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Flow Structures Around a Circular Bridge Pier with a Submerged Prism at Upstream

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Abstract **-** Previous investigations have indicated that local scour around bridge piers and abutments causes around 60% of waterway bridge failures. In order to decrease the potential of pier-scour failure, the authors previously proposed an upstream prism as a new countermeasure against local scour. The proposed prism was examined in a comprehensive experimental program to find the most efficient size, submergence ratio, and installation location of the prism. The experimental results showed that the submerged prism could reduce around 40% of the maximum scour depth, and 60% of the scour-hole volume. In this study, in order to find out how this submerged prism affects the flow structure around the pier and reduces the pier-scour, the flow structure analysis was conducted using particle image velocimetry (PIV). The velocity components were measured for two cases of a single circular pier with and without the submerged prism. Analysis of the results indicated that the proposed prism could change the flow structure at the upstream and downstream of the pier. In fact, this submerged prism formed a wake region behind itself, and the bridge pier was located at this wake region. The produced wake resisted the down-flow at the upstream side of the pier and also disturbed the formation of the horseshoe vortices around the pier. In addition, this submerged prism reduced the strength of wake vortices behind the pier. Consequently, the pier-scour was significantly reduced by the substantial changes in the flow structure.

Keywords**:** Bridge pier, Local scour, Flow structures, Flow-altering devices.

1. Introduction

Bridges on waterways are important structures for transportation. Every year many bridges collapse due to different reasons, including scour, flood, earthquake, fire, collision, wind, overloading, environmental degradation, faulty design, inappropriate construction, low-quality materials, lack of maintenance, etc. Previous investigations indicate that among all the causes, scour is a significant cause and more than 60% of waterway bridge failures are due to this problem. Pier-scour is a specific form of waterway erosion. As defined by Melville and Coleman [1], scour means the lowering of the level of the river bed by water erosion such that there is a tendency to expose the foundations of a bridge.

Pier-scour is caused by the interference of the pier with the flow and characterised by the formation of the scour hole immediately around the pier. Numerous studies have been conducted to understand the mechanism of pier-scour (e.g., Melville and Raudkivi [2], Ahmed and Rajaratnam [3], Ettema et al. [4], Keshavarzi et al. [5-7]). According to Melville and Coleman [1], there are four principal features of the flow structure around a single bridge pier – down-flow, horseshoe vortices, surface rollers, and wake vortices. As shown in Figure 1, down-flow and surface rollers occur upstream of a pier, while horseshoe and wake vortices are formed at the base and the downstream of the pier, respectively. The down-flow impinges on the bed materials. The horseshoe vortex increases the velocity near the bed, resulting in an increase in the sediment transport capacity of the flow. The wake vortex system keeps the sediment suspended. It also acts as a 'vacuum cleaner' with the bed material carried to the downstream side by the eddies shaded from the pier. Therefore, an effective solution to control and reduce the pier-scour can be to change the complicated flow structure around the pier.

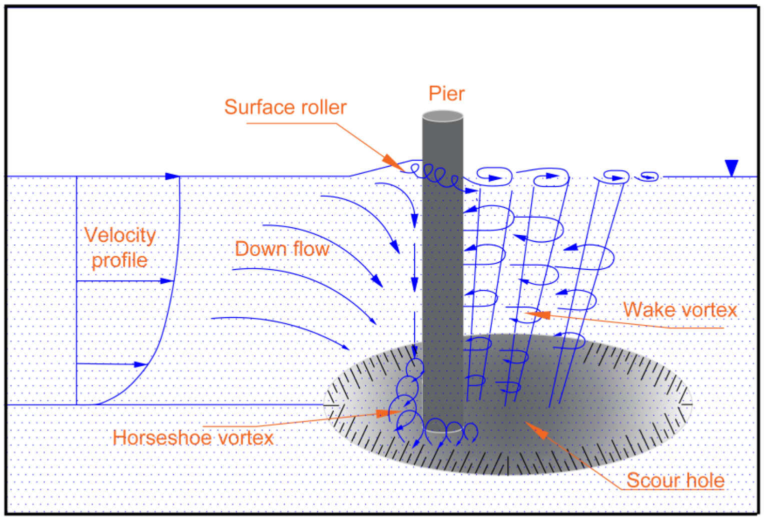


Fig. 1: Flow structure around a bridge pier.

So far only a handful of studies have been conducted to propose a flow-altering device as a pier-scour countermeasure. The brief discussions on some of the proposed flow-altering countermeasures are presented in the following paragraphs.

Iowa vanes have been proposed by Odgaard and Wang [8] as a local scour countermeasure. Iowa vanes are vertical plates installed in the stream bed just upstream of the pier and angled outwards. These devices reduce the scour by deflecting the flow approaching the pier. Lauchlan [9] investigated the use of Iowa vanes for pier-scour reduction under live-bed condition. He concluded that although the maximum scour depth reduction was significant in some tests (30% to 50%), no significant trends were evident in the data.

Melville and Hadfield [10] suggested sacrificial piles, which are a group of piles placed upstream of a bridge pier. These piles deflect the flow and create a wake region behind them to protect the bridge pier from the local scour. They concluded that sacrificial piles could be used when the flow remains aligned and the flow intensity is relatively small. However, the size and shape of the sacrificial piles were remained unclear in their study. Besides, the installation location, number of piles, their configurations and the degree of submergence need further investigations, as a group of the sacrificial piles may trap debris during flood events and produces a large contraction, or blocks the bridge opening.

Slot in the pier has been suggested as a scour countermeasure. The basic principle of using a slot in the pier is either to divert the down-flow away from the bed or to reduce the down-flow impinging on the bed. Kumar et al. [11] concluded that the slot would be practically ineffective if the approach flow had a high obliquity to the slot. As mentioned by Melville and Coleman [1], the presence of debris can block the slot, and flow skewness may render the device ineffective. Beg and Beg [12] stated that slot could not be considered as a sound scour protection device because slot reduces the strength of the pier structure and the likelihood of the slot choking due to debris and floating materials is very high.

Dey et al. [13] found that a threaded pile (helical wires or cables wrapped spirally on the pile to form threads) can reduce the local scour depth around a bridge pier. They stated that cables wrapped spirally on the pier help to diminish the strengths of the down-flow and horseshoe vortices. However, it seems that when the scour hole develops this method cannot protect the pier due to its connection to the pier. Therefore, this countermeasure cannot be considered as an effective method.

Tafarojnoruz et al. [14] carried out a literature review of flow altering countermeasures. They concluded that some flow altering devices might be applicable in the field, but require more research to prove their effectiveness, adequacy and reliability.

Ranjbar-Zahedani et al. [15, 16] showed that an unsubmerged triangular prism could be employed as an effective flow altering devices. The results of their study demonstrated that the proposed prism affected the flow structure significantly, decreasing the strength of both the down-flow and horseshoe vortices and diverting streamlines from upstream of the pier, and consequently reducing the local scour around the pier. However, as this structure is full-depth, there is a chance of accumulation of debris and floating materials around it. To solve this problem Ranjbar-Zahedani et al. [17] proposed a short prism as an effective pier-scour countermeasure. The proposed prism model showed good performance with 40% reduction in the maximum scour depth and 60% in scour volume.

The focus of this study is to find out how this short prism alters the flow structure around the pier and accordingly reduces the local scour around the pier. Therefore, an experimental study of flow structure has been conducted using the particle image velocimetry (PIV), and the results are presented in this paper.

2. Experimental set-up and procedure

A rectangular glass-sided tilting flume with nominal dimensions of 5 m long, 0.3 m wide and 0.45 m deep was used to study the flow structures under a fixed bed condition using PIV. The discharge was supplied from a tank with a circulating pump system and measured using an electromagnetic flow-meter with an accuracy of 0.4%. This flume was also equipped with a downstream flap gate to regulate the water depth. In this study, the advanced 3D printing technology was employed to create the physical model of the pier and the submerged prism accurately.

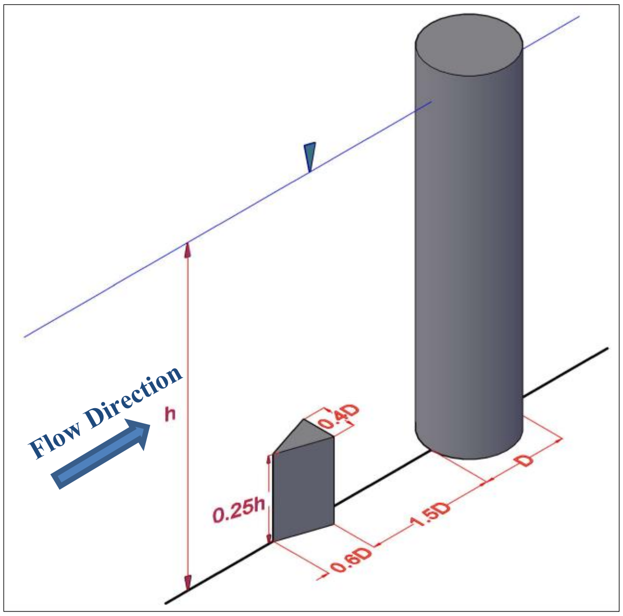
Two experiments were undertaken with the single pier only (as a control test) and the single pier with the upstream submerged prism. The models of the pier and submerged prism were installed on the centre-line of the flume, and the upstream submerged prism was located at a distance of 2.7 m from the inlet section of the flume to achieve fully developed flow. Although all experiments were conducted in a fixed-bed flume with no sediment layer, the geometric and hydraulic parameters were chosen regarding the criteria of local scour around the bridge piers. The pier diameter was carefully chosen so that there was no contraction effect on the depth of scour. According to Melville and Coleman [1], to avoid the contraction effect, the flume width should be at least ten times greater than the pier diameter. In this study, pier with diameter of 25 mm was taken for the tests. The flume width to the pier diameter ratio (W/D) was 12, satisfying the boundary condition criterion, recommended by Melville and Coleman [1]. To avoid the water depth effects on the local scour depth, Melville and Coleman [1] pointed out that the pier diameter to the water depth ratio (D/h) should be less than 0.7. Therefore, the water depth used in the experiments was set to 100 mm to satisfy this requirement. In all tests, the flow rate of 3 l/s was supplied to the flume, and the mean flow velocity (V) was equal to 0.1 m/s. The submerged prism with a lateral base of 10 mm, a longitudinal base of 15 mm, and a height of 25 mm was employed in this study. The clear distance between the pier and the prism was 37.5 mm. Details of the prism dimensions and installation locations were outlined in Ranjbar-Zahedani et al. [17]. Schematic diagram of the pier and submerged prism is shown in Figure 2a.

PIV was used for the study of flow structure in this study. In this method, a number of images are recorded to measure the displacement of particles moving within a narrow light sheet. In PIV, the fluid is seeded with small tracer particles, enabling visibility of the fluid motion. The instantaneous displacement of these seeded particles is used to retrieve information on the flow velocity field. An illustration of the PIV system and its components is provided in Figure 2b.

To collect more accurate data, the seeded particles must be able to match the properties of the fluid used for the investigation. The ideal seeding particles have the same density as the fluid being used and should be spherical. Additionally, the size of the particles should be small enough so that the time to respond to the particle motion of the fluid is reasonably short and accurately follows the flow pattern. In this study, polyamide 2070 was used for the seeding particles, which were spherical with an approximate mean diameter of 5 μm and approximate mean density of 1.016 g/cm^3.

Once the set-up was complete, the seeding particles (polyamide 2070) were added to the flow. These seeding particles were illuminated in the plane of flow at least twice employing a laser within a short time interval. The light scattered by seeded particles was acquired by a high-resolution digital camera. The displacement of seeding particles between two consecutive images determines the fluid velocity. To extract displacement information from the PIV recordings, the images were processed using a software package called VidPIV, version 4.6.

A



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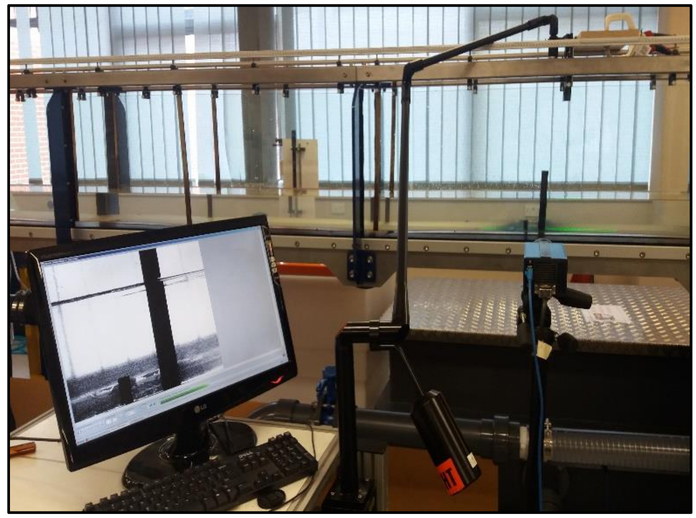

Fig. 2: Experimental set up a) a schematic diagram of the pier and submerged prism, and b) a photograph of PIV system in the laboratory.

3. Results and discussion

The flow structure was studied using the PIV method to find out how the proposed submerged prism reduces the pier-scour. The experiments were carried out for two cases including a single pier and a single pier with the upstream submerged prism. The stream-wise (u) and vertical (w) instantaneous velocity components were determined from analysis of the PIV images collected during the individual experiments. The flow structure around the circular pier in the centreline for two cases with and without the submerged prism were compared, and the results are presented in this section.

Figure 3 shows the contour plots of the stream-wise velocity component (u) in the central vertical plane for the single pier case as well as the single pier with the submerged prism. In this figure, the stream-wise velocity component (u) is normalised by the cross-sectional averaged velocity (V). As expected and also shown in Figure 3a, the value of u/V becomes smaller as the flow approaches the pier. As described by Melville and Raudkivi [2], the approach flow velocity at the stagnation point on the upstream side of the pier is reduced to zero, which increases the pressure. The associated stagnation pressures are the highest near the surface, where the greatest deceleration can be observed, and decreases downwards. This difference in the pressure forms an adverse pressure gradient on the upstream face of the pier in the vertical direction as a result of the approaching boundary layer flow. If this pressure gradient is strong enough, it will be capable of causing a down-flow on the upstream face of the pier. Down-flow interacts with the horizontal layer close to the river bed, forming a horseshoe vortex. Both the down-flow and horseshoe vortex have significant influence on pier-scour.

According to Figure 3b, when the submerged prism is placed at the upstream of the pier, the values of u decrease, and their direction became negative (from pier to the prism) in the gap region between the pier and the submerged prism and from the bed up to the height of the prism. The negative values of u interact with the horizontal layer close to the river bed and consequently can distract the formation of horseshoe vortices.

In the downstream of the pier, the magnitudes and direction of u significantly are changed by the submerged prism. In the case of the single pier (Figure 3a), the high negative values of u indicate the strong wake vortices behind the pier.

The wake vortices can washout the sediment particles and increase the scour depth and volume. Figure 3b reveals that the submerged prism changes both the magnitude and direction of the flow at the downstream of the pier, particularly close to the bed. This change can disturb the wake vortices and consequently reduce the scour.

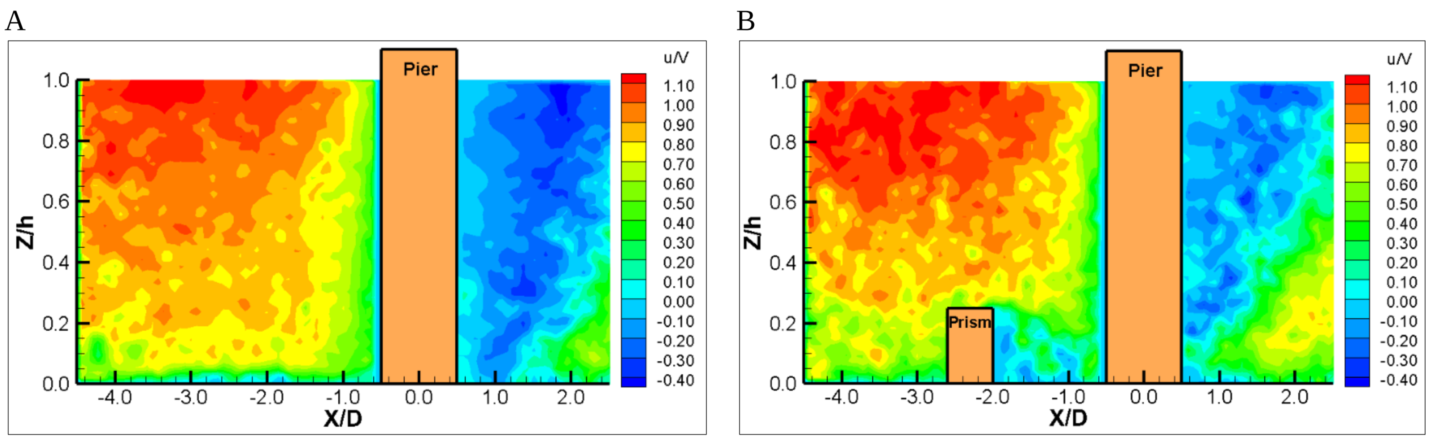

Fig. 3: Contour plots of stream-wise velocity component: a) single pier; b) pier with a submerged prism.

The contour plots of the normalised vertical velocity component (w/V) in the central vertical plane for the single pier case as well as the single pier with the submerged prism are plotted in Figure 4. Referring to Figure 4a, it can be observed that strong down-flows are formed at the upstream of the single pier and near the bed. This system of down-flows impinges the bed and removes the sediments particle from the upstream of the pier. Figure 4b indicates that the submerged prism changes the flow structure and forms a system of upward flow (the positive values of w/V) at the upstream side of the pier near the bed. In fact, a wake region forms behind the submerged prism and the pier is located at this region. This wake vortices and upward flow reduce the strength of down-flow at the upstream of the pier and hence decrease the pier-scour.

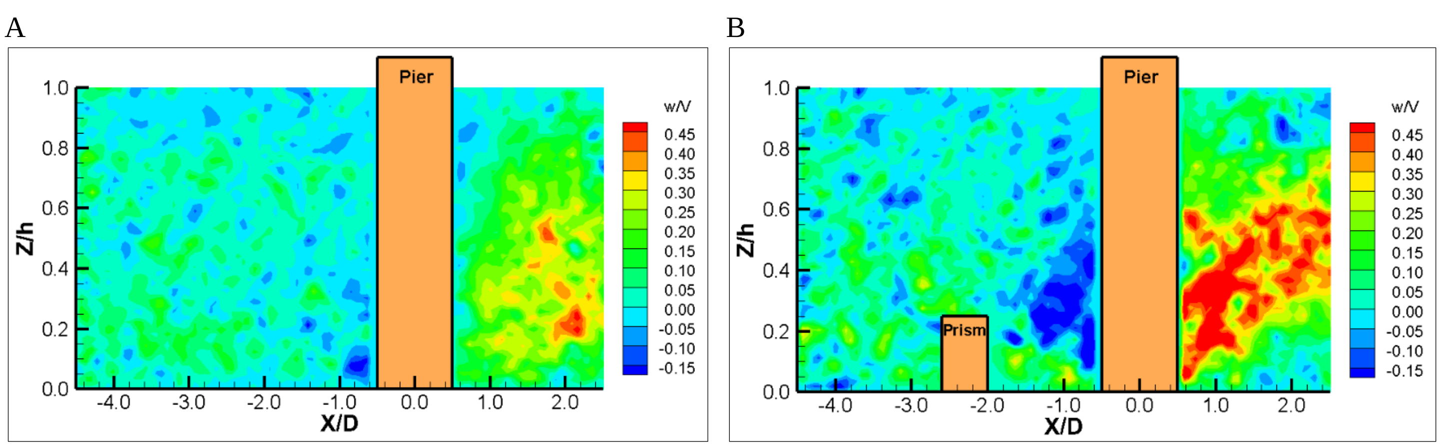

Fig. 4: Contour plots of vertical velocity component: a) single pier; b) pier with a submerged prism.

Figure 5 shows the contour plots of normalised absolute flow velocity (V_a/V) and streamline in the central vertical plane for the single pier case as well as the single pier with the submerged prism. It can be seen from Figure 5 that by installing the submerged prism at the upstream of the pier, the flow structures change around the pier. Figure 5a demonstrates the streamlines impinge to the bed at the upstream of the single pier very close to the bed. However, Figure 5b reveals the existing of upward flow in the gap region between the pier and submerged prism up to the height of the prism. This in the flow pattern reduces the scour around the pier.

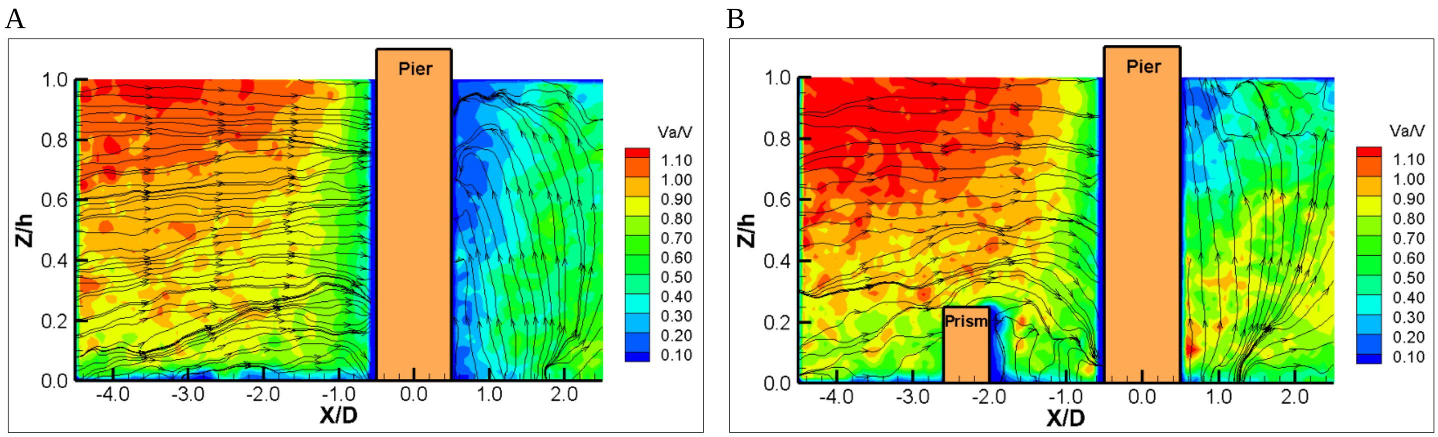

Fig. 5: Contour plots of mean flow velocity and streamlines: a) single pier; b) pier with a submerged prism.

The results, depicted in Figures 3, 4, and 5, reveal that the submerged prism significantly affects the system of vortices around a circular pier. The submerged prism produces a system of wake vortices behind itself. This wake system resists the down-flow and the horizontal layer close to the river bed. Therefore, the strength of down-flow is reduced and the formation of horseshoe vortices disrupted. In addition, the submerged prism reduces the wake vortices behind the pier. Therefore, it can be expected to decrease the scour depth and volume around the pier.

4. Conclusions

In this study, the PIV technique was used to study the effects of a small submerged prism on the flow structure around a circular bridge pier. The optimal dimensions and location of the proposed submerged triangular prism, determined by the authors' previous work, was employed in this experimental study. The findings of this experimental study demonstrate that the proposed submerged prism affects the flow structure around the pier. In fact, the bridge pier is located in the wake region, which is produced by this submerged prism. The produced wake withstands the down-flow at the upstream face of the pier and also disturbs the formation of the horseshoe vortices around the pier. Furthermore, this submerged prism reduces the strength of wake vortices behind the pier. Consequently, it can be stated that the submerged prism reduces the pier-scour by changing the complicated vortices systems including down-flow, horseshoe vortex and wake vortex around the pier. Debris and floating materials will not be blocked by submerged prism due to its short height. The submerged prism can be applied for both new and existing bridge piers to control and reduce the depth and volume of local scour around them.

Notations

D: Pier diameter
h: Water depth
W: Flume width
Q: Flow rate
V: Cross-sectional averaged velocity ($V=Q/(h\times W)$)
u: Stream-wise instantaneous velocity components
w: Vertical instantaneous velocity components
V_a Absolute velocity ($V_a=(u^2+w^2)^{0.5}$)
X Stream-wise direction
Z Vertical direction

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