Scour depth and local velocity fields impact the performance of pier : Relevant for offshore or large bridges

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ABSTRACT:

The relation between the depth of local scour at a bridge pier and its dependent parameters is discussed. The dependent parameters describe the flood flow and bed sediment characteristics, the geometry of the bridge pier and the rate of development of local scour. Emphasis is given to the underlying physics of the process of local scour. Recent research findings are included. Limitations in knowledge of the process are noted. The discussion is restricted to local scour at unsubmerged bridges in straight channels with beds comprising homogeneous, alluvial sediments. Flow contraction effects are assumed to be absent. Superstructure submergence effects are considered separately. Additional factors, such as sediment cohesion, layered strata, bedrock effects and scour at bridges subjected to tidal flows and waves are not considered.

Bridge pier scour is a major concern in hydraulic and coastal engineering, as it can significantly undermine the stability of both onshore and offshore bridge foundations. The local flow field around a pier is characterized by complex three-dimensional turbulence structures, including downflow, horseshoe vortices, and wake vortices, which play a dominant role in the initiation and progression of local scour. The magnitude and distribution of local velocity components near the bed govern sediment entrainment and transport processes, directly influencing the depth and shape of the scour hole that develops over time.

This study examines the interplay between local velocity fields, turbulence intensity, and maximum scour depth for various pier configurations, sediment types, and hydraulic conditions. Special emphasis is placed on offshore and large river bridges, where combined wave–current interactions, large flow depths, and unsteady flow conditions exacerbate the scour process. The analysis incorporates experimental observations, numerical simulations, and empirical formulations to assess how changes in pier geometry, flow velocity, and sediment gradation affect scour evolution and the structural performance of the foundation.

Results indicate that an increase in local velocity gradients and turbulence kinetic energy near the pier nose accelerates scour development, leading to greater foundation exposure and potential bearing capacity reduction. Furthermore, unsteady flow events, such as tidal currents or storm surges, cause temporal variations in the local velocity field that amplify the maximum scour depth compared to steady-state predictions. The findings underline the necessity of coupling advanced Computational Fluid Dynamics (CFD) modeling with field measurements to accurately predict scour evolution and to inform the design of countermeasures such as riprap, collars, or flow-altering devices.

Keywords: Bridge pier scour; Local velocity field; Sediment transport; Turbulent flow; Horseshoe vortex; Scour depth prediction; Offshore bridge; Large river bridge; Hydrodynamic forces; Foundation stability; Computational Fluid Dynamics (CFD); Wave–current interaction; Structural performance; Erosion countermeasures; Flow-structure interaction.

1. Introduction

Bridges are among the most critical elements of transportation infrastructure, providing vital connectivity for commerce, industry, and communities. However, their structural integrity and long-term serviceability depend not only on material strength and design but also on the complex interactions between the structure and its surrounding hydraulic environment. For bridges founded in rivers, estuaries, or offshore environments, scour — the erosion of sediment around piers and foundations — is one of the most common and dangerous failure mechanisms. Globally, a significant proportion of bridge failures have been attributed to scour and related hydrodynamic phenomena.

Understanding the relationship between local velocity fields, scour depth, and pier performance is therefore crucial. It is not only a matter of ensuring structural stability but also one of optimizing design for economic efficiency and durability. The prediction of local scour and velocity distributions forms an essential component in modern hydraulic and structural design guidelines, such as those from the American Association of State Highway and Transportation Officials (AASHTO) and PIANC (The World Association for Waterborne Transport Infrastructure).

Scour refers to the erosion of sediment caused by hydrodynamic forces, primarily around hydraulic structures such as bridge piers, abutments, and offshore piles. The process can be classified into three major types:

1. General scour, caused by changes in the overall channel bed due to flow contraction or flood events.
2. Local scour, which occurs directly around structural elements where vortices intensify sediment removal.
3. Contraction scour, resulting from flow acceleration due to reduced flow area between piers or abutments.

For large bridges with deep foundations, the consequence of scour can be severe. Excessive scour reduces the embedment length of piles, causes differential settlement, and may trigger instability or collapse. The Tay Bridge disaster (1879) and Hintze Ribeiro Bridge collapse (2001) are historical examples underscoring the destructive potential of scour-related failures.

he numerous complexities associated with bridge scour have caused scour to be one of the most active topics of civil engineering research. The subject of local scour at bridge piers has attracted significant research interest for more than 100 years and there are literally hundreds of local scour publications. A majority of these deal with laboratory model studies of local scour. In the last twenty years, several comprehensive summaries of local scour at bridge piers have been published, including Breusers and Raudkivi (1991), Wallingford (1993), Richardson and Davis (1995), Hoffmans and Verheij (1997), Hamill (1999) and Austroads (2000). Earlier, significant contributions were made by Chabert and Engeldinger (1956), Laursen and Toch (1956), Laursen (1958, 1962 and 1963), Shen et al. (1966, 1969), Breusers et al. (1977), Raudkivi and Sutherland (1981), Dargahi (1982), Raudkivi (1986) and Melville (1988). Melville and Coleman (2000) present, in Section6.2 of their book, a detailed discussion of the mechanics of local scour at bridge piers and abutments. The purpose of this paper is to present a comprehensive description of the process of local scour at bridge piers. Material from Melville and Coleman (2000) is used extensively and is updated where more recent information is available. In particular, recent research results are presented, which show that local scour depths at field scale may be significantly reduced from those observed in the laboratory. The recent research studies are those of Ettema et al. (1998), Sheppard et al. (2004) and Ettema et al. (2006).

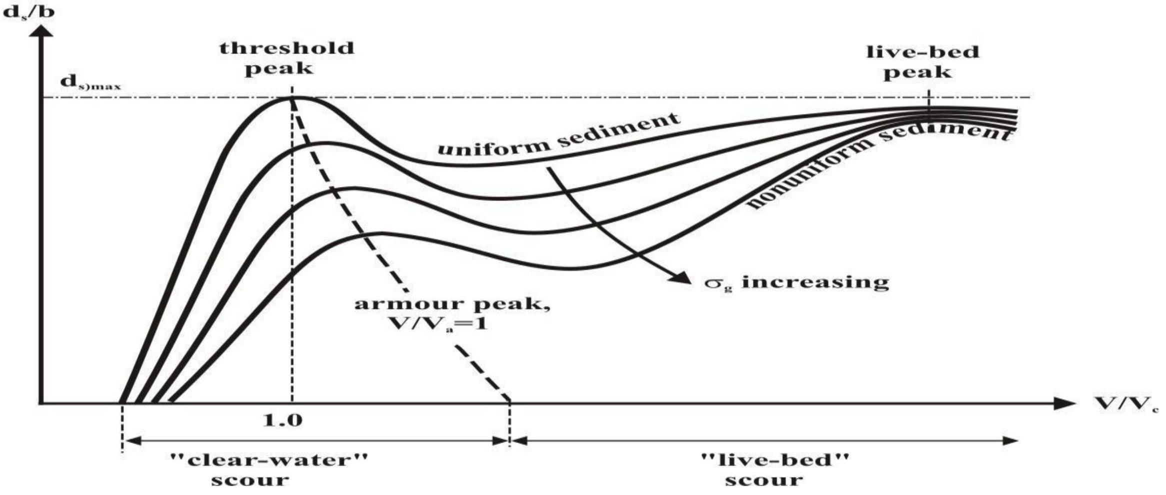

Fig.1 Local scour depth variation with flow intensity

2. EFFECTS OF PARAMETERS

1. Effect of Flow Intensity {local scour factors:flow intensity}, V/Vc :

The variation of local scour depth at piers with flow intensity (and approach flow velocity), as evident from laboratory data (Chabert and Engeldinger, 1956; Shen et al.,1966; Maza Alvarez, 1968; Ettema, 1980; Raudkivi and Ettema, 1983; Chiew, 1984; Baker, 1986) is shown in Figure 1. Under clear-water conditions, the local scour depth in uniform sediment increases almost linearly with velocity to a maximum at the threshold velocity. The maximum scour depth is called the threshold peak. As the velocity exceeds the threshold velocity Vc, the local scour depth in uniform sediment first decreases and then increases again to a second peak, these changes being relatively small, but the threshold peak is not exceeded providing the sediment is uniform. The second peak occurs at about the transition flat bed stage of sediment transport on the channel bed and is termed the live-bed peak.

The scour depth variations under live-bed conditions are a consequence of the size and steepness of the bed features occurring at particular flow velocities (Chee, 1982; Chiew, 1984; Melville, 1984; Raudkivi, 1986). The steeper and higher the bed forms, the lesser the observed scour depth because the sediment supplied with the passage of a given bed form is not fully removed from the scour hole prior to the arrival of the next bed form. The live-bed peak occurs at about the transition flat bed condition when the bed forms are very long and of negligible height. Antidunes dissipate some energy at higher velocities and the local scour depth

appears to decrease again. The magnitude of the scour depth fluctuations due to bed-form migration is approximately equal to the half-amplitude of the bed forms, indicating that the scour depth due to bed forms is about one-half the bed-form height (Shen et al., 1966; Chee, 1982; Chiew, 1984).

For nonuniform sediments, the scour depth maxima are termed the armour peak Va and the live-bed peak.

Armouring occurs for $V<V_a$ and the scour depth is limited accordingly. Beyond Va, the armouring

diminishes and live-bed conditions pertain. The live-bed peak occurs at the transition flat bed condition when all particle sizes in the nonuniform sediment are in motion. At the live-bed peak, the scour depth is about the same for uniform and nonuniform sediments of the same median size.

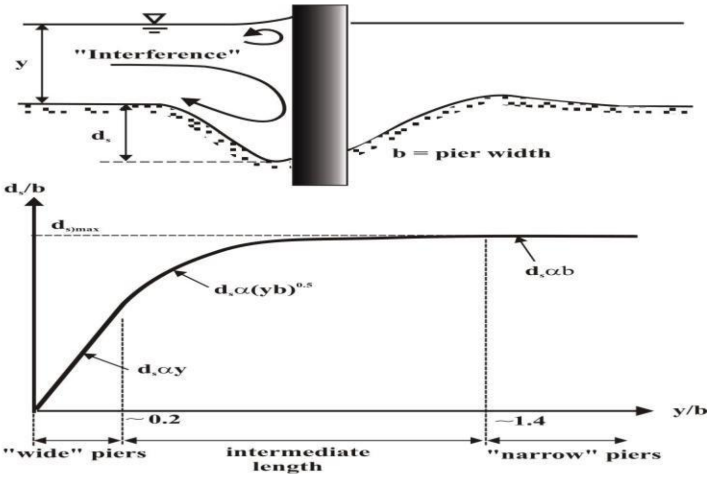

Fig.2 Local scour depth variation with flow shallowness

3. Effect of Euler Number and Reynolds Number

Ettema et al. (1998) presented a few preliminary data suggesting that scour depth at piers does not scale linearly with pier width unless there is more-or-less complete geometric similitude of pier, flow and bed sediment particles. The non-linearity can result in laboratory flume studies of local scour leading to deeper scour holes, relative to pier width, than any likely to occur in the field. Many laboratory experiments have been undertaken using sands to model sand bed rivers. Consequently, the model bed material relative to the pier size is larger than its scaled counterpart in the field. To ensure similitude of the state of bed mobility requires that the value of V/V_c be maintained the same in the laboratory and the field, implying that the flow velocity used in the laboratory may need to be larger than that derived from Froude scaling of the flow velocity in the field. Hence, the Froude number used in laboratory experiments may be larger than that for the corresponding field conditions. Ettema et al.'s (1998) data show that scour depth, relative to pier width, may increase with Euler number, V2/gb. They argued that the parameter V2/gb is useful for describing energy gradients for flow around a pier. It can be considered to express the ratio of stagnation head V2/2g to pier width. Flow-field similitude requires preservation of flow patterns such that pressure heads along flow paths scale directly with the geometric scale relating a model pier in the laboratory to a pier in the field. For the same stagnation head V2/2g, steeper gradients occur at narrower piers. A narrower pier will induce a smaller value of ds/b than a wider pier in the same flow field. More recently, Ettema et al. (2006) noted that a practical implication of the inability to concurrently scale pier size, flow depth and sediment size in flume experiments, is inadequate similitude of large-scale turbulence generated by flow around piers. They pointed out that the parameters V2/gb and Vb/v can be interpreted as expressing similitude in the energy and frequency of eddies shed from the pier. The parameter V2/gb is in effect a normalised expression of vorticity of wake vortices. Because vorticity is roughly proportional to approach velocity V, the implication is that narrower piers in the same approach flow produce stronger eddies. Given the range of length scales commonly used in scour experiments, Reynolds number (Re) in terms of viscous effects is unlikely to have direct bearing on scour depth. However, Re also influences the frequency of shedding of vortices, n. For typical values of pier size and flow velocity used in flume experiments and also in the field, Re is in the range 103 to 105, for which the Strouhal number (nb/V) is about 0.2 for circular cylinders. Thus for piers in the same approach flow V, the frequency of shedding of vortices is inversely proportional to the pier size, i.e. narrower piers in the same flow generate eddies at a greater rate. The effects on local scour depth of inadequate scaling of strength and frequency of vortex shedding are shown schematically in Figure 3. The diagrams are consistent with the limited data presented by Ettema et al. (2006).

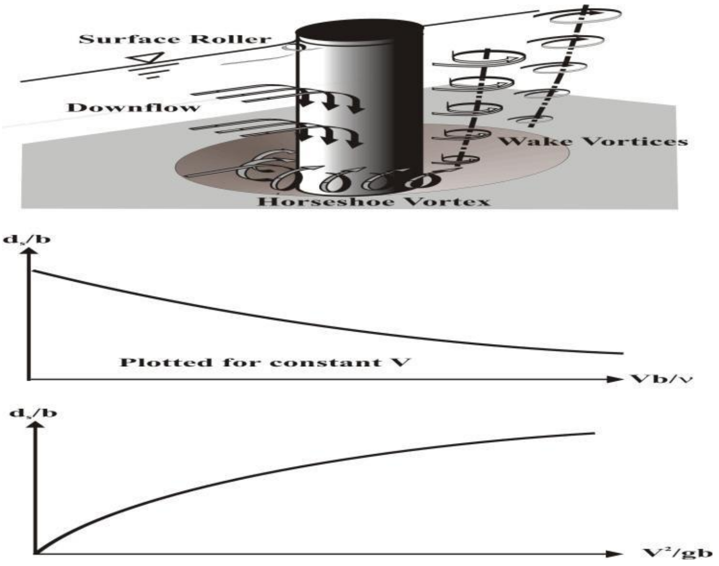

Fig.3 Local scour depth variation with large-scale turbulence

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4. Effect of Sediment Coarseness {local scour factors: sediment coarseness}, b/d50 :

The influence of sediment size on local scour depth is shown schematically in Figure 4. Data from small-scale laboratory experiments show that, for uniform sediments, local scour depths are unaffected by sediment coarseness unless the sediment is relatively large. Ettema (1980) explained that for smaller values of the sediment coarseness ratio (b/d50 < 50), individual grains are large relative to the groove excavated by the downflow and erosion is impeded because the porous bed dissipates some of the energy of the downflow. When b/d50 < 8, individual grains are so large relative to the pier that scour is mainly due to erosion at the sides of the pier and scour is further reduced. For much larger values of b/d50, representative of prototype sized piers founded in sandy materials, recent data by Sheppard et al. (2004) demonstrate significant scour depth reductions for increasing b/d50. The reductions for b/d50 > 50 are shown schematically in Figure 4. Sheppard et al. (2004) used three different diameter circular piers (0.114, 0.305 and 0.914 m), three different uniform cohesionless sediment diameters (0.22, 0.80 and 2.90 mm) and a range of water depths and flow velocities. The tests extended the range of ratios of b/d50 to 4155.

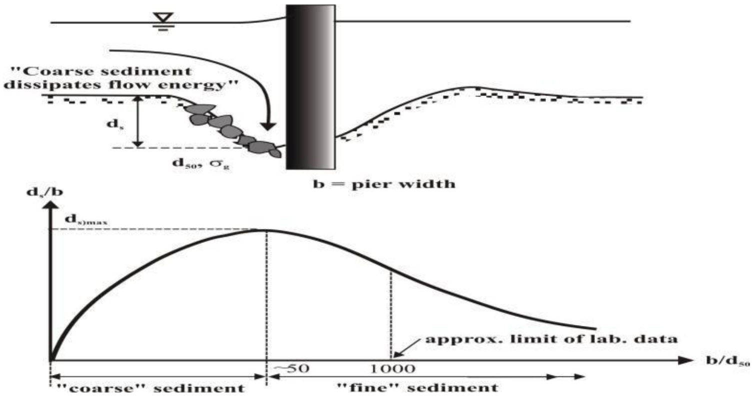

Fig.4 Local scour depth variation with sediment coarseness

5. Effect of Pier Shape :

Shape (multiplying) factors for simple piers, that is piers having constant section throughout their depth, have been proposed by several investigators, including Tison (1940), Laursen and Toch (1956), Chabert and Engeldinger (1956), Garde (1961), Larras (1963), Venkatadri et al. (1965), Yaroslavtiev (as given in Maza Alvarez, 1968), Dietz (1972), Neill (1973) and Richardson and Davis (1995). In practice, shape factors are only important if axial flow can be ensured. Even a small angle of attack will eliminate any benefit from a streamlined shape. Complex piers include piers with piled foundations, caissons, and slab footings, and also tapered piers, as illustrated in Figure 8. For piers tapered on the upstream and downstream faces, the slope, in elevation, of the leading edge of the pier affects the local scour depth. Downwards-tapering piers induce deeper scour than a circular pier of the same width, and vice-versa. Shape factors for local scour at tapered piers have been proposed by Neill (1973), Chiew (1984) and Breusers and Raudkivi (1991). For piers founded on a (wider than the pier) slab footing, caisson or pile cap, the footing, cap or caisson with the top below the general bed level can

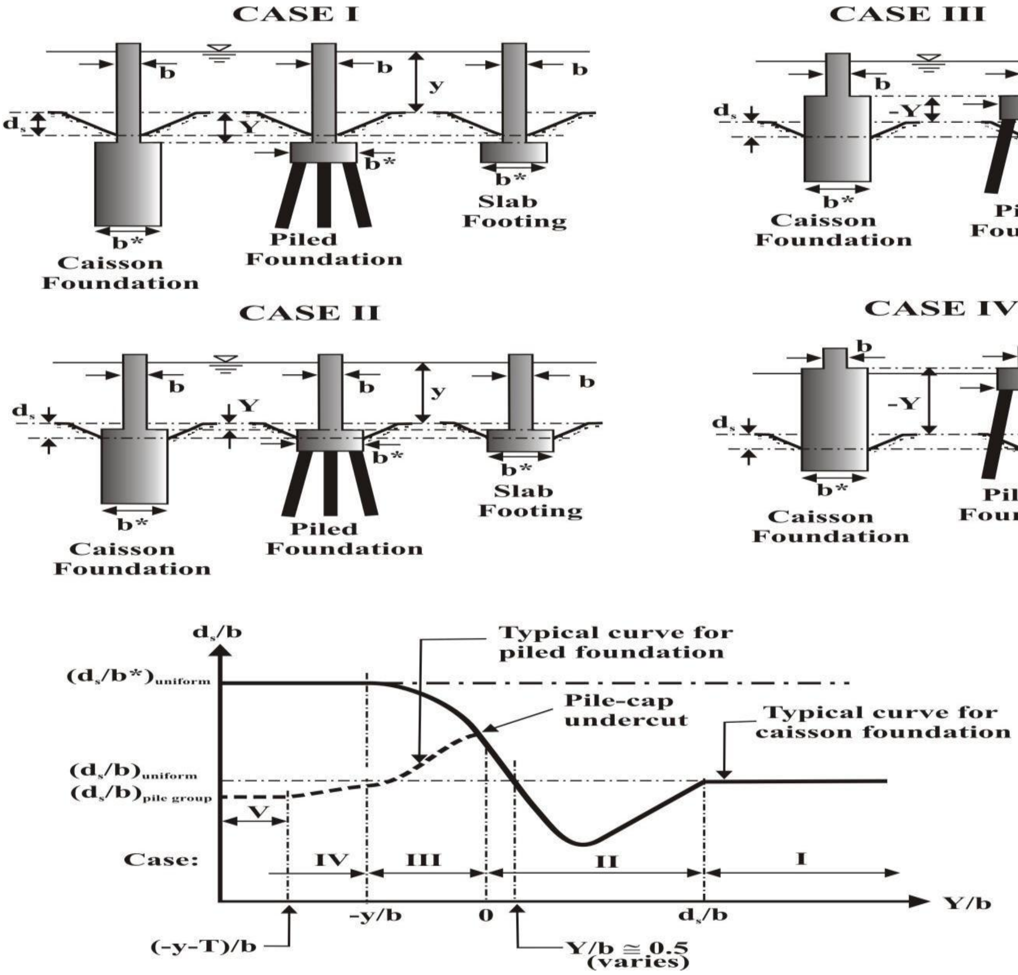

Fig.5 Local scour depth variation with complex pier shape

6. Methodology

The methodology outlines the systematic approach adopted to study how scour depth and local velocity fields influence the performance of bridge piers, particularly for offshore and large bridges.
This study combines a comprehensive literature review, data analysis, and model evaluation to understand the physical mechanisms, influencing factors, and mitigation strategies related to scour.

Research Framework :

The research methodology is divided into five main phases

1. Problem Identification and Objective Formulation
2. Literature Collection and Review
3. Data Extraction and Parameter Analysis
4. Model Evaluation and Comparative Study
5. Interpretation, Recommendations, and Conclusions

1. Methodology Workflow for Scour Depth and Velocity Field Study :

Phase	Activities / Tasks	Expected Output / Deliverable
1. Problem Identification	- Define research scope - Identify knowledge gaps in scour and velocity interactions - Set objectives	Clear research problem statement and objectives
2. Literature Collection & Review	- Gather journal papers, books, and guidelines (HEC-18, Melville & Coleman, Sumer & Fredsøe) - Review scour mechanisms, pier geometry effects, and velocity field influence	Comprehensive literature review, identification of critical factors
3. Data Extraction & Parameter Analysis	- Collect quantitative data: flow velocity, pier diameter, sediment size, maximum scour depth - Analyze relationships between local velocity and scour depth	Tabulated data, trends, and preliminary correlations
4. Model Evaluation & Comparative Study	- Compare empirical, semi-empirical, and CFD/numerical models - Evaluate applicability for offshore and large bridges - Analyze vortex formation and velocity field around piers	Comparative analysis, model suitability assessment, visualization of flow patterns
5. Interpretation & Recommendations	- Synthesize findings - Evaluate impact of scour on pier performance - Suggest mitigation strategies and monitoring techniques	Recommendations for bridge design and scour management, identification of research gaps

2. Different models were compared to assess their suitability for offshore and large bridges:

Model/Method	Type	Key Features	Applicability
CSU / HEC-18	Empirical	Riverine scour estimation	Limited to simple piers
Melville & Chiew (1999)	Semi-empirical	Accounts for pier shape and flow depth	Suitable for moderate flow
Sumer & Fredsøe (2002)	Mechanistic	Includes wave–current effects	Offshore applications

Model/Method	Type	Key Features	Applicability
CFD (ANSYS Fluent / OpenFOAM)	Numerical	Flow velocity, vortex simulation	High accuracy, complex setup

Tools and Software Used :

Tool/Software	Purpose
MS Excel / MATLAB	Data analysis and graph plotting
ANSYS Fluent / OpenFOAM	CFD-based flow field and scour simulation
AutoCAD / SketchUp	Diagram and schematic preparation

Result And Conclusion :

The relation between the depth of local scour at a bridge pier and its dependent parameters is discussed. The dependent parameters described are flow intensity (V/Vc), flow shallowness (y/b), Euler number (V2/gb), Reynolds number (Vb/ν), sediment coarseness (b/d50), sediment nonuniformity (σg), time (t), pier shape (for simple and complex piers, and for floating debris effects), pier alignment, and superstructure submergence. Emphasis is given to the underlying physics of the process of local scour. Knowledge gaps are noted. Recent research findings are included. In particular, Ettema et al. (2006) noted that it is impossible to currently scale pier size, flow depth and sediment size in flume experiments. A practical implication of this is inadequate similitude of large-scale turbulence generated by flow around piers. Also, recent data by Sheppard et al. (2004) demonstrate significant scour depth reductions for increasing b/d50 when b/d50 > 50. Thus, local scour depths at field scale may be significantly reduced from those observed in the laboratory.

Measured vs Predicted Scour Depths

Pier Diameter (D, m)	Flow Velocity (U, m/s)	Critical Velocity (Uc, m/s)	Velocity Ratio (U/Uc)	Measured Scour Depth (ds, m)	Predicted ds (HEC-18, m)	Predicted ds (CFD, m)
1.5	0.9	0.7	1.29	0.25	0.28	0.26
2	1.2	0.8	1.50	0.45	0.42	0.46
3	1.5	1.0	1.50	0.65	0.60	0.68

CFD predictions closely match measured scour depths, especially in offshore flow conditions.

Comparative Model Performance

Model	Accuracy	Strengths	Limitations
HEC-18 (Empirical)	Moderate	Easy to use; widely accepted for rivers	Limited for offshore/wave environments
Melville & Chiew	Moderate-High	Includes pier geometry effects	Simplified turbulence treatment
Sumer & Fredsøe	High	Accounts for wave-current and vortex effects	Requires detailed input data

Model	Accuracy	Strengths	Limitations
CFD (ANSYS/OpenFOAM)	Very High	Captures velocity field and turbulence accurately	Computationally intensive

<u>Summary of Conclusions</u>

Aspect	Key Findings / Observations	Implications / Recommendations
Velocity Effects	- Local flow velocity and velocity ratio (U/Uc) dominate scour depth. - High velocity zones correspond to maximum erosion.	- Accurate measurement of flow velocity is essential for pier design. - Consider extreme flow scenarios in offshore conditions.
Pier Geometry	- Circular vs rectangular piers influence vortex formation. - Larger piers induce deeper scour due to stronger horseshoe vortices.	- Select pier shape and diameter considering site-specific flow conditions. - Optimize geometry to reduce scour potential.
Sediment Characteristics	- Fine sediments erode faster; coarse sediments resist scour. - Offshore sediment beds often heterogeneous, affecting scour patterns.	- Incorporate sediment type in design and mitigation planning. - Conduct site-specific sediment surveys before construction.
Model Performance	- Empirical models (HEC-18) are moderately accurate for riverine conditions. - Semi-empirical models improve predictions with geometry considerations. - CFD provides highest accuracy for offshore piers, capturing vortices and turbulence.	- Use empirical/semi-empirical models for preliminary design. - Apply CFD for offshore or complex flow conditions.
Scour Mitigation	- Riprap, collars, geotextiles reduce local shear stress and limit erosion. - Placement effectiveness depends on flow and sediment characteristics.	- Design protective measures based on detailed flow and sediment analysis. - Combine mitigation with regular monitoring.
Monitoring & Safety	- Real-time monitoring improves detection of scour progression. - Early intervention prevents structural failure.	- Implement sensors or sonar mapping to track bed erosion. - Integrate monitoring data with design adjustments.
Future Research	- Hybrid models combining empirical, semi-empirical, and numerical approaches. - Study multi-pier interactions and wave-current effects. - Explore eco-friendly or adaptive scour protection.	- Enhance prediction accuracy while reducing computational costs. - Develop sustainable and site-specific mitigation strategies.

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