Numerical Modelling for Scour Near Cofferdams Using Eulerian Two-Phase Flow Model

Nishchay Tiwari(✉), Michiel Knaapen, Sina Haeri, and Richard Whitehouse

HR Wallingford, Howbery Park, Wallingford OX10 8BA, UK
n.tiwari@hrwallingford.com

Abstract. Cofferdams play a vital role in water-based construction projects, offering a secure environment by isolating structures from water. However, scour around cofferdams poses significant risks to structural stability, necessitating accurate predictions to guide design and mitigate construction costs. Traditional methods for estimating scour, primarily based on physical experiments and empirical formulas, often fail to capture the complexities of sediment-water interactions. This study presents a Computational Fluid Dynamics (CFD) model using a two-phase Eulerian approach to simulate scour around cofferdams.

The model, implemented in OpenFOAM v2012, integrates advanced intergranular stress models - Kinetic Theory of Granular Flows and μ(I) rheology providing accurate representations of sediment transport under varying flow conditions. Simulations were conducted to analyze the impact of cofferdam geometry and flow velocity on scour depth and sediment dynamics. Results were validated against experimental data from HR Wallingford's General Purpose Flume, demonstrating the model's reliability in predicting scour depths.

Key findings indicate that scour depth is highly influenced by local hydrodynamics controlled by the shape of the structure, highlighting the importance of precise modeling in designing resilient cofferdam structures. This research advances the state-of-the-art in scour prediction by bridging experimental observations with robust numerical methods.

Keywords: Cofferdam Scour · Two-Phase Eulerian Model · Sediment Transport · Computational Fluid Dynamics (CFD) · Hydrodynamic Modeling

1 Introduction

Construction in rivers and estuaries often requires cofferdams to create dry work areas. These temporary structures, typically rectangular for ease of installation, are prone to significant scouring due to water flow and turbulence [1]. Scour effects are notable when cofferdams protrude into waterways or estuarine areas, altering flow patterns and increasing sediment displacement. Studies on local scour around structures like bridge abutments and piers have provided insights into flow acceleration, turbulence, and sediment entrainment [2–4]. However, physical models are inherently limited in capturing the

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complexity of sediment-water interactions under varied flow regimes and non-uniform sediment. These limitations, coupled with practical constraints, highlight the need for advanced simulations.

This study employs a Computational Fluid Dynamics (CFD) model using a Two-Phase Eulerian approach to better simulate sediment-water dynamics and enhance scour prediction accuracy.

2 Numerical Modelling

2.1 Baseline Experimental Case

The baseline configuration utilized an experimental setup designed to study scour around cofferdam structures, employing a General Purpose Flume with dimensions of 25 m in length, 2.4 m in width, and 0.9 m in depth, situated at HR Wallingford [4].These flume experiments were designed to explore the effects of cofferdam geometry, flow conditions, and sediment mobility on scour development. Cofferdams of various shapes, including rectangular, triangular, and rounded designs, were tested. These structures were placed within a 0.5 m deep bed of well-sorted medium-grained quartz sand characterized by a grain size distribution of $d_{10} = 0.326$ mm, $d_{50} = 0.525$ mm, and $d_{90} = 0.673$ mm, with a uniformity coefficient of 1.8. The flow velocities varied between 0.15 m/s and 0.244 m/s, ensuring clear-water scour conditions, with sediment mobility confirmed via the threshold current velocity calculated using the Soulsby method. Scour and deposition patterns were captured using a terrestrial laser scanner to create three-dimensional bed elevation models, and tests ran for 50–75 h to allow the scour depth to stabilize (see Fig. 1). This experimental setup provided detailed insights into local scour depths and sediment deposition patterns under various flow and structure configurations.

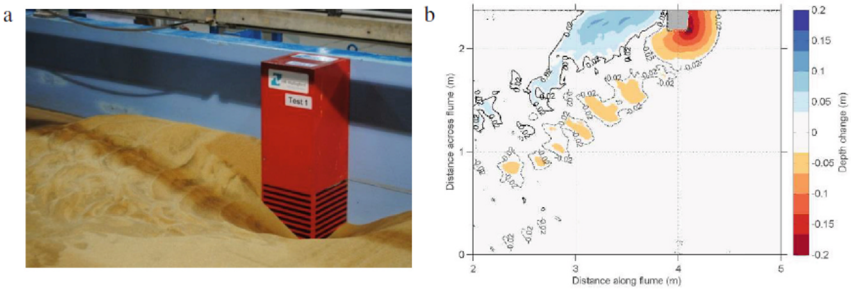

Fig. 1. Test results (flow from right to left); a. photograph of the post-test results (black and red graduations at 10mm spacing) and b. difference in bed elevation between start and end of test.

A baseline case employed for the Computational Fluid Dynamics (CFD) simulations, derived from the experimental setup, featured a flow velocity of 0.244 m/s, and an abutment with a cross-sectional dimension of 0.2m × 0.2m. This case serves as the reference scenario to analyze flow-induced scour dynamics around the structure under well-defined clear-water conditions.

2.2 SedFoam – Two Phase Eulerian Model for Sediment Transport

SedFoam is an advanced numerical framework for sediment transport modeling, built upon two-phase flow solver *twoPhaseEulerFoam.* It addresses the complexity of sediment transport phenomena by modeling sediment and fluid phases as interpenetrating continua, using Eulerian two-phase flow equations. SedFoam incorporates both the kinetic theory of granular flows and dense granular rheology $\mu(I)$ to simulate sediment stresses, enabling it to capture intricate sediment-water interactions such as particle collisions, turbulence modulation, and shear stresses [5]. The model supports laminar and turbulent flow regimes, with turbulence closures like k-ε and k-ω models for accurate representation of flow dynamics. This model is implemented in OpenFOAM v2012.

2.3 Computational Setup

A three-dimensional computational domain was constructed to replicate the experimental setup for studying scour around cofferdams (see Fig. 2). The domain incorporated the baseline cofferdam geometry and was discretized using the *snappyHexMesh* utility, producing a high-quality hexahedral mesh with approximately 2.5 million cells. To minimize the influence of boundary conditions on the flow and scour patterns, the domain was extended, maintaining a 4 m distance between the inlet and the cofferdam geometry and an equivalent distance between the cofferdam and the outlet. This ensured accurate simulation of the hydrodynamics and sediment transport phenomena near the structure.

The computational domain included sand in the lower section, defined using the *setFields* utility. Inlet conditions specified velocity, turbulent kinetic energy (k), and dissipation rate (ω), while Neumann conditions applied at the outlet, except for pressure with a Dirichlet condition. No-slip conditions were enforced on the walls. The *PISO* algorithm solved the equations, running on HR Wallingford's Hydra2 cluster for 3600 s, capturing time-dependent flow and sediment dynamics.

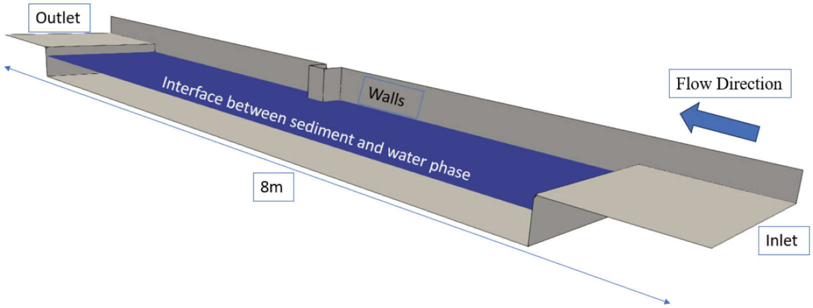

Fig. 2. Computational Domain representing the boundaries and interface between sediment and water.

3 Results and Validation

After 3600 s of simulation, postprocessing was conducted to analyze the results. A contoured surface was extracted based on the volume fraction field, delineating the interface between water and sediment. This interface effectively represents the sediment bedform, capturing the morphological changes in the sediment bed caused by scour and deposition. The extracted bedform provides a detailed representation of both scour depths and sediment accretion patterns around the cofferdam geometry, facilitating quantitative analysis of sediment transport dynamics and erosion near the structure (see Fig. 3).

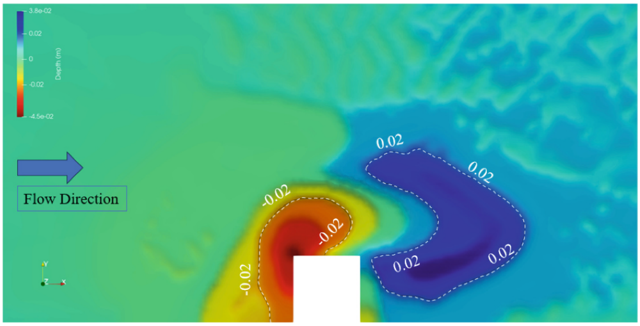

Fig. 3. Sediment bedform around Cofferdam after 3600 s representing Scour and Deposition using sedFoam

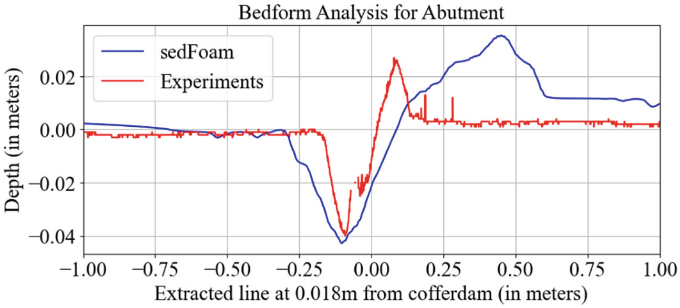

Fig. 4. Comparison of change in bed elevation near Cofferdam between SedFoam and experimental measurements after 3600 s.

Figure 4 presents a comparison between computational predictions using SedFoam and experimental measurements of bedform depth near a cofferdam over 3600 s, along an extracted profile. Both datasets capture the primary morphological changes, including a pronounced erosion zone near -0.15 m on the extracted line, reaching approximately -0.04 m in depth, followed by deposition. The computational model demonstrates acceptable agreement with experimental data, accurately replicating the overall trends of erosion and sediment recovery, with some deviations for accretion likely attributed to localized experimental variability and numerical approximations.

3.1 Comparison Between Cofferdam Geometries

Following the experimental validation, five more distinct structural configurations (see Fig. 5) were simulated at 0.17 m/s for 900 s, each yielding independent results to analyze local scour patterns. The varying structural shapes were designed to study specific scour effects: Structures. A and B examined the impact of increased length parallel to the flow, while Structures C and D explored how changes in planform geometry influenced scour behavior. Structure E investigated the effects of lateral expansion by increasing the width of Structure B, and Structure F analyzed the scour characteristics of a pier, identical to Structure A, which had been positioned adjacent to a wall.

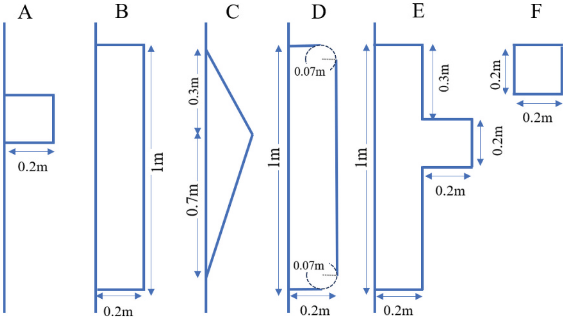

Fig. 5. The cofferdam configurations used in the model experiments are shown. For all structures (A to F), the wall is positioned on the left side. The length of each structure is defined as the dimension extending parallel to the wall, while the width represents the extent to which the structure projects outward from the wall.

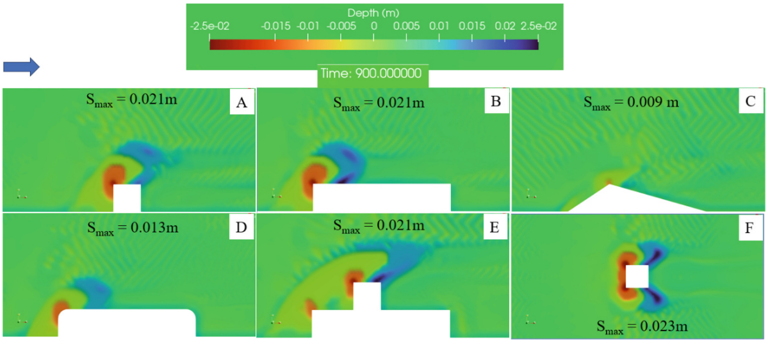

Fig. 6. Scour patterns and Maximum Scour Depth (Smax) for different Cofferdam geometries.

Figure 6 presents simulated scour patterns for the six cofferdam geometries (A to F) under uniform flow conditions, with variations in maximum scour depth (S_{max}). Geometry A, a simple rectangular shape, exhibits moderate scour with an S_{max} of 0.021 m. Geometry B, which increases length along the flow direction, shows a similar S_{max} of

0.021 m, indicating minimal effect from the length extension. Geometry C, with a triangular design, significantly reduces scour to an S_{max} of 0.009 m due to its streamlined shape minimizing flow disturbances. Geometry D, featuring curved edges, mitigates concentrated flow effects at the corners, resulting in a reduced S_{max} of 0.013 m compared to Geometry A. In contrast, Geometry E, a wider and more complex structure, not only matches Geometry A's S_{max} of 0.021 m but also introduces additional zones of scour. These multiple scour regions likely result from increased turbulence and secondary flow separations caused by the complex geometry. Geometry F, a freestanding pier-like structure, experiences the highest S_{max} of 0.023 m due to unrestricted vortex formation around the base, which intensifies local scour.

4 Conclusions

This study demonstrates the effectiveness of a CFD model using the two-phase Eulerian approach to predicts sediment scour around cofferdams. Incorporating advanced sediment transport framework like SedFoam, the model accurately replicates complex sediment-water interactions and hydrodynamic conditions, validated against experimental data with reliable scour depth predictions. Comparative analysis highlights that streamlined, curved-edge designs reduce scour by minimizing flow disturbance, while wider, complex structures increase scour intensity. Freestanding piers show the highest scour due to unrestricted vortex formation. These findings underscore the need for optimized cofferdam designs to mitigate scour and enhance resilience, and illustrate the use of CFD as a robust tool for engineers to improve performance in diverse flow conditions.

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