

Article

Advanced Numerical Simulation of Scour around Bridge Piers: Effects of Pier Geometry and Debris on Scour Depth

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Abstract: Investigating different pier shapes and debris interactions in scour patterns is vital for understanding the risks to bridge stability. This study investigates the impact of different shapes of pier and debris interactions on scour patterns using numerical simulations with flow-3D and controlled laboratory experiments. The model setup is rigorously calibrated against a physical flume experiment, incorporating a steady-state flow as the initial condition for sediment transport simulations. The Fractional Area/Volume Obstacle Representation (FAVOR) technique and the renormalized group (RNG) turbulence model enhance the simulation's precision. The numerical results indicate that pier geometry is a critical factor influencing the scour depth. Among the tested shapes, square piers exhibit the most severe scour, with depths reaching 5.8 cm, while lenticular piers show the least scour, with a maximum depth of 2.5 cm. The study also highlights the role of horseshoe, wake, and shear layer vortices in determining scour locations, with varying impacts across different pier shapes. The Q-criterion study identified debris-induced vortex generation and intensification. The debris amount, thickness, and pier diameter (T/Y) significantly affect the scouring patterns. When dealing with high wedge (HW) debris, square piers have the largest scour depth at $T/Y = 0.25$, while lenticular piers exhibit a lower scour. When debris is present, the scour depth rises at $T/Y = 0.5$. Depending on the form of the debris, a significant fluctuation of up to 5 cm was reported. There are difficulties in precisely estimating the scour depth under complicated circumstances because of the disparity between numerical simulations and actual data, which varies from 6% for square piers with a debris relative thickness $T/Y = 0.25$ to 32% for cylindrical piers with $T/Y = 0.5$. The study demonstrates that while flow-3D simulations align reasonably well with the experimental data under a low debris impact, discrepancies increase with more complex debris interactions and higher submersion depths, particularly for cylindrical piers. The novelty of this work lies in its comprehensive approach to evaluating the effects of different pier shapes and debris interactions on scour patterns, offering new insights into the effectiveness of flow-3D simulations in predicting the scour patterns under varying conditions.

Keywords: scour; bridge piers; debris impact; pier geometry; flow-3D simulations; hydraulic conditions



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1. Introduction

Bridges are crucial for transportation systems. However, the persistent erosive forces due to obstructing the flowing water pose a constant danger to their foundational strength and stability. This natural phenomenon, known as “local scour,” not only threatens structural integrity but also provides a unique opportunity to enhance the stability and longevity of bridges through innovative solutions. Local pier scour is a challenging hydraulic process resulting from sediment erosion close to bridge piers, causing structural instability, compromised asset reliability, and emergency issues [1,2]. As climate change intensifies, the risk of scour is expected to increase, placing 20% of European bridges at risk over the

next twenty years, with Austria, Portugal, Spain, and Italy being particularly vulnerable. To protect bridge structures, there is a growing need for early detection and adaptable, cutting-edge methodologies [3]. One such critical factor exacerbating the scouring process is the accumulation of debris near bridge piers. Debris floating, such as lumber, limbs, and other objects, may alter the flow and movement of particles surrounding the pier's base. The accumulation of debris may restrict flow, resulting in variations in velocity and fluctuation regimes that modify the scour depth and the scouring processes [4–6].

Furthermore, the interaction between the accumulating debris and the pier shapes impacts the scour process. A comprehensive understanding of these interactions, especially involving diverse pier designs, remains limited despite prior research. Various pier designs may affect the amount of scour and debris flow differently. For example, the number of debris accumulating around a pier may affect the deterioration forces operating on its base. Research into the intricate interplay between the debris effect, scour processes, and various pier shape designs can offer significant insights into potential solutions and innovations [7,8]. When debris builds up on bridge piers, it modifies the flow pattern, enhances the functional dimensions of the piers, and enhances the turbulent flow and particle activity, all of which may lead to significant scour concerns [7]. The researchers also conducted laboratory investigations to predict the scour depth around debris accumulation on piers with different shapes, sizes, orientations, and arrangements. The study suggested better empirical equations that can predict the scour depth by looking at the amount and shape of debris blocking the flow, as well as the size of the sediment particles. The authors of [8] investigated how debris affects the degeneration (scour) of pier foundations, especially with a focus on the standard sharp-nose design; using regular sand as a base, the researchers replicated the accumulated debris in three configurations: cylinders, half-pyramids, and plates on the upstream side of the pier. The findings indicate that erosion is reduced when trash is placed near the riverbed.

Moreover, these researchers emphasized the need to monitor debris even in the absence of floods. Their research showed that the erosion caused by debris is comparable to that caused by deep-flow conditions in the absence of debris during periods of low flow. In addition, ref. [9] proposed a novel method for evaluating the extent of soil erosion surrounding the pier in the event of accumulated debris. Current approaches for assessing the magnitude of water-induced sediment erosion rely on the visible width of the pier combined with debris, which might result in possible inaccuracies in different situations. The study presents a new “debris factor” measurement. The factor is a quantitative measure that considers the quantity and density of debris on the pier, the water flow speed, and the sand particles' dimensions.

Many techniques have constraints that restrict their practicality in real-world scenarios. Experimental scour testing is often restricted to a small number of significant bridge projects because of the substantial expenses and work required. The current design standards prioritize analytical solutions to overcome these difficulties due to their practicality and cost-effectiveness [10]. However, the primary challenge associated with analytical methodologies is verifying the hypotheses and modifications used in complex bridge scenarios. These tactics often presume that scour events conform to a one-dimensional scenario, concentrating just on the depth of the scour. The horseshoe-shaped vortex's unique three-dimensional (3D) features pose difficulties in accurately using traditional methods to predict erosion events near piers [11].

Computational fluid dynamics (CFD) is a very effective technology for forecasting erosion near bridge piers. This sophisticated computer program adeptly examines the intricate interplay between hydrodynamics and artificial structures, skillfully addressing fluid flow concerns [11]. Numerical models, which rely on sediment transport principles, assess and measure the extent of pier scouring. Navier–Stokes models depict the flow of a three-dimensional field around a riverbed bridge pier. The fluctuating shear stress exerted on the stream's bed is a critical hydrodynamic phenomenon concerning the initiation and transportation of sand particles. The computer findings accurately depict the flow patterns

and processes encountered during inspections, effectively determining the maximum scour value. CFD can be used to predict erosion around the pier accurately. Nevertheless, hydrodynamic considerations complicate scouring predictions. Various approaches and actual data are required to ensure accuracy when using CFD to analyze and forecast scour [12].

The examinations of local pier scouring have mainly focused on specific pier geometries and debris placement in limited areas. The majority of these works have used an experimental methodology, focusing specifically on circular forms [6,13–17]. Nevertheless, there is a lack of thorough studies on the combined impacts of various debris types and piers, especially in experimental and numerical domains. Prior studies have primarily focused on analyzing cylindrical pier configurations, particularly on studying the effects of debris hits in controlled laboratory settings. Further investigation is required to explore a broader range of pier designs and conduct a methodical examination of how these structures interact with different combinations of debris. The absence of a thorough investigation may limit the comprehension of scour phenomena occurring at bridge piers and impact the relevance of research results in practical scenarios.

This study aims to fill these gaps by analyzing and replicating the erosion process around different bridge pier designs with varying arrangements of debris using flow-3D HYDRO 2022R2 (Research version) software. The simulations' accuracy will be validated by comparing the outcomes with the experimental data from our previous work [18]. This study provides novel insights into how pier geometry and debris impact the scouring depth and morphology by examining the impact of these factors on scour patterns. The software application flow-3D was used to simulate the dynamics of fluids and the transport of sediments. The model was refined iteratively to reproduce the results acquired from experimental testing accurately. The domain was defined with precise boundary conditions, and realistic simulation was achieved using high-resolution mesh planes.

This research builds on our previous study [18], which experimentally investigated the impact of debris on scour patterns around bridge piers. The earlier study was limited to six pier shapes: cylindrical, square, rectangular, oblong, oval, and lenticular, affected by six different debris shapes such as a rectangular block, a high and low wedge, a half circle, and a triangular bow. The experimental data from that study were used as input for the numerical simulations in this current research. The current study expands on this by including thirteen different pier designs affected by six debris shapes. However, due to the significant time required for numerical simulations, the analysis of debris effects has been selectively applied. Specifically, the numerical simulations focus on cylinder and square pier designs under the influence of debris, with relative thicknesses (T/Y) of 0.25 and 0.5, while omitting the scenario where the debris relative thickness is 1. The study examines the differences between these pier designs and debris arrangements to understand scouring processes comprehensively. The contribution of this research lies in its use of high-resolution CFD simulations validated against the complete experimental data, providing a broader exploration of pier and debris configurations than previously studied. The CFD investigation provided data on velocity, pressure variations, and vortex formation, emphasizing the impact of the pier's structure and debris on the fluid flow. The concordance between experimental and numerical findings was evaluated using statistical measures such as the Nash–Sutcliffe Efficiency (Nash) and the coefficient of determination (R^2). These measurements provide valuable insights into process features that could be improved. The study highlights the vital importance of the shapes and arrangements of piers and debris in developing scour patterns.

2. Hydraulic Experiments: Pier Shapes and Debris Configurations

The laboratory study carried out by the Research and Design Center Laboratory, Ministry of Water Resources in Iraq, was distinguished by its careful accuracy. Figure 1 showcases a visible transparent channel with measurements of 12.50 m in length, 0.3 m in width, and 0.5 m in depth. The setup was powered by a high-capacity electrical pump

capable of discharging up to 90 L/s, guaranteeing the necessary flow for the testing. The essential elements of the system consisted of an initial sluice gate with flowing straighteners, a subsequent filter for flow regulation, and a regulated scouring zone that measured 6, 0.15, and 0.3 m (length, depth, and width). This scouring area contained an upstream wooden box to maintain the consistent roughness of the bed. A volumetric flow meter with $\pm 1\%$ accuracy and an integrated electronic gauge inside the flume discharge system with $\pm 0.05\%$ precision ensured precise flow readings. A flow straightener is installed to ensure a uniform flow pattern, thereby reducing disruptions. This hydraulic system also facilitated water recirculation, enhancing the efficiency of the experiments. These experiments focused on a sediment recess with a bridge pier and underlying base material. Medium river sand was used with finer particles ($D_{50} = 0.93$ mm). The flume maintained an average water depth of 12 cm and a standard velocity of approximately 0.29 m/s. The investigation sought insights into the turbulent characteristics and scour processes surrounding different pier geometries.

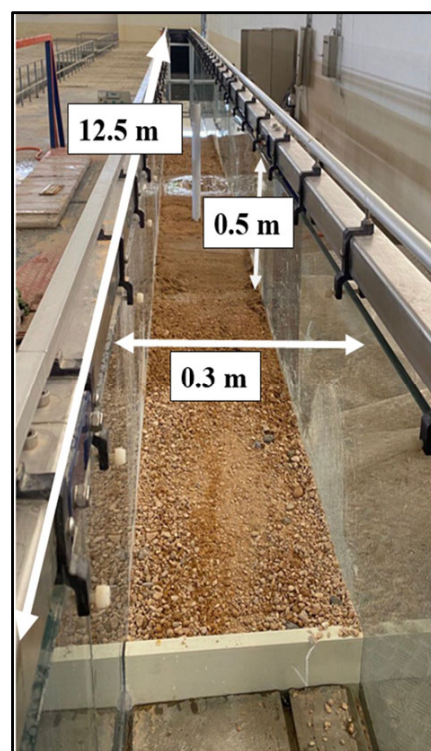


Figure 1. Experimental flume for investigating turbulent characteristics and scour processes around varied pier geometries.

Pier configurations were examined, including cylindrical (C), lenticular (LE), ogival (OG), rectangular (RE), oblong (OB), elliptical (EL), octagonal (OC), double-circular (DC), Joukasaky (JO), rectangular chamfered (REC), diamond (DI), square (S), and polygonal (PO) shapes, adhering to standardized dimensions of 2.5 cm in width, except for cylinder, square, diamond, and polygonal shapes; the elliptical shape had a uniform length of 10 cm, as shown in Figure 2.

The laboratory investigation into the sizes and configurations of debris accumulations adhered strictly to well-established testing parameters set forth by numerous experts in the field. Figure 3 visualizes the various debris configurations scrutinized in our study. The dimensions of these configurations were subjected to stringent standardization, with the width (W) set at 0.12 m, length (L_u) at 6 cm, and thickness (T) at both 3 cm and 6 cm.

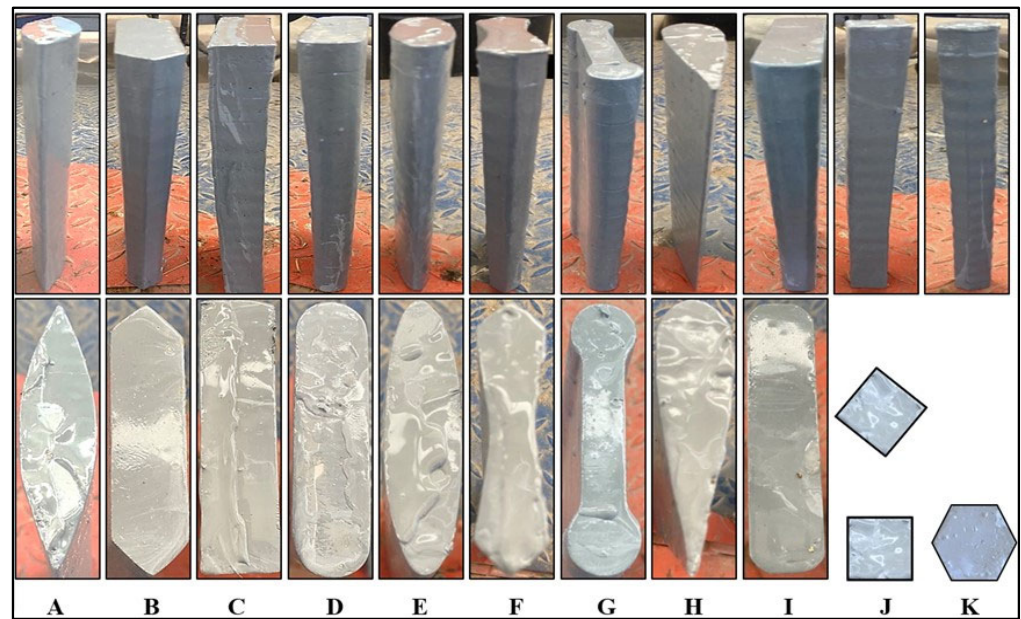


Figure 2. Pier shapes are employed in experimental and numerical models including, (A) lenticular (LE), (B) ogival (OG), (C) rectangular (RE), (D) oblong (OB), (E) elliptical (EL), (F) octagonal (OC), (G) double-circular (DC), (H) Joukasky (JO), (I) rectangular chamfered (REC), (J) diamond (DI) and square (S), and (K) polygonal (PO) shapes.

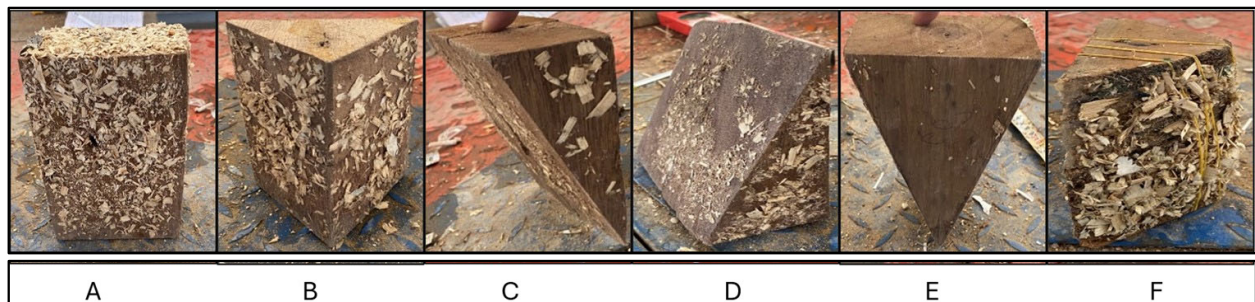


Figure 3. Six uniform debris configurations were employed during the experiments, (A) rectangle, (B) triangle bow, (C) high wedge, (D) low wedge, (E) triangle yield, and (F) half circle.

A comprehensive assortment of forms was meticulously selected to emulate real-world scenarios of woody debris accumulation. These configurations included the rectangular profile (R), characterized by a simple and straightforward rectangular contour. The half-cylinder structure (HC) displayed a curvilinear upstream aspect, while the triangle bow morphology (TB) resembled the upstream-pointing bow of a maritime vessel. The Triangle Yield Sign Configuration (TY) featured a planar upstream facade, widening at the summit and tapering to an apex at the base. The high wedge formation (HW) was distinguished by an upstream facade with a conspicuous bulge directing the flow downward, and the low wedge formation (LW) highlighted an extensive volume for the lower extremity and an upper-oriented downstream surface. The selection of the six debris shapes in this experiment is grounded in their close resemblance to real-world debris accumulations observed around bridge piers. These shapes were chosen based on both natural formation tendencies and the constraints of experimental conditions. For instance, rectangular blocks and low wedges are commonly seen in consolidated debris masses, particularly those comprising thin branch layers, which have been frequently documented around piers. The selection of accumulation debris design aligns with previous studies, such as [7], emphasizing the occurrence of triangular-in-depth configurations in debris accumulation scenarios. The representative geometries used, including idealized forms like inverted half-cones, triangle

bows, and half-cylinder shapes, have been validated by prior research [19,20]. Additionally, the dimensions of these debris' shapes were carefully evaluated based on mean ranges reported in the existing literature, primarily from field surveys, localized analyses, and established laboratory guidelines as outlined in [7,19,21–23]. This approach ensures that the chosen debris shapes are reasonable and precisely established, providing a solid basis for the study's findings on scour patterns around bridge piers.

3. Sediment Model in Flow-3D

The sedimentary model built into flow-3D is a complex computer tool carefully made to study how sediment transport and scour behave, especially near bridge foundations. This sophisticated model encompasses two fundamental modules, namely the drifting and lifting modules, revealed in complete detail in the work referenced [24].

The drifting module is important because it creates the force that keeps the sediment grains moving through the fluid medium. This module assumes that the mobility of sediment particles should be preserved. In contrast, the lifting module primarily extracts materials from the sand bed by exploiting the bed shear stress. The simulation incorporates a drag model for particle formation, which is triggered when sand particles attain a predefined cohesive material fraction. Within the fluidic domain of flow-3D, a dynamic amalgamation of compacted and suspended particles prevails. It is imperative to underscore that the concentration of suspended particles directly modulates the fluid's viscosity, intensifying it proportionally with the increase in concentration. An exponential drag term, symbolized as follows, is integrated into the momentum formula, as expounded in Ref. [24], capturing the solid-like response.

$$\frac{\partial u}{\partial t} + u \cdot \Delta u = \frac{-\Delta P}{\bar{\rho}} + \frac{\Delta \tau}{\bar{\rho}} + g - K_u \quad (1)$$

$$\bar{\rho} = \rho_l + f_s(\rho_s - \rho_l) \quad (2)$$

To unravel the mathematical intricacies of this model, several vital parameters are introduced: $\bar{\rho}$ represents the mean concentration density of the bed materials and ρ_s and ρ_l denote the densities of the sediment particles and the liquid, respectively. The drag constant, denoted as K , dictating the interplay between sediments and the shear stress, undergoes calculation utilizing Formula (3), which was introduced by [24].

$$K = \begin{cases} 0 & f_s < f_{s,co} \\ \left(\frac{f_{s,cr} - f_{s,co}}{f_{s,cr} - f_s} \right) \left(\frac{f_{s,cr} - f_{s,co}}{f_{s,cr} - f_s} - 1 \right) & f_{s,co} < f_s < f_{s,cr} \\ \infty & f_{s,cr} < f_s \end{cases} \quad (3)$$

This computation involves variables such as f_s (particle fraction), $f_{s,co}$ (component consistency, wherein particle contact transpires and viscosity remains independent of sediment content), and $f_{s,cr}$ (critical solid segment). Additionally, the determination of particle local velocity vectors, u_{drift} and u_{lift} , establishes an essential component and is calculated through Equations (4) and (5).

$$u_{drift} = \frac{f_l}{18\mu} \frac{d^2}{\bar{\rho}} \nabla P (\rho_s - \rho_l) \quad (4)$$

$$u_{lift} = \alpha n_s \sqrt{\frac{\tau - \tau_{crit}}{\bar{\rho}}} \quad (5)$$

The fluid part, indicated as f_l , complexly connects with these equations. The mean sediment diameter, represented as d and μ , as determined by Equation (6), contribute fundamentally to these calculations.

$$\mu = \mu_l \left(1 - \frac{\min(f_s, f_{s,co})}{f_{s,cr}} \right)^{-1.55} \quad (6)$$

As a sophisticated computer tool for simulating sediment dynamics, including transport, erosion, and deposition, the flow-3D sedimentation model is beneficial in fluid settings, such as rivers, and in the vicinity of hydraulic infrastructure. According to Refs. [24–29], the strengths and weaknesses of this model are listed below.

1. Simulating unstable 3D mobile bed processes strongly suits flow-3D, improving the accuracy and realism of sediment transport models in dynamic situations.
2. Since non-cohesive sediment scenarios are common in natural sediment transport processes, the program is well-suited to handle them. It is very adaptable for a variety of applications because of this feature.
3. The steepest angle at which a material on a sloping surface stays stable is known as the crucial angle of repose, and flow-3D can mimic this angle. This is essential for correct sediment movement modeling on sloping surfaces.
4. The program is helpful for several applications, such as sedimentation basins, bridge pier and abutment scour, local scour around hydraulic structures, river and coastal morphodynamics, and reservoir flushing.
5. The program accurately models the intricate relationships between sediment transport and fluid flow, mainly changes in load from suspended to bed, depending on the environment. This interaction is necessary for precise sediment behavior predictions.
6. To correctly portray variations in fluid activities brought on by sediment concentration, flow-3D modifies the fluid viscosity depending on the concentration of suspended particles.
7. The model's capacity to replicate the critical shear stress and its consequences for bed surface sediment erosion increases its predictive accuracy for sediment transport in various hydraulic conditions.

The weaknesses are as follows:

1. New users may encounter a high learning curve due to flow-3D's complete capabilities and complexity. It takes a lot of time and effort to become proficient with the program, particularly for those not experienced with sophisticated modeling tools.
2. The model has limitations, especially in dealing with cohesive soils such as silts and clays, where its performance is less effective.
3. The program cannot accurately replicate coarse sediment particles' behavior. The model's underlying assumptions could not accurately represent the dynamics of bigger particles, which might result in errors in certain situations.
4. When applied to cases with substantial grain sizes, the model's sediment transport theory may be unreliable, requiring users to exercise caution.
5. Due to the sediment transport theory's empirical nature and the turbulence models' inherent approximations, carefully calibrating the parameters may be necessary to obtain accurate results for specific applications.

4. Turbulence Modeling with the RNG

In fluid dynamics analysis, simulations have emerged as a vital tool for evaluating system performance due to the increasing complexity of systematic approaches. Among various software programs, flow-3D distinguishes itself by utilizing the FAVOR and VOF algorithms to precisely estimate the positions of the free surface and objects, respectively. This program provides 3D instantaneous results across various flow scenarios and dynamic phenomena, deploying specially crafted numerical techniques [24,30]. Specifically tailored for investigating fluid and gas motion, with a keen emphasis on free-surface phenomena

and particle transport, flow-3D proves instrumental in simulating scouring around bridge piers. The simulation uses a finite difference method to solve three-dimensional equations. It employs the renormalized group (RNG) standard and large eddy equations to control the viscosity of the water flow.

The RNG model is an advanced version of the standard $k-\epsilon$ model for turbulence modeling. It excels in predicting turbulence and monitoring the Reynolds stress and viscous pressure. Due to its resilience, the RNG model is highly effective at solving production problems. It enhances the core $k-\epsilon$ model with intermediate turbulence, irregular flows, and mass movement.

The governing equations for k (turbulent kinetic energy) and ϵ (turbulent dissipation rate) in the RNG model provide a comprehensive structure that aids in understanding turbulent dynamics. These equations are as follows.

$$\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\nu}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + v_i \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \epsilon \quad (7)$$

$$\frac{\partial \epsilon}{\partial t} + u_i \frac{\partial \epsilon}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\nu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_i} \right) + C_1 \frac{\epsilon}{k} v_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_2 \frac{\epsilon^2}{k} \quad (8)$$

$$\nu_i = C_\mu \frac{k^2}{\epsilon} \quad (9)$$

where the variables are defined as follows:

k and ϵ are the turbulent kinetic energy and dissipation rate, respectively;

u is the velocity vector;

ν is the kinematic viscosity;

ν_t is the turbulent viscosity;

σ_k and σ_ϵ are the turbulent Prandtl numbers for k and ϵ , respectively;

C_1 , C_2 , and C_μ are empirical coefficients with typical values of 1.44, 1.92, and 0.09, respectively.

The LES model differs significantly from Reynolds-Averaged Navier–Stokes (RANS) models like $k-\epsilon$ and $k-\omega$ by directly resolving most turbulent fluctuations. This provides a more detailed representation of turbulence using a kinematic eddy viscosity approach:

$$\nu_T = (cL)^2 \sqrt{2e_{ij}2e_{ji}} \quad (10)$$

where c is a constant value between (0.1–0.2), e_{ij} is the strain rate tensor components in the (i) and (j) directions, and L is the length scale.

The LES model offers superior accuracy in capturing detailed turbulent structures, making it particularly valuable for complex flows like those around bridge piers. However, the primary disadvantage of the LES model is its high computational cost. It requires finer meshes and longer computation times, making it resource-intensive compared to RANS-based models. This can be a limiting factor for large-scale simulations or scenarios where computational efficiency is critical. Additionally, the increased demand for computational resources does not always translate to proportionate gains in practical accuracy, especially in cases where the detailed resolution of small-scale turbulence is not essential.

5. Analysis of Sediment Stability

The non-dimensional Shielding coefficient is a significant statistic that indicates the long-term dependability of particles while studying sediment transport patterns. To obtain the necessary quantity, one may calculate the product of the shear-induced pressure at the topmost

point of the particle layer and the apparent weight of a single particle [24]. The complicated arithmetic behind this variable may be summarized using the following equation:

$$d_* = d \left[\frac{\rho(\rho_s - \rho)g}{\mu^2} \right]^{-\frac{1}{3}} \quad (11)$$

Here, d indicates the diameter of sediment particles, and g represents gravitational acceleration. Subsequently, for the computation of the critical shear stress (τ_{cr}) for particles within a flat riverbed, the formulation adopts the following expression:

$$\tau_{cr} = \rho g(s - 1)d_{50}\theta_{cr} \quad (12)$$

In this context, d_{50} denotes the mean diameter of sediment particles, s represents the specific density, and θ_{cr} encapsulates the critical Shields number. For flatbed scenarios, the Soulsby–Whitehouse equation is employed [31]. A salient observation is the impact of gravity, imparting a tangential force component on a sloped bed interface. This gravitational influence significantly influences the stability of bed materials, contingent on the gradient of the flow field. Consequently, as the velocity ascends, the gradient undergoes an ascent, diminishing as the velocity descends.

6. Transfer Rate Simulation with Nilsen's Method

The comprehensive examination of scour phenomena, integral to hydraulic engineering, necessitates understanding the intricate dynamics governing the material transfer rate. Achieving precise scour estimates is contingent upon the adept manipulation of particle transport equations [32], which serve as a theoretical cornerstone for delineating the intricate interplay of sediments in the water. Within this scholarly pursuit, a pivotal focus is directed toward computational modeling, leveraging the capabilities of flow-3D software—a sophisticated tool renowned for its prowess in hydraulic simulations. Central to this study is a meticulous exploration of a specific methodology advanced by Nilsen in 1992 [33], a seminal contribution that propels the research forward and establishes the bedrock upon which the entire investigative framework is constructed. At the heart of this methodological approach lies a mathematical formulation encapsulated by the following expression:

$$\Phi_i = \beta_N \theta_i^{0.5} (\theta_i - \theta_{cb,i}^t) C_b \quad (13)$$

Φ_i is the dimensionless transfer of bed loads; β_N is a coefficient for the number of particles; θ_i is a parameter for sediment concentration; $\theta_{cb,i}^t$ is the critical sediment concentration; and C_b is a coefficient that accounts for the effects of bed material properties.

The intricacies of this formula unfold within the computational realm of flow-3D, affording a detailed examination of sediment transport and scour phenomena, consequently contributing significantly to the overarching field of hydraulic engineering.

7. Numerical Modelling Setup and Validation Processes

The accurate estimate of scouring around piers is of paramount importance. To this end, a sophisticated numerical model, flow-3D, was developed, mirroring the conditions of a physical model. This model was designed to simulate the complex interactions between fluid dynamics and sediment transport. The simulation commenced with establishing steady-state explanations of hydraulics, which served as the initial condition for subsequent sediment transport simulations. A single sediment species, characterized by $D_{50} = 0.93$ mm, was utilized to activate the sediment model. The specified parameters include a critical Shields parameter of 0.033, an entrainment coefficient of 0.018 as a default value, bed roughness/ $D_{50} = 3$, and a bed-load coefficient of 8.0. The domain height is 30 cm, comprising 15 cm of sediment height and 12.0 cm of water depth; the remaining portion is air. The domain width aligns with that of the flume. Following the recommendations of Refs. [34,35], the flow field surrounding the pile exhibits a negligible influence beyond a

space of 12 d from the inlet to the pier center. Accordingly, the geometry parameters were configured with a length of sixty times the pier diameter (1.5 m) and a length from the pier center to the upstream end of thirty-two times the pier diameter (0.8 m). Boundary conditions were meticulously applied in this study. The average velocity boundary is strategically assigned at the inlet at 0.29 m/s, and the flow elevation is 0.12 m. The downstream area, recognized to be outflow boundaries at the bottom, and lateral walls were identified as walls. No-slip boundary conditions were applied at solid surfaces, resulting in zero tangential velocity.

To make the model more accurate, two higher-resolution mesh planes were drawn around the elliptical pier in the x and y directions, as shown in Figure 4a–c. The intricacies of the mesh design constitute a pivotal factor influencing model accuracy, contingent upon factors such as the volume and count of cells and their strategically intensified distribution. It is noteworthy that the mesh design can also impact the duration of the simulation.

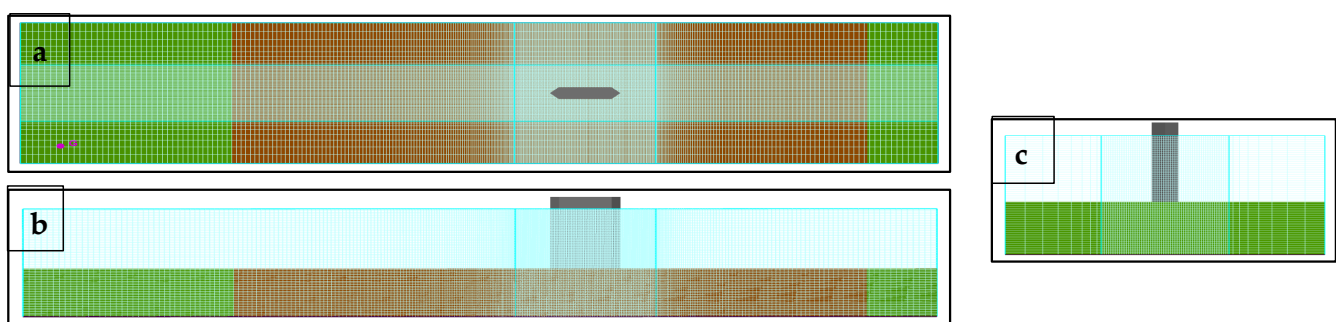


Figure 4. Detailed view of the computational domain with mesh representation: (a) top view, (b) side view, and (c) front view.

The mesh properties include the x and y axis meshing intensity, quantity, and size. Figure 4b shows the upper perspective, and the intensification is squarely arranged around the pier, with the pier in the middle of the square. For enhanced precision in results, the dimensions of grid cells near the pier were reduced compared to other sections. The mesh size within the scour zone was set at 0.5 cm, remaining at 0.8 cm in other model regions. The assigned values were established through a systematic trial-and-error process, aiming to align the simulation outcomes with the results obtained from experimental trials.

After validating the numerical results' conformity with laboratory results, several key parameters were calibrated and employed in the numerical simulations. The Fractional Area/Volume Obstacle Representation (FAVOR) technique employed in flow-3D offers a simple yet powerful meshing capability. Employing diverse techniques to enhance numerical stability and compute parameters like interfacial areas, advection, stress, and the presence of solid barriers [24], as illustrated in Figure 5a,b, this methodology adeptly captures intricate features within the computational domain without relying on a fitted grid. The simulations continued until a state of equilibrium in the scour depth was achieved, with the obtained results undergoing a comparative analysis with observations from the physical model. The turbulence calculations around the pier involved the application of the renormalized group (RNG) model [36]. While alternative turbulence models, such as the large eddy simulation (LES) technique, may yield more favorable outcomes, their adoption is linked to an extended computational timeframe [37]. This study chose a less intricate turbulence model due to many computational cases to ensure acceptable results within a more efficient computational duration.

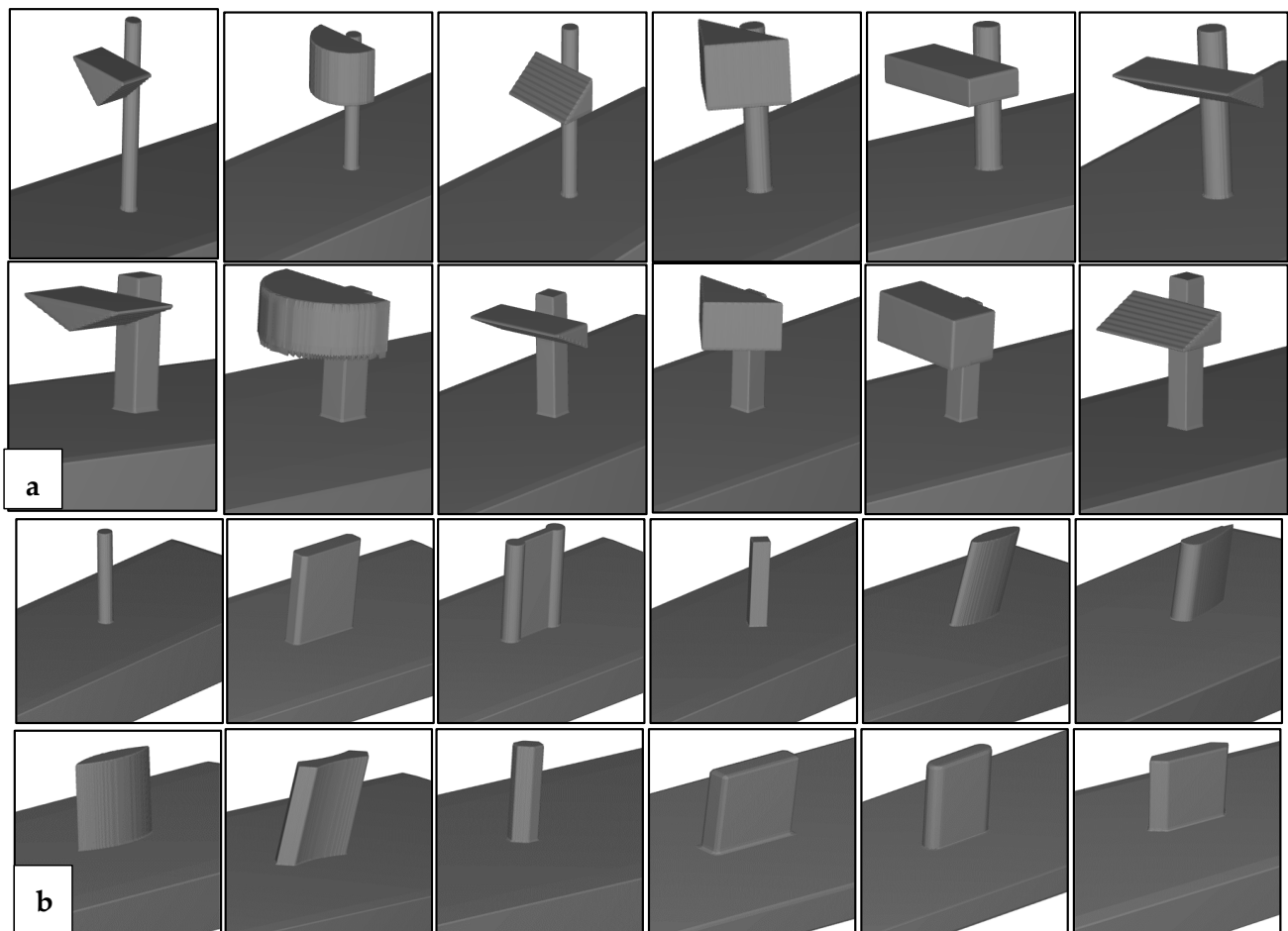


Figure 5. The FAVOR technique in flow-3D meshing includes (a) square and cylindrical piers with six debris shapes and (b) various pier shapes without debris accumulations.

8. Results and Discussion

8.1. Hydraulic Implications of Pier and Debris Shapes

The physical characteristics of different pier shapes significantly impact the complex scour patterns surrounding these structures. Figures 6–8 illustrate these patterns and the relative scour depth (Z_s/D). In the absence of debris, the scour depth (Z_s) is primarily influenced by the pier shape under uniform flow rates and consistent hydraulic conditions. Due to their streamlined design, lenticular piers exhibit lower Z_s/D values than other shapes. This streamlined profile facilitates a smoother flow diversion, reducing the intensity of vortices and, consequently, the scouring that occurs.

Conversely, square piers demonstrate the highest scour depth (Z_s) without debris, a finding attributed to their geometric design, which promotes vortex formation. This observation is consistent with findings from previous studies [8,22,38], which also noted higher scour depths around square piers. This outcome aligns with previous research but extends the understanding by analyzing various pier shapes. This comprehensive analysis provides a deeper understanding of how different pier geometries influence scour, emphasizing that geometric variations significantly impact the scour patterns and depths.

Scouring involves three types of vortices: horseshoe, crosswise flow, and wake vortices, each contributing to the complexity of the process. Horseshoe vortices are particularly prevalent around diamond, square, and polygonal piers. These piers have sharp corners and flat surfaces that disrupt flow, increasing turbulence and vortex formation. This interaction causes flow separation and the bifurcation of the shear layer at the pier sides, raising bed shear stresses, consistent with the findings in multiple studies [39–41]. These

studies indicate that a higher shear stress and turbulence intensify scouring, resulting in deeper and more localized scour holes. The increased turbulence and localized peak scour observed in these piers suggest that their geometric design is critical in exacerbating the scour process, making them more susceptible to damage under high-flow conditions.

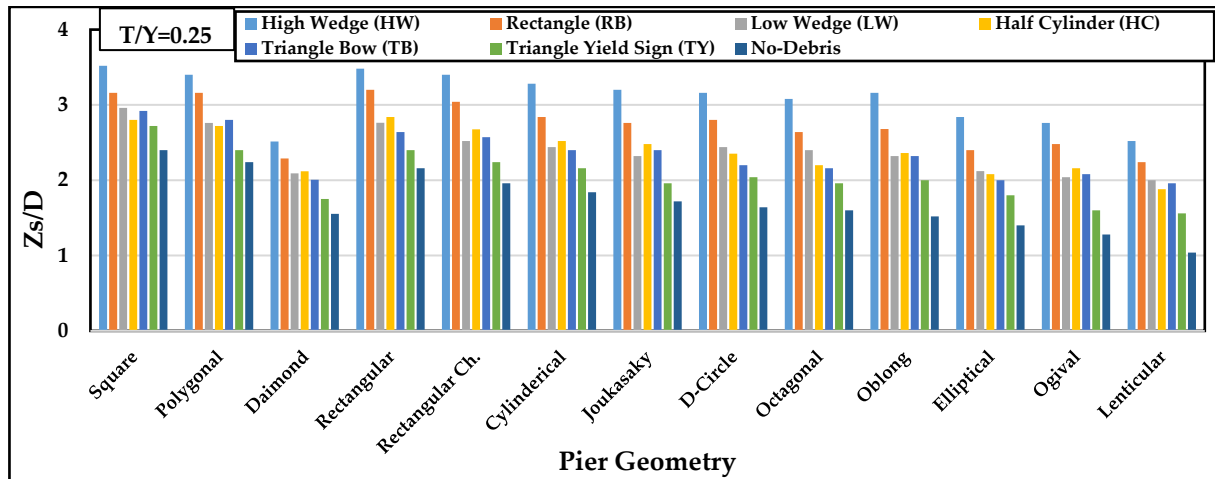


Figure 6. The maximum relative scour depth (Z_s/D) following encounters with debris for ($T/Y = 0.25$).

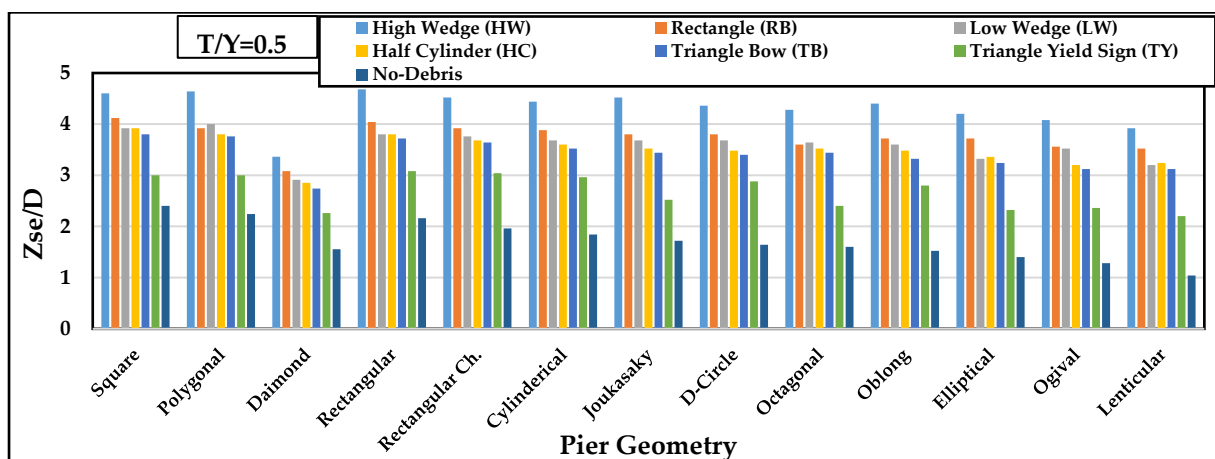


Figure 7. The maximum relative scour depth (Z_s/D) following encounters with debris for ($T/Y = 0.5$).

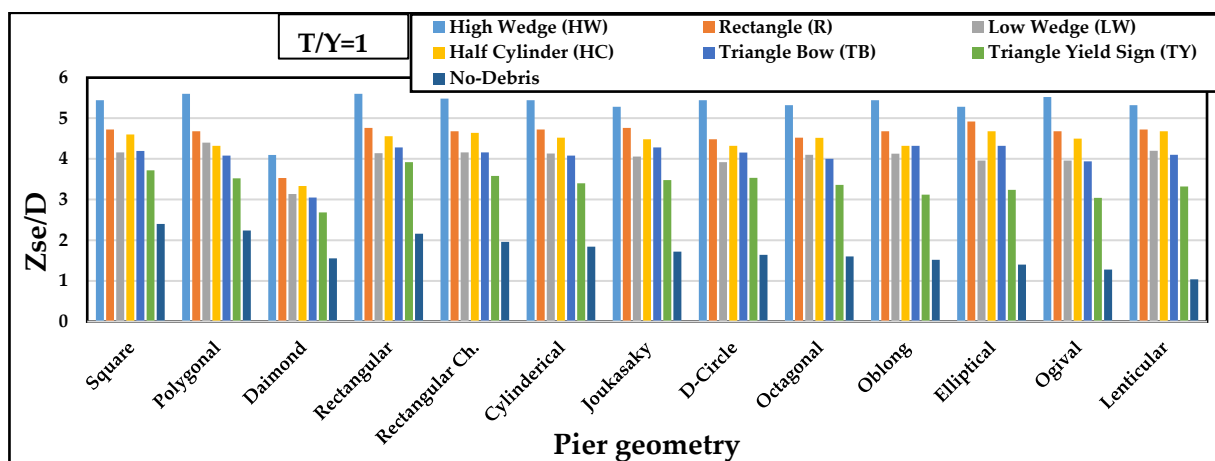


Figure 8. The maximum relative scour depth (Z_s/D) following encounters with debris for ($T/Y = 1$).

Figures 6–8 further explore scouring with debris, showing interactions with six identical debris configurations. The debris orientation is characterized by the relative debris depth (T/Y), with values of 0.25, 0.5, and 1.0. At $T/Y = 0.25$ (Figure 6); the square pier exhibits the highest Z_s/D values, especially with high wedge (HW) debris, whereas the lenticular pier shows decreased scour depths. This finding highlights the intricate interplay between the pier shape and presence of debris, which was not fully captured in previous studies, including our earlier work [18], where only six pier shapes were tested under the influence of six debris shapes. The current study's inclusion of 13 pier shapes provides a more comprehensive dataset, enhancing our understanding of these dynamics and offering a broader perspective on the impact of pier geometry on scour.

At $T/Y = 0.5$ (Figure 7), polygonal and rectangular piers show increased scouring effects across most debris types, further emphasizing the importance of the pier shape in determining scour processes. This contrasts with the earlier findings in [18], which focused on a narrower range of pier designs and thus did not capture some of the interactions observed in the present study. The increased scour observed in polygonal and rectangular piers at this debris depth suggests that these shapes may be particularly vulnerable to scour when debris is present, a critical insight that has implications for the design and maintenance of such structures.

Figure 8 indicates that at $T/Y = 1$, Z_s/D values are consistent for all pier shapes with HW debris but vary for other debris shapes. This consistency at $T/Y = 1$ across different pier geometries with HW debris suggests a potential design strategy for improving resilience to debris-induced scour, a consideration not fully explored in prior research, including [18]. This suggests that, in certain conditions, particularly with high wedge debris, the effect of the pier shape on scour depth may diminish, leading to a convergence in scour behavior. This finding could inform the development of more robust design strategies for bridges in areas prone to high debris accumulation.

These findings underscore the intricate relationship between pier geometry, debris shape, and relative depth in influencing Z_s/D values. The expanded scope of this study—testing 13 different pier shapes—provides a more robust understanding of these processes, suggesting the need for further research to fully capture the variability in scour behavior under different conditions. The convergence of scour behavior at $T/Y = 1$ for HW debris could inform the design of more resilient bridge piers, highlighting a critical area where the results of this study can contribute to practical engineering applications.

In summary, while this study builds upon the experimental framework established in [18], it significantly broadens the scope by incorporating a more comprehensive range of pier shapes and debris configurations, leading to a deeper and greater understanding of the factors influencing scour depth. This expanded analysis offers valuable insights not captured in earlier research, thereby addressing a crucial gap in the literature associated with bridge scour.

Effect of Pier Shape Factor on Maximum Scour Depth

Given the variety of scour models initially designed for cylindrical pier structures, selecting the cylindrical pier shape as the baseline model was logical. This choice was reinforced by its extensive use in previous research, as highlighted in Ref. [38]. The study also indicates the pier shape factor (S.Fp), which quantifies the ratio of the scour depth caused by non-cylindrical pier designs (Z_s (non-circular)) to that caused by cylindrical piers (Z_s (circular)). This factor was crucial for comparing how different pier shapes affect the scour depth relative to the cylindrical pier, as discussed in Ref. [18]. This comparison provided insights into the hydraulic behavior around various pier geometries. The study employed Equation (12) to offer a quantitative explanation of this influence and systematically analyzed the impact of different pier shapes. This analysis is essential for developing practical solutions to mitigate scouring around bridge piers, as mathematically expressed by the following:

$$SF_p = \frac{Z_s(\text{non-cylindrical shape})}{Z_s(\text{cylindrical pier})} \quad (14)$$

Figure 9, developed from Ref. [18], illustrates the shape factor values for each pier shape, excluding the effects of debris. The experimental results for the tested pier shapes showed the square pier with a higher pier shape factor of 1.3, while the lenticular shape had a lower value of 0.57.

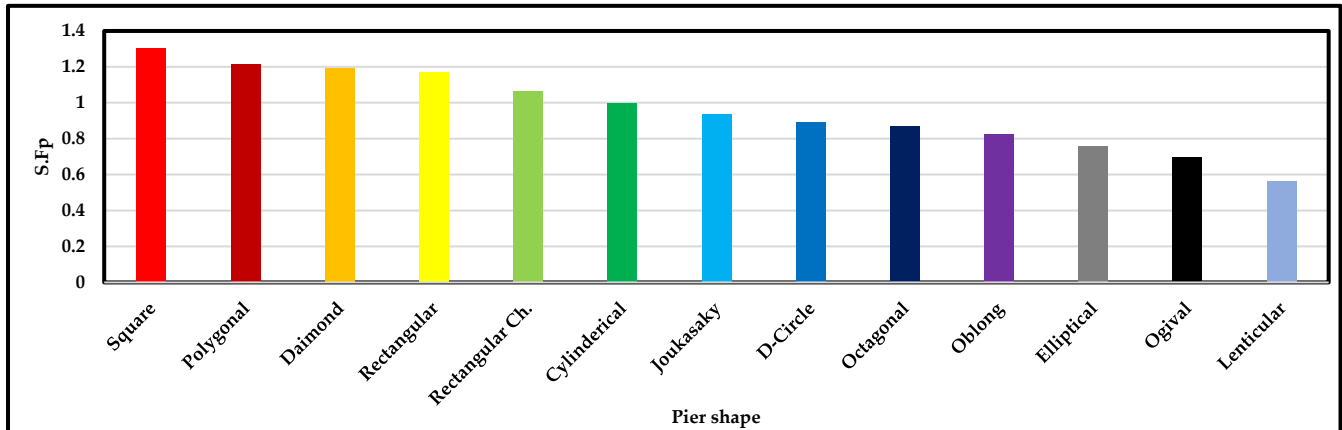


Figure 9. Analysis of the shape factor for thirteen distinct pier geometries developed from [18].

Figure 10 illustrates the average scour depths and the standard deviation (*STV*) data. It clarifies the variation in scour depths across each pier form group, regardless of the debris shape and obstruction ratios (*A*%). This figure indicates how important pier shape is as a factor that affects the scour depth variability by looking at the trend of *STV* for each mean scour depth for each pier shape. The square shape exhibits a lower *STV* value than other forms, regardless of the obstruction ratios. Its symmetrical design is believed to contribute to more predictable scour patterns. These findings indicate that the pier's form significantly impacts the variation in the scour depth, surpassing the effect of debris shape. Shapes included cylindrical, Joukasaky, double-circular, and octagonal shapes have moderate *STV* values, which suggests that there is more variety in the scour depths. The curved shapes of the profiles might cause intricate flow patterns, leading to increased and less predictable erosion around the piers. Even though obstruction ratios change, the fact that *STV* values tend to be higher shows that pier design has a more significant impact on scour depth variability than debris shape. Oblong, ogival, elliptical, and lenticular geometries exhibit different *STV* values depending on the obstruction ratio. These designs' uneven and asymmetrical profiles may lead to varying scour depths, especially when blockage ratios are more excellent. These forms' intricate geometries may influence various scour patterns but to a lesser degree than circular shapes. However, the *STV* pattern confirms that the form of the pier has a dominant impact on the variation in the scour depth compared to the shape of the debris.

To summarize, the *STV* data indicate that the form of the pier has a crucial influence in determining the variability in the scour depth. Although the form of debris may cause variation, particularly in piers with varied shapes, the constant pattern of *STV* values emphasizes the need to consider the pier and debris shape when predicting the scour depth and designing bridge foundations. As shown in Figure 11, the *STV* values change for different pier shapes depending on the shape of the debris. The debris shape factor significantly determines the local scouring depth around different pier shapes.

Refs. [16,22] support these experimental deductions, supporting the reliability of the results. Using the standard deviation as a statistical tool is crucial in understanding the intricate interactions between variables in scour-depth analysis. It provides deeper insights into hydraulic processes, particularly when considering different debris types and pier shapes.

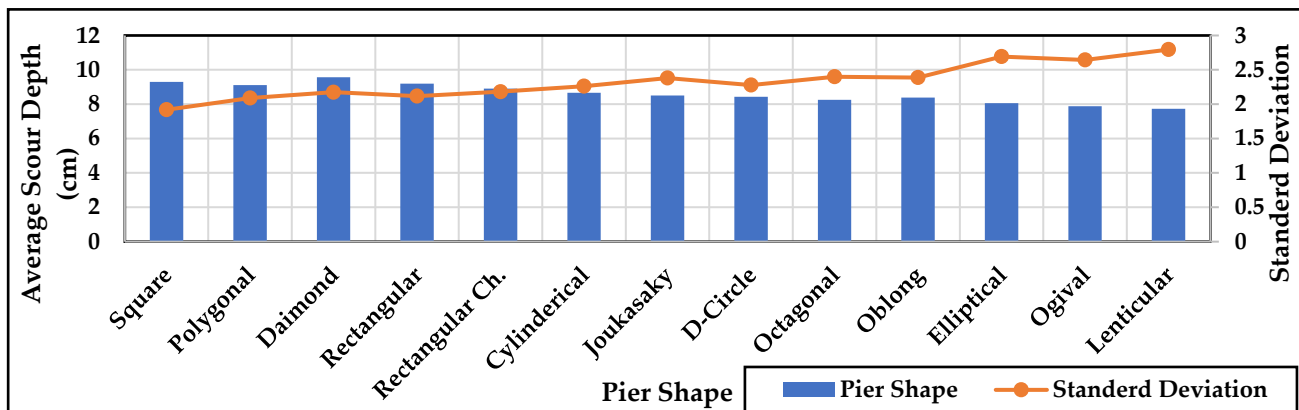


Figure 10. Standard deviation analysis of average scour depth for different pier shapes.

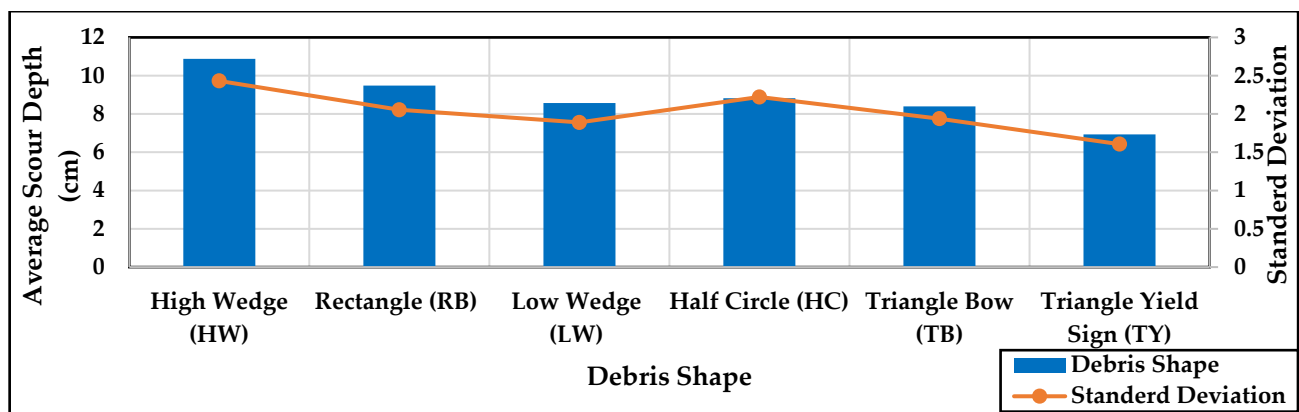


Figure 11. Standard deviation analysis of average scour depth for different debris shapes.

8.2. Numerical Evaluation of Local Scour Patterns around Different Piers Design

As mentioned earlier, the primary objective of further research is to thoroughly analyze the complicated processes related to the impact of debris on scour development on the upstream side of various pier designs. This research aims to identify the conditions that lead to the emergence of maximal local scour. To help with this ambitious project, the computational strengths of the flow-3D program, which is well-known for its ability to simulate the dynamics of fluids and sediment movement, have been used. This adaptable tool allows for running a series of thoroughly prepared simulations.

The investigation begins with a basic scenario where an isolated pier is situated in an area free of debris, preserving the simplicity of the hydraulic setting. Figure 12a–m illustrate detailed profiles along the area's length and width, providing a comprehensive view of the scour patterns around the bridge piers. These figures compare different pier geometries: square, rectangular, rectangular chamfered, diamond, polygonal, cylindrical, octagonal, double-circular, Joukasaky, elliptical, ogival, oblong, and lenticular. All geometries maintain consistent proportions and are subjected to identical flow discharge and hydraulic conditions. The visual representations in Figure 12a–m reveal the extent of the resulting scour hole depths observed in different test scenarios. The piers' geometric design has a significant impact on the primary scour areas downstream as well as the overall morphology of the affected zone. Among the tested shapes, the square pier, with a scour depth of 5.8 cm, exhibits the most pronounced scouring.

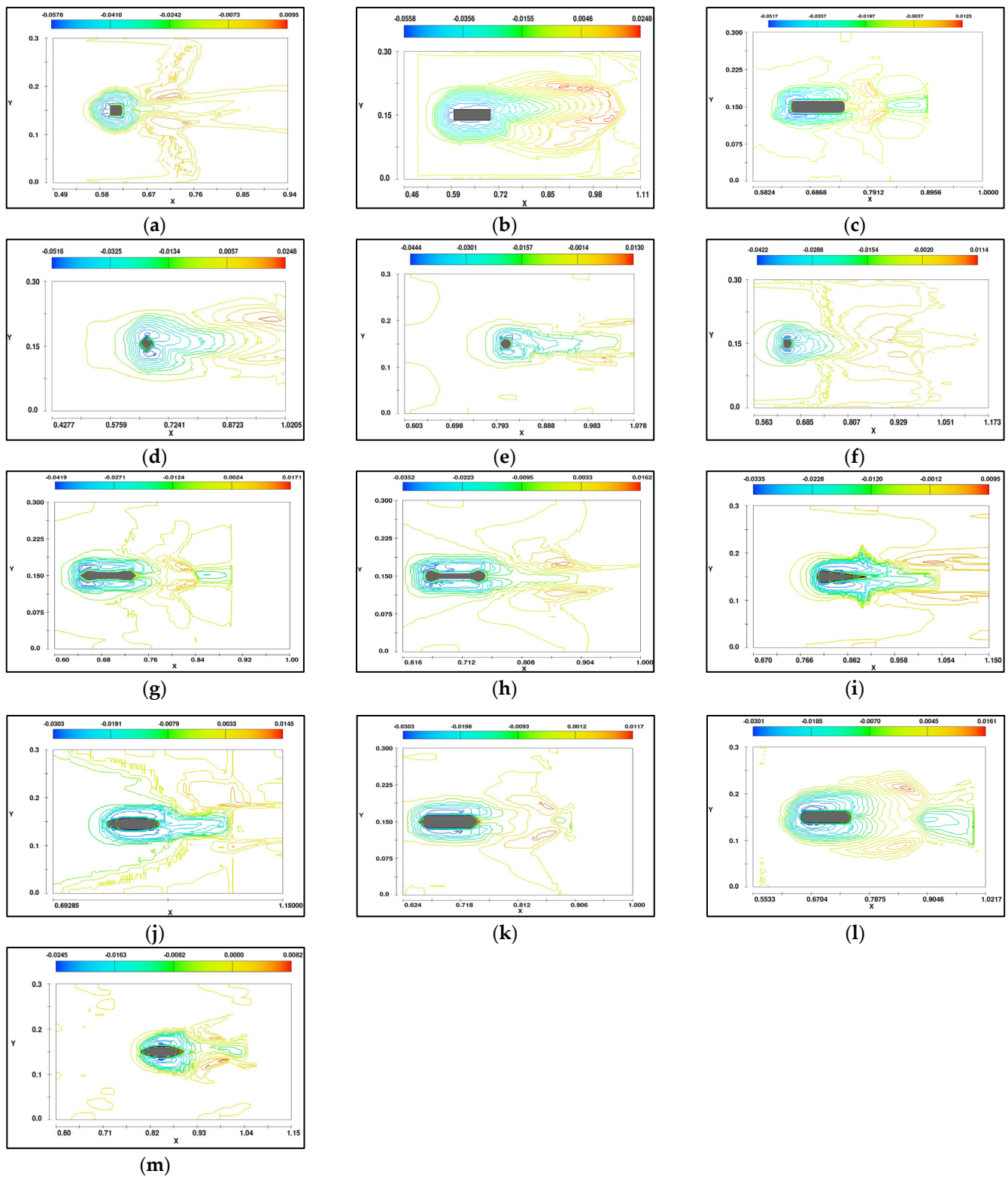


Figure 12. The local scour distribution around the different piers shapes includes (a) square, (b) rectangular, (c) rectangular chamfered, (d) diamond, (e) polygonal, (f) cylindrical, (g) octagonal, (h) double-circular, (i) Joukasky, (j) elliptical, (k) ogival, (l) oblong, and (m) lenticular.

In contrast, the lenticular shape, with a scour depth of 2.5 cm, shows the least scouring. Notably, square, polygonal, rectangular, rectangular chamfered, and cylindrical piers have peak scour depths upstream of the structures. In a divergent pattern, the rest of the shapes

undergo their maximum scour at the connection of the pier sides, while the diamond shape's peak scour is symmetrically positioned between its two sides. These variations are closely related to the formation and behavior of different vortices around the piers. Three primary types of vortices are crucial to understanding the differences in scour patterns: horseshoe vortices, wake vortices, and shear layer vortices. Horseshoe vortices, which form at the pier's base, cause upward lateral deformations and are a significant factor in the upstream scour for square, polygonal, and cylindrical piers. Wake vortices, which develop behind the pier, contribute to a downstream scour and are particularly influential in the scour patterns observed. Shear layer vortices, which occur due to flow separation at the pier's sides, exacerbate bed shear stresses, further influencing the location and severity of peak scour.

In a controlled flume environment, the pier is a critical hydraulic obstacle that disrupts the uniform flow of water. The flow, moving at a steady velocity of 0.29 m/s, encounters the pier, resulting in distinct variations in flow patterns, as depicted in Figure 13. This illustration shows how the otherwise uniform flow changes dramatically upon reaching the cylindrical, square, lenticular, and ogival piers. A notable increase in velocity, represented by dark blue–red vectors, indicates flow reversion within the scour hole, which initiates a vortex at the pier's base due to the downward flow. The reduction in velocity near the upstream side of the pier is significant, causing a pressure differential around the pier. This pressure difference exacerbates the formation of vortices on both sides of the pier. The flow velocity distribution at the corners of ogival, square, and polygonal pier shapes explain the maximum scour depths observed at these locations. The most significant velocity is intense at these angular points, resulting in the highest scour depth.

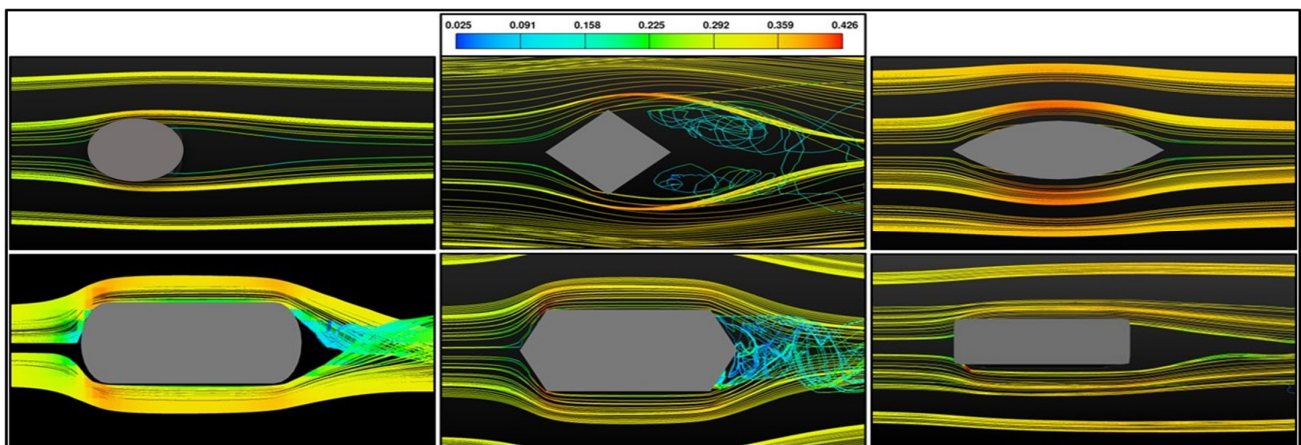


Figure 13. The flow velocity patterns around different pier shapes.

In contrast, the highest flow velocity in the lenticular pier is evenly spread along both sides, impacting a greater surface area and leading to smaller scour depths but a giant scour hole. Using computational fluid dynamics (CFD) dramatically improves the study by offering comprehensive data for assessing various pier forms. This comprehensive study emphasizes the critical role of pier geometry in shaping the flow dynamics inside the flume.

8.3. Numerical Evaluation of Debris–Pier Interaction

This research numerically investigates the impacts of six debris configurations on two pier shapes, square and cylindrical. Figures 14 and 15 present a detailed examination of the numerical (NUM) and experimental (EXP) scour depth results for cylindrical and square pier shapes across various debris shapes and submergence levels ($T/Y = 0.25$ and $T/Y = 0.5$). The goal is to recognize the impact of debris characteristics and submergence on the alignment between numerical simulations and laboratory experiments. At $T/Y = 0.25$, the mean difference between the EXP and NUM results for the cylindrical pier shape is

1.23 units (18% difference), indicating a considerable difference under conditions of reduced debris impact. The average variation grows to 2.9 units (32%) at $T/Y = 0.5$, indicating a significant disparity in the illustration of the scour depth between both methods. This demonstrates the difficulties in effectively predicting the scour depth under enhanced debris effect circumstances related to the cylindrical pier design. The average discrepancy between experimental and numerical findings for the square pier form for $T/Y = 0.25$. However, the average difference drops to 0.45 units (6%), indicating an improved alignment in the numerical depiction of the scour depth, demonstrating more precise measurement under lower debris effect circumstances. At $T/Y = 0.5$, the average discrepancy is 2.2 (22%), highlighting the difficulties of adequately representing the complicated flow characteristics and debris effects coupled with the mentioned pier form.

The observed disparities between simulated and experimental findings show that debris form or submergence level impacts the numerical model's effectiveness. The reduced discrepancies at $T/Y = 0.25$ illustrate the model's improved ability to accurately represent scour depth fluctuations if the debris effect is minimized. The increasing disparities at $T/Y = 0.5$, on the other hand, suggest difficulties in effectively predicting the scour depth under more complicated flow circumstances, particularly concerning the cylindrical pier design. The significant variances for the cylindrical pier form at $T/Y = 0.5$ needed more research into the model's description of the dynamics of flow and debris reactions particular to this configuration. Recognizing the complexities of these connections is critical for increasing numeric algorithms' prediction powers.

Additionally, the various approaches taken to assess the sediment entrainment threshold condition impact the local scour and countermeasure definition, resulting in conflicting findings. Both numerical and experimental studies might be skewed due to subjective evaluations [42]. Regarding sediment entrainment, the experiments' critical flow velocity (V_c) is about 20% lower than what is used in flow-3D models. Flow-3D uses the Shields' technique (1936), in contrast to the equations of [43] in the experiments. This draws attention to a critical factor that affects differences between numerical and experimental results. Flow-3D is a computational fluid dynamics (CFD) program that can numerically manage multi-scale, multi-physics flow problems for transient, three-dimensional solutions. When contrasted with experimental data, these numerical simplifications may lead to discrepancies, which capture the whole complexity of physical processes.

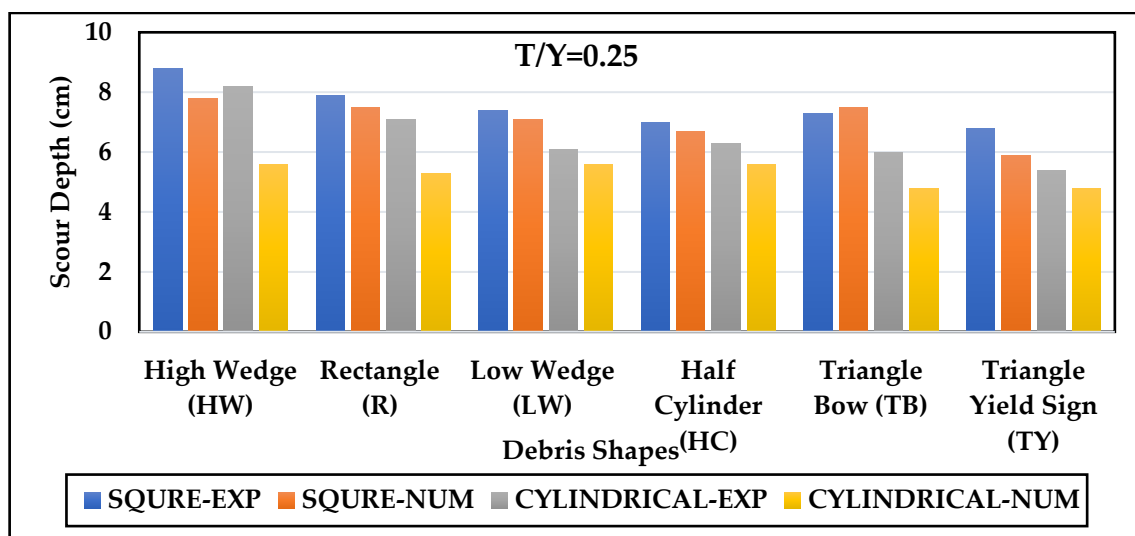


Figure 14. Cont.

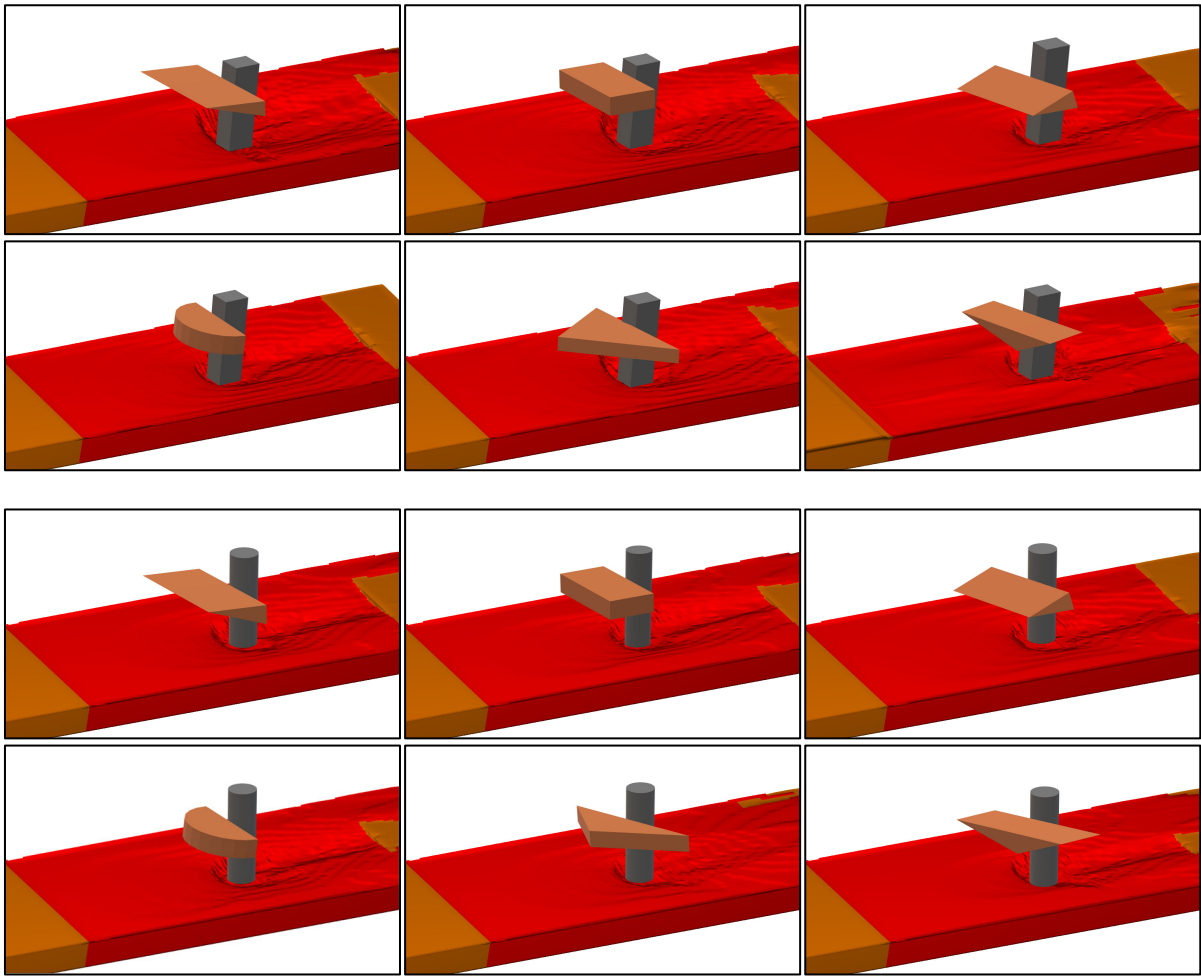


Figure 14. Comparative scour depth value for square and cylindrical piers across various debris shapes when debris relative thickness (T/Y) cases equal to 0.25.

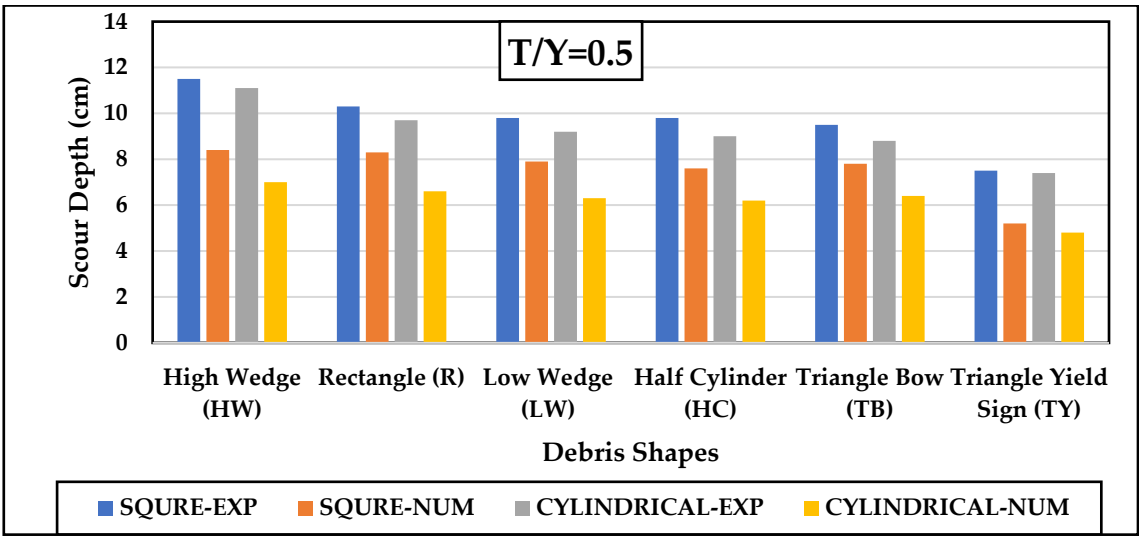


Figure 15. Cont.

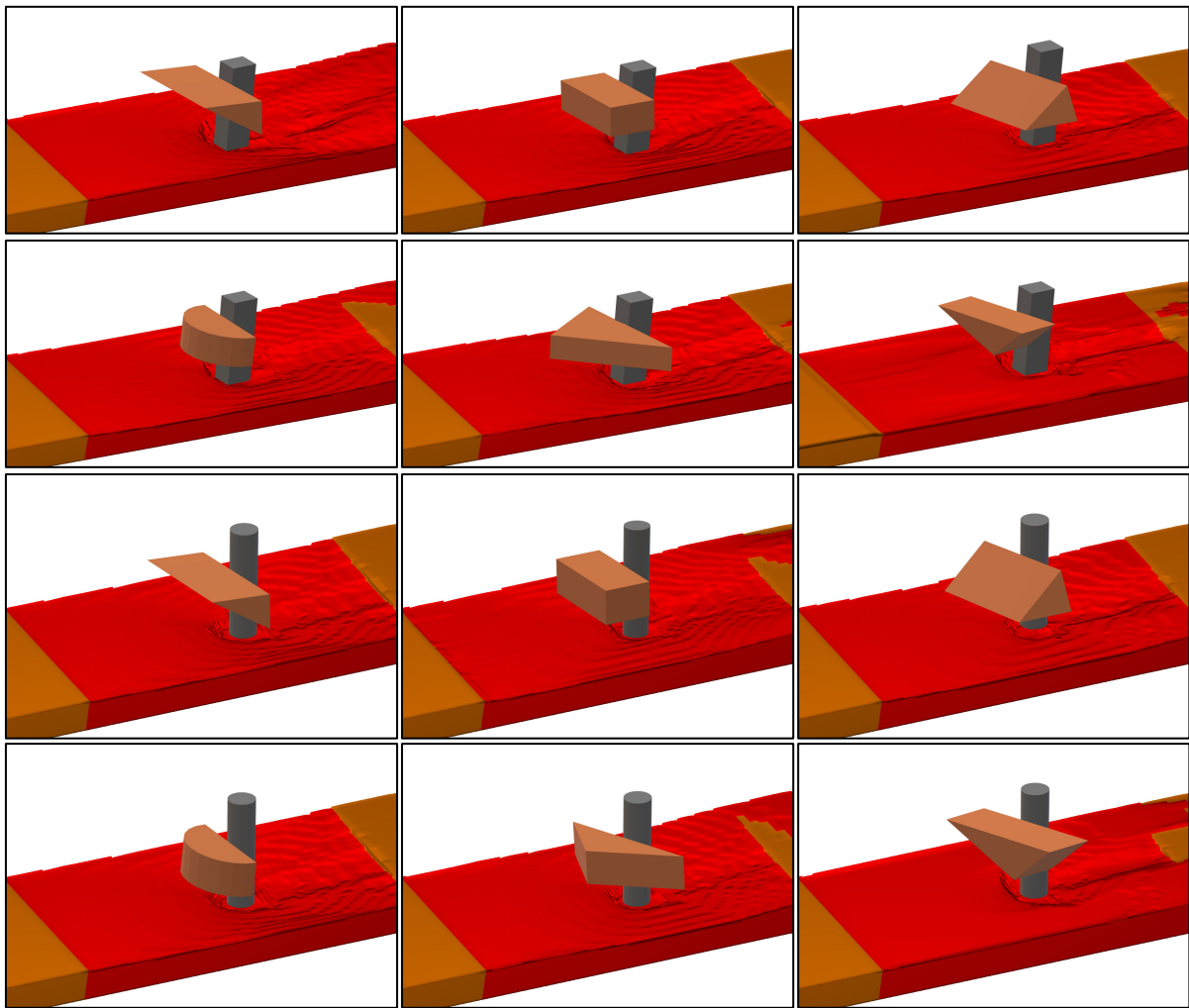


Figure 15. Comparative scour depth value for square and cylindrical piers across various debris shapes when debris relative thickness (T/Y) cases equal to 0.5.

When analyzing fluid flows in flow-3d, the Q-criterion is a crucial analytical tool for observing vortices. This paper investigates the Q-criterion's theoretical foundations and practical use in the flow-3D program. The Q-criterion is a precise and quantitative method for finding vortices in a flow field. The scalar field, derived from the second invariant of the velocity gradient tensor, shows regions where the strain is less critical than rotational motion. The mathematical definition of the Q-criterion is as follows: $Q = \frac{1}{2}(\mathbf{u}_{ij}^2 - \mathbf{u}_{ij}\mathbf{u}_{jij}) = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2) > 0$, where $\|\Omega\|$ represents the magnitude of the rotation rate tensor, while $\|S\|$ represents the magnitude of the rate-of-strain tensor. A positive Q value ($Q > 0$) indicates a region where the rotational effects (vorticity) dominate over the strain rate effects, signifying the presence of a vortex. The velocity gradient tensor ($\nabla\mathbf{u}$) is calculated using the velocity field data acquired from the flow-3D simulation. The rotation rate tensor (Ω) and the rate-of-strain tensor (S) are generated from this tensor. The next step is determining the Q-value at every node in the flow field. In the absence of any debris, as shown in Figure 16a, the Q-criterion visualization reveals the existence of vortex formations primarily located downstream of the cylindrical pier. The contours display elevated Q-values in proximity to the pier, suggesting the presence of robust vorticity zones. These vortices result from flow separation and the creation of a wake behind the pier. The analysis indicates periodic vortex shedding in the wake region. Additionally, there is flow separation on the sides of the pier, resulting in counter-rotating vortices and high Q-values close to the pier, indicating the presence of solid vortex cores. The introduction of rectangular debris with a depth of 3 cm causes substantial alterations in the flow patterns and vortex formations

around the pier, as shown in Figure 16b. The debris modifies the optimal flow trajectory and generates extra areas of detachment and reconnection. The fundamental changes observed include a disrupted symmetry of the vortex shedding, more substantial vorticity regions near the edges of the debris due to increased flow separation points, and an elongated wake region downstream of the pier with intensified turbulence, as evidenced by the spread of high Q-value regions. With a six cm thickness debris, the effect on the flow and vortex patterns becomes more pronounced, as shown in Figure 16c. The presence of larger debris significantly impacts the effective cross-section and induces more substantial changes in the flow field. The main observations include an intensified disruption in the flow due to larger debris, resulting in increased flow separation and reattachment, thereby creating more extensive regions with high Q-values. Additionally, the vortex patterns become more complex and irregular compared to the case with 3 cm of debris, indicating higher turbulence levels and instability in the wake. Furthermore, the wake region becomes more turbulent, with larger areas of high Q-values extending further downstream, demonstrating the more significant influence of the larger debris on the overall flow field.

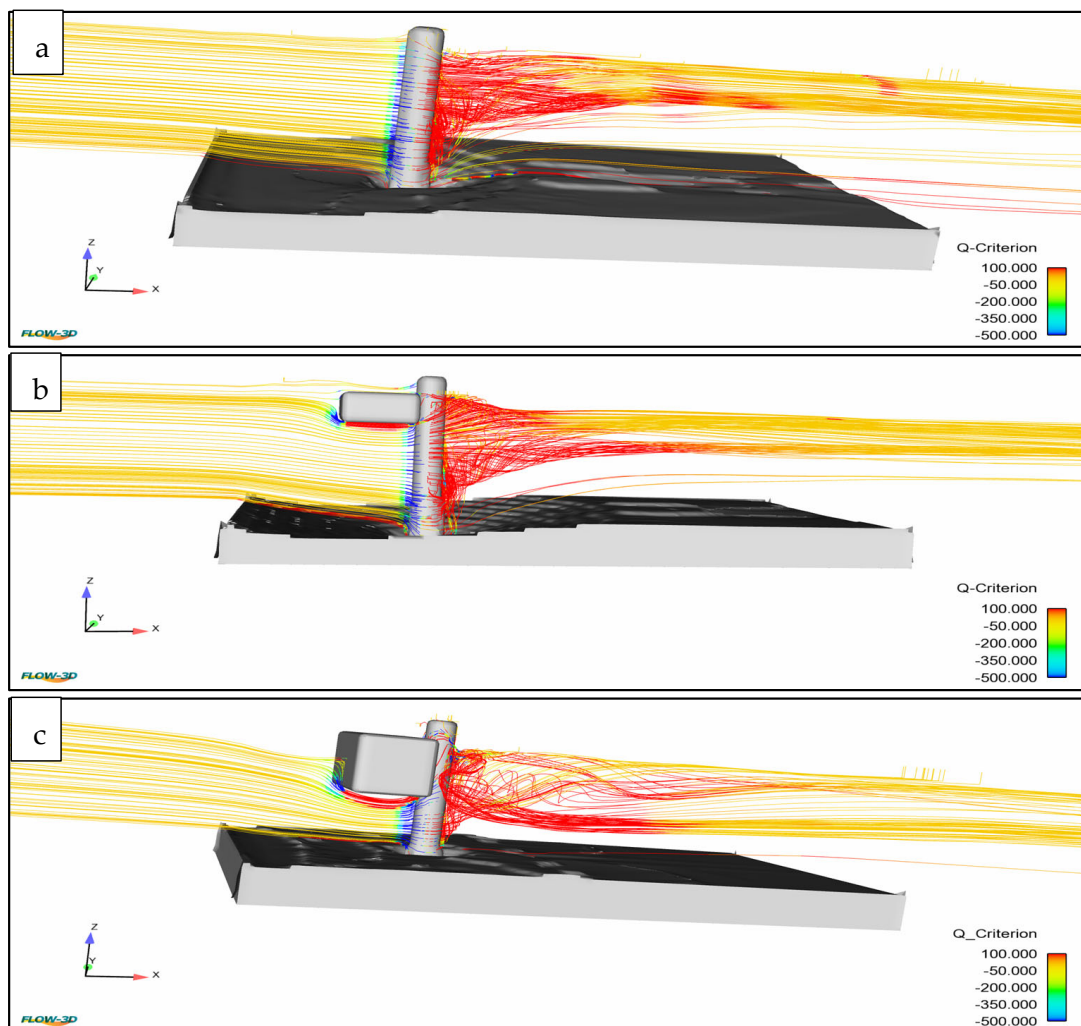


Figure 16. Q-criterion flow visualization around a cylindrical pier includes (a) without debris, (b) 3 cm thick rectangular debris, and (c) 6 cm thick rectangular debris.

Significant distinctions become apparent when comparing the cases of no debris, 3 cm debris, and 6 cm debris. The magnitude and extent of vortices, as measured by the Q-criterion, increase with the size of the debris. An increased debris size leads to elevated and broader Q-value areas. Debris significantly alters the flow route, creating extra areas

where the flow separates and reattaches, which are critical for assessing the likelihood of local scouring near the pier. Debris impacts the flow patterns behind the pier, resulting in more intricate and turbulent wake areas, which, in turn, has consequences for the stability and erosion patterns around the pier.

8.4. Verification of Numerical Results Using Experimental Data

The evaluation phase was commenced to verify and evaluate the findings and establish the margin of error between the flow-3D data and the experimental observations. The Nash–Sutcliffe Efficiency (NSE), the root mean squared error (RMSE), and the mean absolute percentage error (MAPE) were employed to test how well the numerical model worked with various types of debris, pier shapes (square and cylinder), and depth ratios (T/Y). The key metrics NSE, RMSE, MAPE, and R^2 are presented in Table 1 below.

Table 1. Performance metrics of flow-3D for square and cylindrical piers across different T/Y ratios.

Metric	Pier Shape	$T/Y = 0.25$	$T/Y = 0.5$
NSE	Square	0.168	−2.560
NSE	Cylinder	−1.555	−6.560
RMSE	Square	0.247	0.917
RMSE	Cylinder	0.590	1.238
MAPE	Square	6.79%	22.80%
MAPE	Cylinder	17.91%	32.32%
R^2	Square	0.65	0.86
R^2	Cylinder	0.34	0.84

When $T/Y = 0.25$, the square piers' NSE value of 0.168 indicates a modest correlation between the experimental and numerical data, suggesting that the model has a reasonable predictive capacity for square piers under these conditions. In contrast, the NSE score for cylindrical piers is −1.555, indicating a poor fit and that the numerical model struggles to accurately predict scouring depths for cylindrical piers with a reduced debris impact. The RMSE values further highlight these discrepancies, with square piers showing an RMSE of 0.247, indicating closer alignment with experimental data, while cylindrical piers have an RMSE of 0.590, pointing to more significant deviations. According to MAPE data, square piers exhibit a lower error rate of 6.79%, suggesting a better overall performance, whereas cylindrical piers have a higher error rate of 17.91%, reflecting the challenges in accurately modeling the scour for this geometry.

When examining the ratio $T/Y = 0.5$, the observed patterns for $T/Y = 0.25$ continue but with intensified differences. The NSE value for square piers decreases to −2.560, indicating a significant reduction in model reliability. In contrast, the NSE value for cylindrical piers drops further to −6.560, demonstrating a substantial incapability of the numerical model to accurately predict scouring depths under increased debris effects. The corresponding RMSE values for square and cylindrical piers are 0.917 and 1.238, respectively, which confirm the more significant deviations of the numerical results from experimental data as the debris impact increases. The MAPE values also reflect this trend, with square piers showing an error rate of 22.80% and cylindrical piers displaying a higher error rate of 32.32%, indicating substantial predictive challenges in both cases, though this is more evident for cylindrical piers.

Figure 17 supports a study of the flow-3D model's effectiveness in estimating scour depths for cylindrical and square piers at various T/Y . However, the coefficient of determination (R^2) values for square piers are much lower than those for cylindrical piers, suggesting that the model's ability to estimate scour depths for square-shaped piers accurately may be diminished. The flow-3D simulation provides more accurate scour depth

predictions for circular piers, especially when the T/Y ratio is 0.25, as measured by the R^2 values. However, it is essential to recognize that R^2 values alone provide a restricted view of the model's overall efficacy. Additional elements, such as the model's complexity and the size of the database, are critical for a thorough evaluation of the framework.

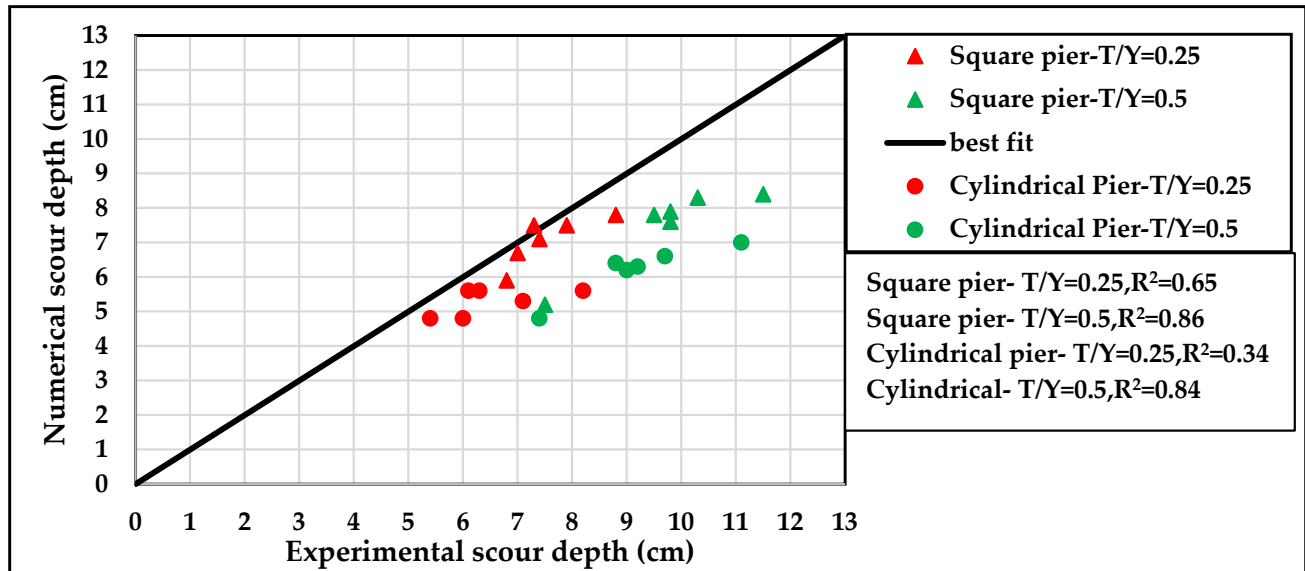


Figure 17. Assessing flow-3D's accuracy in predicting scour depths for cylindrical piers: a detailed examination at different (T/Y) ratios.

Although there is a strong correlation between numerical and experimental results for cylindrical piers, examining the variance distribution yields fascinating insights. The cylindrical pier, characterized by its rounded form, has a higher degree of inaccuracy because all data points fall outside the projected range. This disparity implies that effectively representing the intricate geometry with the existing mesh resolution may be difficult, emphasizing the need for more refinement. On the other hand, the square pier has a comparatively lower error rate of about 58.33%, regularly diverging from the expected data range because of its less complex design. This finding underscores the advantage of square pier designs in flow-3D simulations. The simple, straight-edged geometry of square piers makes mesh generation easier, improving the accuracy of scour predictions.

9. Conclusions

This study provides comprehensive insights into the dynamics of local scouring around different bridge pier shapes, encompassing both hydraulic implications and numerical evaluations of debris impact. The collective findings contribute essential knowledge to bridge pier design and scour mitigation. The results show the following:

1. **Pier Shape Influence:** The pier's shape is crucial in determining the scour depth. Among the pier shapes tested, square piers result in the deepest scour, with maximum depths reaching 5.8 cm, whereas lenticular piers exhibit the least scour, with a maximum depth of 2.5 cm. This indicates that angular pier shapes are more susceptible to severe scouring than more streamlined shapes.
2. **Impact of Debris:** Debris significantly modifies scouring patterns. At a debris-to-pier diameter ratio (T/Y) of 0.25, square piers undergo the highest scour depths, particularly with high wedge (HW) debris, due to the intensified vortex interactions. In contrast, lenticular piers show less scour. At $T/Y = 0.5$, the scour depth increases with the presence of debris, with variations up to 5 cm depending on debris shape. This highlights the critical role of debris in enhancing scouring around piers.

3. **Vortex Dynamics:** The study reveals that vortex formation—horseshoe, wake, and shear layer vortices—significantly determines scour patterns. Debris affects these vortices, increasing scour around less hydrodynamic pier shapes. The Q-criterion analysis revealed vortex formation and intensification due to debris.
4. **Numerical Simulation Accuracy:** The numerical simulations using flow-3D align reasonably well with experimental data under more straightforward conditions. However, discrepancies arise with complex debris interactions and higher debris submergence depths. Errors range from 6% for square piers with minimal debris impact to 32% for cylindrical piers with more significant impact. This indicates that while the simulations are helpful, they have limitations in accurately predicting scour under more complex conditions.
5. **Numerical Simulation validation:** The validation of numerical results using statistical metrics such as a Nash–Sutcliffe Efficiency (NSE) of 0.85, root mean squared error (RMSE) of 0.92 cm and mean absolute percentage error (MAPE) of 5.6% confirmed the model's robustness, especially for cylindrical piers. However, some discrepancies were noted for square piers at higher submergence levels, indicating potential areas for further refinement in numerical modeling techniques.

10. Practical Implications and Limitations

10.1. Practical Implications

The study highlights the importance of the pier shape in reducing scouring depths, with lenticular and elliptical designs proving more effective than square piers. This insight is valuable for selecting pier geometries that minimize scour risks, leading to safer and more durable bridges. Advanced simulation tools like flow-3D enhance the precision of predicting high-scour areas around piers. This capability enables targeted maintenance efforts, reducing the need for costly repairs and significantly improving bridge safety. The research also provides insights into vortex patterns around different pier shapes, informing the development of more efficient scour protection techniques, such as optimized collars, riprap, or scour aprons suited to specific hydraulic conditions. Debris impact is another critical factor, especially for cylindrical piers. The findings suggest that pier designs which are less vulnerable to debris-induced scour should be considered in areas prone to debris, or additional protective measures should be implemented. Overall, the practical application of flow-3D underscores the value of cutting-edge simulation tools in bridge design, allowing for the detailed analysis of hydraulic behaviors and contributing to safer and more informed engineering decisions.

10.2. Limitations and Future Research

While flow-3D provides valuable insights, its accuracy is influenced by factors such as turbulence models and mesh resolution. The discrepancies between computational and experimental results, particularly for cylindrical piers, highlight the need for further model refinement. The study reveals a significant variation in the estimation of scour across different debris types. Enhancing the modeling of debris interactions with piers in future research will be crucial for improving the accuracy of scour predictions. Differences in sediment entrainment thresholds between numerical and experimental methods suggest the need for more precise modeling techniques. Incorporating advanced turbulence models or alternative sediment transport equations could improve accuracy. Current research focuses on a limited range of pier and debris geometries, with numerical simulations conducted over varying time intervals to capture the progressive development of scour depth. Varying the simulation time for each case allows for a more accurate assessment of how scouring evolves over time around different pier shapes (cylindrical and square) and under the influence of different debris shapes, providing insight into both short-term and long-term effects. Expanding future studies to include a broader spectrum of geometries, including complex or hybrid designs, would provide a deeper understanding of scour performance. While the research relies on numerical simulations and laboratory tests, field

validation in real-world conditions would be beneficial to confirm the findings' applicability and enhance the model's predictive capabilities.

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