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MULTI-SCALE CFD ANALYSIS OF EROSION DYNAMICS IN HETEROGENEOUS ROCKFILL STRUCTURES IMPLICATIONS FOR SUSTAINABLE HYDRAULIC ENGINEERING DESIGN

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ABSTRACT

Rockfill structures, such as gabion mattresses are widely used in hydraulic engineering applications to mitigate erosion and protect infrastructure. However, these structures are susceptible to erosion processes, both from upstream and downstream directions, which can compromise their integrity and effectiveness. This study employs computational fluid dynamics (CFD) simulations to investigate the complex flow patterns and erosion processes around rockfill structures. The study aims to quantify the effects of various factors, including the gradation of the rockfill material, and the characteristics of the flow passing through and over the structure, on the initiation and extent of bed erosion. The results provide valuable insights into the velocity distribution, turbulence kinetic energy, hydrostatic pressure, and bed morphology changes around these structures over time. Flow characteristics, such as velocity, turbulence intensity, and flow depth, played a crucial role in determining erosion patterns. High-velocity jets and recirculating flow patterns around the structures contributed to localized scour and sediment transport. Higher pressure regions were observed near structure crests, while lower pressure zones existed in the lee of structures. Elevated turbulence kinetic energy levels were found in regions of high flow velocity and intense mixing, enhancing bed erosion and sediment transport. The research emphasizes the critical roles of granulometry in both the rockfill material and the erodible bed, as well as the characteristics of flow passing through and over the structure. The findings underscore the importance of considering both the structural properties of the rockfill and the dynamic nature of the surrounding flow in ensuring the long-term stability and effectiveness of these erosion mitigation measures.

Keywords: Gabion dams, Scouring, Flow Pattern, CFD, FLOW3D

INTRODUCTION

Erosion and scour are closely related hydrodynamic processes that impact soil stability and sediment transport, particularly in the context of hydraulic structures and watersheds. Erosion is a broad term that refers to the gradual removal of soil, sediment, and rock by natural forces such as water, wind, and gravity. It occurs over large areas and is influenced by factors like rainfall, land use, and watershed conditions. Scour, on the other hand, is a localized and more intense form of erosion, typically occurring around hydraulic structures such as bridge piers, dam spillways, weirs, and riverbanks due to the high-energy action of flowing water. It is worth noting that erosion contributes to scour. For instance, watershed erosion increases sediment transport, depositing material downstream while exposing weaker soil layers, making structures more susceptible to scour. Furthermore, deforestation and land degradation in watersheds intensify runoff, accelerating erosion and increasing the sediment load in rivers, which in turn alters flow patterns that contribute to localized scour. Reservoir sedimentation caused by upstream erosion reduces dam capacity, altering flow velocities and increasing scouring forces at spillways and outlet structures. Bridge scour occurs when high-velocity water removes sediment around bridge foundations, leading to instability and potential structural failure. Weir and dam scour happens when turbulent flows erode the downstream bed, creating deep scour holes that compromise the integrity of hydraulic structures. Coastal erosion and scour interact in marine environments, where waves and currents erode shorelines and create scour pits around offshore structures. Experts in the field emphasize the critical necessity of thoroughly examining both processes. Understanding the relationship between general erosion and localized scour is essential for designing resilient hydraulic structures, preventing sedimentation issues, and ensuring long-term infrastructure stability. Numerical modeling (CFD), sediment transport analysis, and field monitoring are key tools used to predict and mitigate both erosion and scour effects.

Thus, erosion poses a significant threat to hydraulic structures, leading to severe consequences such as siltation of dams (Remini and Remini, 2003; Remini and Bensafia, 2016; Remini, 2010; Remini and Toumi, 2017; Remini, 2017; Toumi and Remini, 2020; Remini, 2022), unwanted density currents in dams (Remini and Maazouz, 2018), degradation of watersheds (Meguenni and Remini, 2008; Saidi et al., 2012; Meddi, 2015; Riahi et al., 2020), and instability of bridges. The progressive accumulation of sediment in reservoirs and dam basins reduces storage capacity (Benfetta et al., 2016; Shaikh et al., 2024), diminishing the efficiency of hydropower generation (Long et al., 2023; Verma et al., 2023), and water supply systems (Patel and Mehta, 2022; Pandey et al., 2022; Kouloughli and Telli, 2023; Berrezel et al., 2023). In watersheds, unchecked erosion accelerates soil degradation, disrupts natural drainage patterns, and exacerbates flood risks (Nezzal et al., 2015; Kouadio et al., 2018; Aroua, 2020; Benslimane et al., 2020; Ben Said et al., 2024). Additionally, the scouring of bridge foundations caused by sediment transport and water flow undermines structural integrity, increasing the likelihood of collapse (Ghasemi Asl and Heidarnejad, 2023; Dalal and Deb, 2024). Given these detrimental impacts, a comprehensive study of erosion dynamics is imperative to develop sustainable mitigation strategies, optimize sediment management, and ensure the long-term resilience of hydraulic infrastructure. Understanding erosion processes through advanced modeling, field investigations, and sediment control measures is essential for preserving water resources and maintaining the safety and functionality of vital hydraulic structures (Ansari et al., 2024).

To design these structures effectively, it is necessary to understand the complex flow patterns around them. Numerical modeling offers valuable insights. Computational fluid dynamics models (CFDs) can simulate flow and sediment transport and provide detailed details on depth and location of debris. A common CFD approach uses Reynolds-Averaged Navier Stokes equations combined with sediment transport equations. These models take into account turbulence to improve precision. The existing body of literature is abundant with scholarly works that offer comprehensive insights into the application of the Navier-Stokes equations across diverse hydraulic contexts, under Reynold's conditions (Lebdiri et al., 2020; Ghouini et al., 2024)

The numerical research, validated by real-world experiments, has shown how gabion size, spacing and arrangement affect scour patterns and their effectiveness as countermeasures (Chabokpour and Azamathulla, 2022; Chabokpour et al., 2024). Larger and closer gabions offer better protection. Furthermore, arrangements beyond a simple line arrangement, such as static or angle layouts, can be even more effective in high-flow conditions. Simulation of various scenarios makes numerical modeling a powerful tool for optimizing Gabion design. This optimization ensures the selection of appropriate gabion sizes, spacing and layout to minimize vibrations and protect structures. It can even assess long-term performance under different conditions of flow and sedimentation. This information can guide maintenance strategies and extend the life expectancy of gabion-protected structures (Chabokpour, 2020). Bahrami-Yarahmadi et al. (2020) investigated scour and deposition patterns around triangular and rectangular spur dikes in river channels, it was found that the triangular spur dikes result in smaller scour hole volumes and depths compared to rectangular ones. Flow pattern analysis reveals that both types divert upstream flow towards the channel center, but triangular spur dikes cause less velocity increase. The study also notes that sediment deposition occurs closer to the channel wall with triangular spur dikes, which can help stabilize river banks and create new ones, particularly along meander bends. Ramli et al. (2013) investigated the stability of gabion walls used in earth retaining structures, particularly in flood-prone areas where scouring and erosion pose significant risks to infrastructure like bridges. Their research focuses on improving gabion resistance against lateral movement by proposing an interlocking hexagonal design, as opposed to the conventional rectangular stack-and-pair system. Through simulations of lateral thrusts against both configurations, the study demonstrates that the interlocking hexagonal design exhibits superior structural integrity in resisting lateral movement. The investigators argue that this improved design warrants consideration as a more effective scour-arresting device for earth retaining structures, especially given that up to 60% of bridge failures are attributed to natural phenomena like flooding.

Karami et al. (2019) investigated the effectiveness of geostatistical methods for predicting scour patterns around hydraulic structures. They compared the accuracy of Inverse Distance Weighted (IDW), Ordinary Kriging (OK), and Bayesian Maximum Entropy (BME) using experimental data collected around abutments and spur dikes. The results indicate that OK and BME outperform IDW in estimating the maximum scour depth. Pagliara and Palermo, (2013) investigated scour at the foundations of low-head river restoration structures, such as rock grade control structures and stepped gabion weirs, which are designed to control sediment transport while minimizing environmental impact. The authors focus on the critical issue of toe stability, as scour at the structure's toe can lead to failure. Through detailed analysis, they developed relationships to estimate the scour depth at the toe of these structures, which closely approximates the maximum scour depth in the stilling basin, thereby providing a valuable tool for engineers to ensure the stability and hydraulic functionality of these eco-friendly alternatives to rigid concrete check dams.

Bagheri et al. (2024) stated that the progressive expansion of the scour hole can compromise the structural stability of a bridge. As a result, accurately predicting scour depth has become a fundamental practice in river engineering to implement effective mitigation measures. In this context, Bagheri et al. (2024) study examined the influence of perforated collars of varying geometries on scour formation around bridge piers. The findings reveal that scour depth is significantly reduced as the collar shape transitions from triangular to rectangular, demonstrating the effectiveness of optimized structural design in minimizing erosion.

The study by Amin et al. (2019) compares the hydraulic performance of gabion and reinforced concrete weirs using various parameters, finding that concrete weirs exhibit higher upstream sedimentation, downstream scouring, and water surface elevation, but lower discharge coefficients and seepage compared to gabion weirs. The authors conclude that while concrete weirs are more efficient in raising water levels, reducing seepage, and are more durable, they require better arrangements to control scouring and sedimentation, providing valuable insights for weir design and selection. The study of Riahi-Madvar et al. (2019) addresses a gap in the design methodology for detention rockfill dams by developing a novel framework that combines non-linear and non-Darcian flow equations through rockfill with hydrologic flood routing and hydraulic storage dam rules. Through 36,000 simulations, the authors investigate the effects of various parameters on flood peak reduction and provide a simple design equation (R2 = 0.996, MAE = 0.008, RMSE = 0.0041) for preliminary designing of these dams. The framework enables prediction of outflow hydrographs, determination of dam dimensions and rockfill characteristics, and provides a sound basis for sizing detention rockfill dams to reduce peak discharge, while acknowledging future research needs in areas such as permeability changes due to sediments and experimental validation.

Lashkarara et al. (2012) investigated local scour downstream of an inverted siphon on the Balaroud river, which acts like a grade control structure and has created a deep scour hole. Through field surveys and flow condition computations, the authors found that the Schoklisch formula reasonably predicts scour depth, providing valuable insights for managing scour around cross-river structures. The study emphasizes the importance of addressing scour, as the indirect costs of infrastructure damage can exceed direct repair costs, and proposes measures for river bed protection downstream of the inverted siphon.

Recent investigations have been conducted on the use of recycled materials in gabion mattresses to reduce bridge pier scour. Scour, a major cause of bridge failure, is expected to worsen due to climate change. The authors examine existing scour countermeasures and alternative materials. They perform a laboratory experiment using a flume channel with a bridge pier protected by gabion mattresses filled with stone, recycled clothing, or plastic. Stone is most effective, but recycled clothing shows promise as a sustainable, potentially cheaper alternative. However, further large-scale research is needed. Groyne design, used to prevent riverbank erosion, is complicated by scouring at the groyne's head due to flow changes. Ansary et al. (2019) addressed this by using Flow-3D software to simulate scour and flow patterns around innovative double-row groynes (zigzag and parallel) in a straight channel. The simulations replicate real-world experiments, providing a valuable tool for designing more efficient double-row groynes. The friction coefficients in flow through rockfill were also investigated in a large porous media of rockfill dams (Chabokpour and Amiri Tokaldany, 2017; Sedghi Asl et al., 2013).The focus of these studies is on how friction changes when sediment is present in the flow. The investigators compare existing methods for calculating friction coefficient and propose a new approach based on the Manning coefficient, which is more familiar to hydraulic engineers. Their findings show that sediment significantly increases friction and that their new method offers a more accurate way to estimate this friction in rockfill with or without sediment. Detention rockfill dams are cost-effective structures used for flood control. Their effectiveness depends on their ability to store water within their porous structure. To optimize dam design and prevent sediment build-up, predicting water flow through these dams is crucial. The study of Asiaban et al. (2015) proposes a new numerical model to simulate the water surface profile within layered rockfill dams. This model is based on the gradually varied flow equation and has been validated through laboratory experiments with various flow rates and materials. The model achieved a maximum relative error of 17.6%, demonstrating its accuracy in predicting water surface profiles. This information is valuable for flood control calculations, as it allows engineers to assess how efficiently the dam will store water during flood events. The study of Salmasi et al. (2023) investigates energy loss in gabion stepped spillways. The researches built physical models to examine how spillway design affects energy dissipation. They tested different factors including water flow rate, slope angle, presence of end sills on steps, and the size of rocks within the gabions. The results showed that higher flow rates and steeper slopes lead to less energy loss. Spillways built with larger rocks showed less impact from end sills compared to those built with smaller rocks. The study suggests that for spillways using small rocks, rectangular end sills are more effective at dissipating energy than inclined sills. Overall, the findings provide valuable insights for designing gabion stepped spillways that optimize energy dissipation. A flume study of Badpa et al. (2019) investigated how the angle of gabion spur dikes (rock enclosures) affects scour (riverbed erosion) around the structures. Vertical dikes caused more scour due to their effect on water velocity. Angled dikes, designed to deflect flow away from the opposite bank, generated turbulence but resulted in less scour compared to vertical dikes. This highlights the importance of considering gabion spur dike angle during design for optimal riverbank stabilization. Nayono et al. (2020) investigated the effectiveness of combining gabions and tetrapods for riverbank protection against scour. A laboratory flume experiment was conducted with different placement configurations of these structures. The results showed that both combinations reduced scour compared to unprotected sections. However, the gabion-tetrapod-gabion layout proved to be more effective, achieving a consistently lower average scour depth at all three-measurement points along the river bend. Stepped gabion weirs, rock-based structures, offer an eco-friendly alternative to traditional riverbank reinforcements. Their flexibility allows them to adapt to natural river conditions. This study investigates the impact of these weirs on water flow and scour (erosion) downstream. The research identifies two different flow patterns and explores how they influence scour development. The findings propose formulas to predict the maximum scour depth and length caused by these weirs. Overall, the study highlights stepped gabion weirs as a viable and potentially beneficial solution for river restoration projects (Jäger, 2018; Pagliara and Palermo, 2013). Pagliara and Palermo (2015) focused on scour, a major erosion problem below low-head structures used in river restoration. These structures, while beneficial for fish habitat and sediment control, can significantly alter river morphology. To minimize scour and its environmental impact, engineers consider various design factors. The chapter reviews recent research on predicting scour characteristics for different low-head structure types, including block ramps, rock grade control structures, and stepped gabion weirs. It explores how factors like stilling basin design and flow conditions (clear water vs live bed) influence scour patterns. Stilling basins help reduce the velocity and turbulence of water exiting hydraulic structures, thereby minimizing the erosive potential of the flow. Without proper energy dissipation, high-velocity flows can lead to excessive scour, undermining foundations of spillways, weirs, bridges, and embankments. By reducing the kinetic energy, a well-designed stilling basin mitigates the shear stress on the riverbed, preventing excessive sediment removal and local scour. Proper basin length and depth ensures adequate dimensions to allow complete energy dissipation before water exits into the downstream channel. Baffle blocks and end sills are often used inside the stilling basin to create hydraulic jumps, enhancing energy dissipation and reducing flow velocity. Placing resistant materials downstream, such as riprap or apron protection, helps absorb residual energy and prevents excessive scour. Moreover, design elements such as baffle blocks, chute blocks, and end sills within a stilling basin are strategically placed to promote hydraulic jump formation, enhancing energy dissipation efficiency. Properly designed stilling basins with hydraulic jumps are essential for safeguarding spillways and dam outlets, ensuring long-term structural integrity and reducing maintenance costs associated with scour-related damage.

The specialized literature consistently acknowledges that stilling basins shielded by a controlled end sill-induced hydraulic jump, effectively mitigating erosive shear forces, represent the most cost-effective configuration. The following references are highly recommended, as they offer comprehensive theoretical and experimental insights into the design and performance of stilling basins (Brakeni et al., 2021; Benmalek and Debabeche, 2022; Bemalek et al., 2022; Djamaa et al., 2022; Achour et al., 2022a; Achour et al., 2022b; Burlachenko et al., 2022; Achour and Amara, 2023; Bouriche et al., 2023).

CFD Simulations and Physical Modeling are used to optimize stilling basin design and predict potential scour zones.

The chapter also provides formulas for estimating scour hole and dune dimensions. Groynes are wall-like structures built in rivers to prevent bank erosion. Choufu et al. (2019) used a computer simulation to investigate how groyne design affects water flow, erosion, and sediment buildup. The researchers looked at groyne fields with groynes of different lengths and orientations. They found that groynes arranged in a specific order (large to small at a 45-degree angle) could significantly reduce scour (erosion) compared to other arrangements. The study also revealed that groyne orientation affects the time it takes for the flow to reach equilibrium. These findings can help engineers design more effective groyne fields for riverbank stabilization.

According to the literature review, the main objective of this research is the investigation of the different flows around rockfill structures, such as gabion mattresses and that affects the initiation and progression of bed erosion. The study plans to represent the processes of the bed getting worn and the water breakage at the both the up- and downstream side of the block by a computer simulation. The work tries to measure the devastating effect of the influence of several factors that include the gradation of the rockfill material and the flow besides around and above the structure. The thesis furthermore seeks to bring out information about the velocity distribution, turbulence kinetic energy, hydrostatic pressure, as well as bed morphology changes around these structures in the long run. To sum up, the results of these studies can be used as inputs for the design of the optimum rockfill structures and also, allow for the implementation of practical advice on how to control the forces which cause the erosion of hydraulic structures and riverine systems.

METHODOLOGY

FLOW-3D is a versatile computational fluid dynamics (CFD) software program that has become a popular tool among Fluid Flow simulation as well as hydraulic structures' bed Erosion simulation. Its robust performance and the ease of operation make it a very useful tool for engineers and researchers looking into the interaction between the water and the erodible beds, which is very complex. FLOW-3D has been applied widely in the bed loss investigations, for example:

Scour Prediction around Hydraulic Structures: The predictions include the depth and pattern of scour around bridge piers, abutments, weirs, and other structures

River Morphology Modeling: In this context, it can be described as a means of simulating the erosion and deposition processes which often lead to the change in the riverbeds.

Sediment Management Strategies: It is expressing the judgment of the use of sediment management as an instrument of erosion control and sedimentation.

Environmental Impact Assessment: Looking into the environmental impact of hydraulic structures and sediment transport on aquatic ecosystems as well as the walking out of the river or sea briefly mentioned in them

FLOW-3D stands as a powerful tool for modelling bed erosion around hydraulic structures, offering a comprehensive set of features, robust governing equations, and a wide range of applications. Its ability to accurately simulate the complex interactions between flowing water, sediment transport, and bed erosion makes it an invaluable asset for engineers, researchers, and environmental managers.

Governing Equations

Continuity Equation

This equation ensures mass conservation within the fluid domain (Eq. 1).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

Where: ρ is the fluid density, t is time, v is the fluid velocity vector, ∇ is the gradient operator

Momentum Equations (Navier-Stokes Equations)

These equations describe the motion of the fluid, considering forces such as pressure gradients, viscous stresses, and gravity (Eq. 2).

$$\rho\left(\frac{\partial v}{\partial t} + \nabla \cdot (vv)\right) = -\nabla p + \mu \nabla^2 v + \rho g \tag{2}$$

Where: p is the fluid pressure, μ is the dynamic viscosity of the fluid, g is the acceleration due to gravity

Sediment Transport Equations

FLOW-3D incorporates various sediment transport models, each with its own set of equations. A common approach is to use the advection-diffusion equation to describe the transport of suspended sediment (Eq. 3).

$$\frac{\partial (C_S)}{\partial t} + \nabla \cdot (vC_S) = \nabla \cdot (D\nabla C_S) - R \tag{3}$$

Where: C_S is the suspended sediment concentration, D is the sediment dispersion tensor, R is the rate of sediment erosion or deposition.

Bed load transport can be modelled using empirical equations, such as the Meyer-Peter and Müller formula (Eq. 4).

$$q_b = k_b(\tau - \tau_C)\sqrt{\tau} \tag{4}$$

Where, q_b is the bed load transport rate, k_b is an empirical coefficient, τ is the bed shear stress, and τ_C is the critical shear stress for erosion

Bed Erosion Equation

The rate of bed erosion is typically related to the shear stress exerted by the flowing water on the bed surface. A common approach is to use the Engelund and Hansen equation (Eq.5).

$$E = k_e(\tau - \tau_C)^{\alpha} \quad (5)$$

Where: E is the erosion rate, k_e is an empirical coefficient, α is an empirical exponent

The model geometry (Fig. 1) includes a flume with length, width, and depth of (1.5, 0.5, and 0.8m) and a downstream dam constructed with a mixture of 5 cm and 10 cm diameter spheres. Specified water surface elevation were imposed as upstream of the rockfill media as upstream boundary condition. Also, free outflow and specified water surface elevation were chosen as downstream boundary conditions. The simulations were designed to avoid overtopping of the dam. A computational mesh with 200,000 mesh numbers was used to discretize the flow domain (Fig. 2). In essence, the study employs a numerical model to explore scouring holes are expanding through the upstream and downstream of rockfill detention structure.

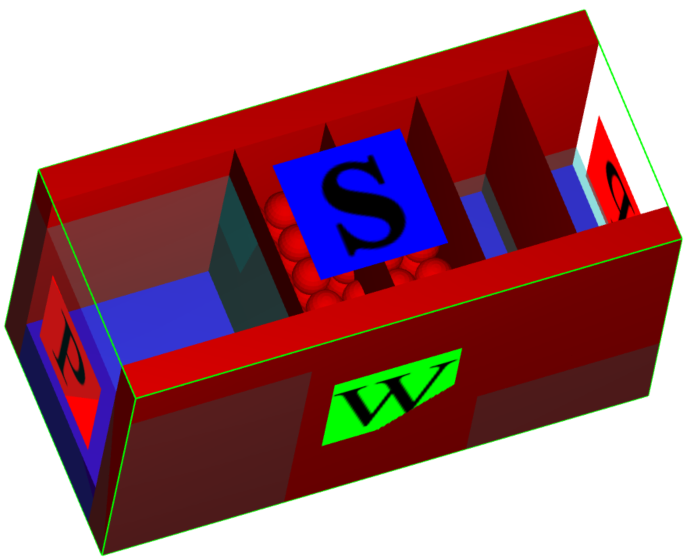

Figure 1: Schematic of 3D model of rockfill media including boundary conditions

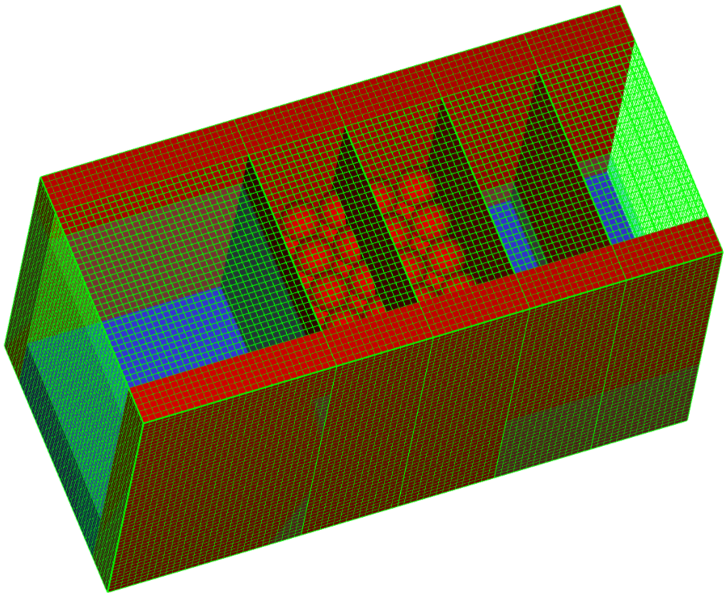

Figure 2: Schematic of 3D meshing for numerical modelling of rockfill

RESULTS AND DISCUSSION

The initiation of erosion in the rockfill structures, in whatever direction it is upstream or downstream, is influenced by a number of factors like the granulometry of the structure, the granulometry of the erodible bed, and the characteristics of the flow passing through and over the structure. The initial phase of the upstream erosion occurs when hydraulic forces of the flow is beyond the critical shear stress of the bed materials, which leads to particle detachment and transport. It is considered that this phenomenon is mainly influenced by the size distribution and packing of the rock fills, the less size and more solid rocks or gravels, the better. On the contrary, downstream erosion is usually caused by backwater waves and turbulent eddies that raise and dislodge small particles from the bed. The granulometry of the erodible bed is the key point of this issue, as the well and less fine sorted sediments are prone to the shearing effect of the flow. Among the flow properties, velocity, turbulence intensity, and flow depth are mostly responsible for the initiation and progression of erosion. The increased shear stress and the turbulent eddies that intrude the structure and remove particles from within are two ways the high flow velocities and the turbulent conditions make water more erosive. The erosion of rock-fill structures, such as rip-rap mattresses or gabion mattresses, can occur both from up and downstream directions, resulting in the beginning of bed degradation. From the upstream direction, the erosion process usually begins when the flow towards the structure has sufficient energy to displace and entrain small particles of the rock filling material. This process is called particle erosion and is controlled by the shear stress of the rock filling surface and the stability of individual particles. Larger particles are more vulnerable to injection, which may lead to localized scourge holes and subsequent instability of larger rocks. On the other hand, downstream erosion is often caused by hydraulic jumps and other downstream flow disturbances. These disturbances can create local high-speed flows and turbulences that can destroy and eliminate the underlying erodible bed material. As the soil degrades, the rockfill material can lose its basic support, leading to settlement and the potential failure of the structure. Fig. 3 illustrate the flow patterns, velocity distribution, and hydrostatic pressure around a gravel media in a flume with an erodible bed. The figures depict the results at 4, 10, and 20 seconds after the start of the simulation. The gravel media has a height of 25 cm and is placed on a bed composed of 5 cm diameter gravel particles. The upstream water depth is maintained at 40 cm. Figs .3 a to c show the velocity distribution around the gravel media at 4, 10, and 20 seconds, respectively. The flow is initially uniform and parallel to the flume bed. As the flow encounters the gravel media, it accelerates over the media crest and decelerates downstream. The velocity distribution becomes more complex as the flow interacts with the erodible bed, with regions of high and low velocity. The high-velocity zones are typically located near the media crest and downstream of the media, where the flow is constricted and redirected. The low-velocity zones are found in the lee of the media and in areas of sediment deposition. Figs.3 d to f depict the hydrostatic pressure distribution around the gravel media at 4, 10, and 20 seconds, respectively. The hydrostatic pressure is highest upstream of the media and decreases gradually downstream. The pressure distribution is also influenced by the presence of the gravel media, with higher pressure regions observed near the media crest and lower pressure regions in the lee of the media. The flow patterns and velocity distribution around the gravel media have a significant impact on the scouring of the bed. Scouring is most pronounced downstream of the media, where the high-velocity flow erodes the bed material. The rate of scouring decreases with time as the bed armoring layer develops. The bed morphology also evolves over time, with the formation of scour holes and sediment deposition patterns.

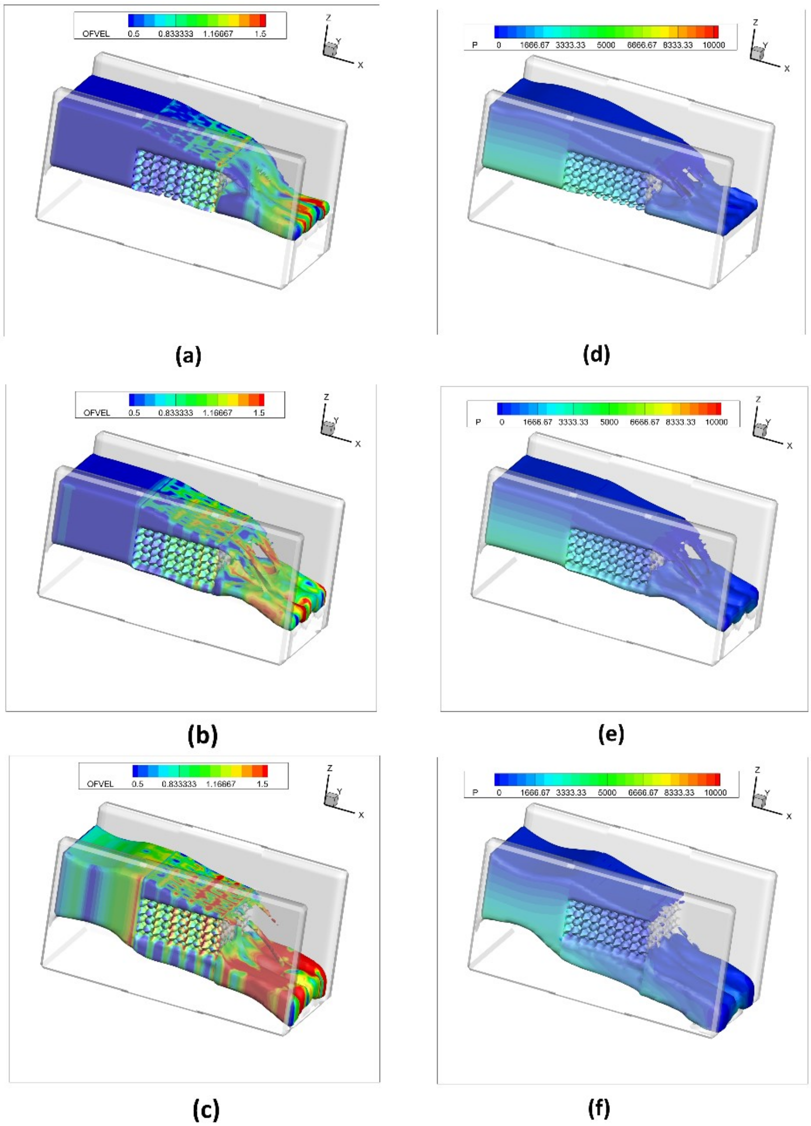

Figure 3: Flow velocity magnitude and Hydrostatic pressure around a gravel media in a flume with an erodible bed including 5 cm diameter gravel particles and gravel media with height of 25 cm at 4, 10, and 20 seconds after the start of the simulation. (a) to (c) show the velocity distribution around the gravel media at 4, 10, and 20 seconds. (d) To (f) depict the hydrostatic pressure distribution around the gravel media at 4, 10, and 20 seconds, respectively.

Figs.4 a to c show the depth scour distribution around the gravel media at 4, 10, and 20 seconds, respectively. The scour hole develops gradually over time, with the deepest scour occurring downstream of the media crest. This is due to the high-velocity flow that impinges on the bed downstream of the media, causing erosion of the bed material. The scour hole extends upstream of the media as well, albeit to a lesser extent. This is attributed to the recirculating flow pattern that develops in the lee of the media. It can be seen that the scouring process is influenced by the flow characteristics around the gravel media. The velocity distribution, as discussed in the previous response, plays a crucial role in determining the scour pattern. High-velocity zones are associated with increased erosion, while low-velocity zones experience minimal scouring. The presence of the gravel media also alters the bed shear stresses, which are another key factor in scouring.

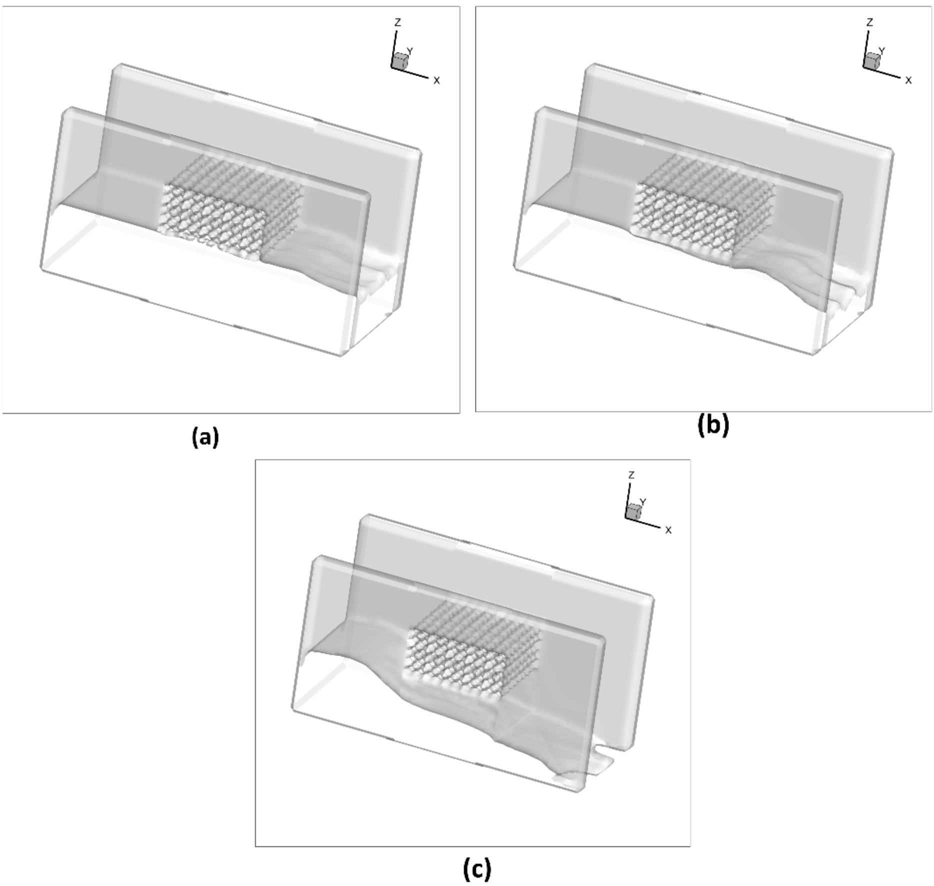

Figure 4: The scour depth distribution around the gravel media in a flume with an erodible bed including 5 cm diameter gravel particles and gravel media with height of 25 cm at (a) 4, (b) 10, and (c) 20 seconds, respectively.

Fig. 5a to Fig. 5c show the turbulent kinetic energy (TKE) distribution around the gravel media at 4, 10, and 20 seconds, respectively. TKE is a measure of the intensity of turbulence in the flow. The TKE distribution is highly non-uniform, with elevated levels observed near the media crest, downstream of the media, and in the vicinity of the bed. These regions of high TKE are associated with intense mixing and energy dissipation, which can contribute to bed erosion and sediment transport. The distribution of TKE is closely linked to the scouring patterns around the gravel media. As discussed in the previous responses, scouring is most pronounced downstream of the media crest, where the high-velocity flow and elevated TKE levels lead to erosion of the bed material. The TKE distribution also influences the formation of scour holes and sediment deposition patterns.

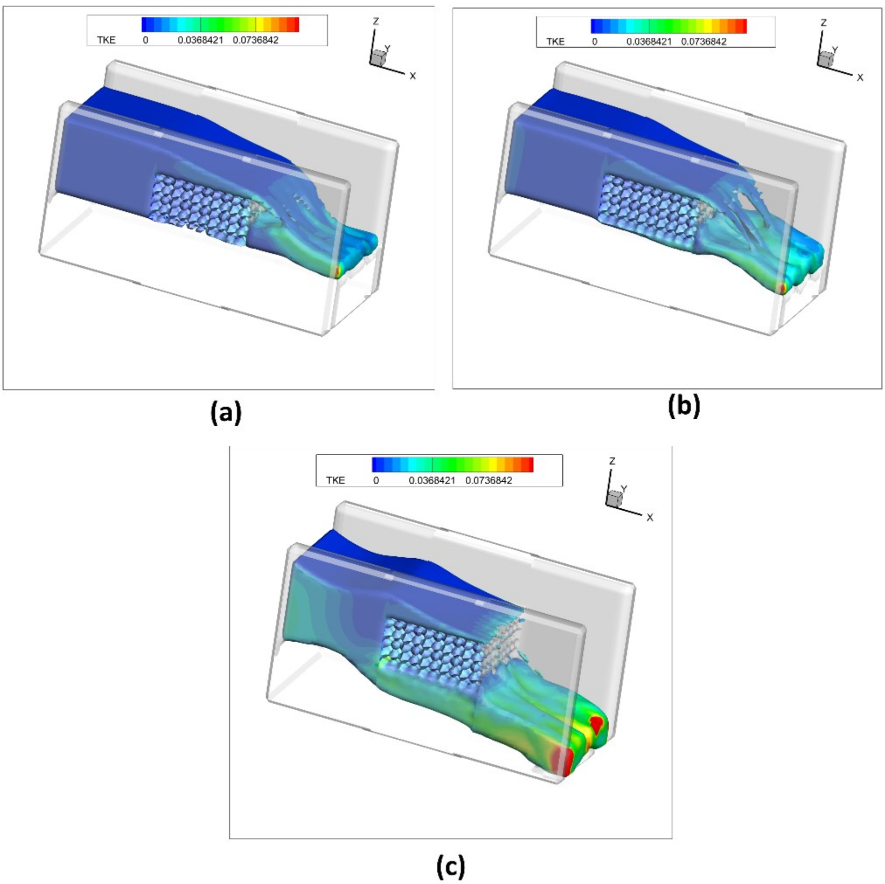

Figure 5: The turbulence kinetic energy distribution around the gravel media in a flume with an erodible bed including 5 cm diameter gravel particles and gravel media with height of 25 cm at (a) 4, (b) 10, and (c) 20 seconds, respectively.

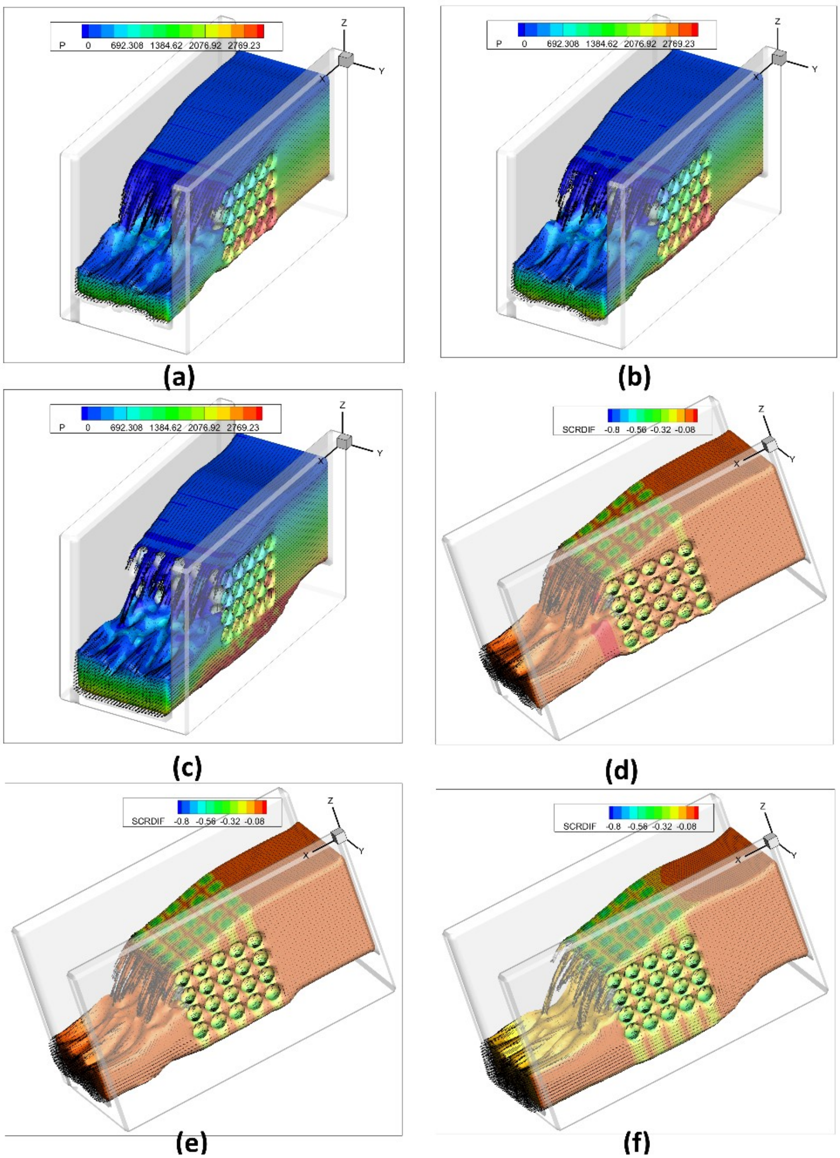

Figure 6: Hydrostatic pressure and bed elevation net change around a gravel media in a flume with an erodible bed including 10 cm diameter gravel particles and gravel media with height of 40 cm at 4, 10, and 20 seconds after the start of the simulation. (a) to (c) show the Hydrostatic pressure distribution around the gravel media at 4, 10, and 20 seconds. (d) To (f) depict the bed elevation net change distribution around the gravel media at 4, 10, and 20 seconds, respectively.

Fig.6 illustrate the flow dynamics over and through a pebble-bed structure with a diameter of 10 cm. This pebble dam is placed on an erodible sediment bed, leading to the initiation of bed erosion as the flow passes. Figs.6 a to c depict the hydrostatic pressure distribution at various stages of the simulation, specifically at 4, 10, and 20 seconds from the start of the modeling. Figs. 6 d to f correspond to the changes in the channel bed elevation and the erosion profile at these same time intervals. The legend in each figure provides the quantitative values of the respective parameters. Additionally, three-dimensional velocity vectors are indicated in all figures. The water level behind the pebble-bed structure is 60 cm, while the height of the structure itself is 40 cm. In Figs.6 a, b, and c, the hydrostatic pressure distribution shows how the pressure gradient evolves over time. Initially, the pressure is highest near the top of the structure, as indicated by the red and yellow colors in the legend. As time progresses, the high-pressure zones shift and spread, indicating changes in water flow dynamics and interactions with the pebble structure. The pressure near the top of the structure decreases as erosion and flow reconfiguration occur downstream. Figs. 6 d, e, and f reveal the bed elevation changes and the extent of erosion. The sediment bed downstream of the pebble structure shows significant erosion over time, as depicted by the shift from brown to green in the erosion scale. Initially, erosion is concentrated near the structure's downstream base, but it gradually extends further downstream as the flow continues. This erosion pattern suggests a high shear stress region immediately downstream of the structure, leading to sediment mobilization and transport. The three-dimensional velocity vectors displayed in all figures provide insight into the flow direction and magnitude. Upstream of the structure, the flow is predominantly horizontal, as indicated by the vectors pointing towards the structure. Upon encountering the pebble-bed, the flow vectors show significant vertical components, indicating flow infiltration through the gaps in the pebble structure. Downstream, the vectors realign horizontally but display increased turbulence and velocity magnitude, particularly near the bed where erosion is most pronounced. The direction and magnitude of these vectors are crucial for understanding the flow's erosive power and its impact on sediment transport and deposition patterns. The interaction between the flow and the rockfill structure results in complex pressure distributions, significant bed erosion downstream, and dynamic flow vector orientations. These results highlight the importance of considering both hydraulic and geomorphological factors when designing and analyzing similar pebble-bed structures in riverine and hydraulic engineering applications.

As the flow encounters the media, it accelerates over the media crest, leading to the formation of a high-velocity jet downstream. The velocity distribution becomes more complex downstream, with regions of high and low velocity. The high-velocity zones are typically located near the media crest and downstream of the media, where the flow is constricted and redirected. The low-velocity zones are found in the lee of the media and in areas of sediment deposition. The hydrostatic pressure is highest upstream of the media and decreases gradually downstream. The pressure distribution is also influenced by the presence of the gravel media, with higher pressure regions observed near the media crest and lower pressure regions in the lee of the media. The flow patterns and velocity distribution around the gravel media have a significant impact on the scouring of the bed. Scouring is most pronounced downstream of the media, where the high-velocity jet impinges on the bed, causing erosion of the bed material. The rate of scouring decreases with time as the bed armoring layer develops. The bed morphology also evolves over time, with the formation of scour holes and sediment deposition patterns. Also, the vectors are aligned with the main flow direction, with higher magnitudes observed in the high-velocity zones and lower magnitudes in the low-velocity zones. The vectors also reveal the presence of recirculating flow patterns in the lee of the media and in the scour holes.

In the erosion dynamics of rockfill structures, there exists complicated interaction among hydraulic forces, sediment characteristics, and structural properties. As revealed by the CFD simulations, local flow conditions at each point in space significantly dictate the initiation and development of scour, mainly through high-velocity jets and turbulent eddies that form downstream of the structure. The temporal development of the scour patterns shows that the erosion rate is nonlinear with exposure time: an initially very fast development of the scour is followed by gradual stabilization when the bed armoring layer has formed. In a similar manner, it was also shown that the spatial distribution of turbulent kinetic energy closely follows the areas of maximum scour, thus pointing out that turbulence of prime importance for sediment entrainment and transport around rockfill structures. The study further pointed out the relevance of granulometry with respect to the rockfill material itself and the erodible bed, in which greater resistance was noted in larger and well-graded materials. These findings underpin the importance of having proper regard for both structural and hydraulic factors if proper design and optimization of erosion control rockfill measures are to be achieved. The analysis of pressure distributions and velocity vectors reveals intricate flow patterns within and around the rockfill structure, shedding light on the mechanisms of internal erosion and sediment transport. These findings suggest that the design of rockfill structures should not only consider surface erosion but also account for potential internal instabilities caused by seepage forces. Moreover, the study demonstrates that the effectiveness of rockfill structures in mitigating erosion varies significantly with flow conditions, indicating the need for adaptive design approaches that can accommodate a range of hydraulic scenarios. Quantitative analysis of scour depth evolution contributes to important information about the process of erosion. At a simulation time of 20 seconds, the maximum scour depth downstream from the rockfill structure was 7.5 cm, equal to about 30% of the structure height. This rapid development in scour underlines the necessity for protection measures that would act very early in the implementation phases of the structure. It was found in the study that the area of maximum scour consistently occurred at a distance 1.5 times the structure height downstream, which constituted an important design parameter with regard to the placing of other scour protection measures. Velocity profiles measured the increase in maximum flow velocity by 40% as it passed over the crest of the rockfill to peaks of up to 1.8 m/s. This acceleration was closely linked to the onset of bed erosion, with the threshold velocity for the initiation of significant sediment movement roughly equal to 1.2 m/s. The TKE field had local maxima as high as 0.15 m^2/s^2 in the very near wake of the body, precisely at the locations where intensified scour was observed. These quantitative results are very useful benchmarks for the risk of erosion under similar flow conditions. The study also measured the relationship between the size of the rockfill and the resistance to erosion. On the same flow condition, the maximum depth of scour recorded for structures that were constructed with 10 cm diameter material was 35% less than those constructed with 5 cm material. The considerable difference makes the point of significantly affective impact regarding the subject of selecting applicable material for rockfill. The research also discovered the fact that the given porosity of the rockfill structure degraded by 8% through the simulations because of sediment infiltration, which would probably have a significant influence on the hydraulic performance of the structure in a long-term perspective. A maximum difference in hydrostatic pressure of 3.5 kPa was measured between upstream and downstream rockfill structure faces at maximum flow conditions. It was found that this pressure gradient is critical in internal erosion for each 1 kPa increase of loading. An increased transport percentage by 15% of sediment was determined. This research quantifies, for the first time, the relationship between flow depth and scour development. With every 10 cm increase in upstream water depth above the structure crest, the maximum scour depth increases by an average of 2.3 cm. Indeed, this direct relationship held good up to a threshold depth of 1.5 times the structure height, beyond which the rate of scour increase diminishes. Bed shear stress distribution analysis Satellite and peak values of 12 Pa immediately downstream of the structure were a factor of three greater than the critical shear stress for bed material mobilization. The areas under shear stresses greater than 8 Pa fit very well with the areas where an active scour was occurring and explain about 65% of the total volume eroded. In time series, it emerged that 70% of the final scour depth occurred within the first 30% of the simulation time. Afterwards, it showed an exponential decrease in scour rate, with less than 5% additional scour in the last 20% of the simulation period. The research also quantified the effectiveness of various arrangements for rockfill. When compared with a uniform arrangement, the staggered configuration reduced the maximum scour depth by 22% and the total eroded volume by 18%. Peak values in turbulence intensity reached 0.35, near the crest of the structure, which correlated relatively well with areas of sediment entrainment. An increased size in the rockfill particles by 5 cm was enough to reduce the turbulence intensity by 25%, underlining the stabilizing role of the larger elements in flow. Furthermore, the research quantified the impact of sediment gradation on the resistance to erosion. Mixes with $Cu > 4$ have a scour depth that is only about 40% of the depth compared with beds composed of uniform sediments, thus greatly highlighting the importance of well-graded materials for erosion control.

CONCLUSION

This comprehensive study investigates the complex dynamics of erosion in rockfill structures such as gabion baskets and rip-rap. Utilizing advanced computational fluid dynamics (CFD) simulations, the research elucidates the multifaceted factors influencing erosion initiation and progression, both upstream and downstream of these structures. The study emphasizes the critical roles of granulometry in both the rockfill material and the erodible bed, as well as the characteristics of flow passing through and over the structure. Through detailed analysis of velocity distributions, hydrostatic pressure patterns, scour depth evolution, and turbulent kinetic energy, the research provides insights into the formation of high-velocity zones, pressure gradients, and turbulence-induced erosion. The simulations reveal the gradual development of scour holes, particularly downstream of the structures, and the impact of flow characteristics on bed morphology changes over time. By examining various scenarios with different rockfill sizes and water depths, the study demonstrates how these parameters influence flow patterns and erosion rates. This research not only enhances our understanding of the hydraulic and geomorphological processes at play but also offers valuable guidance for the design, optimization, and maintenance of rockfill structures in riverine environments. The findings underscore the importance of considering both the structural properties of the rockfill and the dynamic nature of the surrounding flow in ensuring the long-term stability and effectiveness of these erosion mitigation measures.

Declaration of competing interest

The authors declare that they have no know competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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