Stability of substructure Malapedho Bridge in Ngada Regency, East Nusa Tenggara Province

Yohanes Laka Suku | Veronika Miana Radja

Abstract Bridge failure is often caused by problems with the substructure, such as shearing, overturning and foundation subsidence which can cause the bridge structure to tilt and make it unfit for use, and even have the potential to cause the bridge to collapse. Research on the structural stability of the Malapedho Bridge's substructure aims to ensure the strength and stability of the bridge against sliding, overturning, soil bearing capacity and settlement, considering that the bridge had previously collapsed due to flooding. The bridge data used is existing data according to the planning drawings, for bridge loading refers to SNI 1725:2016, and earthquake loading refers to SNI 2833:2016. The safety factor value as a requirement for the strength and stability of the substructure is based on SNI 8460:2017. From the results of the analysis of shear stability, overturning, soil bearing capacity, and settlement of the lower building structure, it was found that the safety factor value exceeds the requirements set by the SNI 8460:2017 standard. Therefore, it can be concluded that the bridge substructure has adequate strength and stability. The research results also indicate that earthquake forces have a significant impact on the shear and overturning stability of the bridge substructure, resulting in a decrease in the strength of the structure.

Keywords: substructure, stability, shear, overturning, bearing capacity, settlement

1. Introduction

The Malapedho Bridge is a bridge that connects Inerie District with Aimere District in the Ndaga Regency, East Nusa Tenggara (NTT) Province. In September 2021, the bridge collapsed due to flash floods and landslides from upstream regions. This bridge was rebuilt in August 2022, with the upper structure using a reinforced concrete beam structure with a span of 20.80 meters and the substructure, namely, abutments and foundations also made of reinforced concrete.

An abutment is a substructure located at the base/end of a bridge that functions to hold and distribute the load from the upper structure and soil pressure to the foundation, and then all the load is distributed to the soil layer where the foundation is built (Y. Deng et al., 2023; Khajavi et al., 2021; Xie et al., 2019). Failures in bridges that often occur are due to failure in the substructure, such as a decrease in the foundation, which will cause the bridge structure to tilt and be unsafe to use and can cause the bridge to collapse (Huang et al., 2020; Liu et al., 2020; Manoppo et al., 2019).

The bridge foundation structure is an important part of the substructure; therefore, it must be planned well so that the load transferred from the foundation to the ground does not exceed the bearing capacity of the soil. Based on the depth, the foundation is divided into two parts, namely, a lower foundation and a deep foundation. Shallow foundations are used if the required soil bearing capacity is shallow (Roy & Koul, 2022; Tripathi & Vishwakarma, 2022). The Malapedho Bridge uses shallow foundations at a depth of 3 m from the riverbed. A river on a bridge often experiences flooding, and due to flooding, hydraulic forces will occur and cause scouring of the structures under the bridge, which can cause failure of the bridge (Fan et al., 2021; Khajavi et al., 2021; Setiati, 2019; Silvia et al., 2020).

Based on the description above, to ensure the strength and stability of the substructure of the Malapedho Bridge, it is necessary to analyze the shear, overturning, soil bearing capacity and settlement stability of the substructure of the bridge. The bridge data used are existing data according to planning drawings; bridge loading refers to SNI 1725:2016 (Direktorat Jenderal Bina Marga, 2016a), and earthquake loads refer to SNI 2833:2016 (Direktorat Jenderal Bina Marga, 2016b).

2. Substructure of the Bridge

The load on the bridge consists of dead load, active earth pressure, traffic consisting of uniform distributed load (UDL), lines (knife edge load, KEL), brakes, and pedestrians, as well as environmental action consisting of earthquake loads and wind (Direktorate General of Highways, 2016b). All of these loads are borne by the substructure of the bridge and transmitted to the subgrade. Therefore, it is necessary to ensure that the structure under the bridge must be stable in carrying the various...
loads acting on the bridge (Y. Deng et al., 2023; Khajavi et al., 2021; Naji et al., 2020). A structure is stable if it does not experience sliding and overturning, and the bearing capacity and settlement that occurs must meet the requirements permitted by regulations (Khajavi et al., 2021; Setiati, 2019; Silvia et al., 2020).

The substructure of a single-span bridge consists of abutments and foundations. The abutments located at the beginning and end of the bridge function to carry the entire load on the superstructure and soil pressure, which then distributes it to the foundation. In shallow foundations, the abutments are integrated with the foundation and must be able to resist the effects of shear and overturning forces (Ibrahim et al., 2019). The shear force is related to the lateral force, and this force must be able to be resisted by the substructure when the ratio between the resisting shear force and shear force is greater than 1.5 (Badan Standardisasi Nasional, 2017).

\[ SF = \frac{H_{px}}{M_x} > 1.5 \]  

where SF = safety factor, \(H_{px}\) = shear resisting force (kN) and \(M_x\) = shear/lateral force (kN). The magnitude of the shear force is the sum of the forces from the superstructure and due to ground pressure. The soil pressure is calculated using the following equation (Badan Standardisasi Nasional, 2017):

\[ \sigma_a = K_u \gamma \cdot Z \]  

where \(K_u\) is the active soil pressure, \(\gamma\) is the soil volume weight \(\left(\frac{\text{kN}}{\text{m}^3}\right)\), and \(Z\) is the embankment height.

The overturning force is caused by the moment at the overturning point from the lateral force; this moment must be resisted by the moment of inertia from the weight of the structure. The structure is declared stable if it meets the following equation.

\[ SF = \frac{M_{px}}{M_x} > 2.00 \]  

where \(SF\) = the safety factor, \(M_{px}\) = the persistent overturning moment on the X-axis (kN.m) and \(M_x\) = the overturning moment on the X-axis (kN.m).

The foundation is part of the bridge substructure, which functions to distribute the load from the superstructure and abutments to the subgrade; therefore, the foundation must be strong and stable. Foundation stability is determined by the bearing capacity of the soil and settlement of the foundation, where the value is influenced by the size of the foundation and the physical and mechanical properties of the underlying soil (Hendry et al., 2020; Roy & Koul, 2022).

The soil bearing capacity is the ability of the subgrade to withstand the load transmitted by the foundation. The soil bearing capacity can be analyzed based on the method proposed by Terzaghi, Mayerhof, Hansen and Vesic (Bowles, 1996). According to Bowles (1996), the Terzaghi and Mayerhof method is used when the ratio between the depth and width of the foundation is \(D/B\leq1\), and the Hansen and Vesic method is used when \(D/B > 1\). The bearing capacity equation according to Terzaghi is as follows:

\[ Q_u = cN_c + D_f \gamma N_q + 0.5 \gamma BN_p S_y \]  

where \(Q_u\) = ultimate bearing capacity \(\left(\frac{\text{kN}}{\text{m}^2}\right)\), \(c\) = soil cohesion \(\left(\frac{\text{kN}}{\text{m}^2}\right)\), \(B\) = foundation width (m), \(D_f\) = foundation depth (m), \(\gamma\) = soil volume weight \(\left(\frac{\text{kN}}{\text{m}^3}\right)\), \(N_c, N_q, N_p\) = Terzaghi bearing capacity factor and \(S_c, S_q, S_y\) = 1 for square foundation shapes. The following equation for the bearing capacity according to Mayerhoff for vertical loads is used:

\[ Q_u = cN_c + D_f \gamma N_q S_q + 0.5 \gamma BN_p S_y \]  

where \(Q_u\) is the ultimate bearing capacity \(\left(\frac{\text{kN}}{\text{m}^2}\right)\), \(c\) is the soil cohesion \(\left(\frac{\text{kN}}{\text{m}^2}\right)\), \(B\) is the foundation width (m), \(D_f\) is the foundation depth (m), \(\gamma\) is the soil volume weight \(\left(\frac{\text{kN}}{\text{m}^3}\right)\), \(d_c, d_q, d_y\) is the foundation depth factor, \(N_c, N_q, N_p\) is the Mayerhoff bearing capacity factor, and \(S_c, S_q, S_y\) is the foundation form factor. The smallest bearing capacity from the two equations above will be used as the bearing capacity of the soil under the bridge foundation. The maximum soil stress (qmax) that occurs must not exceed the bearing capacity of the soil, and the minimum soil stress that occurs (qmin) must be greater than zero so that tensile stresses do not occur (Badan Standardisasi Nasional, 2017; Bowles, 1996). The magnitude of the soil stress is calculated using the following equation:

\[ q_{max} = P_u/A + M_{ux}/W_x + M_{uy}/W_y + q \]  

\[ q_{min} = P_u/A - M_{ux}/W_x - M_{uy}/W_y + q \]
where $P_u$ is the axial load, $A$ is the base area of the foundation ($m^2$), $M_{ux}$ is the moment in the x-axis direction (kN-m), $M_{uy}$ is the moment in the y-axis direction (kN-m), $W_x$ is the moment resistance in the x-direction ($m^3$), $W_y$ is the moment resistance in the y-direction ($m^3$) and $q$ is the pressure due to the weight of the foundation footing (kN/m$^2$).

Settlement in the foundation structure can occur immediately when there is a load acting on the structure and long-term settlement due to soil consolidation (Bowles, 1996). Immediate settlement is elastic and often occurs in dry or unsaturated coarse- and fine-grained soils (Bowles, 1996; Conniff & Kiousis, 2007), and the settlement equation follows an elastic theory approach (Bowles, 1996; Timoshenko & Goodier, 1951).

$$S_i = \frac{qB}{E} (1 - \mu^2)I_p$$  \hspace{1cm} (8)

where $S_i$ = direct settlement (m), $q$ = pressure at the base of the foundation (kN/m$^2$), $B$ = width of the foundation (m), $E$ = elastic modulus of the soil (kN/m$^2$), $\mu$ = Poisson’s ratio and $I_p$ = influencing factor. The foundation settlement can also be calculated by modeling the soil reaction as a spring constant ($K_s$) whose magnitude is the ratio between the load ($F$) and displacement ($\delta$), $K_s = F/\delta$ (Bowles, 1996; Gazetas, 1983), and the quantity ($K_s$) can be calculated with the following equation (Gazetas, 1983):

$$K_{sv} = \frac{1.2GL}{(1-\mu)}$$  \hspace{1cm} (9)

$$G = \frac{E}{2(1+\mu)}$$  \hspace{1cm} (10)

where $K_{sv}$ = the vertical spring constant (kN/m), $G$ = the soil shear modulus (kN/m$^2$), $L$ = the foundation length (m) and $\mu$ = the Poisson’s ratio.

3. Materials and Methods

The study began by collecting image data of existing bridges, materials used and soil data. The existing geometric conditions of the bridge are shown in Figure 1 below.

![Figure 1 Longitudinal cut of the Malapedho bridge.](https://www.malque.pub/ojs/index.php/msj)
Table 1 Combination load.

<table>
<thead>
<tr>
<th>No</th>
<th>Combination load description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Serviceability I: MS + MA + TA + TD + TP + TB + EW + FB</td>
</tr>
<tr>
<td>2.</td>
<td>Serviceability II: MS + MA + TA + 1.3TD + 1.3TP + 1.3TB + FB</td>
</tr>
<tr>
<td>3.</td>
<td>Serviceability III: MS + MA + TA + 0.8TD + 0.8TP + 0.8TB + FB</td>
</tr>
<tr>
<td>4.</td>
<td>Serviceability IV: MS + MA + TA + 0.7 EW + FB</td>
</tr>
<tr>
<td>5.</td>
<td>Extreme I: MS + MA + TA + 0.3TD + 0.3TP + 0.3TB + EQ + FB</td>
</tr>
</tbody>
</table>

Source: Direktorat Jenderal Bina Marga (2016a)

4. Results and Discussion

4.1. Soil bearing capacity

The results of investigating the bearing capacity of the soil with CPT are shown in Figure 2. From these data, the end resistance at point 1 is 192 kN/m² at a depth of 1.8 m, and that at point 2 is 191 kN/m² at a depth of 2.4 m; then, for analysis, the data from point 2 are used.

![Figure 2 Results CPT.](image)

The type and consistency of soil are empirically related to the cone resistance (Qc) and friction ratio (FR) of CPT test results, where finer-grained soils (silt-clay) tend to have small Qc values and large FRs, whereas for coarser-grained soils (sand-gravel), Qc is large, and FR is small (Bowles, 1996). The type and consistency of the soil on the Malapedho Bridge are shown in Table 2.

Table 2 Soil Type and Consistency.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Qc average (kg/cm²)</th>
<th>FR (%)</th>
<th>Soil type and consistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.2</td>
<td>20.05</td>
<td>0.26</td>
<td>Pasir berlanau sedang</td>
</tr>
<tr>
<td>0.2-0.8</td>
<td>49.97</td>
<td>0.81</td>
<td>Pasir berlanau lepas</td>
</tr>
<tr>
<td>0.8-1.6</td>
<td>51.24</td>
<td>0.74</td>
<td>Pasir lepas</td>
</tr>
<tr>
<td>1.6-2</td>
<td>64.75</td>
<td>0.73</td>
<td>Pasir lepas</td>
</tr>
<tr>
<td>2-2.4</td>
<td>186.10</td>
<td>0.29</td>
<td>Pasir padat</td>
</tr>
</tbody>
</table>

The average Qc value at a depth of 2.4 m is 186.10 kPa. The soil type is dense sand, with a volume weight (γ) = 20.38 kN/m³, internal friction angle (φ) = 34.0° and cohesion (c) = 0.60 kN/m². According to Bowles (1996), the soil elasticity value (E) and Poisson’s ratio (μ) for dense sand can be taken as E = 90,000 kN/m², and μ = 0.4.
4.2. Structural stability

The results of the combination of loads received by the substructure are presented in Table 3.

<table>
<thead>
<tr>
<th>No</th>
<th>Load Combination</th>
<th>P (kN)</th>
<th>Hx (kN)</th>
<th>Hy (kN)</th>
<th>Mx (kN.m)</th>
<th>My (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Serviceability I</td>
<td>13,744.58</td>
<td>3,114.34</td>
<td>49.077</td>
<td>7,157.351</td>
<td>421.262</td>
</tr>
<tr>
<td>2</td>
<td>Serviceability II</td>
<td>14,023.716</td>
<td>3,189.344</td>
<td>0.000</td>
<td>7,800.101</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>Serviceability III</td>
<td>13,519.016</td>
<td>3,064.344</td>
<td>0.000</td>
<td>6,728.851</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>Serviceability IV</td>
<td>12,728.077</td>
<td>2,864.344</td>
<td>34.354</td>
<td>5,014.851</td>
<td>294.883</td>
</tr>
<tr>
<td>5</td>
<td>Extreme I</td>
<td>13,014.315</td>
<td>5,548.433</td>
<td>2,802.885</td>
<td>17,049.794</td>
<td>12,238.372</td>
</tr>
</tbody>
</table>

Based on Table 3 above, the shear stability, overturning, soil bearing capacity and settlement that occur in the substructure can be controlled. This process is a crucial step in the bridge construction design process to ensure the safety and optimal performance of the structure (Löhning et al., 2023; Naji et al., 2020; Xie et al., 2019). The following is a description of each of these aspects.

4.2.1. Shear stability

The results of the analysis of shear stability are presented in Tables 4 and 5 below.

<table>
<thead>
<tr>
<th>No</th>
<th>Load Combination</th>
<th>P (kN)</th>
<th>Hx (kN)</th>
<th>Hpx (kN)</th>
<th>SF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Serviceability I</td>
<td>13,744.58</td>
<td>3,114.34</td>
<td>9,324.84</td>
<td>2.99</td>
<td>&gt;1.50</td>
</tr>
<tr>
<td>2</td>
<td>Serviceability II</td>
<td>14,023.72</td>
<td>3,189.34</td>
<td>9,513.12</td>
<td>2.98</td>
<td>&gt;1.50</td>
</tr>
<tr>
<td>3</td>
<td>Serviceability III</td>
<td>13,519.02</td>
<td>3,064.34</td>
<td>9,172.69</td>
<td>2.99</td>
<td>&gt;1.50</td>
</tr>
<tr>
<td>4</td>
<td>Serviceability IV</td>
<td>12,728.08</td>
<td>2,864.34</td>
<td>8,639.20</td>
<td>3.02</td>
<td>&gt;1.50</td>
</tr>
<tr>
<td>5</td>
<td>Extreme I</td>
<td>13,014.32</td>
<td>5,548.43</td>
<td>8,832.27</td>
<td>1.59</td>
<td>&gt;1.10</td>
</tr>
</tbody>
</table>

Based on Tables 4 and 5 above, it can be seen that for the stability of the bridge substructure under the Extreme I load combination, the value of the safety factor (SF) decreases significantly compared to the serviceability load. There is a decrease in SF in the Extreme I load combination because the combination takes into account the influence of earthquakes, so the SF value requirement according to SNI 8460:2017 is reduced to SF must be greater than 1.10 (Badan Standardisasi Nasional, 2017). Thus, the overall structure under the bridge is stable against shear. The decrease in the SF value shows that the lateral force due to the earthquake has a major influence on the stability of the bridge substructure (Roy & Koul, 2022; Thomaidis et al., 2020; Xie et al., 2019).

4.2.2. Overturning stability

The results of the analysis of overturn stability are presented in Tables 6 and 7 as follows.

<table>
<thead>
<tr>
<th>No</th>
<th>Load Combination</th>
<th>P (kN)</th>
<th>Mx (kN)</th>
<th>Mpx (kN)</th>
<th>SF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Serviceability I</td>
<td>13,744.58</td>
<td>7,157.35</td>
<td>51,542.19</td>
<td>7.20</td>
<td>&gt;2.00</td>
</tr>
<tr>
<td>2</td>
<td>Serviceability II</td>
<td>14,023.72</td>
<td>7,800.10</td>
<td>52,588.94</td>
<td>6.74</td>
<td>&gt;2.00</td>
</tr>
<tr>
<td>3</td>
<td>Serviceability III</td>
<td>13,519.02</td>
<td>6,728.85</td>
<td>50,696.31</td>
<td>7.53</td>
<td>&gt;2.00</td>
</tr>
<tr>
<td>4</td>
<td>Serviceability IV</td>
<td>12,728.08</td>
<td>5,014.85</td>
<td>47,730.29</td>
<td>9.52</td>
<td>&gt;2.00</td>
</tr>
<tr>
<td>5</td>
<td>Extreme I</td>
<td>13,014.32</td>
<td>17,049.79</td>
<td>48,803.68</td>
<td>2.86</td>
<td>&gt;2.00</td>
</tr>
</tbody>
</table>
Tables 6 and 7 show that the bridge substructure is stable against overturning with SF values greater than 2. The influence of earthquake loads on overturning stability is one of the important aspects that must be considered in the design of bridge substructures. When an earthquake occurs, the bridge structure will experience significant lateral forces, which can cause overturning or loss of stability. The decrease in the SF value in the Extreme I combination indicates that the bridge structure becomes more vulnerable to earthquake loads. The lower the SF is, the closer the structure is to the failure limit. In this context, a decrease in the SF indicates that the strength of the bridge substructure decreases when earthquake loads occur, thereby increasing the risk of structural failure (T. Deng et al., 2019; Zhuang et al., 2020).

### 4.2.3. Soil bearing capacity

The results of the soil bearing capacity analysis are as follows.

Based on Table 8, the permissible bearing capacity \( q_a \) used is 641.37 kN/m². The results of the analysis of the maximum soil stress \( q_{max} = 447,364 \text{ kN/m}^2 \) and the stress that occurs \( q_{min} = 8,274 \text{ kN/m}^2 > 0 \) (no stress occurs) show that the soil’s bearing capacity is strong in carrying the distributed load from the foundation. The strong bearing capacity of the soil plays an important role in supporting the load transmitted by the bridge foundation (Hendry et al., 2020; Naji et al., 2020). Bridge foundations are tasked with transferring loads from the bridge structure to the ground below. When the soil has adequate bearing capacity, the foundation can distribute the load efficiently and safely to the surrounding soil, thereby maintaining the stability and safety of the bridge structure (Y. Deng et al., 2023; Keraf et al., 2018; Manoppo et al., 2019).

### 4.2.4 Foundation settlement

The instantaneous settlement in the foundation was estimated using the elastic equation proposed by Timoshenko & Goodier (1951) and the spring reaction or subgrade reaction (\( K_s \)) by Gazetas (1983). The decrease that occurs must not exceed 25 mm (National Standardization Agency, 2017). The results of the analysis of the estimated decline are presented in Table 9 below.

### Table 8 Soil bearing capacity.

<table>
<thead>
<tr>
<th>No</th>
<th>Equation</th>
<th>Permissible bearing capacity (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Terzaghi dan Peck</td>
<td>807.45</td>
</tr>
<tr>
<td>2</td>
<td>Meyerhof</td>
<td>641.37</td>
</tr>
</tbody>
</table>

### Table 9 Foundation settlement.

<table>
<thead>
<tr>
<th>No</th>
<th>Equation</th>
<th>Settlement (mm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Timoshenko &amp; Goodier (1951)</td>
<td>14.656</td>
<td>&lt; 25 mm</td>
</tr>
<tr>
<td>2</td>
<td>Reaksi tanah dasar (( K_s ))</td>
<td>14.123</td>
<td>&lt; 25 mm</td>
</tr>
</tbody>
</table>

Settlement in substructures is a natural phenomenon that can occur in response to applied loads (Hruštinec, 2018; Löhning et al., 2023). It is important to ensure that any settlement that occurs is within acceptable limits so as not to compromise the function or safety of the structure. Table 8 shows that the estimated decrease in the two elastic equation methods has almost the same value, with a difference of 0.533%. The estimated amount of settlement that occurs is smaller than the maximum requirement of 25 mm, which indicates that the building structure under the bridge is stable against instantaneous settlement (Badan Standardisasi Nasional, 2017). This shows that the structure is able to withstand various applied loads without experiencing significant degradation, which could compromise its performance and safety (Ahmed et al., 2018; Löhning et al., 2023).

### 5. Conclusions

The results of the analysis of the stability of the Malapedho bridge substructure against shearing, overturning, soil bearing capacity and settlement revealed that the Malapedho bridge substructure was stable and strong enough to withstand the forces that caused shearing and overturning. The soil tension that occurs under the foundation is less than the
permitted bearing capacity, and the estimated settlement that occurs is less than the permitted settlement, with a difference of approximately 41.4%.

From this research, it was also found that earthquake forces have a significant influence on the shear and overturning stability of bridge substructures, and the elastic method instantaneous settlement equation according to Timoshenko & Goodier (1951) and Gazetas (1983) can estimate that foundation settlement is almost the same, with a difference of 0.533.

Acknowledgments

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Ethical considerations

Not applicable.

Conflict of interest

The authors declare no conflicts of interest.

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References


