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Experimental Analysis of Surface Modifications on Scour Hole Formation in Straight River Sections

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Abstract

This study dives into the complex issue of erosion around bridge foundations, exploring how sudden changes in a river's cross-section affect scour patterns. We set up two experiments to get a clearer picture: one with a consistent channel shape as a baseline and another where the waterway's geometry was abruptly altered. In the first setup, we tested how different flow speeds influence erosion, giving us a solid understanding of typical scour behavior. The second experiment focused on what happens when the channel suddenly narrows, mimicking real-world conditions like those near bridge supports. Our findings were striking. When the waterway's shape changed abruptly, scour depth increased significantly, especially at higher flow velocities. This happens because the water speeds up in tighter spaces, creating intense turbulence and swirling vortexes around the bridge foundations. These forces dig deeper scour holes, posing a greater risk to structural stability. Compared to the steady channel, the altered setup showed just how much hydraulic geometry can amplify erosion. These results drive home a key point: the design of a river's flow path matters immensely when it comes to protecting bridge foundations. Engineers need to factor in these dynamic hydraulic effects to ensure bridges can withstand the relentless forces of water over time. By understanding how sudden changes in a waterway's shape can worsen scour, this study offers valuable insights for building safer, more resilient bridges. It's a reminder that nature's complexity demands careful consideration in infrastructure design, especially as flow conditions become more extreme. This work underscores the importance of blending hydraulic science with engineering to safeguard critical structures against erosion's destructive power.

1. Introduction

Scouring is a critical phenomenon in hydraulic engineering, sediment transport, and the stability of hydraulic structures, particularly around bridge foundations. The formation and expansion of scour holes can lead to significant instability, especially during extreme hydrological events such as floods, where increased flow ve-

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locities exacerbate the problem. This phenomenon often results in severe structural damage or even catastrophic failure of critical infrastructure, such as bridges and dams. Understanding the mechanisms of scour formation, its temporal development, and the final configuration of scour holes is essential for designing durable and stable hydraulic structures, particularly in complex environments where scouring poses a significant risk (Chabert and Engeldinger, 1956; Melville and Coleman, 2000; Ettema et al., 2017).

Systematic research on scouring around bridge foundations began in Germany in the early 20th century. Pioneering work by Chabert and Engeldinger (1956) at the Chatto Laboratory laid the foundation for understanding scour and flow dynamics around bridge piers. Their studies focused on the relationship between flow conditions, sediment properties, and scour depth, emphasising the importance of geometric and hydraulic factors in the scouring process. Concurrently, Larsen and Touche (1956) investigated how riverbank characteristics, sediment properties, and hydraulic flow parameters influence scour development. They highlighted the critical role of foundation geometry and flow conditions in determining scour depth (Larsen and Touche, 1956; Richardson and Davis, 2001).

Early investigations into the mechanics of local scour around bridge piers laid a strong foundation for modern scour prediction and mitigation strategies. Chabert and Engeldinger (1956) conducted pioneering experiments to model the temporal development of scour depth and observed that maximum scour typically occurs near the critical threshold between sediment incipient motion and clear-water conditions. Their work also explored early protective measures, such as riprap and other erosion-control methods, to reduce scour severity around hydraulic structures (Chabert & Engeldinger, 1956; Melville & Sutherland, 1988). These studies were instrumental in shaping the understanding of how flow and sediment interactions influence scour dynamics, and they provided a basis for subsequent empirical and theoretical models. In the following decades, significant progress was made in identifying the hydraulic and sedimentological factors that govern scour formation. Shen et al. (1969) were among the first to recognise the horseshoe vortex as a primary mechanism responsible for sediment removal around bridge foundations. They proposed an empirical formula for estimating equilibrium scour depth based on foundation diameter, flow depth, and velocity, which became a widely used tool in engineering practice (Shen et al., 1969; Ettema et al., 2017). Further experimental studies in the 1970s expanded on these findings, examining the influence of sediment grain size, foundation geometry, and flow conditions on scour depth (Shen et al., 1977; Melville & Sutherland, 1988).

In the 1980s, researchers began to explore the complex relationship between flow velocity and sediment transport in determining scour depth. Chiew and Melville (1987) conducted controlled experiments to investigate the effects of flow velocity, sediment size, and flow depth on scour around cylindrical piers. They observed that when flow velocity exceeds the critical threshold for sediment motion, increasing the velocity up to twice that threshold actually reduces the maximum scour depth. This counterintuitive result highlighted the nonlinear nature of sediment transport and flow interactions in scour development (Chiew & Melville, 1987; Guan et al., 2020). Melville and Sutherland (1988) later synthesised these findings into a comprehensive method for predicting maximum scour depth, incorporating a wide range of variables such as flow characteristics, sediment properties, and pier geometry. Their framework remains one of the most widely referenced approaches in bridge scour estimation and design (Melville & Sutherland, 1988; Pandey et al., 2021). This period marked a shift toward more systematic, integrated models that combined hydraulic and sedimentological principles.

The 1990s saw a growing emphasis on the influence of foundation geometry and sediment heterogeneity on scour behavior. Broussers and Radkivi (1991) investigated how variations in foundation cross-sectional area affected scour depth, finding that larger cross-sectional areas tended to increase scour, while reduced areas led to less scour. Their findings underscored the importance of optimising foundation design to minimise scour risk (Broussers & Radkivi, 1991; Zhang et al., 2022). Around the same time, Kothyari et al. (1992) examined the temporal evolution of scour under both steady and unsteady flow conditions. They proposed a predictive relationship that divides unsteady flow hydrographs into quasi-steady segments, allowing for more accurate estimation of time-dependent scour depth. Their research also emphasised the role of primary vortices in initiating and sustaining scour around bridge piers (Kothyari et al., 1992; Wang et al., 2020). These studies deepened understanding of how time-varying flows influence scour development, which is particularly relevant in natural river systems subject to fluctuating hydrological conditions.

In more recent years, attention has turned to the effects of foundation orientation and tilt on scour reduction. Bozkus and Yildiz (2001) experimentally investigated the influence of tilting cylindrical piers in straight channels using a 5 cm diameter plexiglass model. They found that tilting the pier downstream significantly reduced scour depth, with greater tilt angles resulting in progressively smaller scour holes (Bozkus & Yildiz, 2001; Guan et al., 2020). Salimi (2016) expanded on this work by quantitatively analysing flow patterns and scour depths around both inclined and vertical cylindrical foundations. He reported that for each degree of downstream tilt, scour depth decreased by approximately 1%, providing empirical support for using inclined piers as a scour mitigation strategy (Salimi, 2016; Pandey et al., 2021). Similarly, Bozkus and Cesme (2010) studied paired tilted piers under clear-water conditions with non-uniform sediments and found that tilted configurations consistently resulted in shallower scour compared to vertical ones, particularly in heterogeneous sediment environments (Bozkus & Cesme, 2010). Recent studies, such as those by Khosronejad et al. (2020) and Liu et al. (2019), have further validated the importance of geometric design in minimising turbulence and vortex formation (Khosronejad et al., 2020; Liu et al., 2019). Additionally, modern research has emphasised integrating numerical modeling and machine learning techniques to improve scour prediction accuracy (e.g., Pandey et al., 2021; Wang et al., 2020; Zhang et al., 2022).

. This finding highlighted the potential benefits of using multiple tilted foundations to reduce scour risk (Bozkus and Cesme, 2010; Zhang et al., 2022). Ozlap (2013) studied the effect of foundation tilt on scour depth in groups of three and four foundations. They found that tilted foundation groups experienced less scour than vertical groups, particularly at tilt angles of 10 and 15 degrees. This research demonstrated the potential for using tilted foundation groups to enhance the stability of hydraulic structures (Ozlap, 2013; Wang et al., 2020). Recent advancements in scour research have focused on integrating computational fluid dynamics (CFD) and machine learning (ML) techniques to predict scour depth and optimise foundation designs. For instance, Guan et al. (2020) utilised CFD simulations to model the complex flow patterns around bridge piers, providing insights into the spatial distribution of scour holes. Their findings demonstrated that CFD models could accurately predict scour depth under varying flow conditions, offering a powerful tool for engineers (Guan et al., 2020; Pandey et al., 2021). Similarly, machine learning algorithms have been used to analyse large datasets of scour measurements, enabling the development of highly accurate predictive models. Zhang et al. (2022) applied artificial neural networks (ANNs) to predict scour depth around bridge piers, achieving a correlation coefficient of over 0.95 between predicted and observed values. These advancements highlight the potential of data-driven approaches in scour research (Zhang et al., 2022; Wang et al., 2020). Another emerging trend is the use of eco-friendly scour protection systems, which can reduce scour depth by up to 30% while also providing ecological benefits (Ettema et al., 2017; Pandey et al., 2021). These innovative approaches align with the growing emphasis on sustainable engineering practices. Scouring remains a critical challenge in hydraulic engineering, with significant implications for the stability and durability of bridge foundations and other hydraulic structures. Over the past century, researchers have conducted extensive studies to understand scour formation mechanisms and develop effective mitigation strategies. Key findings include the importance of foundation geometry, sediment properties, and flow conditions in determining scour depth, as well as the potential benefits of inclined foundations and foundation groups in reducing scour risk. Future research should continue to explore innovative design solutions, advanced modeling techniques, and sustainable scour protection measures to enhance further the resilience of hydraulic structures to scour.

Table 1. Comprehensive Timeline of Research on Scour around Bridge Foundations: Key Findings and Innovations

Year	Researcher(s)	Key Findings
1956	Chabert and Engeldinger	Developed models for estimating scour depth, highlighted maximum scour near particle movement thresholds, and explored protection methods.
1956	Larsen and Touche	Studied geometric and hydraulic factors, including base shape, riverbank characteristics, and flow parameters.
1969	Shen et al.	Identified the horseshoe vortex as a critical factor and proposed an empirical formula for scour depth based on foundation diameter, upstream flow depth, and flow velocity.
1977	Breusers et al.	Expanded studies on flow depth, sediment particle size, and foundation diameter, emphasising their effects on scour depth in clear water conditions.
1987	Chiu and Melville	Investigated the influence of flow speed and sediment size on scour depth and noted a reduction in scour with increasing flow speed beyond the threshold.
1988	Melville and Sutherland	Developed a method for calculating maximum scour depth using flow, sediment, and foundation characteristics.
1991	Broussers and Radkivi	Found that foundations with increased cross-sectional area increase scour, while reduced cross-sectional areas decrease scour.
1992	Kotiari et al.	Examined temporal changes in scour depth under uniform, non-uniform, and layered sediments, providing a formula for scour depth over time.
2001	Bozkosh and Yaldiz	Studied the effect of tilting single cylindrical foundations, finding that increased tilt angles reduce scour depth.
2006	Salimi	Investigated base tilt in upstream, downstream, and perpendicular directions, showing downstream tilts significantly reduce scour depth.
2010	Bozkosh and Cheshme	Reported that tilted foundation pairs in non-uniform sediments result in lower scour depths compared to single vertical foundations.
2013	Ozlap	Found that groups of tilted foundations (3 or 4 bases) reduce scour depth compared to vertical base groups.
2020	Abdollahi et al.	Investigated the use of foundation gaps for scour mitigation, finding that gaps effectively reduce the horseshoe vortex and maximum scour depth.
2021	Al-Madhhachi and Jasim	Studied the impact of sediment layering on scour, demonstrating that layered sediments with larger particles resist deeper scouring.

2024	Aghamajidi et al.	Investigated the impact of surface modifications on bridge scour hole geometry, finding that structured surface designs significantly alter flow patterns and reduce maximum scour depth.

Esmaili Varki et al. (2013) investigated the effect of geometric and hydraulic factors on scouring characteristics around the inclined base group with foundation. Based on their experimental results, they reported that changes in flow speed relative to depth significantly affect maximum scour depth. In addition to flow speed, relative depth also significantly affects scour depth: reducing relative depth (the ratio of flow depth to foundation width) from 3 to 1 increased scour depth by 28%. Also, by comparing different numbers of foundation placement (in the form of the ratio of the distance between the foundation and the surface of the foundation to the width of the foundation between +1 and -1), they observed that the change in the number of foundation placement has a significant effect on scouring depth, so that the maximum and minimum scouring depth is the order occurs in the relative number +1 and -0.5.

Determining scour depth is important because it indicates the flow's potential for destruction around the structure; for this reason, it plays a key role in designing foundation dimensions for structures exposed to water. If the scour depth at the foundation location is significant and exceeds the foundation depth, the foundation's stability is at risk, and the possibility of destruction and collapse of the bridge deck increases, which can cause serious life and financial risks during floods. Therefore, this study examines the erosion profile of the bridge base due to changes in the flow section.

2. Material and Methods

2.1. Dimensional Analysis and Local Scour Parameters

Many effective parameters influence local scour around hydraulic structures. These parameters range from flow characteristics and sediment properties to structural geometry and environmental conditions. Simultaneously considering the effects of all these variables is highly challenging and complex because of their inherent variability and interdependence. Therefore, researchers often focus on a select set of parameters that have the greatest impact on local scour, based on previous studies and experimental findings. By narrowing the scope, the analysis can be more targeted and meaningful, providing actionable insights for both theoretical understanding and practical applications.

In this study, we selected critical parameters that significantly influence local scour for analysis. These include flow velocity (V), water depth (h), sediment size (d), sediment density (ρs), water density (ρ), gravity (g), and characteristic dimensions of the structure, such as pier diameter (D). These parameters are not only easily measurable in laboratory and field experiments but also widely recognised in the existing literature for their substantial impact on the scour process. Table 2 summarises the measurable variables considered in the experiments, followed by the derivation of dimensionless factors that are instrumental in characterising and predicting scour behavior.

To gain deeper insight into the interactions among the various factors influencing local scour and to make the results applicable across different scenarios and scales, a dimensional analysis was carried out based on the Buckingham π-theorem. The main goal of this method is to minimise the number of governing variables by forming dimensionless groups, simplifying the system while preserving its core physical characteristics.

In this analysis, the scour depth (S) is treated as the primary dependent variable. It is influenced by several independent variables, including flow velocity (V), flow depth (h), pier diameter (D), sediment size (d), fluid density (ρ), sediment density (ρs), and gravitational acceleration (g).

The functional relationship can be initially defined as:

S = f(V, h, D, d, ρ, ρs, g)

By applying dimensional analysis, the variables are grouped into the following key groups

Table 2. Dimensionless parameters.

#	Dimensionless Group	Expression	Description
1	Froude Number (Fr)	$Fr = V / \sqrt{g h}$	Ratio of inertial to gravitational forces; defines the flow regime (subcritical/supercritical).
2	Relative Pier Diameter	D / h	Represents the pier's geometric influence relative to flow depth; affects flow obstruction.
3	Particle Reynolds Number (Rep)	$Rep = V d / \nu$	Indicates sediment-fluid interaction at the particle scale; important for predicting sediment motion.
4	Density Ratio	ρs / ρ	Compares sediment to fluid density; impacts sediment lift and transport initiation.
5	Shields Parameter (θ)	$\theta = \tau / ((\rho s - \rho)\, g\, d)$	Defines the critical condition for particle movement; essential for estimating onset of sediment transport.

Figure 1 schematically illustrates the key parameters affecting local scour geometry and serves as the basis for the subsequent dimensional analysis.

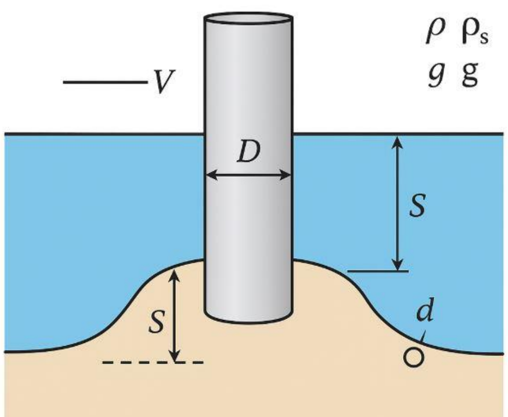

Figure 1. Schematic representation of the main parameters influencing local scour around a cylindrical pier embedded in a sediment bed

By transforming the governing variables into these dimensionless groups, the analysis becomes more universal, enabling comparison with results from other studies and facilitating the development of predictive models.

The dimensionless factors derived through this process provide valuable insights into the dominant mechanisms driving local scour. For instance, the Froude number helps determine whether the flow is subcritical, critical, or supercritical, each of which significantly alters the scour pattern. Similarly, the Shields parameter measures the critical conditions under which sediment particles are mobilised, directly influencing the onset and progression of scour.

Through this dimensional approach, the study not only simplifies the analysis but also enhances its applicability to diverse hydraulic conditions. This method allows engineers and researchers to scale up laboratory findings to real-world scenarios, thereby improving the reliability and effectiveness of hydraulic designs. Future studies could expand this framework by incorporating additional dimensionless parameters to account for factors such as sediment cohesion, pier shape, or time-dependency in scour evolution.

Table 3. Dimensions and quantities used in local washing.

Quantity	Symbol	Next

Local scour depth of the bridge	d_S	L
Mass per unit volume of fluid	ρ	ML^{-3}
Kinematic viscosity	ϑ	$L2T^{-1}$
acceleration of gravity	g	LT^{-2}
Average diameter of substrate particles	d_{50}	L
Mass per unit volume of sediments	ρ_s	ML^{-3}
Depth upstream of bridge foundation	y	L
Average flow speed	v	LT^{-1}
Bridge base diameter or width	d	L
Bridge base length	L	L
Dynamic viscosity	μ	$M L^{-1}T^{-1}$

$$d_S = f_1\left(U, g, \rho, \mu, U_C, d_s, d, d_{50}, Y, \alpha\right) \quad (1$$

$$\Pi_1 = \alpha \quad (2$$

$$\Pi_2 = \mu^a u^b B^c \rho \quad (3$$

$$\Pi_2 = \left(ML^{-1}T^{-1}\right)^a \left(LT^{-1}\right)^b \left(L\right)^c \left(ML^{-3}\right) \quad (4$$

$$\Pi_2 = M^{a+1} L^{-a+b+c-3} T^{-a-b} \quad (5$$

To convert variables into dimensionless parameters, apply the Buckingham Pi theorem. The first step is to identify a suitable set of repeated variables, typically denoted as m=3 m , which will serve as the foundation for constructing the dimensionless groups. These repeated variables are carefully chosen to represent different aspects of the problem. Specifically, one variable represents the fluid characteristics (such as density or viscosity), another accounts for flow characteristics (such as velocity or discharge), and the final variable represents geometric characteristics (such as a characteristic length or diameter). The selection process ensures that the repeated variables collectively include all fundamental dimensions—mass (M), length (L), and time (T). This combination is critical for maintaining dimensional consistency in the resulting dimensionless parameters.

In practice, the choice of repeated variables is not arbitrary; a set of criteria guides it. First, the variables should be independent of each other, meaning they should not exhibit a direct relationship or redundancy in their definitions. Second, they should be universally applicable across a range of experimental or theoretical conditions. Lastly, to enhance the physical interpretability of the dimensionless groups, the selected variables should capture the primary influences of the system being studied. For example, in the case of local scour, the fluid density (ρ), the flow velocity (V), and a characteristic length such as the pier diameter (D) are often selected as repeated variables. Together, these variables capture the critical aspects of the fluid, flow, and geometry and form the basis for analysing scour behavior.

Once the repeated variables are determined, the remaining variables in the system are expressed in terms of these repeated variables to form dimensionless groups. This process involves combining the repeated variables and the additional variables using powers that balance the fundamental dimensions. The resulting dimensionless groups, often referred to as Pi terms, encapsulate relationships among the system's variables in a form independent of units of measurement. For instance, common dimensionless groups in local scour studies include the Froude number, Reynolds number, and relative depth. Table 4 illustrates an example of repeated variable selection and their corresponding dimensional forms. These dimensionless parameters not only simplify the analysis but also facilitate comparison across different studies and experimental setups, ensuring broader applicability and relevance.

Table 4. Dimensions of hydraulic agents.

Agent type	Symbol	Next
Speed	U	LT^{-1}
gravity	g	LT^{-2}
Specific mass of the fluid	ρ	ML-3
Dynamic viscosity	µ	$ML^{-1}T^{-1}$
Threshold movement speed	U_C	LT^{-1}
Scouring depth	d_S	L
Base diameter	d	L
Sediment particle diameter	d_{50}	L
Flow depth	Y	L
The narrow width of the waterway	L	---

Next, from solving the above equations will be achieved:

$$\Pi_1 = \frac{L}{d}$$

$$\Pi_2 = \frac{\rho D u}{\mu} \tag{6}$$

$$\Pi_3 = \frac{\sqrt{gY}}{U} \tag{7}$$

$$\Pi_4 = \frac{U_c}{U} \tag{8}$$

$$\Pi_5 = \frac{d_{50}}{d} \tag{9}$$

$$\Pi_6 = \frac{d_s}{d} \tag{10}$$

$$\Pi_7 = \frac{Y}{d} \tag{11}$$

A relation to dimensionless numbers is obtained for different states of design goals:

$$\frac{d_s}{d} = f_2\left(\frac{L}{d}, \frac{\rho D u}{\mu}, \frac{\sqrt{gY}}{u}, \frac{U}{U_c}, \frac{d_{50}}{d}, \frac{y}{d}\right) \tag{12}$$

$$\frac{d_s}{d} = f_3\left(\frac{L}{d}, Fr, \frac{U}{U_c}\right) \tag{13}$$

2.2. Specifications Channel

The experiment was conducted with a length of 10 meters, a width of 30 cm and a height of 50 cm. The walls are made of transparent plexiglass, and the bottom of the channel is made of steel (Figure 2).

To mitigate turbulence typically generated by water pumping, the system is carefully engineered using a series of interconnected components that work together to produce a smooth, regulated flow. A key part of this setup is a flume installed at the inlet of a flow-stabilisation tank. The flume moderates the energy of the incoming water, allowing it to enter the system at a steady rate.Water is delivered through an 8-inch (0.203 m) diameter pipe into the calming basin. At the pipe outlet, a custom mesh screen is used to disperse the incoming high-velocity water stream. This mesh acts as the first barrier against turbulence by spreading and breaking up the flow uniformly. Next, the water passes over a flow-diffusing plate which helps dissipate remaining momentum, allowing the flow to settle before entering the test channel.This well-ordered sequence ensures laminar flow conditions, especially in the downstream channel where flow uniformity is critical. The design avoids sudden changes in flow patterns, which often cause turbulence in hydraulic systems.The system incorporates multiple 1,000-liter tanks beneath the channel that act as intermediate storage and support continuous water circulation. A centrifugal pump, capable of delivering up to 80 litres per second, maintains this circulation and ensures consistent pressure and volume. To precisely regulate flow conditions, an electromagnetic flowmeter monitors flow in real time. This instrument is essential for maintaining desired flow characteristics during experimental procedures by providing continuous data for adjustments. Integrating the pump, flowmeter, and tanks creates an efficient, flexible system ideal for controlled experimental environments. Laminar flow is characterized by smooth, parallel layers of fluid that move without mixing or crossing paths. In this flow regime, the fluid particles travel in straight lines, minimizing energy loss and turbulence.

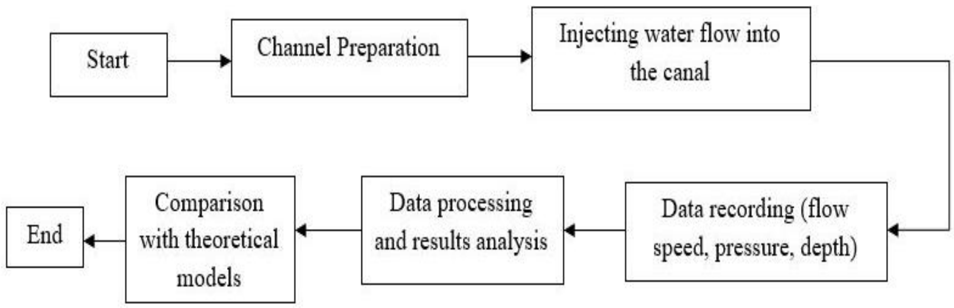

Figure 2. Front view of the laboratory flume.

This is ideal for experimental hydraulic setups where precision is essential. The presence of laminar flow is usually confirmed by calculating the Reynolds number, which determines whether flow is laminar, transitional, or turbulent.

Table 5. Reynolds Number Calculation in this test.

Flow Velocity (V) [m/s]	Pipe Diameter (D) [m]	Kinematic Viscosity (ν) [m²/s]	Reynolds Number (Re)	Flow Type
0.50	0.203	1.0e-06	101500	Turbulent

In addition to the physical components, the system is equipped with a robust electrical and control framework that enhances its operational reliability. This framework coordinates the operation of all components, from the pumps to the flowmeters, enabling real-time adjustments to flow parameters. For example, the control system can easily modify the flow rate, allowing researchers to quickly adapt the water flow to the specific needs of each experiment. This flexibility is crucial for conducting a wide range of hydraulic experiments, as it ensures that the system can accommodate different flow rates, turbulence levels, and other conditions. Moreover, the system's built-in redundancy, such as backup pumps and additional flow-calming measures, ensures smooth operation even if a component fails. These design features not only enhance the reliability of the water circulation system but also ensure that experiments can be conducted without interruptions or inconsistencies.

Finally, the overall design prioritises ease of operation and efficiency. The integration of advanced components such as the electromagnetic flowmeter, centrifugal pump, and electrical control system makes the system user-friendly and adaptable. Researchers can quickly set up and adjust the system to create the desired flow conditions, enabling them to focus on conducting experiments rather than troubleshooting operational issues. Furthermore, careful tank placement and sizing, combined with the control system's precision, ensure the water supply remains consistent and stable throughout the experimental process. This reliability and control are essential for accurate, repeatable results, making the water circulation system a critical asset for research conducted within the flume.

2.3. Test Steps

The experiments in this study were carried out as stated in Table 6, including the experiment on the rectangular base in the gradually changed sections at the movement threshold speed. The movement threshold speed was determined visually using a trial-and-error method (by changing the flow rate and depth).

Table 6. Test scenarios.

L/d	Changed width (cm)	The relative speed	Movement threshold speed, etc.) Cm/s	Fr	Tested dis-charges	Threshold flow rate (m3/s)	Water height cm)	Number of tests
15	Main channel width (30)	U/Uc=0.95	06/8	0.45	50	50	15	3
		U/Uc=0.85		0.40	45			
		U/Uc=0.75		0.36	40			
4/13	8/26	U/Uc=0.95	04/8	0.42	47	47	15	3
		U/Uc=0.85		0.37	42			
		U/Uc=0.75		0.33	37			
8/11	6/23	U/Uc=0.95	8	0.40	45	45	15	3
		U/Uc=0.85		0.36	40			
		U/Uc=0.75		0.31	35			
2/10	4/20	U/Uc=0.95	01/8	0.32	36	36	15	3
		U/Uc=0.85		0.28	31			
		U/Uc=0.75		0.24	27			

To model changes in the flow section of PVC plates. A width of 16 mm was used, and the length of each section was 90 cm at three heights (6, 12, and 18 cm (Figures 3-5).

Figure 3. The base of the door change section L/d=13.4.

The image appears to show an experimental flume setup designed to study sediment transport or scour around a vertical structure in a flow channel. The channel contains sedimentary material, such as gravel or sand, evenly distributed across the bed. The central vertical structure could represent a pier, groin, or another hydraulic element used in river engineering. The setup likely examines flow-sediment interactions, such as scour depth, pattern formation, or stability under different flow conditions.

The scour zone around the structure suggests localized erosion due to the interaction between the flow and the vertical element. This phenomenon is critical for understanding structural stability, as excessive scouring could undermine the foundation. Such experiments are commonly conducted to validate hydraulic theories, improve designs, or develop protective measures to mitigate scouring effects in natural and engineered water systems. Let me know if you'd like more details or analysis on this!

Figure 4. The base of the door change section L/d=11.8.

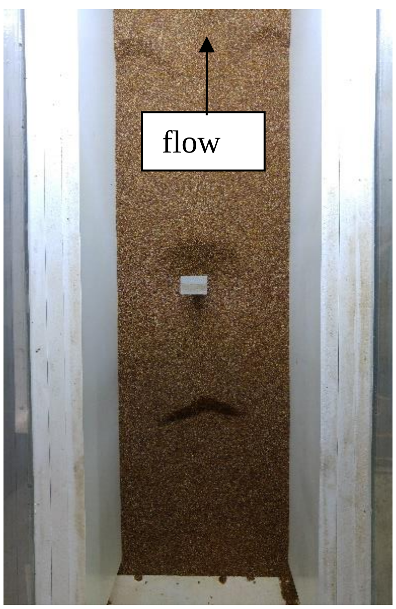

Figure 5. The base of the door change section L/d=10.2.

2.4. Bed Sediments

To conduct experiments aimed at achieving the maximum scouring depth, it was essential to use sediments with uniform granularity. According to Chiew and Melville (1987), sediment uniformity plays a significant role in reducing local scouring. Specifically, they recommended that the geometric standard deviation of sediment particles should be less than 1/3 to ensure uniformity. For this study, sediments passing through Sieve No. 18 and retained on Sieve No. 20 were selected. These sediments were used to create a sedimentary bed in a three-meter-long section of the flume, positioned between two false bottoms. The sediment layer was 1.5 m long and 14 cm thick, with an average particle diameter of 0.95 mm. The absence of fine particles and clay in the sediment sample indicated that the sediments were thoroughly washed, ensuring uniformity and consistency in the experiments (Chiew and Melville, 1987; Ettema et al., 2017).

3. Results and discussion

3.1. Temporal Development of Local Scouring

Local scouring around bridge foundations is a time-dependent process, with scour depth increasing over time until it reaches equilibrium. Understanding the temporal development of scour holes is critical for bridge designers, as it allows them to predict the maximum scour depth and design foundations accordingly. Figure 5 illustrates the time development curve of the scour hole for a bridge foundation under constant flow conditions. The curve shows how scour depth evolves and eventually stabilises as the scour hole reaches equilibrium. This information is invaluable for engineers, as it provides insights into the long-term stability of bridge foundations and helps in designing effective scour protection measures (Melville and Sutherland, 1988; Pandey et al., 2021).

3.2. Influence of Sediment Uniformity on Scour Depth

Sediment uniformity has a profound impact on local scour. Non-uniform sediments, characterized by a wide range of particle sizes, tend to reduce scour depth compared to uniform sediments. This is because larger particles in non-uniform sediments act as a protective layer, resisting the flow's erosive forces. In contrast, uniform sediments, with particles of similar size, are more susceptible to scouring, as there are no larger particles to shield the bed from erosion. Using uniform sediments in this study ensured that the maximum scour depth could be achieved, providing a worst-case scenario for bridge foundation design (Kothyari et al., 1992; Al-Madhhachi and Jasim, 2021).

3.3. Role of Flow Conditions in Scour Development

Flow conditions, including velocity, depth, and turbulence, play a critical role in local scour development. Higher flow velocities increase the erosive forces acting on the sediment bed, leading to deeper scour holes. Similarly, greater flow depths create stronger pressure gradients around the foundation, further exacerbating scour. Turbulence, particularly the formation of horseshoe vortices, is a key driver of scour around bridge piers. These vortices create localized areas of high shear stress, which erode the sediment bed and contribute to the formation of scour holes. Understanding the interplay between flow conditions and scour development is essential for designing resilient bridge foundations (Shen et al., 1969; Guan et al., 2020).

3.4. Implications for Bridge Design and Scour Mitigation

The findings from this study have significant implications for bridge design and scour mitigation. By understanding the temporal development of scour holes and the influence of sediment uniformity and flow conditions, engineers can design foundations that are more resistant to scouring. Additionally, non-uniform sediments or engineered scour protection measures, such as riprap or geotextiles, can help reduce scour depth and enhance the stability of bridge foundations. Future research should focus on integrating these findings into predictive models and developing innovative scour mitigation techniques to ensure the long-term safety and durability of hydraulic structures (Richardson and Davis, 2001; Zhang et al., 2022).

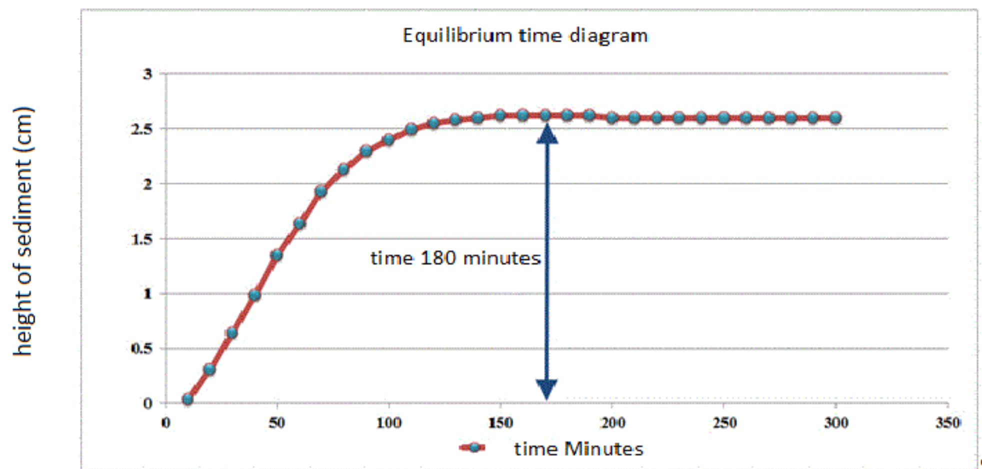

Figure 6. Equilibrium time curve

The experiment was conducted in two distinct categories: the witness test and the experiment involving sudden changes in the waterway. The first test involved no sudden changes in the waterway, while the second category examined the impact of abrupt changes in the channel's geometry on the scour process. The overall approach of both categories was similar, focusing on the assessment of scour behavior under different flow conditions.

Before starting the tests, sections were installed in the channel to control and restrict the flow, ensuring that the water flow could be accurately adjusted for the experiment. The surface of the bed sediments was leveled using a precise leveling tool to ensure an even starting condition. The overflow height was set to 15 cm, and clear water was gradually introduced into the channel from downstream. This careful process was necessary to prevent any unevenness in the sediment surface, which could affect the accuracy of the test. After allowing the water to rise and ensuring the sediments were moistened, the flow was increased at a controlled rate. Initially, the flow was kept at a low speed to allow the sediment to settle and create a stable starting point for the experiment. The water level was carefully monitored to ensure that the sedimentary area was covered by at least a few centimeters of water before proceeding to the next phase.

Once the water reached the overflow, and the sediment area was properly submerged, the flow rate was gradually increased until the desired flow conditions were achieved. At this stage, the movement of the sediments was closely observed to identify the point at which the sediments began to show signs of movement. The velocity at which this occurred was measured using a speedometer, and the speed was recorded as the threshold velocity for sediment movement. This step is crucial in determining the critical velocity at which the flow is capable of initiating scour in the sediment bed.

The experiment continued for a total of 180 minutes, after which the pump was turned off, and the water flow was gradually reduced. During this time, the system allowed the sediments to settle and stabilize, ensuring that the topography of the sediment bed was not further altered by the flow. Once the water drained out of the channel, a drainage valve installed at the bottom of the channel was opened to facilitate the removal of water. The scour profile was then measured using a laser meter, which was employed in combination with a grid plate that had 1x1 cm dimensions. This allowed for precise measurements of the changes in the bed topography caused by the scour process, providing valuable data on the extent and characteristics of the scour hole.

In the second category of the experiment, sudden changes in the waterway geometry were introduced. This involved modifications to the shape and cross-section of the channel to create abrupt transitions that would generate turbulence and potentially accelerate scour. The effect of these changes was carefully monitored to compare the scour profiles with those observed in the first category, where no such geometric alterations were made.

By comparing the results of both categories, we were able to assess the impact of sudden changes in the waterway on the scour process. The data gathered from the laser measurements of the scour profiles provided valuable insights into the behavior of sediment movement under varying flow conditions. This experiment helped in understanding how changes in flow velocity, channel geometry, and sediment characteristics influence the development and depth of scour around bridge piers or other hydraulic structures.

The experimental setup and careful measurement techniques ensured the accuracy of the results, and the findings of this study contribute to the ongoing efforts to mitigate scour in hydraulic engineering applications. By understanding the critical velocities and the effects of sudden changes in the waterway, engineers can design more effective structures to minimize the risk of scour and enhance the stability of bridges and other infrastructure.

3.5. Research findings

Figures 7-11 are a comparison between the scouring depth of the bridge foundation in the sudden change of the waterway side (L/d=10.2, 11.8, 13.4, 15) according to the graphs, as can be seen, the amount of erosion is reduced in the sudden change of the waterway by decreasing the width of the channel (increasing the narrowing of the section) and this decrease in the depth of scouring can be justified by reducing the width of the channel by the panels (changing the section flow) narrowing the cross-section of the flow lines with more compression and as a result more turbulence travel their way along the narrowed waterway and the downward currents that collide with the base cause the foundation to dig.They are created with more power.

In graphs (11) to (13) comparing scouring profile in relative speeds (U/Uc=0.75, 0.85, 0.95) maybe. As can be seen from the charts in all (L/d=10.2, 11.8, 13.4, 15) the sudden change of the base scouring channel increases with the increase of the flow speed. The more the sudden change of the waterway increases and the higher the speed flows in the changed section due to the increased compression of the flow lines, which when it hits the base, creates a vortex and turbulence around the support. The depth of the scour hole increases.

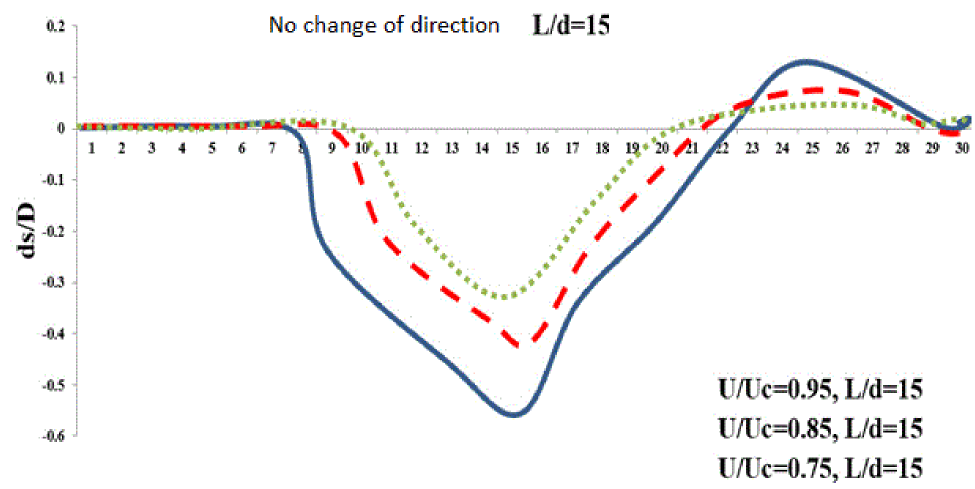

Figure 7. Comparison between the amount of scouring of the base in the case of no sudden change in the section of the waterway in relative velocities (U/Uc=0.75, 0.85, 0.95).

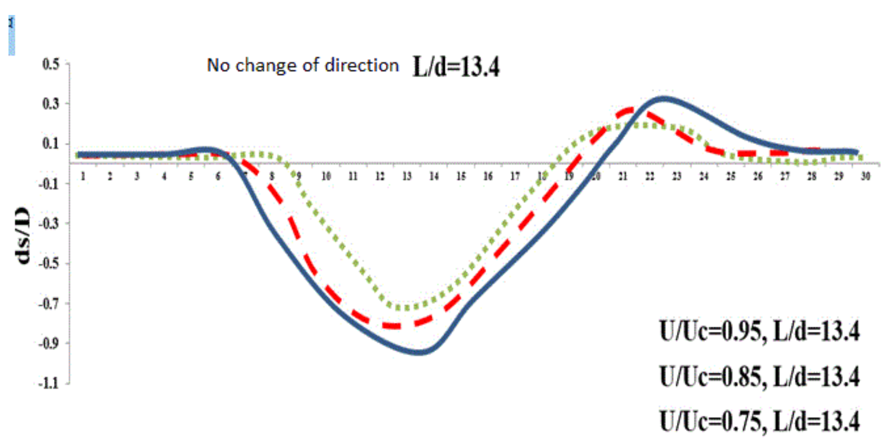

Figure 8. Comparison between the scour rate of the base in the stateL/d=13.4at relative velocities (U/Uc=0.75, 0.85, 0.95).

This graph illustrates the relationship between the dimensionless scour depth (ds/D) and the relative position along a longitudinal axis for different flow velocity ratios (U/Uc). Here, dsdsds represents the scour depth, D is the diameter of the vertical structure or obstacle, and L/d=13. signifies a constant ratio of the system's length to diameter. The flow velocity ratio (U/Uc) compares the actual flow velocity (U) to the critical velocity (Uc) needed to initiate sediment movement. The graph compares three cases: U/Uc=0.95 (solid blue line), /Uc =0.85 (dashed red line), and U/U_c = 0.75 (dotted green line).

The results show a clear relationship between the flow velocity ratio and the scour depth profile. At U/U_c = 0.95, the flow velocity is very close to the critical velocity, resulting in the deepest scour, where the maximum scour depth reaches approximately −1.0 (in dimensionless terms). This indicates severe erosion caused by the higher flow energy, which has enough strength to remove substantial amounts of sediment from around the structure. As the flow velocity decreases to U/Uc=0.85 and U/Uc=0.75, the scour depth decreases significantly, with the minimum dimensionless depth reaching approximately −0.7 and −0.5-0.5−0.5, respectively. This highlights the strong dependency of scour intensity on flow velocity, with lower velocities reducing the energy available for sediment transport and erosion.

The graph also depicts zones of sediment deposition, where ds/D>0, following the regions of maximum scour. After sediment is eroded and transported downstream, it settles in these deposition zones, creating positive peaks in the profile. The magnitude and extent of both scour and deposition zones are influenced by the flow velocity ratio U/Uc=0.95, the deposition zone exhibits more pronounced peaks compared to the lower velocity ratios, reflecting the greater sediment transport capacity of higher flows. These observations are critical for understanding and predicting sediment transport mechanisms and their implications for hydraulic structures, such as bridge piers or groins. Properly accounting for these interactions in design and maintenance can help mitigate the risks associated with excessive scour, ensuring long-term structural stability and environmental balance.

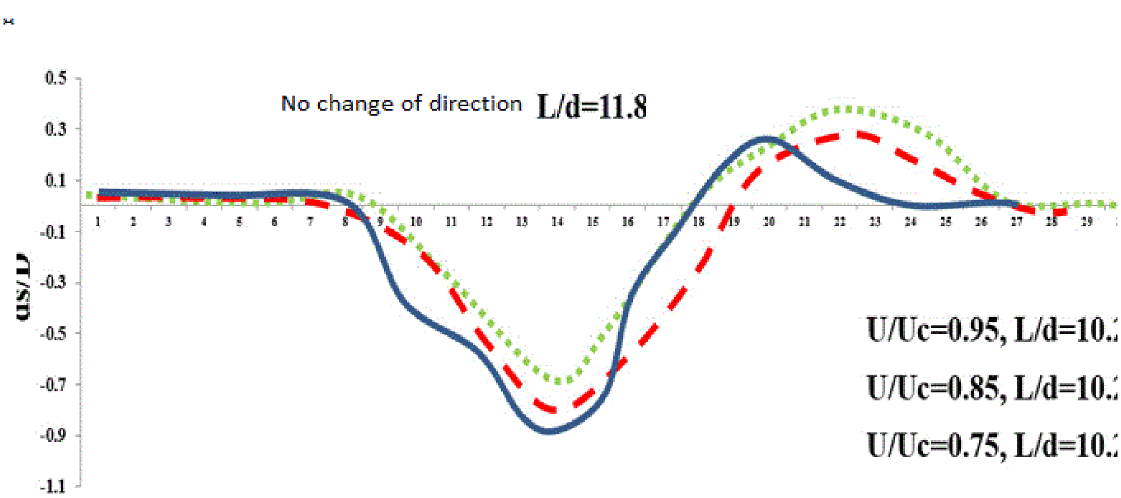

Figure 9. Comparison between the amount of scouring of the base in the stateL/d=11.8at relative velocities (U/Uc=0.75, 0.85, 0.95).

The graph illustrates the relationship between the dimensionless scour depth (ΔS/D) and distance along the bed, with varying flow velocity ratios (U/Uc) and length-to-diameter ratios (L/d). Three distinct scenarios are analyzed based on the flow velocity ratios: U/Uc = 0.95, U/Uc = 0.85, and U/Uc = 0.75, where "U" represents the flow velocity, and "Uc" is the critical velocity for sediment movement. The solid blue line, dashed red line, and dotted green line represent these respective scenarios.

In all cases, the graph shows that maximum scour depth occurs near the midpoint of the flow and progressively decreases as the flow approaches the downstream end. For higher flow velocity ratios (U/Uc = 0.95), the scour depth is significantly deeper, indicating stronger erosive forces due to increased flow energy. In contrast, lower velocity ratios (U/Uc = 0.75) demonstrate reduced scour depth, signifying diminished erosion capacity. The graph underscores the influence of flow velocity and length-to-diameter ratios on scour depth, critical for understanding sediment transport and designing scour mitigation strategies.

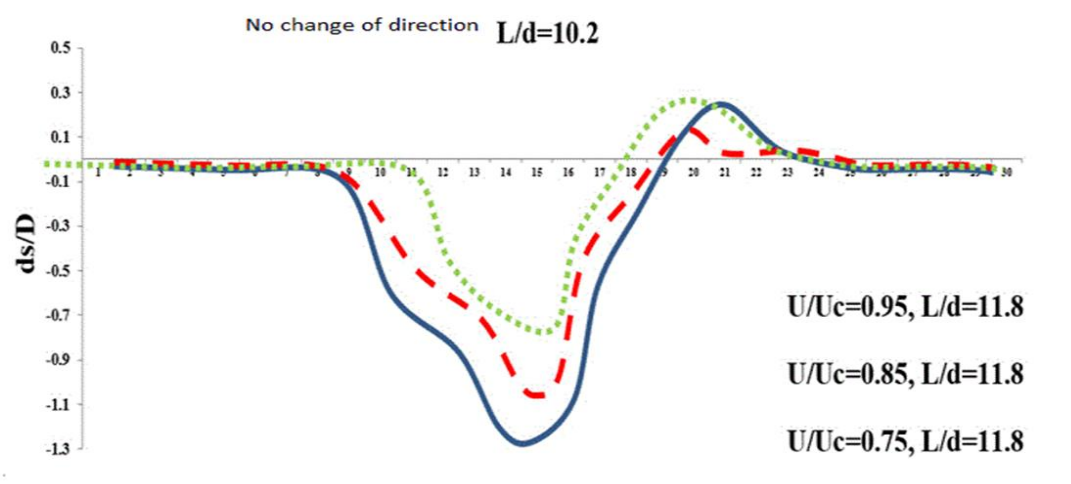

Figure 10. Effect of Relative Velocity and Channel Geometry on Scour Depth Profile (ds/D) at Various Flow Ratios (U/Uc).

The graph illustrates how the relative scour depth (ds/D) changes with dimensionless distance along the channel under varying flow velocities relative to critical velocity (U/Uc) and different length-to-diameter ratios (L/d). The plot shows how these parameters affect the scour profile, maintaining a consistent flow direction while the length-to-diameter ratio (L/d) varies between 10.2 and 11.8. Three distinct lines—green, red, and blue—are plotted to represent different flow velocities, specifically U/Uc = 0.95, U/Uc = 0.85, and U/Uc = 0.75.

In the first case, with U/Uc = 0.95 (blue line), the scour depth reaches its greatest extent, with a maximum scour depth of approximately -1.1 ds/D. This indicates that near-critical flow velocities result in the most pronounced scouring effect. The deepest erosion occurs closest to the foundation, followed by a gradual reduction of scour downstream. At such high velocities, the flow's erosive force is significantly strong, causing considerable sediment displacement and deep scour holes in the channel. The rapid erosion near the foundation suggests that high flow velocities can increase the vulnerability of hydraulic structures to scouring, necessitating robust design considerations to mitigate such effects.

The red dashed line, representing U/Uc = 0.85, shows a slight reduction in the scour depth compared to the U/Uc = 0.95 scenario. The scour hole remains prominent, but it is shallower, reflecting a less intense erosive force at these subcritical flow velocities. The shallower scour suggests the flow has less capacity to displace sediment, leading to less severe erosion. While erosion is still evident, the effects are less destructive, resulting in smaller scour holes. This highlights the importance of controlling flow velocities to reduce the magnitude of scour around foundations, especially when flow velocities are subcritical.

The green dotted line, corresponding to U/Uc = 0.75, shows the shallowest scour depth. The profile appears much more stable, with minimal downward sediment movement, indicating that lower flow velocities are less effective at eroding the channel bed. As flow velocity decreases, the scouring process slows, leading to a more uniform channel profile with significantly reduced scour depth. This suggests that when flow velocities fall well below the critical velocity, the potential for significant scour development diminishes. With less force exerted by the flow, sediment remains more intact, and the channel profile degrades less. This reinforces the idea that maintaining lower velocities can effectively minimise the risk of scour around foundations.

The relationship between flow velocity and scour depth is essential for understanding the dynamics of sediment transport and erosion in riverine environments, particularly around bridge piers or other hydraulic structures. When flow velocities approach or exceed the critical velocity, the increased flow energy causes greater sediment displacement, leading to deeper scour holes. Conversely, when flow velocity is well below the critical value, the scouring effect becomes less pronounced, and channel stability improves. Therefore, controlling flow velocities in hydraulic engineering projects is crucial to prevent excessive scour and ensure the long-term stability of structures.

Additionally, the length-to-diameter ratio (L/d) affects the scour profile. While the graph does not explicitly focus on L/d, the variation in this parameter influences the extent of turbulence and vortex formation around the structure. A higher L/d ratio may alter the flow dynamics around the foundation, affecting both the depth and the shape of the scour hole. For example, a larger L/d ratio could lead to stronger vortices and potentially deeper scour near the foundation. Therefore, a comprehensive understanding of both flow velocity and L/d ratio is necessary to accurately predict scour behavior and design effective mitigation strategies.

In conclusion, the graph provides valuable insights into how varying flow velocities and the length-to-diameter ratio impact the scour profile. As flow velocity increases, scour depth becomes more significant, with near-critical velocities resulting in the most severe erosion.

Conversely, as flow velocity decreases, scour depth lessens and the channel profile stabilises. These findings underscore the importance of controlling flow velocity to mitigate scour risk, especially in environments where foundations or other structures are at risk of erosion (Figures 11-13).

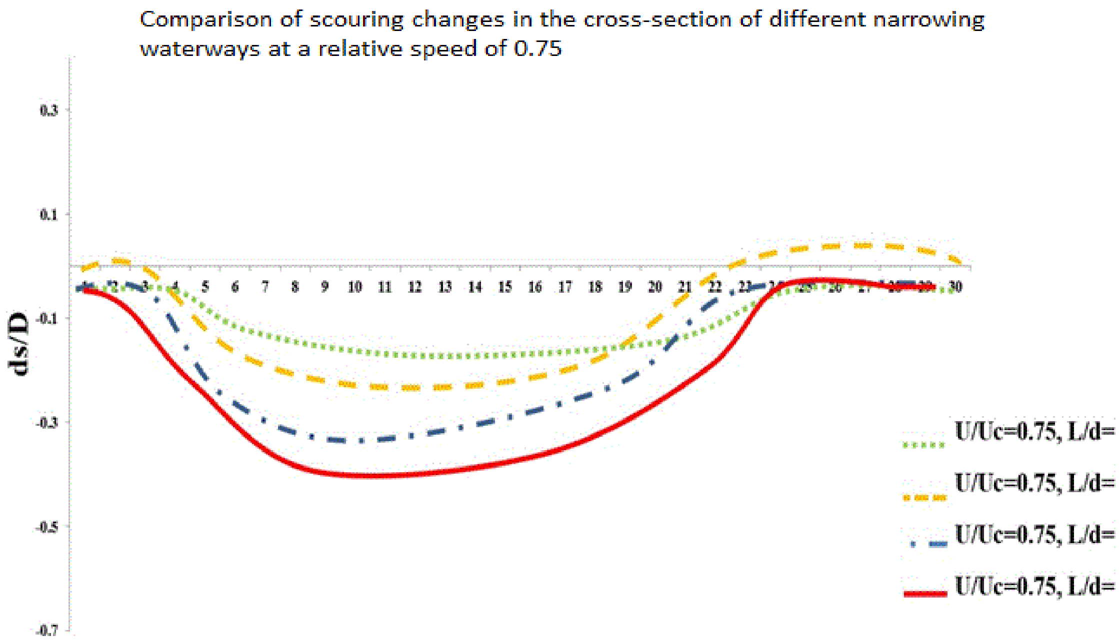

Figure 11. Comparison between the amount of scouring in different modified stages (L/d=10.2, 11.8, 13.4, 15) at a relative speed of 0.75.

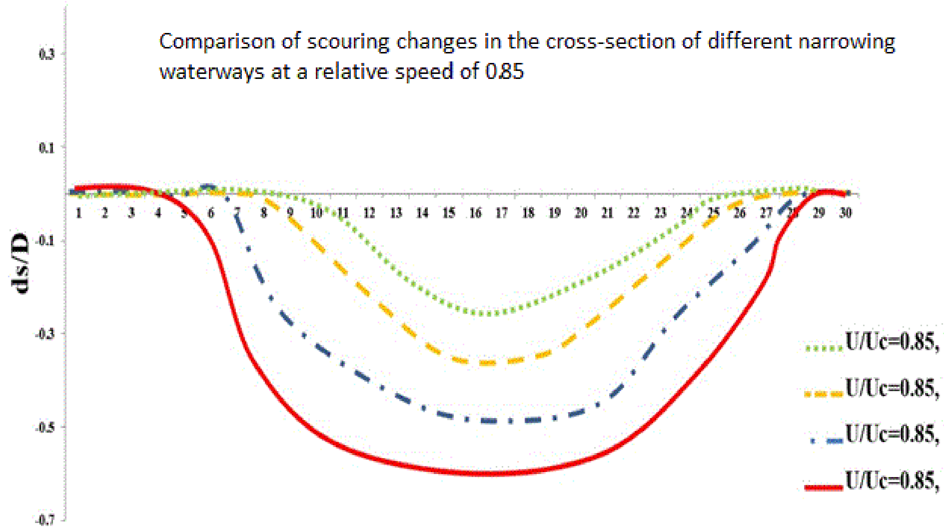

Figure 12. Comparison between the amount of scouring in different changed sections (L/d=10.2, 11.8, 13.4, 15) at a relative speed of 0.85.

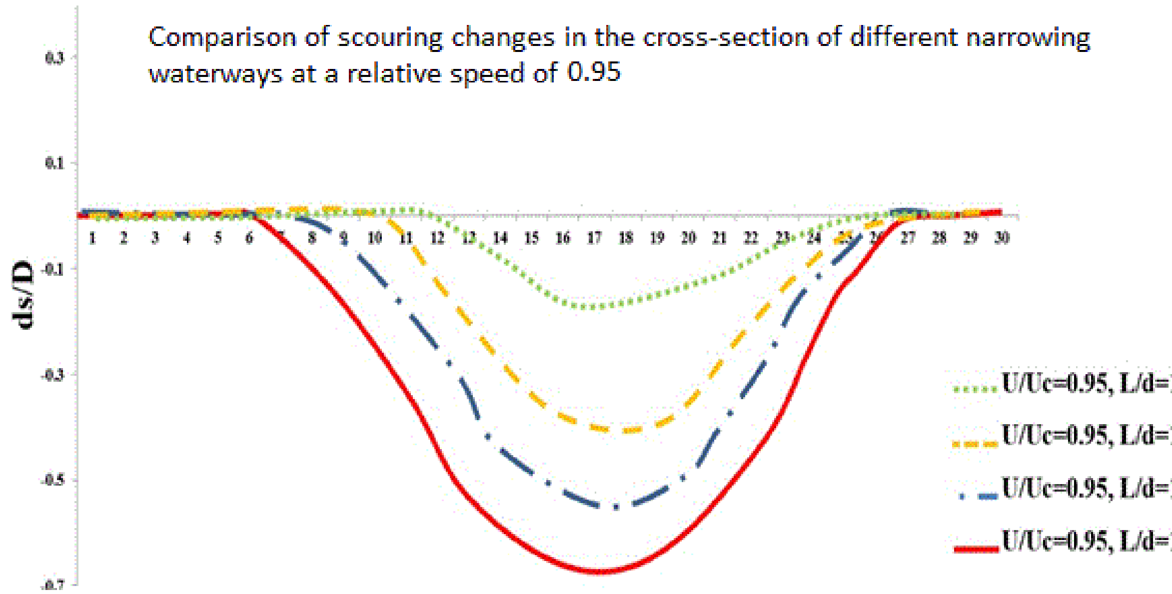

Figure 13. Comparison between the amount of scouring in different changed sections (L/d=10.2, 11.8, 13.4, 15) at a relative speed of 0.95.

4. Conclusion

The study of scour profiles at varying flow velocities reveals critical insights into the interaction between hydraulic conditions and structural stability. As flow velocity increases, the scour channel becomes more irregular, characterized by intensified turbulence and stronger vortices around bridge piers and support structures. These vortices deepen the scour hole and exacerbate erosion, posing significant challenges for the long-term stability of hydraulic structures. These findings highlight the need to prioritize stability through careful consideration of hydraulic conditions and structural designs.

One key observation is the enhanced stability of cylindrical foundations when placed in smooth waterway cross-sections devoid of abrupt changes. Maintaining a consistent threshold velocity while avoiding sudden geometric transitions can significantly reduce the severity of scour. This emphasizes the role of geometric uniformity in both channel and foundation design to mitigate the adverse effects of erosion. Geometric inconsistencies, particularly in sections with sudden lateral changes, result in heightened risks of localized scour. Numerical models further corroborate these findings, demonstrating a greater likelihood of deeper scour in areas where cross-sections narrow or vary in height abruptly. Gradual transitions in channel geometry emerge as a critical design factor for minimizing scour.

The results align closely with recent research, such as that of Khosronejad et al. (2020), which underscores the importance of smooth transition zones for reducing localized scour around bridge piers. Likewise, Liu et al. (2019) identified sharper geometric changes as catalysts for intense vortex formation and turbulence, leading to deeper scour. These studies reinforce the conclusions drawn from this research, emphasizing that smoother waterway profiles can significantly alleviate scour-related challenges at hydraulic structures. Understanding threshold velocities for particle movement in areas with variable geometries further informs design strategies to minimize scour and enhance structural stability.

In addition to the observed effects of velocity and geometric transitions on scour profiles, this study underscores the role of flow dynamics in shaping scour behavior. As flow lines compress under higher velocities, the resulting turbulence not only deepens the scour hole but also broadens the impacted area around structural foundations. This phenomenon highlights the need for an integrated approach to hydraulic structure design, where both flow dynamics and structural geometry are considered in tandem. Engineers should aim to balance flow distribution and structural stability to achieve a resilient design that can withstand varying hydraulic conditions.

Another critical aspect is how sediment characteristics interact with flow dynamics. The threshold velocity for particle movement varies with sediment size and composition, affecting the extent and depth of scour. This suggests that a thorough understanding of sediment transport dynamics is essential for designing waterways and structures that can effectively resist erosion. Incorporating sediment-specific considerations into design frameworks can further optimize scour mitigation strategies, especially in regions prone to high-velocity flows.

Lastly, the study highlights the importance of advanced numerical modeling tools in understanding scour mechanisms. Numerical simulations provide detailed insights into flow patterns, turbulence intensities, and the interaction between hydraulic forces and structural geometry. Such tools enable engineers to predict scour behavior under different scenarios, facilitating more informed design choices. By integrating numerical modeling with empirical data, future research can further refine strategies to minimise scour and enhance the resilience of hydraulic structures (Tables 5, 6).

Table 7. Comparison of key findings from recent studies.

Study	Key Findings	Relevance to Current Research
Khosronejad et al. (2020)	Highlighted the importance of smooth transition zones to reduce localized scour.	Reinforces the need for geometric uniformity in waterway designs.
Liu et al. (2019)	Observed sharper geometric changes leading to intense turbulence and deeper scour.	Aligns with findings on the role of gradual transitions in reducing scour.

Table 8. Parameter Comparison across Studies.

Parameter	Current Study	Khosronejad et al. (2020)	Liu et al. (2019)
Geometric Transitions	Emphasis on gradual transitions to minimize scour.	Focus on smooth transition zones.	Identified sharp changes increasing turbulence.
Flow Velocity Impact	Higher velocities deepen and broaden scour holes.	Not explicitly analyzed.	Turbulence intensity linked to velocity.
Numerical Modeling Tools	Used to predict scour behavior and refine designs.	Not a primary focus.	Limited to observational analysis.

These comparisons underscore the alignment of the current study with recent research while highlighting areas for further exploration, particularly in integrating numerical models and empirical data to refine scour mitigation strategies. By building on these findings, engineers can develop more resilient hydraulic structures.

This study emphasises the critical role of geometric consistency and hydraulic design in mitigating scour around bridge piers and support structures. The findings reveal that increased flow velocities lead to more pronounced irregularities in scour profiles, driven by intensified turbulence and vortex formation. Cylindrical foundations exhibit greater stability in smooth waterway cross-sections, underscoring the importance of uniform channel geometries in reducing scour. The research also highlights the heightened risk of deeper scour in sections with abrupt geometric changes, such as narrowed cross-sections or varying heights. Gradual transitions in channel geometry, coupled with a clear understanding of threshold velocities for particle movement, emerge as key strategies for mitigating scour. Recent studies by Khosronejad et al. (2020) and Liu et al. (2019) corroborate these findings, further reinforcing the importance of smooth transition zones in reducing localized scour. Engineers should prioritise designing waterways and hydraulic structures with gradual geometric transitions to minimise turbulence and vortex formation. Incorporating insights from numerical modeling and sediment transport dynamics can further optimize scour mitigation strategies. By adopting these principles, hydraulic structures can be made more resilient, ensuring their long-term stability and functionality in high-velocity flow conditions.

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