

# Investigation of local scour development mechanism around river bridge piers with varied 3D shapes ~focusing on the flow velocity field and bed shear stress~

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**ABSTRACT:** Bridge failures due to local scour from heavy rainfall have been reported more frequently in recent years, potentially linked to climate change (e.g. Saburomaru Bridge in Oita, Japan, 2024; Awanogawa Bridge in Yamaguchi, Japan, 2023). One possible countermeasure against local scour is to propose a new bridge pier shape, which has been experimentally shown to be effective; for example, Vijayasree et al. (2019) conducted model tests on piers with different horizontal cross-sections and found that sharper leading edges reduced scour depth. Kosaka (2024) varied the vertical cross-sectional shapes and demonstrated that vertically curved piers reduce scour induced displacement. However, the mechanisms underlying scour mitigation through pier shape modification remain unclear. This study integrates water channel model tests and finite volume method (FVM) simulations to clarify how the 3D shape of piers influences local scour. Three types of pier shapes were considered: namely, standard, pentagonal, and curved piers. In model tests, the evolutions of the scour depth and pier displacement were measured. Flow fields were obtained via Particle Image Velocimetry (PIV) to validate FVM, and 3D scour hole shapes were reconstructed using Structure from Motion (SfM) to consider the effect of the evolved scour hole in FVM. Numerical methods employed steady-state Reynolds-Averaged Navier-Stokes (RANS) equations and the shear stress transport (SST)  $k-\omega$  turbulence model to evaluate flow velocity fields and bed shear stress. Key findings are as follows: The flow velocity field from simulations generally agreed with PIV measurements, confirming the validity of the numerical methods. The pentagonal pier suppressed downward flow but concentrated high-velocity flow along the sides, which promoted scour along the sides and pier displacement. The curved pier generated low-velocity vortices and dispersed flow along the sides, reducing scour progression and pier displacement.

**KEYWORDS:** Local Scour, numerical methods, bridge pier, river disaster, bed shear stress.

## 1 INTRODUCTION

In recent years, damage to river bridges due to local scour induced by heavy rainfall has been reported more and more frequently. For instance, on July 1, 2024, severe rainfall caused the Saburomaru Bridge on National Route 386 in Oita Prefecture in Japan due to local scour, resulting in a prolonged road closure (Watanabe et al., 2025). The Saburomaru Bridge is a relatively new prestressed concrete (PC) bridge (constructed in 1966) whose piers are elongated towards the flow direction, and this configuration is generally considered to be less susceptible to collapse. Nevertheless, it was damaged by a flood discharge below the historically recorded maximum (Watanabe et al., 2025). Furthermore, Awanogawa Railway Bridge in Yamaguchi Prefecture in Japan, erosion of the sheet piles forming a pentagonal enclosure led to the displacement of the pier in July 2023. These incidents suggest that there is room for re-evaluation of existing pier geometries and sheet pile configurations typically adopted as scour countermeasures.

Meanwhile, the effect of the geometry of a bridge pier on local scour development around the pier have been conducted by several researchers. Vijayasree et al. (2019) experimentally investigated the variation in scour depth for five types of bridge piers with different horizontal cross-sections. Their findings suggested that pier shapes with a pointed nose contribute to reducing scour depth at the upstream end of the pier. On the other hand, due to construction constraints, studies on three-dimensional pier shapes with varied vertical cross-sections have not been extensively performed. In response, Kosaka and Watanabe (2024) experimentally demonstrated that some three-dimensional geometries of river bridge piers may suppress scour progression, pier displacement, and pier instability. It has been shown that, compared to conventional piers with modified horizontal cross-sections, such as standard or pentagonal piers, curved piers with modified vertical cross-sections can delay the progression of pier displacement due to local scour (Fig. 1) (Kosaka and Watanabe, 2024). However, the mechanisms underlying the delayed displacement of the curved pier have not yet been fully understood.

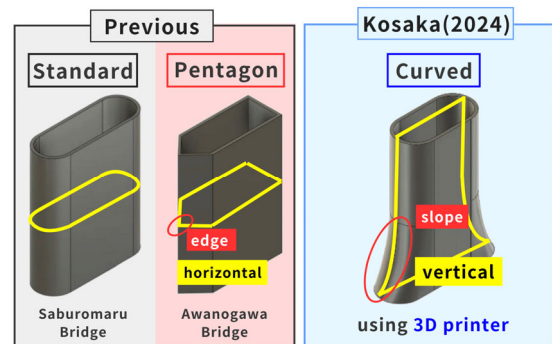


Figure 1. Prevalent pier shapes in Japan (left) and novel 3D pier geometry (Kosaka and Watanabe, 2024) (right).

Furthermore, numerical analyses have been conducted to predict scour depth for better understand of the scour development process. Rouland et al. (2005) performed numerical analysis simulating the scour development around a circular bridge pier by considering the bed shear stress acting on the riverbed and sediment transport, employing three-dimensional computational fluid dynamics. However, they reported that their numerical analysis underestimated the scour depth compared to the scour depth observed in their model test (Rouland et al., 2005). Their results highlighted difficulties in predicting the scour evolution around a bridge pier even for a simple shape, and moreover, hitherto few studies simulated the scour development around a pier with a more complex shape.

Considering these challenges, the present study combines physical model experiments with numerical simulations employing the Finite Volume Method (FVM), the latter validated by the experimental results. By evaluating the flow velocity field and bed shear stress acting on soils around piers with a variety of shapes, this research investigates the differences in local scour development mechanisms arising from the different three-dimensional geometries of river bridge piers.

## 2 METHODS

This study employs two primary methodologies: physical model experiments and numerical analysis. In the physical model experiments, the scour progression process was observed and measured for three types of pier geometries with different horizontal and vertical cross-sections, as illustrated in Figure 1: a standard pier, a pentagonal pier, and a curved pier. These experiments were conducted using a medium-sized flume (Fig. 2). All pier models shared common specifications: a transverse width of 70 mm, a height of 250 mm, an embedment depth of 58 mm, and a density of 1.7 t/m<sup>3</sup>, with detailed specifications presented in Table 1.

Table 1. Pier Specifications.

Pier	Standard	Pentagon	Curved
Major axis length of the bottom [mm]	201.39	180.25	201.39
Major axis length of the top [mm]	201.39	180.25	140
Base area [mm <sup>2</sup> ]	13043.8	11313.8	13043.8
Weight [kg]	5.543	4.807	3.605

Kashima No. 4 silica sand was used as the bed material. The median particle diameter ( $D_{50}$ ) is 0.75 mm, and the coefficient of uniformity ( $D_{60}/D_{10}$ ) is 1.45. Furthermore, the relative density of the ground is 79%. The flume has a channel length of 1612 mm and a width of 604 mm, representing a scale of 1/30 to 1/20. The bed slope is 1/400 (Fig. 2). For further details, please refer to Takezaki et al. (2023).

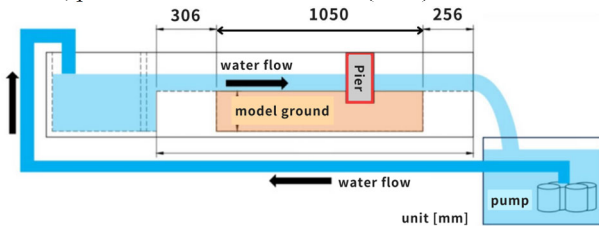


Figure 2. Prevalent pier shapes in Japan (left) and novel 3D pier geometry (Kosaka and Watanabe (2024)) (right).

The flow rate was gradually increased, and the pier's horizontal displacement and scour depth were obtained. Furthermore, to validate the numerical analysis, the flow field at the upstream end of the pier was visualized using Particle Image Velocimetry (PIV) with an LED light sheet, tracer particles (specific gravity: 1.01), and a high-speed camera. Additionally, 3D shape data of the scour hole, obtained by photographing the area around the pier under temporarily static water conditions during the experiment using Structure from Motion (SfM), were subsequently used in the numerical analysis detailed below.

In numerical analysis, a fluid analysis employing the Finite Volume Method (FVM) was conducted to determine the flow velocity field and bed shear stress distribution around the pier. As this involved turbulent flow analysis with a Reynolds number of approximately 20,000, SimpleFOAM, a steady-state turbulent flow solver implemented in OpenFOAM (Jasak, 2009), was used. The Reynolds-Averaged Navier-Stokes (RANS) model served as the turbulence model, and the Shear Stress Transport (SST)  $k-\omega$  model (Menter, 1992) was used as the eddy viscosity model. ParaView (Ayachit, 2015) was utilized for visualizing the fluid analysis results and calculating streamlines. To accurately reproduce the evolution of the scour hole, 3D shape data were generated from videos of the pier

vicinity using Structure from Motion (SfM). Based on these data, the simulation domain was defined, and the flow velocity field and bed shear stress distribution during scour progression were determined (Fig. 3). The coarsest mesh size was set to 12 mm in the horizontal direction and 6 mm in the vertical direction; cells near the pier and riverbed were subdivided, up to one-eighth of its original size. A symmetry plane was considered at the central axis of the pier, slip conditions were applied to the side walls, and a zero-pressure gradient was set for the outflow boundary. The inflow velocity was defined using the atmBoundaryLayer condition (based on a logarithmic law), which incorporated the experimentally measured surface flow velocity from the time the 3D scour hole data were obtained.

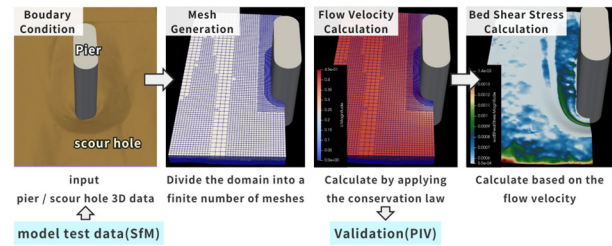


Figure 3. Procedures of Finite Volume Method.

## 3 VALIDATION OF NUMERICAL METHOD

To validate the numerical analysis, the flow field at the upstream end of the pier derived from Particle Image Velocimetry (PIV) in physical model experiments was compared with the corresponding results from the numerical analysis. First, the flow velocity distribution for the curved pier under flatbed conditions was compared. For the downward flow and horseshoe vortex near the pier—both crucial for scour progression—the direction and magnitude of velocity vectors from the numerical analysis (Fig. 4) showed generally good agreement with the PIV measurements (Fig. 5).

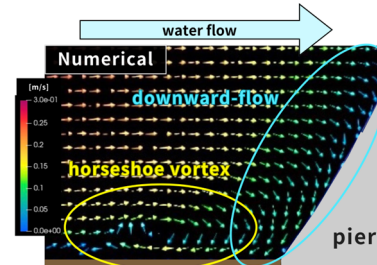


Figure 4. Flow field on a flatbed in numerical analysis.

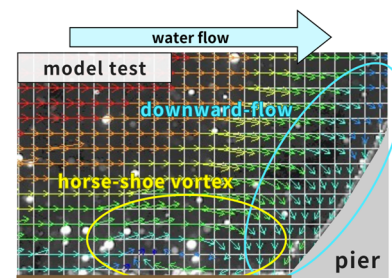


Figure 5. Flow field on a flatbed in model experiments.

Next, for the standard pier, a comparison of the flow field above the scour hole is conducted. The results from the numerical analysis and the model test were in general agreement in terms of the velocity of the downward flow (Figure 6). However, the direction of the downward flow was approximately 45° in the numerical analysis, whereas it was about 30° in the physical model experiment. A possible reason for this discrepancy is that in the physical model experiments,

the approximately 1.5 mm thickness of the LED light sheet might have led to the inclusion of out-of-plane velocity components.

Although minor discrepancies exist, the velocity vectors (in terms of direction and magnitude) of the downward flow and horseshoe vortex—critical elements in scour progression—from the numerical analysis show generally good agreement with the PIV measurements, both under flatbed conditions and during scour progression. Thus, it can be concluded that the numerical analysis employed in this study is accurate enough to investigate the flow field around a variety of piers with an evolving scour hole.

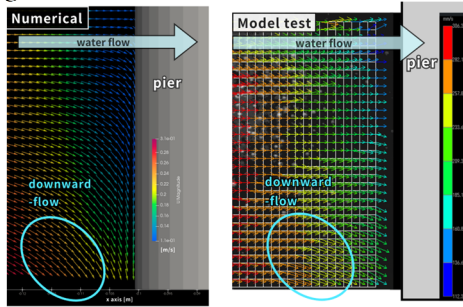


Figure 6. Flow field around the upstream edge with the scour hole existing (Left: numerical analysis, Right: physical model experiment).

#### 4 LOCAL SCOUR DEVELOPMENT MECHANISM

The evolutions of the displacement of all the piers, which were induced by the progress of the local scour, are compared in Fig. 7. The horizontal displacement is defined as positive in the upstream direction. For the pentagonal pier (with a modified horizontal cross-section), its horizontal displacement tends to increase more significantly than that of the standard pier. This suggests that the pentagonal pier does not effectively mitigate scour damage. Conversely, for the curved pier (with a modified vertical cross-section), the progression of horizontal displacement was suppressed as the flow rate increased, compared to the standard pier. This indicates the curved pier is effective in mitigating the displacement due to the scour damage.

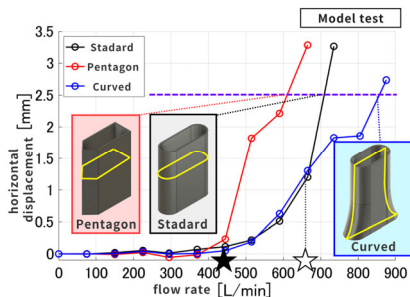


Figure 7. Relationship between flow rate and horizontal displacement of each pier.

Next, the local scour development mechanisms for the pentagonal and curved piers are discussed by comparing them with the standard pier. This investigation proceeds in three steps: (1) Evaluating the susceptibility to local scour by comparing the scour hole data obtained via Structure from Motion (SfM) analysis. (2) Comparing the distribution of bed shear stress on soils, which causes the scour of the soils. (3) Visualizing the flow velocity fields to identify the flow patterns responsible for the above differences. Observational results from the physical model experiments are also presented to substantiate these analyses.

In the illustrations of bed shear stress (Fig.9, Fig. 12), regions are color-coded based on the critical bed shear stress calculated using Iwagaki's formula (Sekine, 2005).

Regions below the critical value (indicating no sediment movement) are shown in white, while regions exceeding it (inducing sediment movement) are depicted in shades of blue or green.

#### 4.1 Pentagonal Pier

This section compares the pentagonal pier with the standard pier. A comparison of the scour hole data obtained through SfM at the same flow rate (indicated by ☆ in Fig. 7) reveals that while scour at the upstream end of the pentagonal pier was suppressed, scour along its sides was severer (Fig. 8). This increased susceptibility to scour along the sides is explained by the bed shear stress distribution at the same flow rate (indicated by ★ in Fig. 7). For the pentagonal pier, a significantly large bed shear stress, locally exceeding the critical value, was observed near the pier on its anterolateral sides (Fig. 9), which might cause the deeper scour around the side of the pentagonal pier as shown in Fig. 8. The cause for this locally high bed shear stress is, in turn, elucidated by the flow velocity fields at the same flow rate (indicated by ★ in Fig. 7). While the standard pier exhibits a downward flow, the pentagonal pier does not; instead, high-velocity flow is concentrated along its sides (Fig. 10). These results suggest that although the pentagonal pier can prevent downward flow, the concentration of flow near its sides promotes scour on these anterolateral aspects, which might lead to the earlier collapse of the pentagonal pier. This observation is qualitatively consistent with the experimental results (Fig. 7) where the pentagonal pier collapsed laterally and with the real-world case of the Awanogawa Railway Bridge.

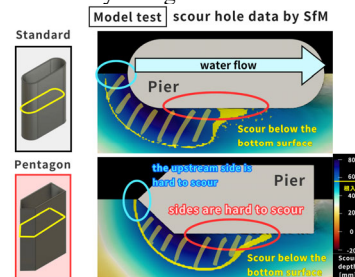


Figure 8. Comparison of scour hole between Standard pier and Pentagon pier.

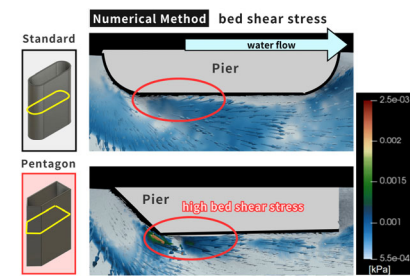


Figure 9. Comparison of bed shear stress between Standard pier and Pentagon pier.

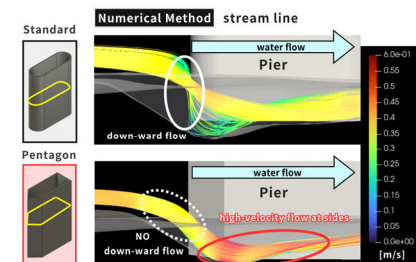


Figure 10. Comparison of streamline between Standard pier and Pentagon pier.

## 4.2 Curved Pier

This section compares the curved pier with the standard pier. A comparison of the scour hole data obtained through SfM at the same flow rate (indicated by ☆ in Fig. 7) shows that for the curved pier, the scour at the upstream end was not significantly different from that of the standard pier, while the scour along its sides was suppressed (Fig. 11). This suppression of scour along the sides can be explained by the bed shear stress distribution (Fig. 12) at the same flow rate (indicated by ☆ in Fig. 6). For the curved pier, regions near its sides exhibit bed shear stress below the critical value, which prevents sediment particle movement around its sides (Fig. 12). Fig. 8c compares streamlines around the upstream end of the standard and curved piers at the same flow rate (indicated by ★ in Fig. 7). Although the curved pier exhibits a downward flow, a low-velocity vortex forms near the bed at its upstream part (Fig. 13). Additionally, the flow clearly disperses along the pier's sides, weakening the current in its immediate vicinity (Fig. 13). This suggests that for the curved pier, although downward flow occurs, its displacement is suppressed because the low-velocity vortex and the dispersion of flow inhibit scour along the sides. This observation is qualitatively consistent with the experimental findings that the area near the curved pier is less prone to scour and that the transverse width of the scour hole is larger than that of the standard pier.

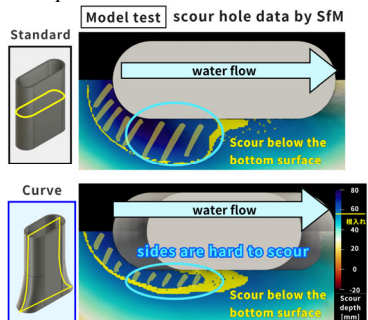


Figure 11. Comparison of scour hole between Standard pier and Curved pier.

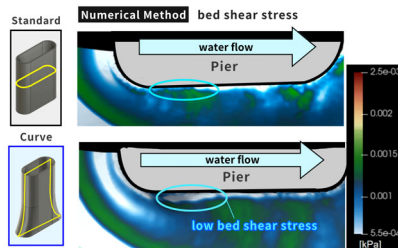


Figure 12. Comparison of bed shear stress between Standard pier and Curved pier.

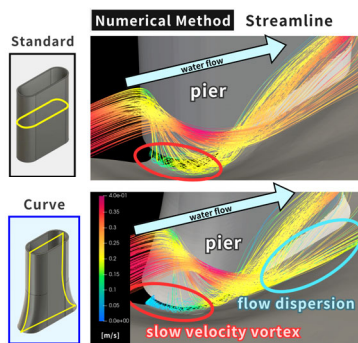


Figure 13. Comparison of streamline between Standard pier and Curved pier.

## 5 CONCLUSIONS

In this study, physical model experiments and numerical analyses were conducted to investigate the differences in scour development mechanisms for three types of river bridge pier geometries by evaluating flow fields and bed shear stress. The flow fields from the numerical analysis showed good agreement with the measurements from the physical model experiments, particularly regarding the velocities of the downward flow and horseshoe vortex near the pier base.

Furthermore, the validated numerical analysis suggested that while the pentagonal pier prevents downward flow, it causes flow to concentrate along its sides. This promotes scour on the anterolateral aspects, leading to the earlier collapse of the pier. This finding is qualitatively consistent with both experimental results and real-world phenomena. Conversely, the analysis indicated that for the curved pier, a low-velocity vortex and flow dispersion along its sides around its upstream tip scour and suppress pier displacement. This result is also qualitatively consistent with experimental findings.

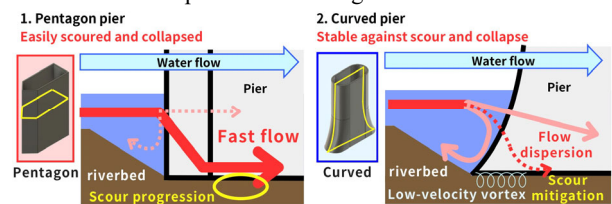


Figure 14. Local scour development mechanism of pentagon pier and curved pier.

## 6 REFERENCES

- Ayachit, U. (2015) *The ParaView guide: a parallel visualization application*. Clifton Park, NY: Kitware, Inc.
- Jasak, H. (2009) 'OpenFOAM: open source CFD in research and industry', *International Journal of Naval Architecture and Ocean Engineering*, 1(2), pp. 89-94.
- Kosaka, Y. and Watanabe, K. (2024) 'Effect of 3D pier geometry on local scour-induced instability around bridge pier foundations', in *Proceedings of the 59th Conference of the Japanese Geotechnical Society (JGS)*, Asahikawa, The Japanese Geotechnical Society. (in Japanese).
- Menter, F. R. (1992) *Improved two-equation k-omega turbulence models for aerodynamic flows*. NASA/TM-19930013620. Moffett Field, CA: NASA Ames Research Center.
- Roulund, A., Sumer, B. M., Fredsøe, J. and Michelsen, J. (2005) 'Numerical and experimental investigation of flow and scour around a circular pile', *Journal of Fluid Mechanics*, 534, pp. 351-401.
- Sekine, M. (2005) *Idōshō nagare no suirigaku [Hydraulics of mobile bed flow]*. Tokyo: Kyoritsu Shuppan Co., Ltd. (in Japanese).
- Takezaki, S., Watanabe, K. and Shimakura, C. (2023) 'Experimental study on the effect of grain size distribution of bed materials on destabilization of a river pier caused by local scouring', in *Proceedings of the 11th International Conference on Scour and Erosion*, Copenhagen.
- Vijayasree, B. A., Eldho, T. I., Mazumder, B. S. and Ahmad, N. (2019) 'Influence of bridge pier shape on flow field and scour geometry', *International Journal of River Basin Management*, 17(1), pp. 109-129.
- Watanabe, S., Morimoto, T. and Watanabe, K. (2025) 'Investigation of the July 2024 scour damage to the Saburōmaru Bridge on the Kagetsu River', in *Proceedings of the 21st Conference of the Japanese Geotechnical Society (JGS) Kanto Branch*, Tokyo, The Japanese Geotechnical Society, Kanto Branch. (in Japanese).