

Study on the Stability of Riverbed Protection Blocks Considering Subsurface Seepage Pressure

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1. Introduction

Riverbed protection works are hydraulic structures installed on riverbeds to prevent erosion and bed degradation caused by flowing water. They dissipate the energy of high-velocity flows through hydraulic jumps, thereby improving downstream flow conditions. When downstream bed degradation occurs and the downstream water level decreases, the position of the hydraulic jump may shift, altering the flow field and pressure distribution around the protection blocks and consequently affecting the hydrodynamic forces acting on them and their stability.

Yamamoto et al. (2018) observed the displacement and washout of riverbed protection blocks following downstream bed degradation through movable-bed experiments. Yang et al. (2020) further conducted numerical simulations and identified two key mechanisms: increased lift forces near the hydraulic jump front and maximum drag forces acting on the downstream-end blocks. However, their simulations mainly covered the first 50 s of the simulation, during which the hydraulic jump formed and developed within the protected section. The subsequent evolution of the hydraulic jump and its effects on the hydrodynamic forces acting on the blocks remain unclear. Therefore, extending the simulation period is necessary to evaluate the overall stability of riverbed protection works.

In this study, two-dimensional numerical simulations are performed using OpenFOAM, coupling the Volume of Fluid (VOF) method with the Darcy resistance term. Based on the numerical model of Yang et al. (2020), the simulation period is extended to 100 s. The study focuses on the evolution of the hydraulic jump during the 50 – 100 s period and the corresponding changes in hydrodynamic

forces and sliding safety factors of the protection blocks, thereby evaluating their stability.

2. Numerical Simulation

In this study, the Volume of Fluid (VOF) method is employed to capture the free surface. Porosity and the Darcy resistance term are incorporated into the momentum equation to describe seepage flow through the riverbed. The PIMPLE algorithm is used for pressure - velocity coupling, while the standard $k - \varepsilon$ turbulence model is adopted for turbulence closure. Numerical simulations are performed to investigate both open-channel flow and seepage flow through the porous riverbed. The governing equations and numerical parameters are described below.

(1) Governing Equations

The fluid is assumed to be incompressible, and its motion is governed by the Navier-Stokes equations.

$$\frac{\partial(\rho\vec{U})}{\partial t} + \nabla \cdot (\rho\vec{U}\vec{U}) - \nabla \cdot \mathbf{T} = -\nabla p + \rho\vec{g} + \vec{F}_\sigma \quad (1)$$

where p is the pressure, $\vec{g}$ is the gravitational acceleration vector, $\vec{F}_\sigma$ is the surface tension term, and $\mathbf{T}$ is the stress tensor.

In the porous medium beneath the riverbed protection blocks, seepage flow occurs and can be assumed to be laminar. Under this assumption, the flow can be described by Darcy's law:

$$\vec{u}_p = -\frac{K}{\mu}(\nabla p - \rho\vec{g}) \quad (2)$$

where $\vec{u}_p$ is the seepage velocity in the porous medium, K is the permeability, μ is the dynamic viscosity of the fluid, p is the pressure, ρ is the fluid density, and $\vec{g}$ is the gravitational acceleration vector.

By incorporating the porosity γ and adding a Darcy resistance source term to Eq. (1), the governing momentum

equation for seepage flow in the porous medium is obtained as follows:

$$\frac{\partial(\rho\vec{U})}{\partial t} + \nabla \cdot (\rho\vec{U}\vec{U}) - \nabla \cdot \mathbf{T} = -\nabla p + \rho\vec{g} + \vec{F}_\sigma - \frac{\gamma\mu}{K}\vec{U} \quad (3)$$

(2) Volume of Fluid (VOF) Method

The phase fraction transport equation for the two-phase flow model is expressed as follows:

$$\frac{\partial\alpha}{\partial t} + \nabla \cdot (\alpha\vec{U}) - \nabla \cdot (\alpha(1-\alpha)\vec{U}_r) = 0 \quad (4)$$

where α is the volume fraction of water, ranging from 0 to 1. $\vec{U}$ is the mixture velocity, and $\vec{U}_r$ is the interface compression velocity, generally directed normal to the interface.

(3) Stability Evaluation Criterion

$$F_s = \frac{\mu}{D} \frac{(W_w - L)}{D} = \frac{\mu}{F_x} \frac{(W_w - F_y)}{F_x} \quad (5)$$

where μ is the coefficient of friction, W_w is the submerged weight of the block, $L = F_y$ is the lift force acting on the block, and $D = F_x$ is the drag force acting on the block.

A higher sliding safety factor F_s indicates greater block stability. An increase in drag force promotes downstream sliding, while an increase in lift force reduces the effective weight of the block, thereby decreasing its sliding stability.

(4) Numerical Simulation Setup

This study adopts the two-dimensional numerical model of riverbed protection works developed by Yang et al. (2020). The computational domain consists of an open-channel flow region, riverbed protection blocks, and an underlying porous medium. The riverbed protection works consist of 12 blocks, numbered sequentially from Block 1 to Block 12 along the flow direction, with Block 1 located at the most upstream position and Block 12 at the most downstream position.

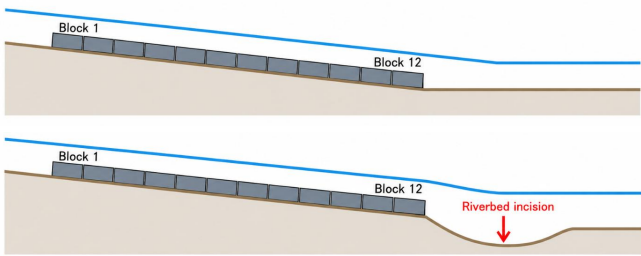


Fig. 1. Schematic illustration of riverbed conditions before and after downstream bed degradation.

Yang et al. (2020) validated the numerical model using experimental results obtained at flow rates of 90 L/s and

150 L/s. Based on this validated model, the present study adopts a flow rate of 180 L/s and uses the numerical results at 50 s as the initial conditions for the subsequent simulation. The simulation is extended to 100 s to investigate the subsequent evolution of the hydraulic jump and changes in the hydrodynamic forces acting on the protection blocks.

To investigate the effects of downstream bed degradation on the stability of riverbed protection blocks, two riverbed conditions are considered: before and after degradation. By comparing the hydraulic jump positions, hydrodynamic forces acting on the blocks, and sliding safety factors under these two conditions, the effects of bed degradation on the flow field and block stability are evaluated.

Furthermore, a weir plate is installed at the downstream end of the computational domain to regulate the downstream water level and hydraulic jump position. Five weir plate heights, ranging from 1 to 5 cm at 1 cm intervals, are considered. For each weir plate height, simulations are conducted under both riverbed conditions, resulting in a total of 10 simulation cases.

3. Results and Discussion

(1) Position of the Hydraulic Jump Front and Peak Resultant Forces

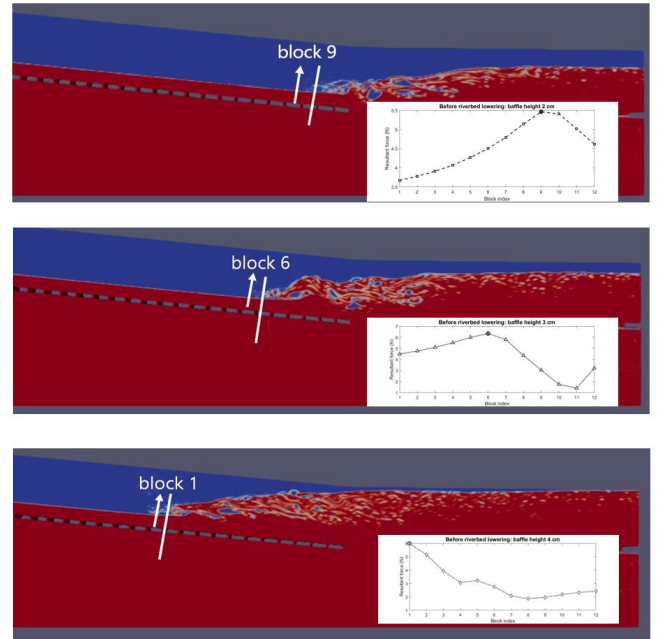


Fig. 2. Resultant hydrodynamic forces on individual blocks and positions of the hydraulic jump front.

As shown in Fig. 2, the position of the hydraulic jump front and the location of the block subjected to the

maximum resultant hydrodynamic force vary with the weir plate height. The maximum resultant hydrodynamic force generally occurs on a block near the hydraulic jump front, suggesting that the location of the peak resultant force is closely associated with the position of the hydraulic jump front. This trend is consistent with the findings of Yang et al. (2020).

(2) Effects of Riverbed Degradation on Hydrodynamic Forces

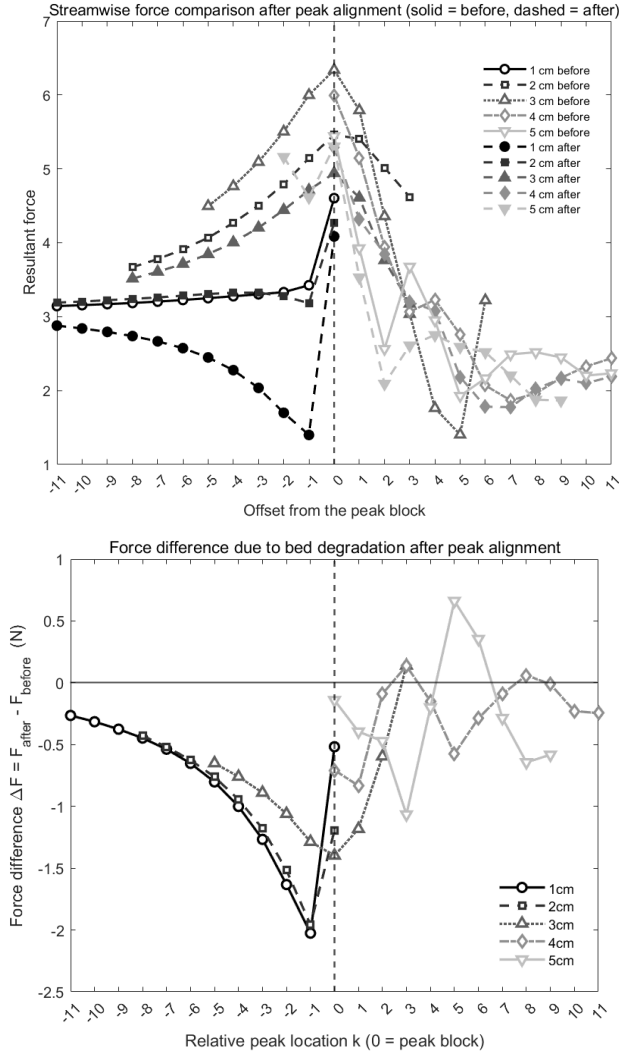


Fig. 3. (a) Streamwise distributions of resultant hydrodynamic force aligned by peak location; (b) differences in resultant hydrodynamic force between the two bed conditions.

As shown in Fig. 3(a) although the locations of the peak resultant force shift after bed degradation, the streamwise distributions generally retain a unimodal pattern, with higher forces near the peak and lower forces on either side. This suggests that bed degradation does not fundamentally alter the overall shape of the streamwise distribution of resultant hydrodynamic force.

As shown in Fig. 3(b), after the peak locations are aligned, most differences in resultant hydrodynamic force are negative, indicating a general reduction in resultant force near the peak following bed degradation. This reduction may be associated with the decrease in downstream water level accompanying bed degradation, as well as changes in the hydraulic jump position and intensity.

(3) Peak Resultant Force Locations and Sliding Stability

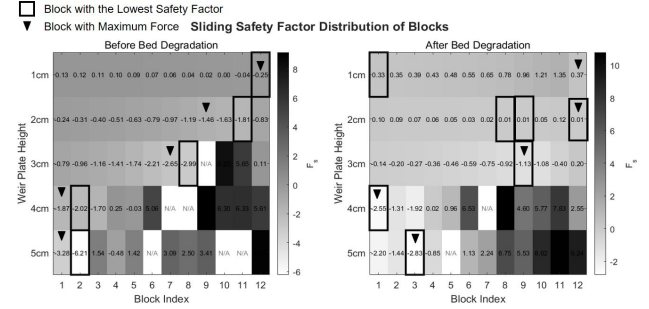


Fig. 4. Sliding safety factors and locations of peak resultant forces before and after bed degradation.

As shown in Fig. 4, blocks with the lowest sliding safety factors are generally located near the peak resultant force locations, indicating an association between sliding stability and the spatial distribution of resultant hydrodynamic force. As the weir plate height changes, the locations of blocks with relatively low sliding safety factors also shift. Furthermore, differences in the sliding safety factor distributions before and after bed degradation may be associated with shifts in the hydraulic jump position and the resulting changes in local hydrodynamic forces.

Fig. 5 shows that relatively large lift forces F_y reduce the effective weight and frictional resistance of the blocks, thereby lowering their sliding safety factors.

When the hydraulic jump is located near the downstream end of the protection works, the downstream blocks experience relatively large drag forces F_x , resulting in lower sliding safety factors F_s . Consequently, these blocks may become critical to overall stability. If interlocking between adjacent blocks is weak or seepage pressure is high, the failure of a downstream block may destabilize adjacent blocks and trigger progressive local failure. Block washout was observed in the movable-bed experiments of Yamamoto et al. (2018), which is qualitatively consistent with the reduced stability of

downstream blocks indicated by the present simulations.

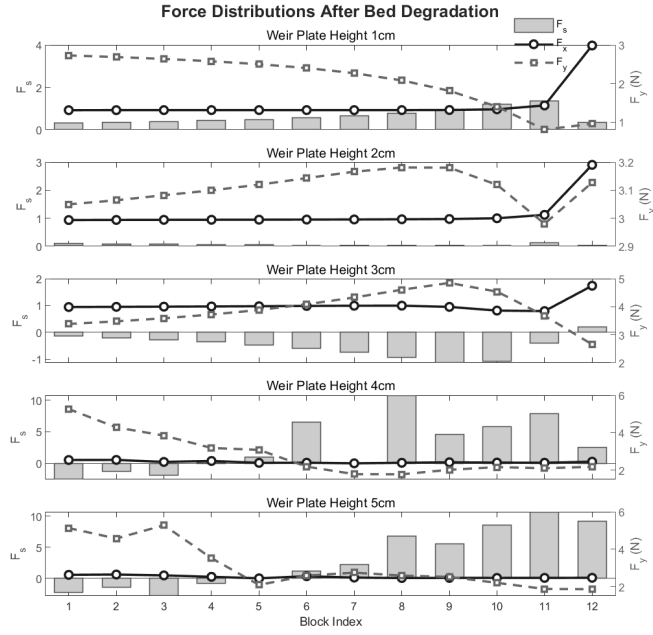


Fig. 5 Longitudinal distributions of F_s , F_x , and F_y at different weir plate heights.

Furthermore, as shown in Fig. 4, at a weir plate height of 1 cm, the block with the lowest sliding safety factor shifts from Block 12 to Block 1 after bed degradation. According to the preceding analysis of hydraulic jump positions, the hydraulic jump is located near the downstream end of the protection works or has not yet formed within the protected section. As shown in Fig. 5, the downstream blocks experience relatively large drag forces F_x , whereas the upstream blocks are subjected to relatively large lift forces F_y . This difference in hydrodynamic loading may partly explain the change in the location of the block with the lowest sliding safety factor after bed degradation. Therefore, under conditions of low downstream water level, attention should be paid to the sliding stability of both upstream and downstream blocks.

(4) Local Seepage Flow Beneath Protection Blocks

As shown in Fig. 6, localized upward seepage is observed beneath some blocks near the hydraulic jump front. Comparison with Figs. 4 and 5 shows that these regions are associated with relatively large lift forces and low sliding safety factors. These observations suggest that upward seepage may contribute to the lift forces acting on the blocks through its influence on the local pressure distribution, thereby affecting their sliding stability.

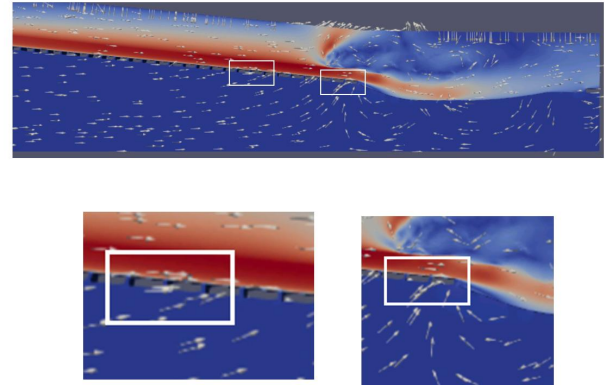


Fig. 6. Local velocity field after bed degradation at a weir plate height of 2 cm

4. Conclusions

This study used OpenFOAM to evaluate the sliding stability of riverbed protection blocks while accounting for subsurface seepage. The main findings are summarized as follows:

(1) Peak resultant hydrodynamic forces generally occurred on blocks near the hydraulic jump front, and their locations shifted with the position of the front. Bed degradation generally reduced the resultant hydrodynamic forces near the peak locations.

(2) Sliding stability was influenced by both lift and drag forces. When the hydraulic jump was located near the downstream end of the protection works, the downstream blocks experienced relatively large drag forces and low sliding safety factors, indicating increased susceptibility to sliding. The location of the block with the lowest sliding safety factor varied with the bed conditions.

(3) Localized upward seepage was observed beneath some blocks with low sliding safety factors. This observation suggests that subsurface seepage may affect sliding stability through its influence on the local pressure distribution.

5. References

- [1] Yamamoto, Y., Nakamura, R., and Suwa, Y.: Research Issues Identified from Hydraulic Experiments on the Deformation of Block-Type Groundsills, *Advances in River Engineering*, Vol. 24, pp. 143-148, 2018.
- [2] Yang, H., Yamamoto, Y., Fukumoto, Y., Hosoyamada, T., Otsuka, S., and Fukushima, M.: Hydrodynamic Characteristics and Stability of Groundsill Blocks with Considering Seepage and Hydraulic Jump in River, *Advances in River Engineering*, Vol. 26, pp. 401-406, 2020.