Oblong Bridge Pier Shape Influence toward Flow Velocity Characteristic and Scour Depth

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Abstract. Flows that occur in rivers are usually accompanied by scouring/erosion and sedimentation/deposition processes. The scouring process that occurs can be caused by river morphological conditions and the existence of river structures that obstruct the flow. Structures such as bridge piers can change flow patterns so that in general can cause local scouring. One method for reducing the scouring that occurs around a bridge pier is to consider the shape of the pier bridge design. One of the most common pier bridge designs is the oblong shape. This research aims to find out the effect of streamlining the oblong pier shape on the change in flow characteristic and scour depth reduction using FLOW-3D numerical modeling.

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

1. Introduction
In making roads for land transportation, crossing river channels is inevitably unavoidable, so bridge-building is necessary. In its design, several aspects have been considered such as the location of the bridge, the hydraulic aspects of the river and the shape of the piers that will provide the flow pattern around it. The bridge structure generally consists of two important buildings, namely the superstructure and the lower structure. One of the main structures under the bridge is a bridge pier which is always in direct contact with the river flow. The main factor causing structural failure is the result of natural disasters (earthquakes, storms, floods/scouring, volcanic eruptions, and tsunamis) [1]. Of the several natural disasters that have occurred, damage to bridge structures due to flooding/scouring ranks first as the cause of failure.

Scouring is a natural phenomenon caused by water flow which usually occurs on riverbeds consisting of alluvial material but sometimes it can also occur in rivers that have high flow velocity and discharge [2,3]. Scouring can cause the erosion of the soil around the foundation of a building that is in a watercourse [4,5]. Scouring usually occurs as part of changes in the morphology of rivers and changes due to man-made structures [6,7]. To avoid damage to the bridge, it is necessary to calculate the prediction of local scouring on the understructure of the bridge, to reduce the risk of damage and avoid a collapse of the dangerous bridge.

This research will analyze the flow and scour patterns on the piers of the Ciu Jung Bridge. Ciu Jung Bridge which functions as a toll road has oblong piers. Based on the results of previous research [8,9] on the efficiency of various pier shapes in reducing flow turbulence and local scouring, this research will carry...
out numerical modeling using the help of the CFD (Computational Fluid Dynamic) program, namely FLOW-3D \[10\], to simulate flow turbulences and local scour around Ciujung Bridge piers, where the original shape of the Ciujung Bridge piers (oblong pier shape) will be replaced with a lenticular pier shape.

2. Methodology

2.1. Bridge Pier Shape

The shape of the pier that will be modeled for simulating the characteristics of flow and sediment scour is the Ciujung oblong pier shape.

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

The pier has a length of 10 meters and a width of 3 meters. The size of the pier that will be used in numerical modeling is adopted from the size of the 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 oblong-shaped piers (Figure 1). 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 the 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 (Figure 2). 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 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). Moreover, the maximum speed 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 the oblong pier 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 oblong pier shape model. Based on Figure 5 and 6, it can be seen that the closer to the pier and when it is around the pier, the flow velocity ($U$) will be increased. This happens because of the narrowing of the river cross-sectional area ($A$) which occurs due to obstacles from the
under-bridge structure, wherein 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 2.259 m/s at a distance of 25.2 meters, and flow discharge ($Q$) is equal to 840.565 m$^3$/s with a flow depth ($d_0$) of 6.52 meters from the surface of the flow in the direction of the z-axis.

![Figure 5. Comparison of flow velocity (U) against longitudinal distance (Pier 1 and 3)](image1)

The highest flow velocity ($U_{\text{max}}$) is 8.305 m/s at a distance of 36.93 meters, and the flow discharge ($Q$) is equal to 1240.565 m$^3$/s with a flow depth ($d_0$) of 0.27 meters from the flow surface along the z-axis. For piers 2 and 4, the lowest flow velocity ($U_{\text{min}}$) is 2.287 m/s at a distance of 26.1 meters, and the flow discharge ($Q$) is equal to 840.565 m$^3$/s with a flow depth ($d_0$) of 1.81 meters from the flow surface in the direction of the z-axis. The highest flow velocity ($U_{\text{max}}$) is 8.841 m/s at a distance of 17.11 meters,

![Figure 6. Comparison of flow velocity (U) against longitudinal distance (Pier 2 and 4)](image2)
and the flow discharge (Q) is equal to 1240.565 m³/s with a flow depth (d₀) of 0.15 meters from the flow surface along the z-axis. This indicates a velocity spike when the flow hits the pier. Flow is called subcritical if Fr < 1, critical if Fr = 1, and supercritical if Fr > 1.

Figure 7. Comparison of Froude Number (Fr) against longitudinal distance (Pier 1 and 3)

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. At a distance of 0 to 5 m, the value of Fr > 1, which indicates that the flow that occurs is critical. The closer to the pier, the value of Fr < 1. When around the pier, the value of Fr soars up to reach a maximum value of 7.01 at a distance of 19.8 m, and flow discharge (Q) of 1040.565 m³/s with a flow depth of 0.1 meters from the flow surface in the direction of the z-axis. Based on Figure 8, the flow before pier 2 shows the value of Froude number below and equal to one. At the same time around the pier, Froude number soared to a value of 7.2 at a distance of 17.1 meters with a flow discharge (Q) of 1240.565 m³/s, at a flow depth of 0.15 meters from the flow surface along the z-axis. Then, between the piers, Froude number stabilized below 1 for all three flow variations. Froude number fluctuates around pier 4, with a maximum value of 7.8 at a distance

Figure 8. Comparison of Froude Number (Fr) against longitudinal distance (Pier 2 and 4)
of 34.2 meters, with a flow discharge (Q) of 1040.565 m³/s, at a flow depth of 0.1 meters from the surface flow in the direction of the z-axis. Froude number spike continues at a longitudinal distance of 52 meters after passing through pier 4. This indicates the supercritical area is around the pier and after the pier.

### 3.2. Scour Depth Analysis

The comparison that will be shown is the relationship between scouring depth and time (scour development against time on 4 piers at 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 Figure 9, it can be seen that the scour that occurs on the oblong pier has increased the depth of the scour which was initially large and then over time, the increase in scouring 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 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. In the trend of 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).

![Figure 10. Scour development against time (pier 3, point 1)](image-url)
Figure 11. Elevation contours of oblong pier shape (a) $Q = 840.565 \text{ m}^3/\text{s}$; (b) $Q = 1040.565 \text{ m}^3/\text{s}$; (c) $Q = 1240.565 \text{ m}^3/\text{s}$

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 shows the maximum scour depth against time for the results of the study, compared to the results of previous researchers, namely [11] who used cylindrical piers with a critical flow velocity parameter of $U/U_c$ of 0.71, [12] which uses a cylindrical pier with a critical flow velocity parameter of $U/U_c$ of 0.9, and [13] 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 $Q = 1240.565$ 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 ($0.5d_{max}$) 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 oblong pier, the flow velocity reaches its peak when around the pier. This is because around the pier, there is a 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 supercritical 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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