstream section of the flume did the discharge measurement.

Both bed profile and depth of flow were measured by a point gauge having an accuracy of ± 1 mm. Some coarse gravel was spread on specific length of the upstream side in order to distribute the inflow uniformly.

A tail gate was situated at the end of the channel to control the flow depth at desired levels. The sediment used in all tests was uniform sand with a mean size diameter $d_{50}=0.41$ mm and its grain size distribution curve is shown in Figure 3. The geometric standard deviation of the grain size distribution was 1.9 less than 2, that were selected to maintain clear water condition without formation of ripple according to Hoffmans [21]. Length of working section equals to 1.8 m and its thickness equals to 8 cm.

Figure(2) The grain size distribution curve for sediment that used in test



To avoid wall effect on scouring process, “the pile diameter should not be more than 10% of the flume width” [22]. Therefore, in this study a circular pile of diameter 50 mm made of steel with smooth surface was used.

Experiment of equilibrium time was done at two different flow intensity (v/v_c), The critical velocity was evaluated from Melvill's equations [23] as follows:

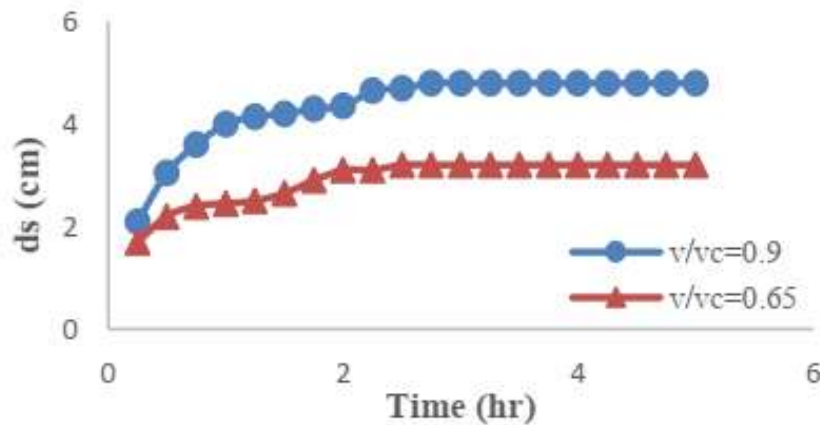
$$v_c/v_{*c} = 5.75 \log(5.53y/d_{50}) \quad (4)$$

$$v_c = 0.0115 + 0.0125d_{50}^{1.4} \quad (5)$$

$$0.1 \text{ mm} < d_{50} < 1 \text{ mm}$$

The results are shown in Figure 4; it can be seen that approximately 95% of scouring [24] occurs during the first 2 hours. Therefore, in all experimental runs, duration of 3 hours was selected for each run at which equilibrium time conditions occur

Figure (3) Scour depth variation with different duration



5. PILE SHAPE MODELS

Proposed Final Dimensions (based on Melville & Coleman, 2000 – Bridge Scour and Ahmad et al., 2018 – Experimental Study of Scour Around Piles of Different Shapes):

1. Circular Pile

- Diameter (D) = 2.5 cm
- Total length = 60 cm
- Exposed length above the bed = 40 cm
- Embedded depth in the bed = 20 cm

2. Square Pile

- Side length (B) = 2.5 cm (equal to the diameter of the circular pile for fair comparison)
- Total length = 60 cm
- Exposed length above the bed = 40 cm
- Embedded depth = 20 cm

3. Triangular Pile

- Side length (a) = 2.5 cm
- Total length = 60 cm
- Exposed length above the bed = 40 cm
- Embedded depth = 20 cm

Reason for selecting these dimensions:

- Maintain a uniform cross-sectional area across all shapes to ensure a fair comparison.
- A diameter/side of 2.5 cm is common in scale model laboratory experiments and provides clear visibility in measuring scour patterns around the pile.

figure(4) pile shape models



6-STUDY AREA

The figure clear that this map represents a grid survey of the study area around the pile, where each square measures 1.5 cm × 1.5 cm in reality, and the squares are numbered (1–106) to allow tracking of the depth or scour reading after each experimental run (RUN).

The purpose of this design is:

- To determine the change in depth at each point relative to the pile with variations in pile shape or the number of runs.
- The blue arrow indicates the flow direction, which is important for understanding the areas of sediment deposition or increased scour.
- The center of the figure contains the pile, and the surrounding squares represent the measured points in all directions.

figure (5) Location of reading

y-axis ↑	72	71	70	69	68	67	66	19	29	39	49	
	77	76	75	74	73	64	11	20	30	40	50	
	81	80	79	78	62	5	12	21	31	41	51	
	84	83	82	60	1	6	13	22	32	42	52	
	86	85	pile			2	7	14	23	33	43	53
	88	87				3	8	15	24	34	44	54
	91	90	89	59	4	9	16	25	35	45	55	

	95	94	93	92	61	10	17	26	36	46	56
	100	99	98	97	96	63	18	27	37	47	57
	106	105	104	103	102	101	65	28	38	48	58
0,0	X – axes 										

RESULTS:

The experiments were conducted, and the results were obtained, as illustrated in the following figures:

Figure (6) The comparison between scour depth and run (discharge) for different pile group at point 1

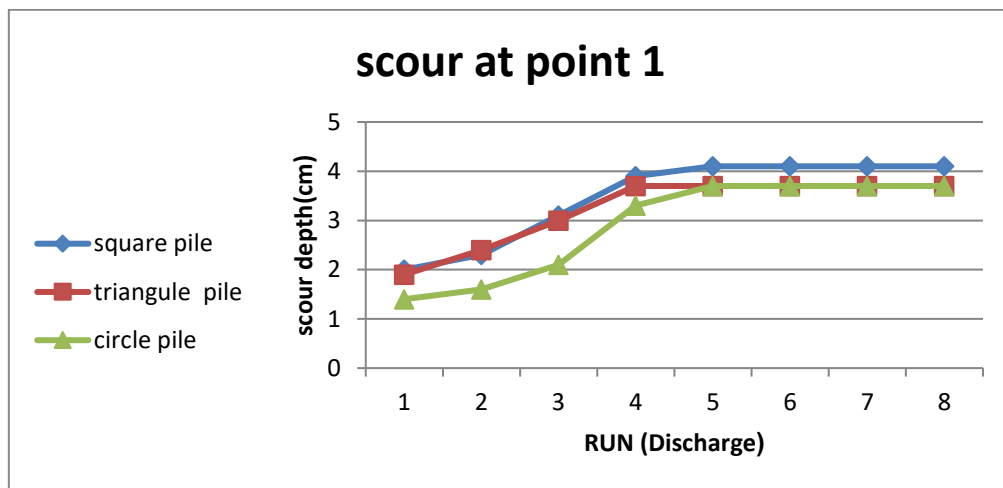


Figure (7) The comparison between scour depth and run (discharge) for different pile group at point 2

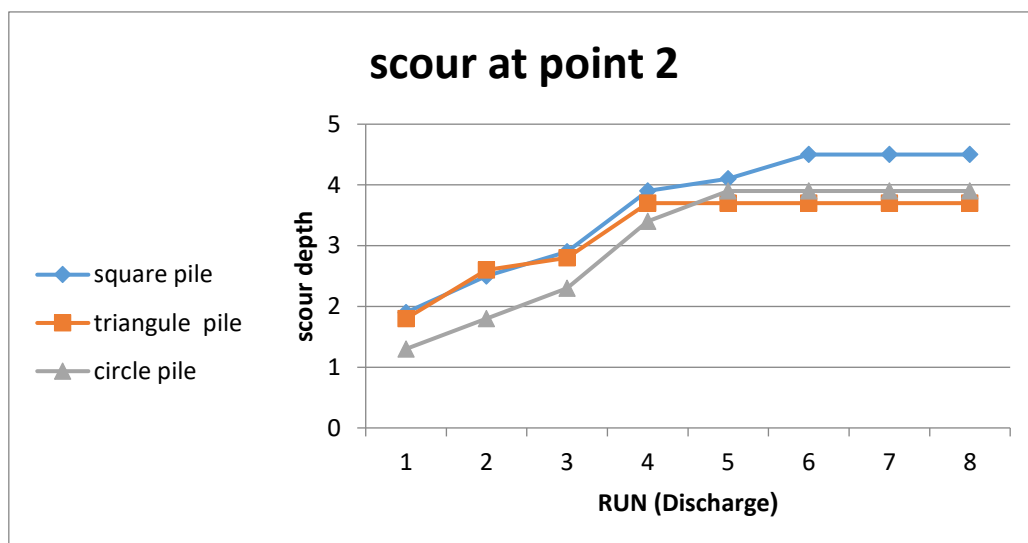


Figure (8) The comparison between scour depth and run (discharge) for different pile group at point 3

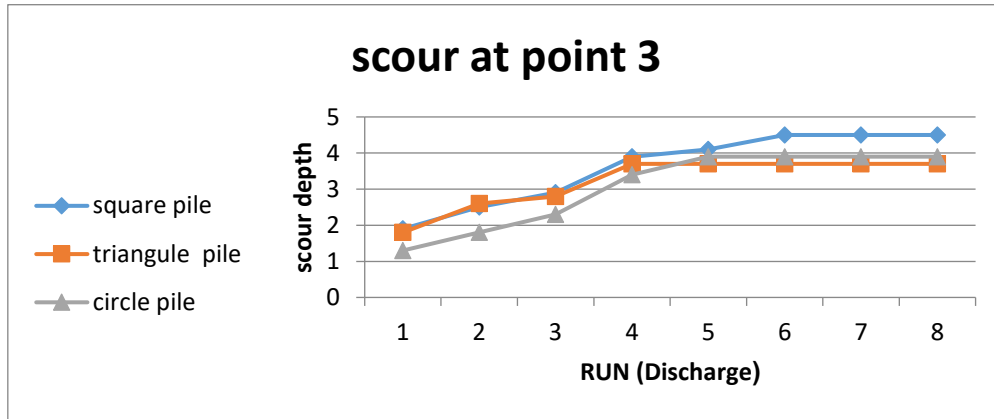


Figure (9) The comparison between scour depth and run (discharge) for different pile group at point 4

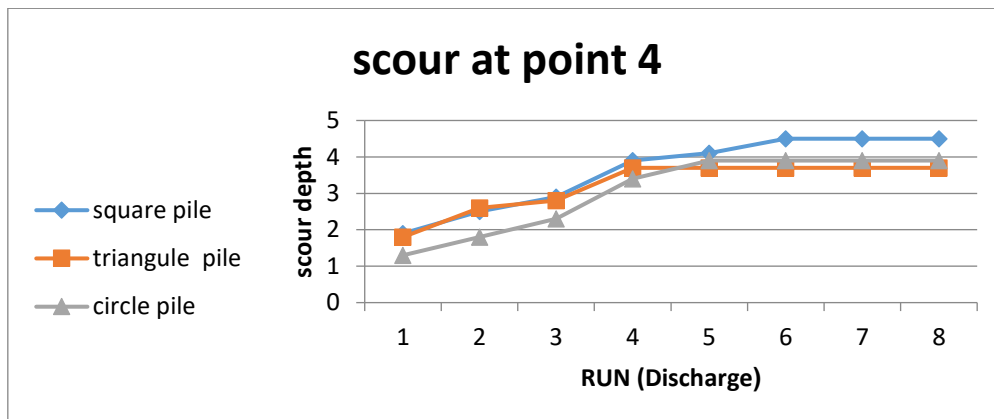


Figure (10) The comparison between scour depth and run (discharge) for different pile group at point 59

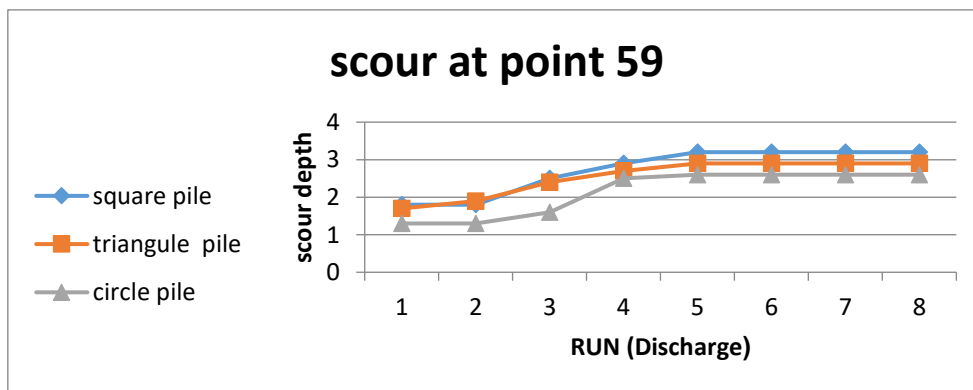


Figure (11) The comparison between scour depth and run (discharge) for different pile group at point 60

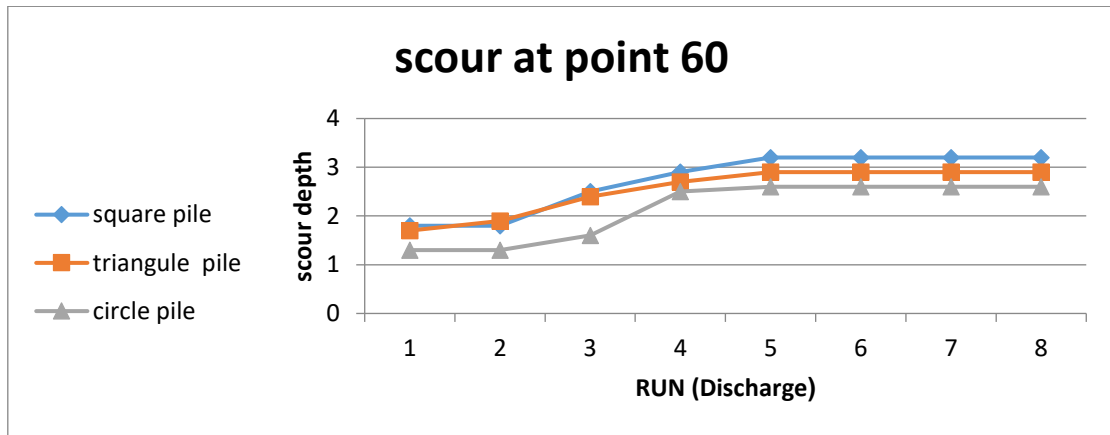


Figure (12) The comparison between scour depth and run (discharge) for different pile group at point 82

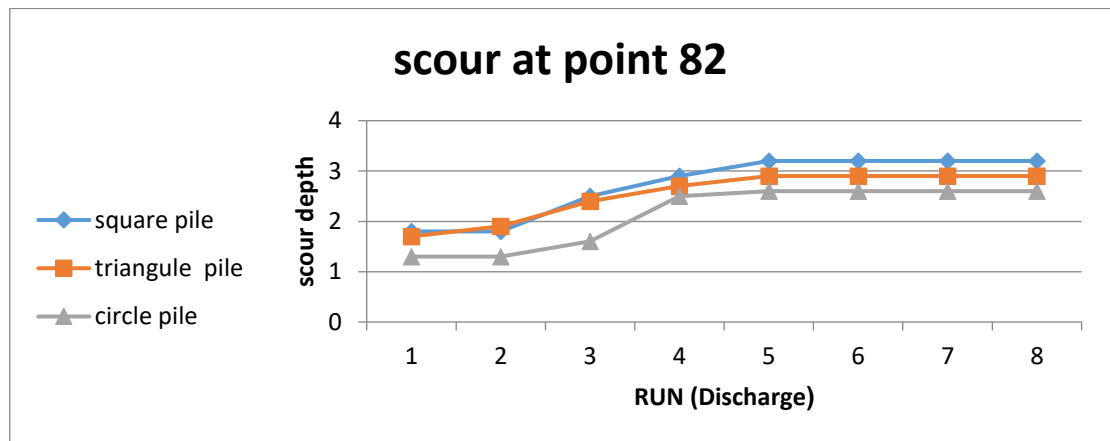
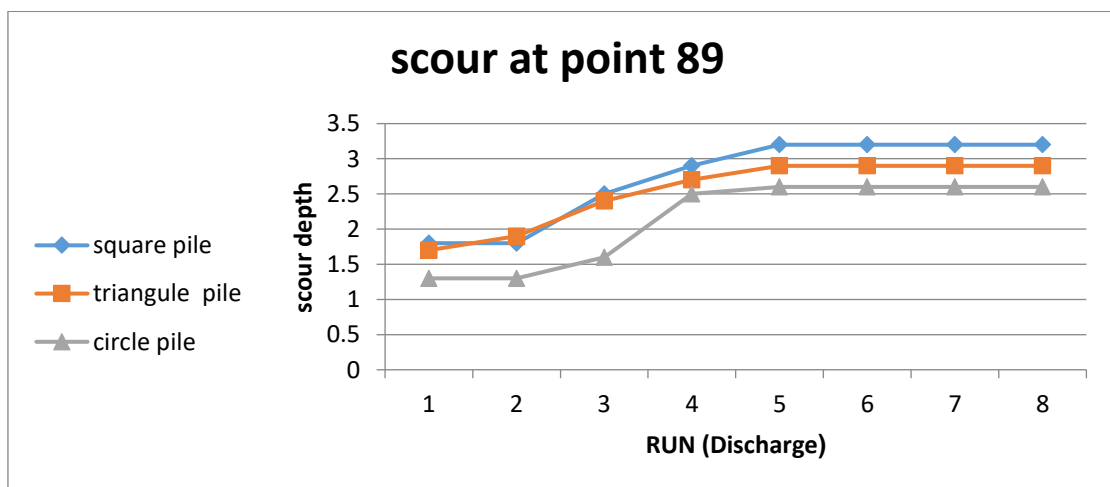


Figure (13) The comparison between scour depth and run (discharge) for different pile group at point 89



The results of scour tests around three different pile shapes—square, circular, and triangular—under the influence of water flow, without vertical loading, indicate that pile geometry has a significant impact on the extent of local scour in sandy soils [33]. The measured scour values, representing actual sediment displacement rather than structural resistance, show that circular piles generally perform best, exhibiting the lowest scour rates at most measurement points, particularly under low and medium flow intensities. This superior performance is attributed to their streamlined shape, which reduces flow turbulence, distributes pressures more evenly, and minimizes the formation of vortices and lateral soil drag forces [23, 32].

In contrast, square piles exhibited the highest scour values, reaching peak levels of 5.0 at points such as 7, 8, and 9 under high flow intensity. This is due to their sharp corners, which induce abrupt boundary layer separation and generate strong wake vortices, thereby increasing lateral erosion and forming deeper scour holes [1, 25]. These findings indicate that square piles are less suitable in applications where scour minimization is critical.

Triangular piles demonstrated intermediate performance, with scour values lower than square piles but generally higher than circular piles. Their geometry provides a compromise between streamlined flow and structural stability, producing moderate vortex intensity and gradual flow separation [28].

As flow intensity increased from Run1 to Run5, scour progressed around all pile shapes; however, the relative advantage of circular piles remained evident [27]. Some negative values were observed at points 38, 39, and 46, likely due to sediment deposition in "hydraulic shadow" zones, where flow velocity decreases and material settle [25]. From point 70 onwards, scour values stabilized at low and similar levels for all shapes, indicating that the system had reached an equilibrium between hydraulic forces and soil resistance [26].

Based on these observations, it can be concluded that circular piles are optimal for reducing scour in sandy soils, making them preferable for hydraulic structures such as bridge foundations and irrigation channels, whereas square piles are not recommended in scour-sensitive environments [29, 24].

Discussion

The experimental results provide compelling evidence that pile geometry exerts a decisive influence on the magnitude and spatial distribution of local scour around pile foundations. The variation in scour depth among square, circular, and triangular piles under identical hydraulic conditions is clearly illustrated in Figures (6)–(13), which present the relationship between scour depth and discharge across multiple measurement points.

The square pile exhibited moderate scour depths, with maximum values ranging between approximately 2.0 and 2.5 meters near the upstream face and along the side surfaces. As demonstrated in Figures (6)–(9), the square pile consistently yielded the lowest scour values relative to the other tested geometries. The sharp corners induced flow separation and promoted the formation of horseshoe vortices, resulting in localized and relatively symmetrical scour patterns. Downstream of the pile, reduced velocities contributed to diminished scour depths and observable sediment deposition.

The circular pile recorded slightly higher scour depths, typically ranging from 2.5 to 2.6 meters. Across Figures (6)–(13), the circular pile occupies an intermediate position—exhibiting scour magnitudes greater than the square pile but consistently lower than those observed around the triangular pile. The streamlined profile of the circular pile facilitated smoother flow reattachment, yielding a more uniform scour distribution. Nevertheless, strong vortices remained present near the pile base, producing substantial

but more diffusely distributed erosion. Downstream scour remained minimal due to the attenuated wake region.

The triangular pile demonstrated the most pronounced scour, with maximum depths ranging from 4.8 to 5.0 meters, particularly concentrated near the upstream apex. As evident in Figures (10)–(13), the triangular geometry consistently resulted in the highest scour depths across the full discharge range. The acute upstream angle amplified local flow acceleration, intensified vortex formation, and increased bed shear stresses, producing highly asymmetric scour patterns. This configuration generated deeper and more extensive scour compared with both circular and square piles.

Collectively, the results confirm that sharper edges and acute flow-facing angles significantly enhance turbulence intensity and near-bed shear stresses, thereby increasing scour severity. Circular piles, by contrast, promote smoother flow transitions and consequently exhibit more evenly distributed scour. Square piles tend to produce moderately intense scour due to their blunt edges, which distribute flow separation over broader regions. The consistency of these trends across Figures (6)–(13) reinforces the robustness of the experimental findings, with the triangular pile emerging as the most vulnerable to scour and the square pile as the least.

For all pile shapes, the greatest scour occurred at the upstream face, driven primarily by horseshoe vortex formation. Downstream scour depths were systematically lower, reflecting flow deceleration and sediment deposition within the wake zone. These observations underscore the critical importance of incorporating pile geometry into scour assessment frameworks and foundation design practices. Understanding the interaction between structural geometry and local hydrodynamics is essential for implementing effective mitigation strategies—such as riprap placement, collars, or optimized pile shapes—aimed at enhancing the resilience and service life of hydraulic structures.

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