The effect of bridge abutment shape variation toward flow velocity characteristic

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Abstract. Lots of bridge failure phenomenon caused by scour on pier foundation or abutment. One of the most important factors of the bridge is the abutment. Abutment is a structure, built at the edge of the bridge. Abutment is designed to hold the weight of the bridge and over the bridge. The structure of abutment usually planted in to the river. One of methods to minimize the scour impact is considering the shape and design of abutment. This research aims to find out the effect of abutment model or shape variation (semi-circular end abutment, wing wall abutment and spill through abutment) toward the change of velocity using Flow-3D for numerical modeling, the physical test to validation the flow condition and analyze the characteristic sediment transport pattern using Hjulstörm curve. The result of research state that the spill through abutment is the most effective model to keep the stability of flow velocity around the abutment. Correlation between Froude Number (Fr) with Relative Longitudinal Distance Ratio is discussed in this paper. Then, Hjulstörm curve shows that with bed material diameter ($d_{50}$) of 0.54 mm, sediment transport in the entire abutment model located at erosion zone.

Keywords: Abutment, sediment transport, velocity, Hjulstörm curve, Flow-3D

1. Introduction
Bridge is a structure construction that used to connect two sections of the road and used as infrastructure for land traffic. In designing bridge construction, there are several aspects must be considered such as the location of the bridge, the hydrodynamic aspects of the river and the shape of the lower structure (pier, abutment) which will provide the flow pattern around it [1].

From the hydraulic aspect of the river, with presence of bridge lower structure such as abutment, it will cause the changes flow characteristics such as speed and turbulence that causing damage at bridge lower structure. Some of previous studies [2,3] which state that when the stream in the river approaches the abutment, there will be an increase of pressure due to rising water levels. The increase of pressure will cause a down-flow formation, so it potentially to scour the lower structure or abutment. Type or model of abutment will affect the flow velocity characteristic around the abutment and the flow velocity have linear relationship with the depth of scour [4]. Bridge scour is one of the main causes of bridge failure. To prevent this condition, it is very crucial to thoroughly understanding the river behavior changes at the upstream and downstream area of bridge and barrage constructions [5].
Local scour around the bridge abutment can be minimized by considering the shape and the design of abutment model. The effective design will provide the flow which has the smallest effect on scour around the bridge abutment [6]. One of parameters affecting the scour depth is flow velocity. Hence, the study of the effect of abutment shape variation toward velocity characteristic changes needs to be studied for further.

2. Methodology
2.1. Study Area
The flow characteristic was investigated in open channel flow (Figure 1). The experiment was conducted at the Hydraulic and Fluid Laboratory of Civil Engineering Department, Bina Nusantara University.

2.2. Model Analysis
The analysis of velocity characteristic around the abutment examined by using 3D numerical model (Flow-3D) and using AutoCAD to make the geometry of abutment model. For the dimension of geometry abutment model, this experiment used laboratory scale (in Figure 1) so the result of this numerical test can be compared with the physical test. There are several steps to run the numerical analysis which are input the geometry model, fluid properties, boundary condition (velocity and water level), meshing, setup the output data and then run the simulation [6].

The result from flow velocity analysis using Flow-3D is the value of flow velocity at each observation location that shows at Figure 2. Then the analysis will continue using Microsoft Excel by shorting the data result to find out the maximum flow velocity at each longitudinal distance (y). After
that, the maximum flow velocity that has been obtained in each longitudinal distance \((y)\) is presented in graphical form.

3. Results and Discussion

In Figure 3 shows the graph of variation abutment model toward the flow velocity \((v)\) at longitudinal section \((y)\) when the discharge \((Q)\) in maximum condition 0.00645 m\(^3\)/s. From the graph can be known that the flow velocity \((v)\) will increase when there is a contraction of channel cross section, this is in accordance with the principle of continuity which states that the discharge along the water channel is constant \((Q = v \times A)\). So, when the channel cross section \((A)\) shrinks, the flow velocity \((v)\) will increase.

Graph from Figure 3 states that the model or shape of abutment will affect the flow characteristic in open channel flow. It can be seen at longitudinal direction \((y)\) equals to 1.2 m until 2.0 m, the flow velocity after passing the semi-circular end abutment model can be stabilized more quickly than the other models of abutment. For spill through abutment model, it can be seen when the longitudinal direction \((y)\) equals to 0.7 m until 1.0 m, the flow velocity will decrease before reach the abutment. At wing wall abutment model, the flow velocity after the abutment can’t return to stable quickly like other models of abutment.

From the previous study by Nenny and Hamza \([7]\), the flow velocity will affect the depth of scour. The grater of the flow velocity, the greater of the scouring depth. Hence, the wing wall abutment model will have the higher risk of scouring depth that can occur after the abutment section.

From Figure 4, it can be concluded that the flow characteristics before passing the hydraulic structure or abutment are sub-critical \((Fr < 1)\), then the flow characteristics when passing through the abutment are critical \((Fr = 1)\), and the flow characteristic after passing the abutment become super-critical \((Fr > 1)\) until the flow characteristic return to initial condition or stable condition \([8]\).

From the graph in Figure 4, shows that the shape or model of abutment will affect the flow characteristic in the open channel. It can be seen when the longitudinal distance \((y)\) is 1.20 m until 2.00 m, the flow characteristic that produce from semi-circular end abutment model can be stable faster than the other abutment model. Otherwise, the wing wall abutment model still in the super critical condition when the longitudinal distance \((y)\) is 2.00 m.

![Graph of Variation Abutment Model toward the Flow Velocity at Longitudinal Section](image-url)
Figure 4 shows that there is a vortex system around the abutment. The vortex system starts to occur when the upstream flow hit the abutment wall then causing a downward flow direction. Then the downward flow will move partially to other side (downward side) of the abutment. Flow that moves vertically or downward will go to the river bed and produce the vortex system on the upstream side of abutment. Then the vortex that occurs in the downstream of abutment is caused by the flow that moves around the abutment and then crashing into the wall at downstream side of the abutment [9]. Spill through abutment model produce a better flow pattern or stream lines compared with other abutment model in this research. Figure 5 also shows that the vortex system occurs on both side (upstream and downstream) of abutment with a better pattern compared with other models. Then the spill through abutment produce the lowest flow velocity based on graph form Figure 3. Based on previous study by Mellville [10], spill through abutment model has a smaller shape coefficient value than the other two models. Which means the depth of scour that produce by spill through abutment can be smaller than semi-circular end model and wing wall model.

Figure 6 shows the non-dimensional parameter which is the correlation between Froude number with the relative longitudinal distance ratio ($y_i/y$) for entire variation model. The relative longitudinal distance ratio is the certain observation location ($y_i$) compared with total longitudinal distance ($y$). The location that be observed start from $y = 0.9$ m until $y = 1.2$ because there is a contraction of channel due to the abutment in that range so the velocity and Froude number will increase significantly. Hence, this analysis presents the correlation of non-dimensional parameter at range $y = 0.9$ m until $y = 1.2$ m.

The equation resulted from the development of theoretical studies can be used to determine the flow characteristics that are effective based on the effect of their shape or model (see Table 1). The boundary conditions of the flow characteristic equation are the abutment located at the middle of relative longitudinal distance ratio ($y_i/y = 0.5$), the maximum flow velocity is 1,0089 m/s and the minimum flow velocity is 0,3189 m/s.
Figure 5. Streamline Abutment Models (a) Semi-Circular End (b) Spill Through (c) Wing Wall

Table 1. The Equation of Froude Number toward Relative Longitudinal Distance Ratio

| Abutment Model                | Equation         | Regression |
|-------------------------------|------------------|------------|
| Semi-Circular End Abutment    | $Fr = 0.8161 \frac{y}{y} + 0.5914$ | 0.7538     |
| Wing Wall Abutment            | $Fr = 0.9715 \frac{y}{y} + 0.7153$ | 0.8906     |
| Spill Through Abutment        | $Fr = 1.0178 \frac{y}{y} + 0.5325$ | 0.877      |

Hjulstörm curve is a curve that connects the grain size of bed material with the flow velocity. The diameter of bed material used the result of sieve analysis, where the grain size $d_{50}$ is 0.54 mm. Then the flow velocity used the maximum value from the result of the velocity analysis. Figure 7 shows the sediment transport pattern at entire models of abutment.

The sediment transport process occurs due to the high velocity which make the material can move from upstream to downstream. Then, the material will be deposited when the velocity slowing down. When the velocity rises again, the material can be moved again, and it occurs repeatedly until it reaches the deposition zone at downstream [11]. Based on Figure 7 the flow velocity that needed to move the bed material which form of medium sand from stationary conditions are ranges at 20 cm/s to 30 cm/s. Figure 7 shows that the sediment transport pattern occurs similar with other conditions. The scouring process that occurs at each observation location is at the transportation zone and erosion zone or above the fall velocity threshold. Fall velocity indicates the bed material conditions that have been transported and in settling positions. The bed material and the velocity that exceeds the threshold will causing the bed material be transported and eroded and allow the scouring to occur.
**Figure 6.** Correlation between Froude Number with Relative Longitudinal Distance Ratio

![Figure 6](image)

**Figure 7.** (a) Hjulstöm curve, (b) enlargement Figure

The erosion velocity threshold is a boundary which indicates that shows a condition has begun to occur an intensive erosion process. If the relationship between the bed material and flow velocity
located at this boundary, then the scouring process will occur intensively [13]. However, the scouring process not only occur in the erosion zone and transportation zone. At deposition zone, scouring can also occur under certain conditions.

Figure 7 shows that the all variation model that observed located above the erosion velocity threshold. This shows that the bed material can be eroded intensively and then transported to another location. From all three models that have been analyzed, the biggest flow velocity occurs around the wing wall abutment model which is equals to 91.59 cm/s.

The Hjulstörm curve cannot fully described the scouring process of bed material at observation location. This is caused by limitation that can affect the accuracy of information on the sediment transport. The limitations include ignorance of both the density of rocks and the distribution of flow velocities in a channel cross section. Rock density is one of the important parameters in determining the sediment transport process. It is important because the gravitational force will affect the grain size of bed material. Rock with bigger density will be easier to settle. This curve only uses grain size parameter, so the result is less accurate.

4. Conclusion
The present study focuses on numerical simulation of flow velocity around the three abutment models and the sediment transport process. The effect of abutment shape variation toward the velocity changes is examined by using 3D numerical model (Flow-3D). It was found that the shape of abutment will affect the flow velocity around the abutment. Spill through abutment model is the most effective model to keep the stability of flow velocity around the abutment. In sediment transport analysis, the grain size of bed material that used is 0.54 mm or medium sand type. The result of sediment transport analysis indicates that the bed material has potential to eroded intensively and then transported to another location. And for further study, it’s very important to find out the depth of scour or how much the depth of bed material that can be eroded. The study for turbulence characteristics around the variation of structures need to be studied in detail.

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