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RIPRAP PROTECTION TO CONTROL SCOURING ON BRIDGE PIERS IN KUALA SAMBOJA RIVER

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ABSTRACT
Kuala Samboja Bridge located on Balikpapan-Handil II pivot street is a link between drivers from Balikpapan to Handil (Kuala Samboja) and vice versa. Built in 1992, this bridge is the only link between Balikpapan and Kuala Samboja (Pradana et al., 2022). Based on previous research conducted in 2022, there are indications of local scour on the Bridge pillars. This research aims to design a protection structure around the bridge pillars using riprap revetment. The scour depth is determined through two stages, which are direct measurement using an echosounder and calculation using the HEC-18 and Salim & Jone methods. The discharge used is the dominant discharge ($Q_{dominant}/Q_{2yr}$) of 366.34 m^3/second. The scour depth that occurs around the bridge pillars by measurement is 0.946 meters. The calculation results of the scour depth around the bridge pillar using HEC-18 method is 1.941 meters, while scour depth using Salim & Jone method is 1.429 meters (envelop curve) and 1.178 meters (best fit curve). Salim & Jone method provides the closest results to the field measurements because this method considers the pillar group factor, while the HEC-18 method does not. Riprap revetment is designed to protect and reduce the intensity of scour around the Kuala Samboja bridge pillars. Based on the calculations that have been carried out, the required riprap rock dimensions are at least 0.37 feet or 12 cm, while the dimension of the riprap is 0.8 meters in depth, 6.5 meters in width and 8 meters in length.

Keywords:
Local Scour, Bridge Pier, Protective Structures, Riprap Revetment, Kuala Samboja

INTRODUCTION
Balikpapan-Handil II pivot street located in Samboja Sub-district, is one of the provincial roads that connects Balikpapan City with Handil Village, Kuala Samboja Bridge is a bridge located on pivot street Balikpapan-Handil II, built in 1992, this bridge is the only link between Balikpapan pivot street and Kuala Samboja [11]. Based on previous research conducted by [11], there are indications of local scour on the Kuala Samboja Bridge pillars, the calculation of the depth of local scour using the Froehlich method resulted in a scour depth of 0.741 m and 0.922 m using the Laursen & Toch method. As a response, this study attempts to design riprap revetment to prevent further scouring around bridge pillars. The scour depth is determined through two stages, which are direct measurement using an echosounder and calculation using the HEC-18 and Salim & Jone methods using dominant discharge. Rivers or open channel according to [15] are channels where water flows with a free water level. In open channels, such as rivers (natural channels), flow variables are very irregular in space and time. These variables are channel cross section, roughness, base slope, flow discharge turns and so on [12]. As one of

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the main sources of human life, rivers plays an important role in the environment. Changes in river shape, water quality and quantity, including flooding can jeopardize the lives of residents around the river and their economic and social activities [13]. Although rivers experience a wide range of flows, their shape and geometry are generally governed by the dominant flow at a given return period. This flow controls the dimensions of the river under non-flood flow and its cross section is constant and stable under this flow [5]. Dominant discharge is the flow that controls the shape of a river cross section and does not change the cross section over a long period of time. In principle, the dominant discharge has a short return period with a high frequency of occurrence. In other words, dominant discharge refers to a steady flow that results in a balanced regime in the river such as natural floodin. [13]. Dominant discharge is a discharge that contributes the most to the average annual sediment [16]. The dominant discharge ($Q_{dominant}$) is the discharge equivalent to the bankfull discharge (Q_b) which is also equivalent to the 2-year return time flood (Q_{2year}) [6,9,10,14]. Scour is defined as the enlargement of flow accompanied by the removal of material through the action of fluid motion. Local scour occurs at a flow velocity where sediment transport is greater than sediment supply. Sediment transport will increase with increasing sediment shear stress, scour occurs when changes in flow conditions cause an increase in base shear stress [4].

METHODOLOGY

This research is divided into four stages, namely: 1) Preparatory stage and preliminary survey, 2) Main survey, 3) Hydrological and scour analysis, 4) riprap design.

Preparatory stage consists of administrative preparation and literature study. Administrative preparation aims at forming a survey team and survey plan as well as communicating with related agencies. Preliminary survey is conducted to picture the existing conditions of water body, river situation, bridge pillars condition and to identify any potential problems that could hamper survey activities later. The next stage is main survey, which is focused on topographic survey using a Total Station and bed bathymetry of Kuala Samboja River using echosounder, river flow discharge measurement using current measuring instrument and buoy and lastly, measurement of the scour depth that occurs around the bridge pillars. The topography of the riverbank is measured as far as 35 m from the riverbank towards the land and 1000 m long from STA 0+000 downstream ward to STA 1+000 (Figure 1a). A river bed bathymetric survey is conducted using echo sounding technique (Figure 1b). Echo sounding was conducted along 100 m from STA 0+450 to STA 0+550. The water depth data, obtained from echo sounding technique are corrected with the change of water level due to tide during measurement. For this reason, the water depth measurement is conducted simultaneously with tide observation (Figure 1c). River flow discharge measurement is conducted after bathymetric survey is finished; river flow discharge measurement is conducted on STA 0+000 using buoys (Figure 1d). Bed sediment is collected and brought to the laboratory for testing its gradation. Furthermore, hydrological analysis is performed to determine the design rainfall depth, flood hydrograph and dominant discharge. Following hydrological analysis, scour analysis is conducted to verify the occurrence of the riverbed scour using Shields Diagram, and to determine the depth of local scour that occurred around the pillars of Kuala Samboja bridge using HEC-18 method and Salim & Jone method. Lastly, riprap design is conducted using Anderson equation to determine the effective rock dimension and to determine the dimension of the revetment.

RESULTS AND DISCUSSION

River geometric survey

Figure 2a and 2b presents the contours of river bed obtained from bathymetric survey, 2a presents the contours of river bed from STA 0+000 to STA 1+000, figure 2b presents more detailed contours around Kuala Samboja bridge pillars. While figure 3 demonstrates the existing cross section of Kuala Samboja bridge (STA 0+500).

Scour measurement around Kuala Samboja bridge pillars

Scour measurement is determined from the difference between the bottom depth STA 0+450 and STA 0+500. Scour measurement illustration can be seen on figure 4. From figure 4, it is determined that the difference between STA 0+450 and STA 0+500's bottom depth is 0.946 meters.

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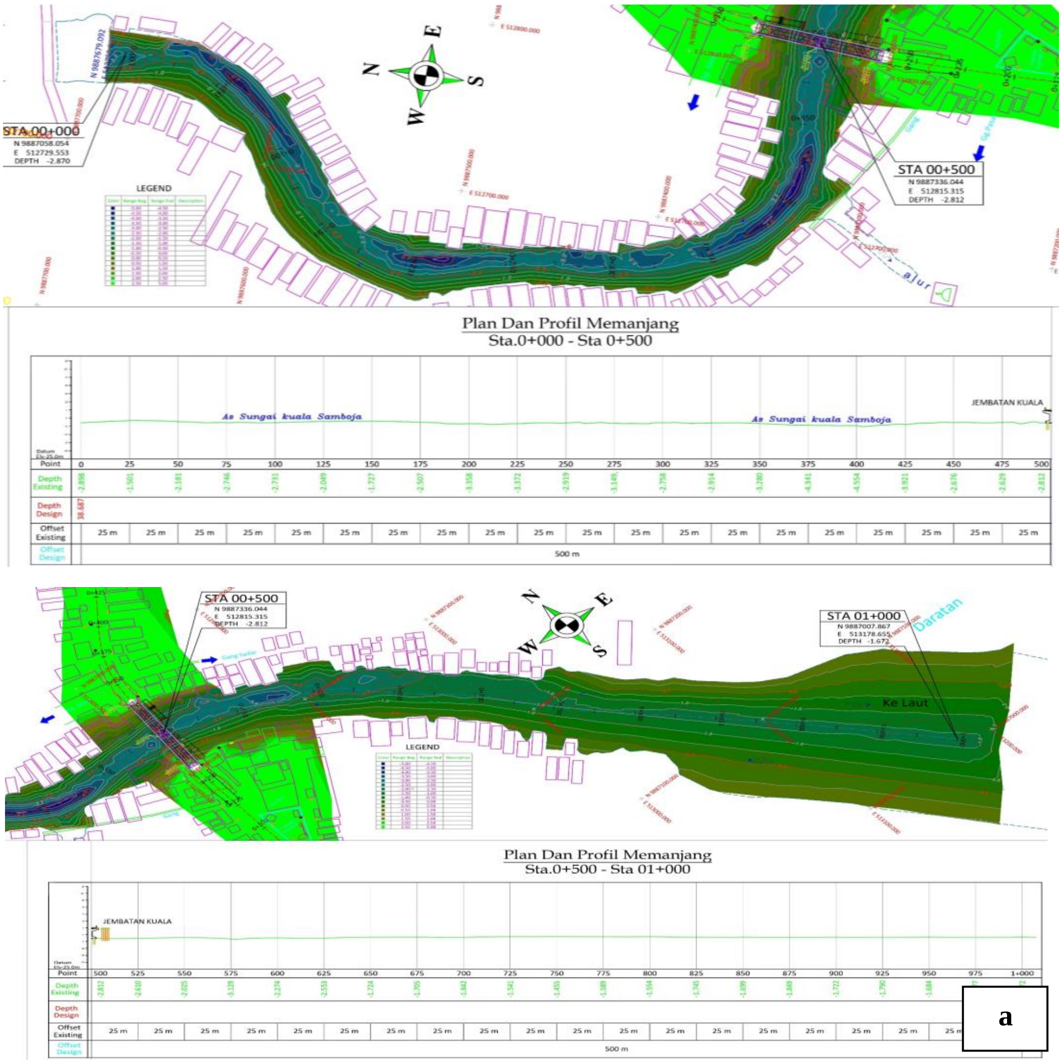
Figure 1. Main Surveys a. Topological survey. b. Bed bathymetry survey. c. Peil scale for observation. d. River flow discharge measurement



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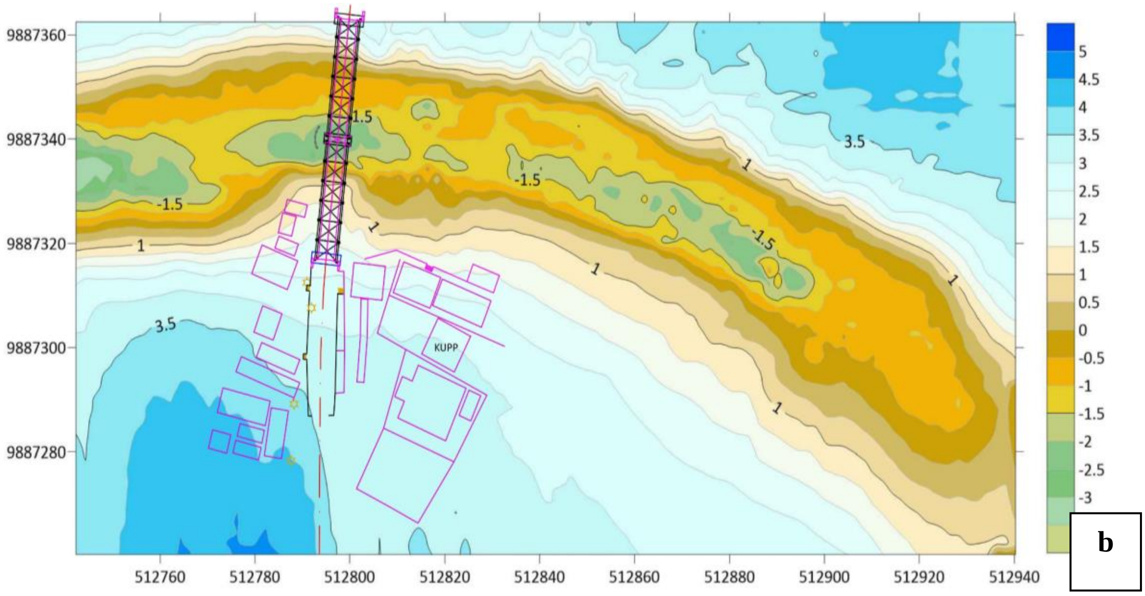

Figure 2. Contours of river bed from bathymetric survey a. River bed contour b. Contour around Kuala Samboja bridge pillars

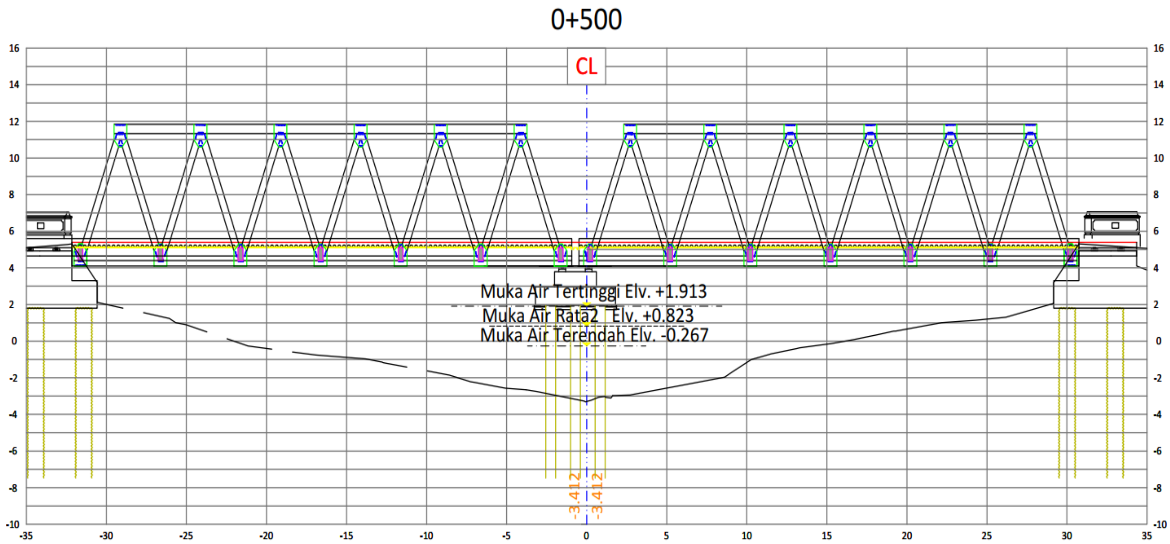

Figure 3. Existing cross section of Kuala Samboja bridge (STA 0+500)

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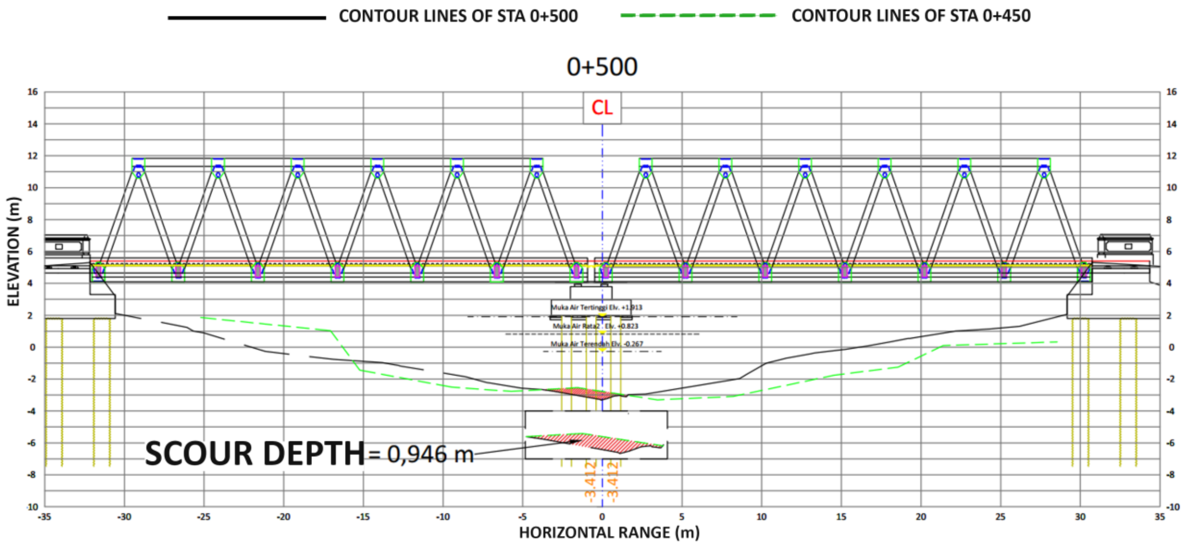

Figure 4. Scour depth measurement illustration

Rainfall depth

Historical river flow data are not available for the studied reach because there is no measurement station near the location. Fortunately, the rainfall data is well recorder. In this study, the flood and average flow hydrograph are estimated from rainfall data with a rainfall-runoff model using synthetic unit hydrograph model. Frequency distribution analysis is performed for the daily rainfall data recorded in last 23 years, it is found that Log Pearson type III distribution can represent the frequency distribution of annual maximum daily rainfall in Samboja watershed. Hourly rainfall distribution can be determined using Mononobe method [11].

$$R_t = \frac{R_{24}}{t}\left(\frac{t}{T}\right)^{2/3} \quad \text{.......}(1)$$

Where: Rt = average rainfall intensity from the initiation of rain up to time-t (mm/hour), T= duration of rain event (in this case 5 hours) and R_{24} = rainfall depth (mm).
Rainfall depth at time-t can be determined by:

$$R_T = t \times R_t - [(t-T).R_{(t-T)}] \quad \text{.......}(2)$$

Where: R_T = rainfall depth at time-t (mm), T = duration of rain event, t = time
Effective rainfall can be estimated by:

$$Rn = C \times R \quad \text{.......}(3)$$

Where: C = runoff coefficient whose value is largely determined by the type of land cover and cultivation. Tabel of C values for various land cover is given in [3].

Flood hydrograph

The Nakayasu synthetic unit hydrograph model is used to develop a 2-year flood hydrograph for the study site (Figure 5). The input for this model is effective rainfall depth, area of watershed, and river length. A complete description of this procedure can be seen in [11]. Based on Figure 5, the peak flow for 2-year flood, Q_{2year} is 366.34 m^3/second. This will be considered as Dominant discharge ($Q_{dominant}$).

Discharge and flow velocity rating curve

River flow velocity measurement data (Table 1) is used as the basis calculation of discharge rating curve as well as flow velocity rating curve. There are some parameters that must be known before measuring the river flow velocity which are.
Submerged buoy height, d = 0.3 m
Track length = 150 m
Correction based on peil scale = 2.48

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Data from Table 1 is used to form the flow velocity rating curve (Figure 6a), based on figure 6a the equation $U = 0.0014h^{4.6314}$ with $R^2 = 0.8477$. After U equation is acquired, the flow velocity calculation is continued until depth 5.086 using forecast feature on excel. Calculation results can be seen on Table 2 and flow velocity rating curve can be seen on Figure 6b. Furthermore, calculation is continued by calculating the river flow discharge, results of flow discharge calculation based on measurement data can be seen on Table 3. Data from Table 3 is used to form the discharge rating curve (Figure 7a), based on figure 7a the equation $Q = 0.0178h^{6.2672}$ with $R^2 = 0.9574$. After Q equation is acquired, the discharge calculation is continued until depth 5.086 using forecast feature on excel. Calculation results can be seen on Table 4 and discharge rating curve can be seen on Figure 7b.

Dominant depth and dominant flow velocity

Figure 6b is used to determine dominant depth ($h_{dominant}$) and figure 7b is used to determine dominant flow velocity ($U_{dominant}$), both will be used to calculate the local scour depth around Kuala Samboja's bridge pillars using HEC-18 method and Salim & Jone method. From fig 8a and 8b, $h_{dominant}$ equal to 4.85 meters and $U_{dominant}$ equal to 2.20 meters.

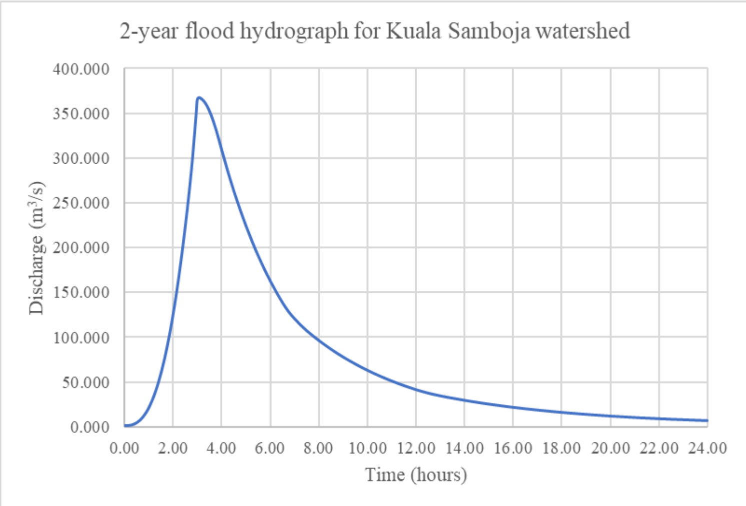

Figure 5. 2-year flood hydrograph for Kuala Samboja watershed

Table 1. River flow velocity measurement data

Peil scale reading (m)	Dept, h (m)	Section	Submerged buoy height, d (m)	Depth of water from the riverbed, h (m)	α	k_p	Track length, L (m)	time (seconds)	Velocity, U (m/s)
1.1	3.58	Left	0.3	0.7	0.429	0.812	150	231.0	0.527
		Middle	0.3	1.7	0.176	0.795	150	211.8	0.563
		Right	0.3	2.1	0.143	0.793	150	226.2	0.526
1.2	3.68	Left	0.3	0.7	0.429	0.812	150	211.2	0.577
		Middle	0.3	1.7	0.176	0.795	150	220.8	0.540
		Right	0.3	2.1	0.143	0.793	150	178.8	0.665
1.3	3.78	Left	0.3	0.7	0.429	0.812	150	181.2	0.672

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Peil scale reading (m)	Dept, h (m)	Section	Submerged buoy height, d (m)	Depth of water from the riverbed, h (m)	α	k_p	Track length, L (m)	time (seconds)	Velocity, U (m/s)
		Middle	0.3	1.7	0.176	0.795	150	166.2	0.717
		Right	0.3	2.1	0.143	0.793	150	180.0	0.661
1.4	3.88	Left	0.3	0.7	0.429	0.812	150	162.0	0.752
		Middle	0.3	1.7	0.176	0.795	150	171.0	0.697
		Right	0.3	2.1	0.143	0.793	150	159.0	0.748
1.5	3.98	Left	0.3	0.7	0.429	0.812	150	139.8	0.872
		Middle	0.3	1.7	0.176	0.795	150	130.2	0.916
		Right	0.3	2.1	0.143	0.793	150	145.2	0.819

Table 2. River flow velocity measurement data until depth 5.086

Depth, h (m)	Flow velocity, U (m/s)	Description
3.586	0.563	Measured
3.686	0.540	
3.786	0.717	
3.886	0.697	
3.986	0.916	
4.086	0.949	Forecasted using Excel
4.186	1.062	
4.286	1.184	
4.386	1.318	
4.486	1.463	
4.586	1.620	
4.686	1.790	
4.786	1.974	
4.886	2.172	
4.986	2.386	
5.086	2.616	

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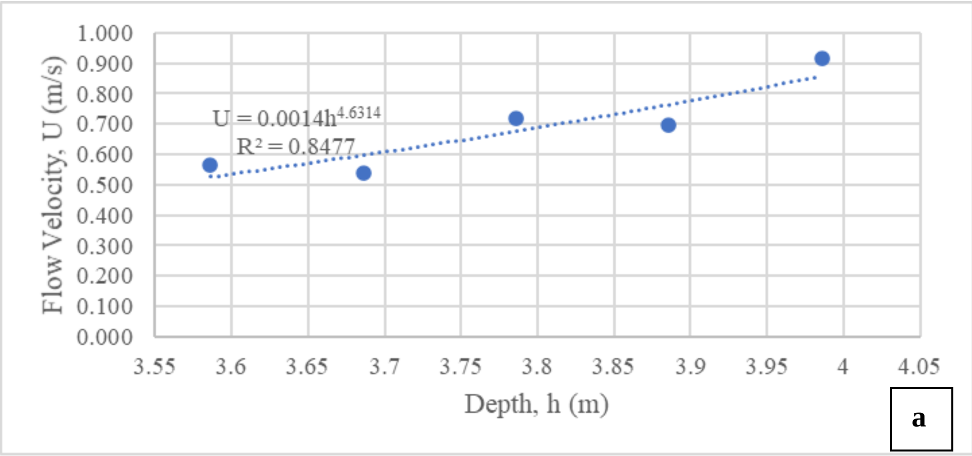

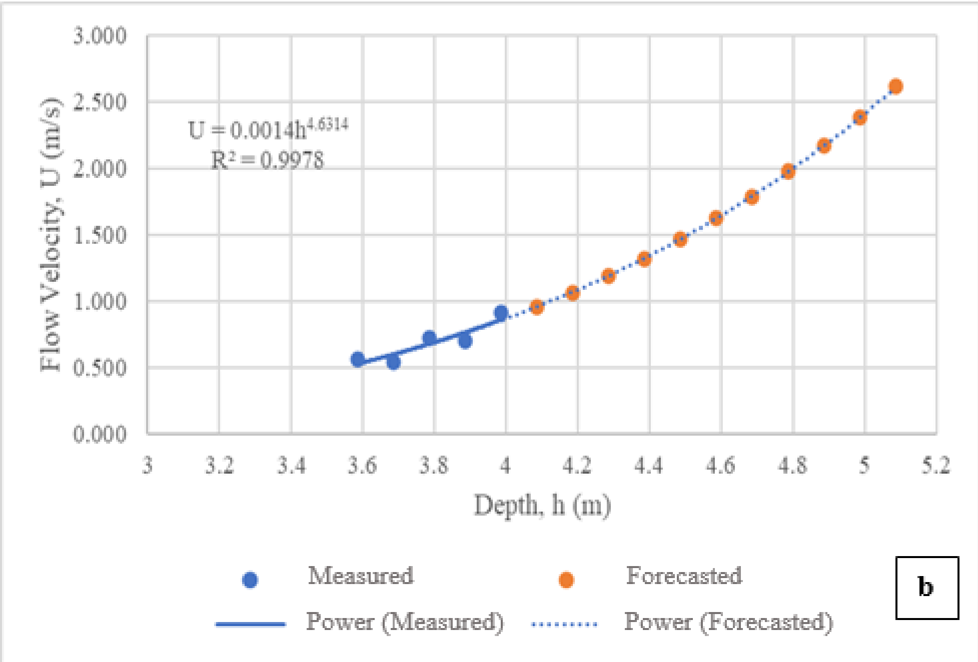

Figure 6. a. Flow velocity rating curve based on measurement b. Flow velocity rating curve forecasted using Excel

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Table 3. River flow discharge measured data

Depth, h (m)	Wetted cross sectional area, A (m^2)	Discharge, Q (m^3/s)	Description
3.586	100.890	55.619	Measured
3.686	105.750	59.348	
3.786	110.688	77.537	
3.886	115.714	82.880	
3.986	120.825	107.919	

Table 4. River flow discharge until depth 5.086

Depth, h (m)	Wetted cross sectional area, A (m^2)	Flow discharge, Q (m^3/s)	Description
3.586	100.89	55.619	Measured
3.686	105.75	59.348	
3.786	110.688	77.537	
3.886	115.714	82.880	
3.986	120.825	107.919	
4.086	127.132	120.656	Forecasted using Excel
4.186	132.261	140.398	
4.286	137.468	162.786	
4.386	142.754	188.102	
4.486	148.116	216.647	
4.586	153.556	248.748	
4.686	159.071	284.755	
4.786	164.661	325.046	
4.886	170.326	370.023	
4.986	176.066	420.120	
5.086	181.879	475.797	

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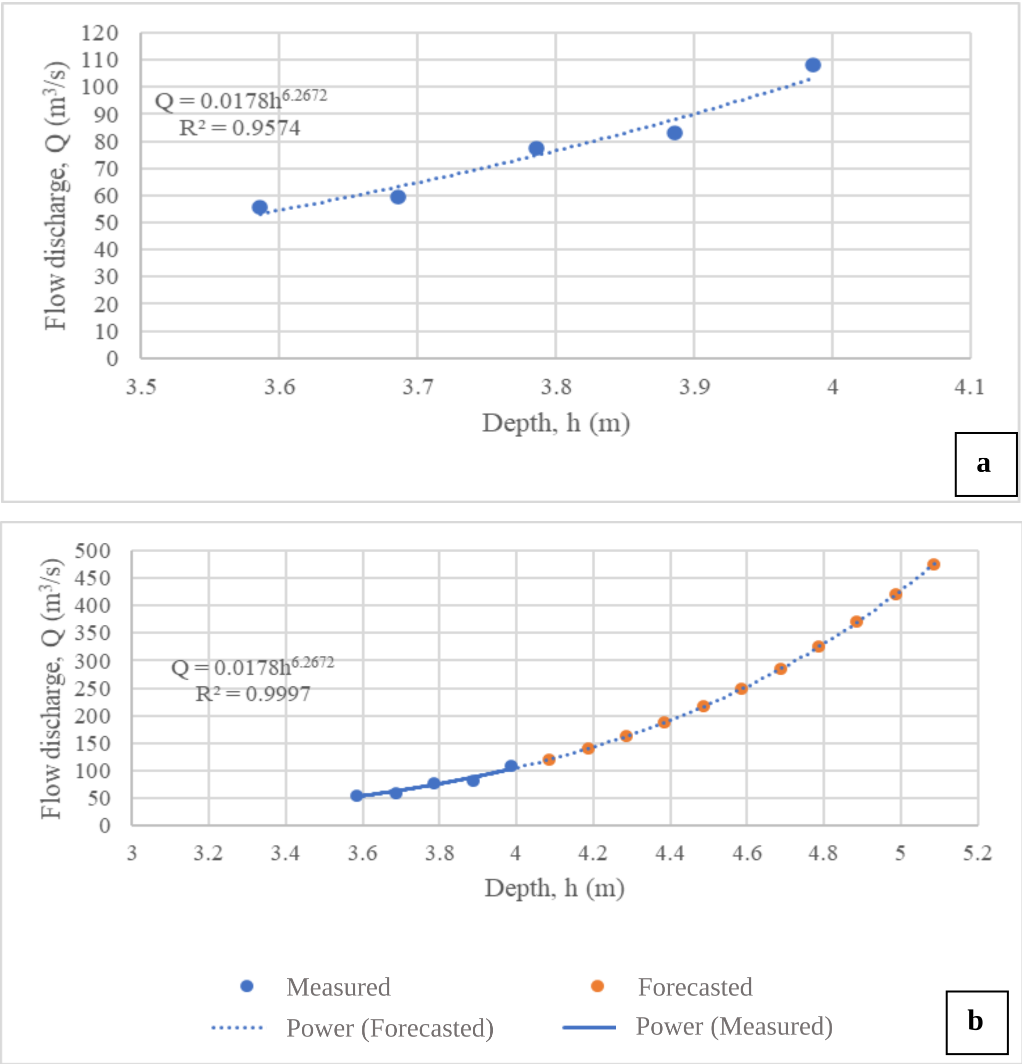
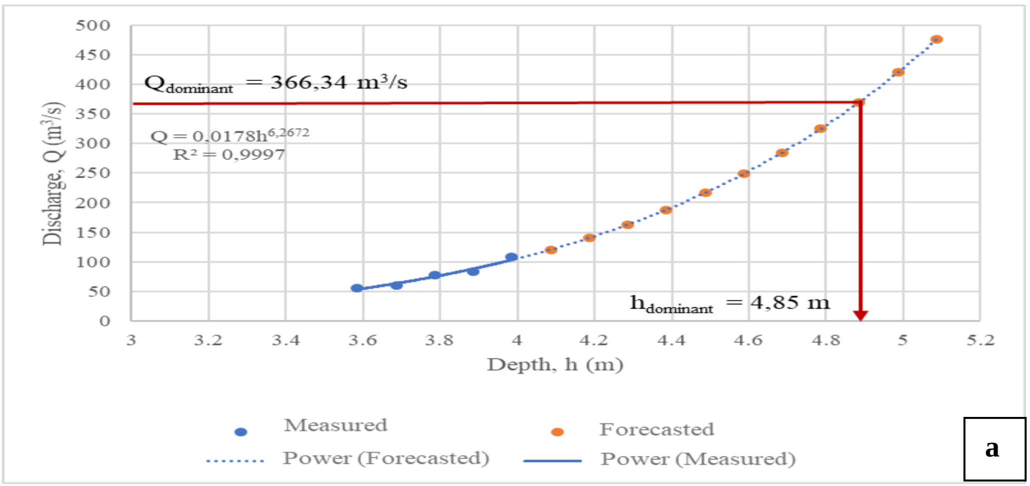


Figure 7. a. River flow discharge rating curve based on measurement b. River flow discharge rating curve forecasted using Excel



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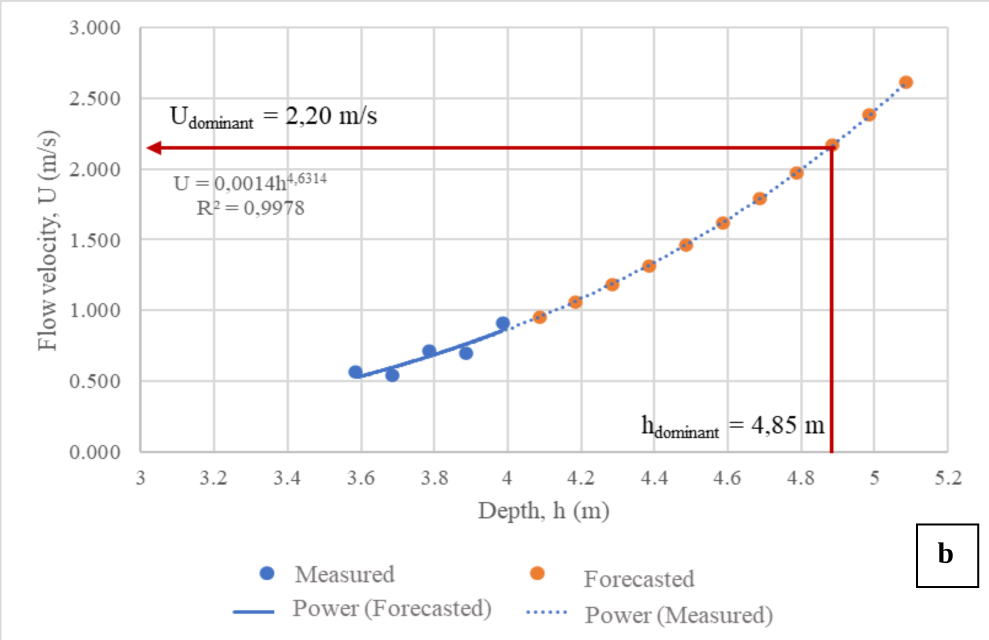

Figure 8. a. River dominant discharge and dominant height b. Dominant River flow velocity ad dominant height

Bed sediment gradation

Several laboratory tests conducted to determine bed sediment gradation, laboratory tests consist of specific gravity test, sieve analysis test and hydrometer test. All tests are carried out based on the applicable Indonesia National Standard (SNI) which can be referred to [1,2]. Grain size distribution graph can be seen on Figure 9. Based on figure 9, bed sediment gradation is poorly graded with d_{50} size equals to 0.07 mm. d_{50} size will be used to calculate local scour depth around Kuala Samboja bridge pillars, critical river bed shear and will be used to determine the bed type of the river.

Critical river bed shear

Calculation of critical friction stress is done after the sediment grain size composition is obtained. From the tests that have been carried out, the following data were obtained. Sediment diameter ($d_{50} = D_s$) is 0.07 mm, water kinematic viscosity (v) is 0.000001306 m2/s, gravitational acceleration (g) is 9.81 m2/s, water volume weight (γ) is 10000 N/m3 and sediment volume weight (γ_s) is 18142.30256 N/m3. The first step is to calculate the Reynolds value (R*).

$$R_* = \frac{U_* . D_s}{v} \quad \text{......} \quad 4$$

Which can then be reduced to:

$$R_* = \frac{D_s}{v} \times \left[0{,}1 \times \left(\frac{\gamma_s}{\gamma} - 1\right) \times g \times D_s\right]^{1/2} \quad \text{......} \quad 5$$

Where: R* is the Reynolds value, U* is the critical velocity, D_s is the sediment diameter and v is the kinematic viscosity of water. The calculation results show that the Reynolds value is 0.40, the Reynolds value obtained is then entered into the shields diagram which can be seen in Figure 10. From figure 10 it can be seen that, if R* = 0.40 then τ_* = 0.29 N/m2. If τ_* = 0.29 then τ_c can be found using the equation below.

$$\tau_c = \tau_* \times (\gamma_s - \gamma_w) \times D_s \quad \text{......} \quad 6$$

From the calculation, it is found that the value of τc is 0.16529 N/m2.

Slope calculation

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Slope (S) of the riverbed is calculated using the difference of upstream and downstream riverbed elevation on STA 0+000 (upstream) and STA 0+800 (downstream) riverbed and then divided by the length between STA 0+000 and STA 0+800. Riverbed elevation on STA 0+000 is -2.898 m, riverbed elevation on STA 0+800 is -1.554 m and the length between STA 0+000 and STA 0+800 is 800 m. Slope calculation are shown below.
S = (upstream riverbed elevation – downstream riverbed elevation)/length
S = 0.00168.

Maximum bed shear (τ_β max)
After the slope value is obtained, the calculation is then continued by calculating the frictional stress of the riverbed (τ_β max). Illustration of the calculation can be seen in figure 11, from figure 11 it can be seen that, the width of the canal (b) is 20.88 m, the flow height ($h_{dominant}$ = D) is 4.85 m, b / D is 4.31, the slope of the cliff (z) is 5, the wet cross-sectional area (A) is 171.439 m2, the wet perimeter (P) is 63.46, the hydraulic radius (R = A / P) is 2.70 m and the specific gravity of water (τ) is 10000 N / m3. The b/D data is used to draw a line on the frictional stress distribution graph in the trapezoidal channel, as shown in figure 12. Based on figure 12, the following values can be found. If b/D = 4.31, then (τ_b)max/γRS = 1.58. The calculation is then continued by calculating (τb)max.

$$(\tau_b)\,\text{max} = \gamma RS \quad \text{.......... 7}$$

From the equation above, it is known that (τb) max = 71.71 N/m^2. Based on the calculation of (τb) max and τc that has been done, it can be concluded that (τb) max > τ_c. So, it can be concluded that there has been scouring on the riverbed around the Kuala Samboja bridge pillars.

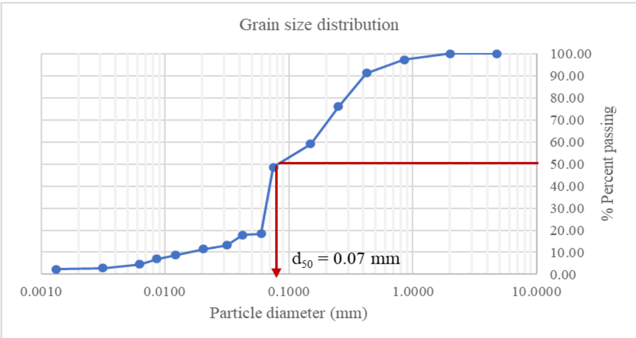

Figure 9. Bed sediment grain size distribution

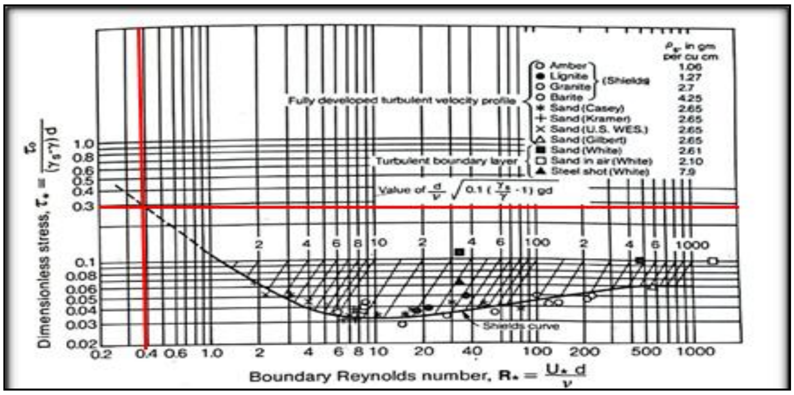

Figure 10 Shields diagram

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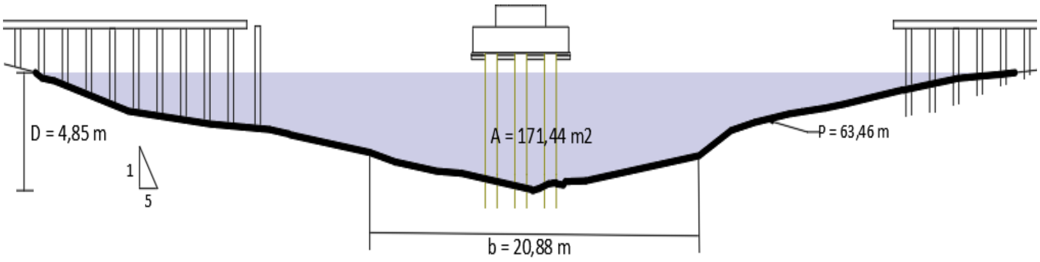

Figure 11. Illustration of maximum bed shear stress calculation

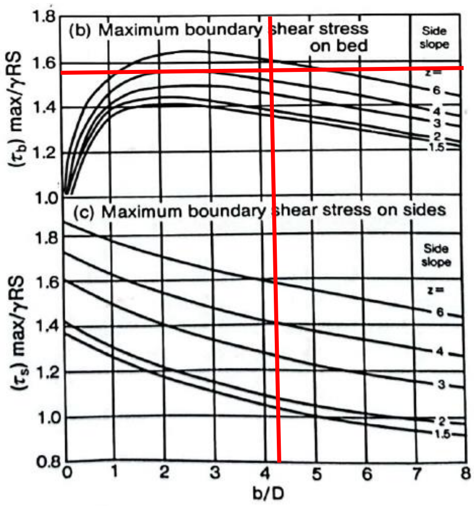

Figure 12 Distributions of boundary shear stress in trapezoidal channels

Local scour depth on piers calculation

From the data that has been obtained, the depth of local scour (y_{se}) on the bridge pillars is then calculated using the HEC-18 method and the Salim & Jone method to calculate the depth of scour on the pillar group.

Local scour depth on piers calculation using HEC-18 method

The HEC-18 method is a scour depth calculation method based on the Colorado State University method and is recommended for calculating scour depths on bridge pillars with live-bed and clear water river flow conditions. In addition to a single pillar, this equation can also be applied to complex pillars and pillars with a wide diameter [7]. Before the calculation is carried out, the following data can be known, the dominant depth ($h_{dominant}$ = y) is 4.85 m, the dominant velocity ($U_{dominant}$ = u) is 2.2 m/s, the diameter of the pillar (b) is 0.75 m, the correction to the pillar shape (K_1) is 1.0, the correction to the flow angle (K_2) is 1.0, the correction to the type of riverbed (K_3) is 1.1, the correction to the size d_{50} (K_4) is 1.0. The calculation of local scour using the HEC-18 method is as follows.

$$fr = \frac{u}{\sqrt{gh}} \quad \text{.......... 8}$$

$$y_s = 2.0yK_1K_2K_3K_4\left(\frac{b}{y}\right)^{0.65} f_r^{\ 0.43} \quad \text{.......... 9}$$

Where, Fr is the Froude value and y_s is the depth of local scour. From the calculation using the above equation, it is found that the depth of local scour that has occurred at the bridge pillar is 1.941 m.

Local scour depth on piers calculation using Salim & Jone method

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The Salim & Jone method is a modification of the HEC-18 method, this method is used to calculate the depth of local scour on group pillars using equation 9. To use this method, the diameter of the collection of pillars is first converted into a single pillar, where the dimensions of this single pillar are the dimensions when all pillars are combined into one. Then multiply the result of the calculation using equation 9 by one of the correction factors below.

$$Ks = 0.57\left[1 - e^{\left(1-\frac{S}{D}\right)} + e^{0{,}5\left(1-\frac{S}{D}\right)}\right] \quad \text{......} 10$$

$$Ks = 0.47\left[1 - e^{\left(1-\frac{S}{D}\right)} + e^{0{,}5\left(1-\frac{S}{D}\right)}\right] \quad \text{......} 11$$

Where, K_s is the correction coefficient, S is the distance between pillars, D is the changed pillar diameter and e = 2.7183. Equation 10 is for the envelop curve, equation 11 is for the best fit curve. The envelop curve gives a more conservative scour depth result while the best fit curve gives a smaller prediction error [8]. This correction factor only considers the effect of pile spacing and pile diameter on the scour depth around the pile group [8,11]. When the number of piles against the flow is 3 or more, this method will give more conservative results [8].
From the calculation using the above equation, it can be seen that the depth of local scour that occurs at the Kuala Samboja bridge pillar is 1.429 for the envelop curve and 1.178 for the best fit curve.

Determination of riprap rock dimensions
The occurrence of sediment grain movement ((τ_b max > $(\tau_b)_c$) on the riverbed indicates that scour has occurred on the riverbed around the Kuala Samboja bridge, in response to this, it is necessary to build a safety building to prevent scour on the riverbed, in this article the author uses riprap as a safety building to prevent scour. The requirement for stable riprap rock is when $(\tau_b)_c > \tau_b$ max, to achieve this stability the size of the riprap rock must be strong in resisting the frictional stress that occurs in the riverbed, the size of the riprap rock can be calculated using equation 6.

$(\tau_b)_{max}$ = 71.71 N/m^2 = 1.5 lbs/ft^2
$(\tau_b)_c > \tau_b$ max
$(\tau_b)_c >$ 1.5 lbs/ft^2
$(\tau_b)_c = 4d_{50}$
$4d_{50} > 1.5$
$d_{50} \geq 1.5/4$
$d_{50} \geq$ 0.37 ft = 11.42 cm ≈ 12 cm.

Based on the above calculation, it is known that the size of riprap rock required is at least 12 cm.

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Riprap design

The riprap design to protect the Kuala Samboja bridge pillars is made based on the size of the riprap rock needed which is then adjusted to the eroded subgrade area at the bottom of the river. From figure 4, it is determined that the dimensions of the riprap to be installed around the Kuala Samboja bridge pillars are 8 m long, 6.5 m wide and 0.8 m thick/depth. Illustrations of riprap stone installation can be seen in figures 12, 13 and 14.

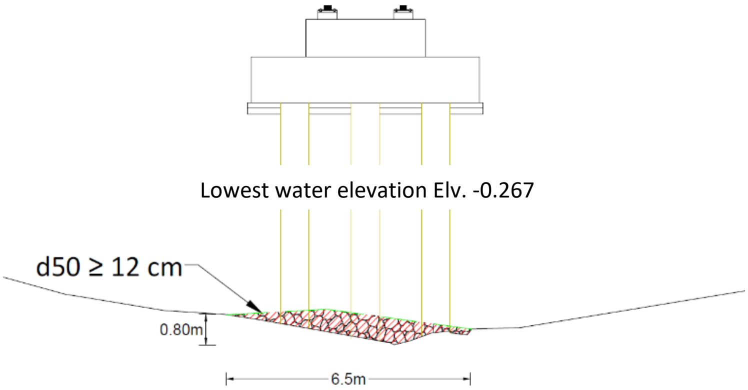

Figure 13. Planned riprap design on Kuala Samboja bridge.

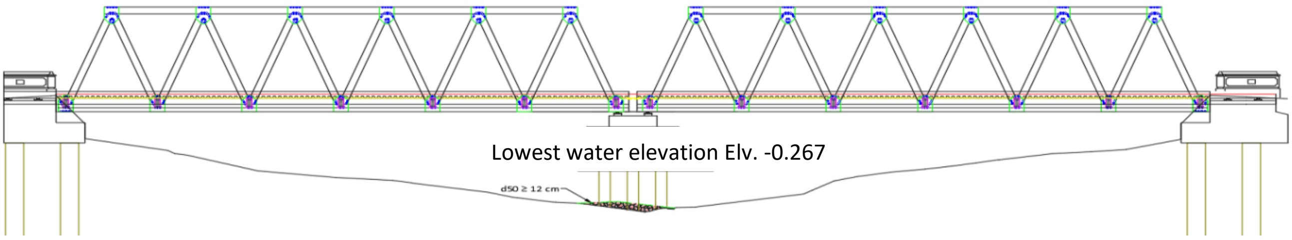

Figure 14. Front view of planned riprap design on Kuala Samboja bridge.

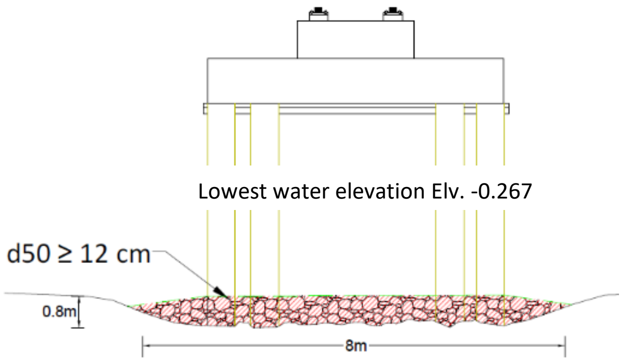

Figure 15. Side view of planned riprap design on Kuala Samboja bridge.

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CONCLUSION

Based on the research results, it can be concluded that:

1. The dominant discharge ($Q_{dominant}$) around the Kuala Samboja bridge pillar is 366.34 m3/s
2. Scouring occurs on the riverbed around the Kuala Samboja bridge pillars, this is evidenced by the value of the frictional stress of the riverbed which exceeds the value of the critical frictional stress of the river ((τ_b) max > τ_c). The scour depth that has occurred around the bridge pillars based on geometry measurements is 0.946 m. The calculation results of the scour depth around the bridge pillar using HEC-18 method are 1.941 meters, while scour depth using Salim & Jone method is 1.429 meters (envelop curve) and 1.178 meters (best fit curve). Salim & Jone method provides the closest results to the field measurements because this method considers the pillar group factor, while the HEC-18 method does not.
3. To protect and reduce the intensity of scour at the Kuala Samboja bridge pillars, the author uses riprap as a protective building around the pillars. Based on the calculation of the amount of riprap rock needed is at least 0.37 ft or 12 cm and the dimensions of the riprap rock pair needed are 8 m long, 6.5 m wide and 0.8 m thick/depth.

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