Liquefaction Vulnerability Analysis using N-SPT Value and Grain Size Analysis on Gumbasa Irrigation Canal in the Post-Disaster Petobo Area, Sulawesi

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Abstract. Strong earthquakes occurred in Central Sulawesi, Indonesia, in late 2018, causing an inheritance disaster, soil liquefaction on Gumbasa Irrigation Canal at Petobo, Sulawesi. Soil liquefaction is a phenomenon of a decreasing soil bearing capacity triggered by strong vibrations in certain soil conditions. It immediately changes the soil characteristic from solid to liquid. Liquefaction vulnerability analysis was done using Idriss-Boulanger's simplified procedure based on SPT value in several spots. The Petobo liquefaction zone has seven boreholes, five of which are located near the Gumbasa Irrigation Canal. The soil sample at those boreholes was taken to the laboratory for further soil testing using grain size analysis. The simplified procedure is intended to calculate the safety factor using Cyclic Resistance Ratio, Cyclic Stress Ratio, and Magnitude Scaling Factor. The liquefaction vulnerability analysis resulted in the AB 1 – AB 3 area near Gumbasa Irrigation Canal, which liquefied. Meanwhile, LP 1 and LP 4 are contrary. LP 1 is located upstream of the canal, whereas LP 4 the downstream. Grain size analysis yields a consistent result that AB 1 – AB 3 soil is quite scattered inside the liquefiable constraint.

Keywords: Soil Liquefaction, Irrigation Canal, SPT Value, Grain Size, CSR, CRR

1. Introduction
On September 28, 2018, a series of earthquakes occurred in Central Sulawesi Province, with a magnitude range of Mw between 5.7 to 7.5 in 7 hours. The earthquake had a mainshock with a magnitude of 7.5 Mw at a depth of 10 km affecting 780,000 people within a radius of 100 km from the epicenter location [1].

The location of Palu City, which is close to the Palu-Koro fault, makes the level of seismic activity high so that it has the potential for earthquakes [2][3]. The earthquake that occurred in 2018 caused a surface rupture of 160 km, stretching from the west coast of the Donggala area to the south of the epicenter [4].

Geologically, the rock formations that dominate the Palu area are generally divided into two, namely Alluvium Coastal Sediments (Qap) and Molasa Celebes Sarasin and Sarasin (QTms)[5]. Meanwhile, the Petobo area consists of quaternary rock dominance from old fan alluvium deposit (QF2) and Alluvial deposit, flood deposit, and old river channel deposit [6]. This condition was also confirmed by field geological investigations, which found that the upper soil layer consisted of loose sand with a thickness ranging from 1-7 meters. The layer of silt in the middle and a layer of clay at the bottom [7].
The series of earthquakes that occurred (Figure 1) triggered liquefaction and landslide disasters at several points in Palu City and its surroundings, namely in Petobo, Jono Oge, Lolu, and Sibalaya [8][9][10]. Liquefaction is an immediate change of granular material from solid-state to liquid state due to increasing pore water pressure and decreasing effective stress [11]. This increase in pore water pressure is associated with continuous cyclic loads or vibrations, generally due to earthquakes, on granular materials such as loose sand with shallow groundwater levels. When liquefaction occurs, the nature of the soil turns into a liquid state. Its shear strength will decrease drastically to near zero, and the soil becomes unable to withstand the structure of the building above it [12]. This phenomenon also affects the plasticity and stiffness of a soil deposit, which gradually changes when subjected to cyclic loads or earthquakes [13].

This study will evaluate the potential for liquefaction in areas that previously experienced liquefaction as a result of the earthquake disaster in 2018. The research location focuses on irrigation canals located in the liquefaction area in Petobo. The Gumbasa Irrigation Canal is estimated to influence...
the potential for liquefaction related to the groundwater level and slopes [14][15]. Liquefaction vulnerability testing will be determined based on Standard Penetration Test data spread over several points taken after the earthquake occurred in 2018. The LP 1 point is located upstream of the irrigation canal. Drilling points of AB 1, AB 2, and AB 3 are located around irrigation canals within the Petobo liquefaction area. LP 4 is the endpoint of the downstream irrigation canal in the Petobo area. Testing samples in the laboratory is carried out mainly on testing the Sieve Gradation Analysis of these points.

Figure 3. Drilling Points around Petobo Irrigation Canal

2. Research Methodology

The study of potential liquefaction vulnerability in this paper was conducted based on SPT data and sieve analysis. The liquefaction vulnerability test based on SPT data will be determined quantitatively using the Idriss-Boulanger 2008 method [11]. The results of the quantitative analysis are then processed by qualitative analysis using the Liquefaction Severity Index method [16] to get a spatial picture of the potential liquefaction area. The sieve analysis test data will then be compared with the analysis result based on SPT data by referring to the liquefaction vulnerability graph based on grain size distribution [17].

2.1 Liquefaction Vulnerability Analysis using N-SPT Value

The liquefaction vulnerability analysis was determined using the Idriss-Boulanger method (2008) [11] to obtain the factor of safety (FS). If the value of FS < 1 is obtained, it can be said to be vulnerable to liquefaction. FS > 1 indicates not susceptible to liquefaction and FS = 1 indicates the critical condition. The equation regarding the safety factor can be seen in the following equation.

\[
FS = \frac{CRR}{CSR}
\]  

(1)
Cyclic Stress Ratio (CSR), interpreted as the average shear stress on the horizontal surface of a soil layer due to an earthquake with effective vertical stress in each layer. Based on laboratory testing, it was found that the appropriate deviation to be used so that it can be equivalent to constant stress is 65% of the maximum shear stress [18]. The following equation can calculate the CSR value

\[
CSR = 0.65 \frac{r_d}{g} \frac{a_{\text{max}}}{\sigma_v} \frac{1}{\sigma_v} \frac{1}{MSF} \frac{1}{K_\sigma}
\]

(2)

\[
r_d = \exp (a(z) + \beta(z)M)
\]

(3)

\[
a(z) = -1.102 - 1.126 \sin \left( \frac{z}{11.73} + 5.133 \right)
\]

(4)

\[
\beta(z) = 0.106 + 0.118 \sin \left( \frac{z}{11.28} + 5.142 \right) M_w
\]

(5)

\[
MSF = 6.9 \exp \left( \frac{-M_w}{4} \right) - 0.058
\]

(6)

\[
K_\sigma = 1 - C_\sigma \ln \left( \frac{\sigma_c}{\sigma_a} \right) \leq 1.1
\]

(7)

\[
C_\sigma = \frac{1}{18.9 - 2.55 \sqrt{(N_1)_{60}}} \leq 0.3
\]

(8)

Where,

- \( r_d \) = Stress Reduction
- \( z \) = Depth of soil layer
- \( M_w \) = Moment Magnitude scale
- \( MSF \) = Magnitude Scaling Factor
- \( K_\sigma \) = Correction factor of overburdened stress
- \( C_\sigma \) = Overburden corrected penetration resistances

Cyclic Resistance Ratio (CRR) is the ratio of cyclic resistance, a parameter of the resistance of a soil deposit to liquefaction. If the CSR value of any soil deposit is more significant than its CRR value, the soil is vulnerable to liquefaction. To get the value of CRR, use the equation with the following formula.

\[
CRR = \exp \left( \frac{(N_1)_{60cs}}{14.1} + \frac{(N_1)_{60cs}}{126} - \frac{(N_1)_{60cs}}{23.6} + \frac{(N_1)_{60cs}}{25.4} - 2.8 \right)
\]

(9)

\[
(N_1)_{60} = N_{in}, C_N, C_E, C_B, C_R, C_s
\]

(10)

\[
(N_1)_{60cs} = (N_1)_{60} + \Delta (N_1)_{60}
\]

(11)

\[
\Delta (N_1)_{60} = \exp \left( 1.63 + \frac{9.7}{FC + 0.01} - \left( \frac{15.7}{FC + 0.01} \right)^2 \right)
\]

(12)

Where,

- \( (N_1)_{60} \) = SPT blow count corrected to ER = 60%
- \( C_N \) = SPT overburden correction factor
- \( C_E \) = SPT correction factor for energy ratio
\( C_B \) = SPT correction factor for borehole diameter
\( C_R \) = SPT correction factor for rod length
\( C_s \) = SPT correction factor for omitting sampler liners
\( (N_t)_{60cs} \) = equivalent clean sand \((N_t)_{60}\)

### 2.2 Liquefaction Severity Index

It is necessary to evaluate areas that tend to be vulnerable to liquefaction [16]. Liquefaction vulnerability in spatial form can be described through a qualitative approach using the Liquefaction Severity (LS) method. This method will classify the severity of liquefaction into several categories, as shown in table 1. The equation used to calculate LS can be seen as follows.

\[
LS = \int_0^{20} P_L(z).w(z)dz
\]

\[
P_L(z) = \frac{1}{1 + \left( \frac{z}{0.9m} \right)^{1.5}} \quad \text{for} \quad F_L \leq 1.411
\]

\[
P_L(z) = 0 \quad \text{for} \quad F_L > 1.411
\]

\[
w(z) = 10 - 0.5z \quad \text{for} \quad z < 20 \text{ m}
\]

\[
w(z) = 0 \quad \text{for} \quad z \geq 20 \text{ m}
\]

Where \( P_L(z) \) determines the liquefaction value based on depth function. The value of \( F_L \) refers to the factor of safety against liquefiable soil [16]. While \( w(z) \) determines the weight factor of soil depth.

| \( L_S \)          | Description                  |
|-------------------|------------------------------|
| \( 85 \leq L_S < 100 \) | Very High                    |
| \( 65 \leq L_S < 85 \)  | High                         |
| \( 35 \leq L_S < 65 \)  | Moderate                     |
| \( 15 \leq L_S < 35 \)  | Low                          |
| \( 0 < L_S < 15 \)     | Very Low                     |
| \( L_S = 0 \)          | Non-Liquefied                |

![Figure 4. Liquefaction potential constraints based on grain size distribution from Tsuchida [17]](image-url)
2.3 Grain Size Analysis
Sieve analysis was performed to measure the grain distribution of the soil samples taken. The distribution of soil grains can be used to measure the vulnerability of a soil deposit to liquefaction events [17]. The graph as a reference in the distribution of soil grains that have vulnerable to liquefy is shown in figure 4. There are two constraints where the more uniform a soil deposit is, the higher the probability of liquefaction occurring.

3. Result and Discussion
The earthquake that occurred in Central Sulawesi in 2018 has triggered liquefaction in several areas, such as Petobo. The liquefaction vulnerability analysis was carried out at a magnitude of 7.5 Mw based on the main shock of previous earthquakes. Calculations have been simulated for the SPT drilling points around the Gumbasa Irrigation Canal in the Petobo area. The maximum peak ground acceleration value (PGA) uses site classification based on SPT value refers to SNI 1726:2019. This case ranges from the medium soil (SD) to soft soil (SE) site classification.

![Figure 5. Cross Section of AB 1 - AB 3 drilling points (modified from [19])](image)

| Borehole | GWL (m) | Site Classification | $PGA_M$ (g) |
|----------|---------|---------------------|-------------|
| LP 1     | 11.2    | Moderate Soil (SD)  | 0.3353      |
| LP 2     | 2.6     | Soft Soil (SE)      | 0.3382      |
| LP 3     | 0.1     | Moderate Soil (SD)  | 0.3440      |
| LP 4     | 0.8     | Moderate Soil (SD)  | 0.3394      |
| AB 1     | 1.5     | Soft Soil (SE)      | 0.3391      |
| AB 2     | 2.4     | Moderate Soil (SD)  | 0.3379      |
| AB 3     | 4.8     | Moderate Soil (SD)  | 0.3368      |
3.1 Liquefaction Vulnerability Analysis

The analysis that has been carried out shows various results. LP 1, located upstream of the Gumbasa Irrigation Canal in the Petobo area, shows no potential for liquefaction. Other SPT drilling points, specifically LP 2, LP 3, and LP 4, located on the perimeter of the Petobo liquefied area, show minimal potential for liquefaction. Contrary to points AB 1 to AB 3, which have a moderate and high tendency, liquefaction has the vulnerability to occur in an earthquake with a previous earthquake strength of 7.5 Mw.

Table 3. The factor of Safety on AB 1

| Depth (m) | N-SPT Value | Soil type | Fines content (%) | (N1)60 | CSR | MSF | $K_a$ | CRR | Factor of Safety |
|-----------|-------------|-----------|-------------------|--------|-----|-----|-------|-----|-----------------|
| 1         | 1           | Sand      | 23.5              | 1.28   | 0.22| 1   | 1.10  | n.a. | n.a.            |
| 2         | 1           | Silt      | 58.3              | 1.28   | 0.25| 1   | 1.09  | 0.11 | 0.42            |
| 3         | 4           | Silty Sand| 40                | 5.08   | 0.29| 1   | 1.08  | 0.13 | 0.45            |
| 4         | 7           | Sand      | 9.1               | 8.05   | 0.31| 1   | 1.06  | 0.12 | 0.37            |
| 5         | 10          | Silty Sand| 21.1              | 10.69  | 0.33| 1   | 1.05  | 0.17 | 0.51            |
| 6         | 9           | Silty Sand| 44.4              | 8.97   | 0.34| 1   | 1.04  | 0.16 | 0.47            |
| 7         | 13          | Sand      | 33                | 13.48  | 0.34| 1   | 1.02  | 0.20 | 0.58            |
| 8         | 16          | Sand      | 28.7              | 15.72  | 0.34| 1   | 1.01  | 0.22 | 0.64            |
| 9         | 17          | Sand      | 7.4               | 15.96  | 0.34| 1   | 1.00  | 0.17 | 0.48            |
| 10        | 17          | Sand      | 36.6              | 15.34  | 0.34| 1   | 0.98  | 0.21 | 0.62            |
| 11        | 19          | Clay      | 51.8              | n.a.   | 0.34| 1   | 0.94  | n.a. | n.a.            |
| 12        | 8           | Sand      | 23.5              | 6.90   | 0.34| 1   | 0.97  | 0.13 | 0.38            |
| 13        | 12          | Clay      | 64.6              | n.a.   | 0.34| 1   | 0.89  | n.a. | n.a.            |
| 14        | 16          | Clay      | 66.8              | n.a.   | 0.33| 1   | 0.87  | n.a. | n.a.            |
| 15        | 25          | Silty Sand| 48.8              | 20.65  | 0.33| 1   | 0.92  | 0.30 | 0.90            |
| 16        | 19          | Silty Sand| 49.4              | 14.96  | 0.32| 1   | 0.93  | 0.20 | 0.61            |
| 17        | 55          | Clay      | 54.4              | n.a.   | 0.32| 1   | 0.82  | n.a. | n.a.            |
| 18        | 41          | Gravely Sand| 24.8            | 33.48  | 0.31| 1   | 0.81  | 1.61 | 2.00            |
| 19        | 19          | Gravely Sand| 6.2               | 13.29  | 0.31| 1   | 0.93  | 0.13 | 0.43            |
| 20        | 24          | Clay      | 60.7              | n.a.   | 0.31| 1   | 0.78  | n.a. | n.a.            |

Figure 6. Liquefaction Factor of Safety in AB 1, AB 2, and AB 3
3.2 Liquefaction Severity Index

After getting the FS value from each point in each depth layer, further analysis to get a spatial picture is then carried out using the liquefaction severity method. QGIS Desktop mapping application software version 3.16.4 is used to process interpolation and interpretation of liquefaction severity values into a map. The map is obtained by classifying it into six categories of liquefaction severity index concerning the SPT drilling points, as shown in Figure 8.

**Table 4. Liquefaction Vulnerability Summary**

| Borehole | Coordinate | Liquefaction Vulnerability | Liquefaction Severity (LS) | Description |
|----------|------------|----------------------------|---------------------------|-------------|
| LP 1     | -0.941594  | 119.923187                 | FS > 1                    | 0.00        | Non-Liquefied |
| LP 2     | -0.941131  | 119.915072                 | FS < 1                    | 14.41       | Very low     |
| LP 3     | -0.937692  | 119.899352                 | FS > 1                    | 0.00        | Non-Liquefied |
| LP 4     | -0.936353  | 119.913040                 | FS < 1                    | 15.02       | Low          |
| AB 1     | -0.937518  | 119.913723                 | FS < 1                    | 67.00       | High         |
| AB 2     | -0.937289  | 119.917116                 | FS < 1                    | 45.02       | Moderate     |
| AB 3     | -0.937151  | 119.920284                 | FS < 1                    | 41.75       | Moderate     |

In the area around AB 1, it is shown in red, indicating a high level of vulnerability to liquefaction. On the other hand, the moderate liquefaction severity level at points AB 2 and AB 3 is shown more yellowish. Meanwhile, the points that are the perimeter area of the liquefaction zone, such as LP 1 to LP 4, are dominated by blue and green colours indicating a lower level of liquefaction vulnerability.
3.3 Grain Size Analysis

The liquefaction susceptibility was determined concerning the grain size distribution graph proposed by Tsuchida [17]. This graph has a pair of constraints that show a high and low probability of liquefaction of a soil deposit. The grain size distribution used in this study used samples at the same location as the previous SPT drilling points. The sieve test analysis was carried out to classify the soil grains from gravel to the finest content, and a hydrometer test was also performed on some samples.
The grain size analysis that has been carried out shows results that are quite in line with the test through the previous N-SPT value. LP 1, LP 2, LP 3, and LP 4, located around the perimeter of the Petobo liquefaction area, have a fairly good grain distribution. The curves can be shown that it tends to slope. While AB 1, AB 2, and AB 3 produce curves that tend to be steeper, showing a more uniform grain distribution and implicating higher liquefaction potential.

4. Conclusion and Recommendation

The calculation of liquefaction vulnerability was performed around the Gumbasa Irrigation Canal in the Petobo area after the 2018 earthquake and liquefaction disaster using an earthquake magnitude of 7.5 Mw. The liquefaction vulnerability results are still high. High vulnerability to liquefaction can be influenced by several factors, such as the height of the groundwater table, the density of the soil, and the distribution of the soil grains. The sieve analysis was performed at the SPT drilling points showed the grain distribution results, which tended to be more poorly graded at points AB 1, AB 2, and AB 3, which had implications for liquefaction's high potential. While at points LP 1, LP 2, LP3, and LP 4, the grain distribution results tend to be better and have implications for the potential for lower liquefaction. Due to the high liquefaction vulnerability at several points around the Gumbasa Irrigation Canal in the Petobo area, mitigation efforts must be carried out before reconstructing the canal.

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