Flow Characteristics and Scour Depth in Lenticular Shaped Pier: Case Study at Ciujung Bridge, Banten

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Abstract. Pier is part of the structure under the bridge. The existence of a pier in the river flow causes changes in river flow patterns. Changes in the flow pattern will result in local scouring around the pier. This study aims to determine the effect of the shape of the pier on the potential for local scour that occurs around the pier, and the flow characteristics around the pier. This study modelled the existing conditions of the Ciujung Bridge, where the Ciujung Bridge uses an oblong pier shape, and the shape will be replaced with a lenticular model pier. FLOW-3D (CFD) software will be used to modelled flow characteristics and the depth of scour that occurs.

Keywords: Pier, flow velocity, scour depth, Froude number, Flow-3D

1. Introduction
River as one of the watersheds cannot be separate from the influence of scour because the flow in the river is accompanied by sediment transport. The flow of water in a river has energy so that it can carry sediment. As a consequence of this sediment transport, a scouring process occurs \cite{1,2}. The need for adequate bridge facilities is a condition to be achieved. A bridge is a structure that crosses a river, allowing vehicles, trains, and pedestrians to pass smoothly and safely. Bridge can be said to have a balancing function in the transportation system because the bridge will control the volume and weight of traffic that can be served by the transportation system. The function of the bridge is to connect two parts of the road that are cut off by obstacles such as deep valleys, river channels and irrigation channels.

The problem that has often been encountered on bridges across rivers is the inadequate functioning of the lower structures of the bridge (foundations, piers, abutments) to support the bridge\cite{3}. In some cases, this has resulted in the collapse of the bridge. Threats to the safety of the structure under the bridge often originate from river dynamics, especially the dynamics of the riverbed around the foundation and bridge piers \cite{4}.

The main cause of damage to the bridge is the bridge pier that is not functioning properly. The lack of proper functioning of the bridge pier occurred due to the influence of the local scouring process that occurs on the riverbed which can slowly endanger the construction of the bridge. Local scouring of a sediment-free flow occurs when the average water velocity is less than the threshold
velocity which causes sediment to move (sediment entrainment)[5]. The flow that occurs in rivers is usually accompanied by a process of scouring / erosion and sedimentation / deposition. The scouring process that occurs can be caused by the morphological conditions of the river and the shape of the pier that blocks the flow[6]. Buildings such as bridge piers can change flow patterns, so that in general they can cause local scouring[7]. A numerical modeling is widely utilized to simulate the scour that occurs around bridge pier, with the help of the CFD (Computational Fluid Dynamic) program, namely FLOW-3D[8]. Therefore this research will carry out numerical modeling using CFD program to simulate scouring of bridge piers.

2. Methodology

2.1. Study Area and Pier Shape of Bridge
Ciujung bridge is connecting a hinterland and rural area of Kendayakan Village, Serang Regency, Banten Province, Indonesia. The river flow discharge of Ciujung River from previous research [9,10] was utilized in this study. The shape of the pier that will be modeled for simulating the characteristics of flow and scour is the lenticular shape (Figure 1).

![Figure 1. Lenticular pier shape](image)

The pier has length of 10 meters and width of 3 meters. The size of the pier that will be used in numerical modeling is adopted from the size of the original Ciujung bridge piers.

2.2. Model Analysis
Numerical modeling will be carried out using the FLOW-3D (CFD) program. Modeling will be carried out for the existing state of the Ciujung Bridge with lenticular-shaped piers (Figure 2). The flow discharge used in modeling is 1240.565 m$^3$/s. The assumption for determining the flow discharge is based on previous research where the range of $Q_{50}$ to $Q_{100}$ of the Ciujung River is 900 to 1200 m$^3$/s. Sediment particle median size ($d_{50}$) that will be used is 0.53 mm.

![Figure 2. (a) Defined boundary conditions of the computational domain; (b) Detail of applied mesh in computational domain](image)

Terrain conditions and pier placement are based on the existing conditions of the Ciujung Bridge, with the contours and cross sections of the river that have been previously measured. The mesh size used is 0.8 meters. The assumption of using this mesh size is the result of the tolerance for
the duration of time required to run the simulation, where the smaller the mesh is used, the more accurate the results will be, but it will take longer to complete the simulation. The time required to run the 120 seconds simulation is about 6 to 8 hours for a mesh size of 0.8 meters, using a computer with 6 cores CPU and 16 GB of RAM. Observation of the results of the flow velocity around the pier will be carried out per 2 piers, namely the pier that is parallel to the longitudinal distance (Figure 3).

![Figure 3. Flow characteristic observation location](image)

The analysis will be carried out in a grid that has been defined in the FLOW-3D software, where the grid is a square with a size of 0.8 meters. The data to be presented is shortened using only the maximum speed in each y grid (longitudinal distance). After that, the maximum flow velocity data that has been obtained on each y grid will be displayed in graphical form.

![Figure 4. Pier locations and Scour observation points](image)

For scour analysis, because in the modeling there are 4 piers, the scour analysis will be carried out on 4 piers, with the observation points that have been determined (Figure 4).

3. Results and Discussion

3.1. Flow Characteristic

Based on the results of the analysis of the flow characteristics of oblongpier shape, when compared to three flow discharges, the comparison value shown in Figure 5 will be obtained. In Figure 5 and Figure 6, it can be seen the relationship between the results of the maximum flow velocity ($U_{\text{max}}$) to the longitudinal distance in the lenticular pier shape model. Based on the graph above, it can be seen that the closer to the pier is and when it is around the pier, the flow velocity ($U$) will increase. This happens because of the narrowing of the river cross-sectional area ($A$) which occurs due to obstacles
from the under-bridge structure, where in this study the structure is a bridge pier. From the results of numerical analysis, for piers 1 and 3, the lowest flow velocity ($U_{\text{min}}$) is 2.28 m/s at a distance of 24.8 meters, and the flow discharge ($Q$) is equal to 840.565 m$^3$/s with a flow depth ($d_0$) of 5.93 meters from the surface of the flow along the z axis. The highest flow velocity ($U_{\text{max}}$) is 6.7 m/s at a distance of 35.2 meters, and the flow discharge ($Q$) is equal to 1240.565 m$^3$/s with a flow depth ($d_0$) of 1 meter from the flow surface, along the z axis. For piers 2 and 4, the lowest flow velocity ($U_{\text{min}}$) is 2.02 m/s at a distance of 24.8 meters, and the flow discharge ($Q$) is equal to 840.565 m$^3$/s with a flow depth ($d_0$) of 2.06 meters from the flow surface in the z axis. The highest flow velocity ($U_{\text{max}}$) is 9.39 m/s at a distance of 36.8 meters, with a flow discharge ($Q$) equal to 1240.565 m$^3$/s at a flow depth ($d_0$) of 0.34 meters from flow surface in the direction of the z axis.

Figure 5. Comparison of flow velocity (U) against longitudinal distance (Pier 1 and 3)

Figure 6. Comparison of flow velocity (U) against longitudinal distance (Pier 2 and 4)
Based on Figure 7, the Froude number that occurs in the flow observation results against the longitudinal distance before pier 1 shows various Fr values. In fact, there was a spike in Froude number at a distance of 1 to 6 meters. The maximum Froude spike that occurs before pier 1 is 6.7 at a distance of 4 meters long, with a flow discharge of \( Q = 840.565 \text{ m}^3/\text{s} \) at a flow depth \( d_0 = 0.06 \) meters from the flow surface along the z axis. The moment before and entering the area around pier 1, there was no visible spike in Froude's numbers. Froude's number is stable <1 (sub critical flow) up to a distance of 32 meters, when it enters the area around pier 3. In the area around pier 3, Froude number increases with a maximum spike of 4.57 at a distance of 36.8 meters, with a flow discharge \( Q \) of \( 840,565 \text{ m}^3/\text{s} \) at a flow depth \( d_0 \) of 0.1 meter from the flow surface in the direction of the z axis. After the flow passed through pier 3, Froude number stabilized <1 (sub critical flow). Based on Figure 8, the flow before pier 2 is stable on average <1 (sub critical flow). Shortly before entering the area around pier 2, it can be seen that Froude number has a small spike of 1.93 at a distance of 8 meters,
with a flow discharge of \( (Q) \ 1040.565 \ m^3/s \) at a flow depth \( (d_0) \ 0.88 \) meters from the unidirectional flow surface along the \( z \) axis. Froude numbers in the area around pier 2 are on average stable below 1 (sub critical flow). This sub-critical flow state lasted until entering the area around pier 4. In the area around pier 4, Froude number increased with a maximum surge of 6.6 at a distance of 30.4 meters, with a flow discharge of \( (Q) \ 1240.565 \ m^3/s \) at flow depth \( (d_0) \ 0.16 \) meters from the flow surface in the direction of the \( z \) axis. After the flow passed through pier 4, Froude number had not shown a decrease, and was still a critical flow over a distance extending to 46 meters.

3.2. Scour Depth Analysis

The comparison that will be shown is the relationship between scour depth and time (scour development against time on 4 piers in each point.

![Figure 9. Comparison of scour development against time between pier locations and observation points](image)

In Figure 9, it can be seen the relationship between the development of the scour depth against time on various piers with different positions, as well as 4 observation points, namely on the upstream, downstream, right side and left side of the pier. Based on the trend graph above, it can be seen that the scour that occurs on the lenticular pier has increased the depth of the scour which was initially large and then over time, the increase in scour will decrease until certain minutes have reached a state of equilibrium (equilibrium scour depth). Scour often occurs at points 1 and 3, namely on the left and right side of the pier. This is because on the left side of piers 1 and 3 there is a narrowing of the cross-sectional area \( (A) \), as well as on the right side of piers 2 and 4. Narrowing the cross-sectional area of the river will cause an increase in flow velocity \( (U) \). The high flow velocity after hitting the pier will produce a vortex system, where this vortex system will cause scouring. This can be proven by the results of the analysis of the flow characteristics around the pier, where in the area around the pier, the flow velocity \( (U) \) is high which is the critical flow \( (Fr>1) \). The smallest scour development was achieved at observation points 2 and 4, until sedimentation occurred.
Figure 10. Scour development against time (pier 3, point 1)

Figure 11. Elevation contours of lenticular pier shape
In the trend of scour development graph (Figure 10), it can be seen that the effect of scour depth \( d_s \) on time with variations in flow discharge \( Q \), where the greater the flow discharge \( Q \) flowing through the bridge piers, the greater the scour depth \( d_s \) that occurs over time until it reaches a state of equilibrium (equilibrium scour depth).

FLOW-3D software can generate terrain elevation contour. In Figure 11, the contour of the terrain elevation can be seen at the end of the simulation. It can be seen the areas that have been scoured not only around the pier, but also around the other riverbeds. From the contour, it can also be seen that some areas have experienced sedimentation.

![Figure 12. Maximum scour depth development over time](image)

Figure 12 shows the maximum scour depth against time for the results of the study, compared to the results of previous researchers, namely 11[5] who used cylindrical piers with a critical flow velocity parameter of \( U/U_c \) of 0.71, 12[6] which uses a cylindrical pier with a critical flow velocity parameter of \( U/U_c \) of 0.9, and 13[7] which uses a cylindrical pier with a critical flow velocity parameter of \( U/U_c \) of 0.73. For the results of the research itself, the trend graph uses \( Q \) 1240 m\(^3\)/s with a critical flow velocity parameter of \( U/U_c \) of 0.62. The graph for the research results indicates that 50\% of the maximum scour depth \( (0.5 \, d_s, \text{max}) \) was achieved at times varying from 20\% to 70\% \( t_p \), depending on the shape of the piers. For piers with a cylindrical shape by previous researchers, 50\% of the maximum scour depth was achieved faster than the research results. The function of the graph above is to show the importance of time in measuring and estimating the scour depth.

4. Conclusion
Based on the results of the analysis of flow characteristics around the lenticular pier, the flow velocity reaches its peak when around the pier. This is because around the pier, there is narrowing of the river cross section which causes the flow velocity to increase. According to Froude number analysis, the area around the pier is a super critical flow area because Froude number is always above one. This is directly proportional to the scour analysis. Scouring often occurs in areas where the river cross section...
is narrowing, namely points 1 and 3. Points 2 and 4, which are located upstream and downstream of the pier, do not experience significant scouring, even sedimentation occurs.

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