Analysis of potential liquefaction using cone penetration test data and grain size distribution test with case study of liquefaction in Lolu Village

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Abstract. Liquefaction is a rare natural disaster and is very closely related to geotechnical engineering, where it occurred in the city of Palu in 2018 ago. One of the Palu liquefaction areas is Lolu Village, which experiences a sizeable lateral movement of up to 150 m. The research aims to identify the potential liquefaction in Lolu Village using the Cone Penetration Test (CPT) data and grain size distribution test. In evaluating liquefaction potential, the CPT data is processed with the Idriss-Boulanger method, referring to the value of soil safety factors based on the ratio between ground resistance to liquefaction (CRR) and earthquake (CSR). Whereas grain size distribution tests are carried out based on ASTM, referring to soil type composition's influence on the level of liquefaction potential. The results from eight CPT in Lolu village shows that liquefaction potential occurs at a depth of 5 to 10 m with varying end resistance and friction ratio values of the soil. Likewise, grain size distribution tests indicate that soil types are dominated by sandy soils vulnerable to liquefaction.

1. Introduction
Liquefaction is a condition in which the soil has lost its shear strength so that the soil's behavior changes from solid to liquid drastically as a result of the earthquake [1]. Liquefaction often occurs on sandy (non-cohesive) soils with a diameter of 0.075 mm < D < 4.75 mm. It is typically found in a soil profile of not too dense sand (N-SPT < 15) and a shallow groundwater level. Thus, soil tends to be saturated with water, and liquefaction can be initiated with a cyclic load that would cause the ground to move, such as an earthquake. According to [2], liquefaction is when an earthquake of certain strength shakes the existing soil until the water aquifer in the soil breaks. Afterward, the pore water pressure would increase against the soil force's direction to the sand-type soil, which has a relatively low density and lose the strength to withstand the loads due to segregation or the absence of friction in the soil. Thus, the soil will be transformed from its solid to the liquid state.

One of the recent liquefaction events occurred in Palu City in 2018 and affected Lolu Village in Jono Oge sub-district, resulting in a lateral displacement of 150 m, which can be seen in Figure 1 and Figure 2 below.
The liquefaction in Palu city occurred due to an earthquake measured as 7.4 Mw with the epicenter as far as 26 km from North Donggala, Central Sulawesi, and a depth of 10 km. The earthquake was known to be a tectonic earthquake due to a shift in the horizontal type plate (strike-slip), namely from the Palu Koro fault activity. The Palu earthquake has a high maximum acceleration of 335 gals in the vertical direction and 333 gals in the horizontal direction, as shown in Figure 3 below.

From Figure 3, the horizontal earthquake acceleration will be used to identify the liquefaction potential in this study due to its direct impact on the soil structure that is traversed and damages the structure of buildings above the ground level. Likewise, the results from Watkinson [5] of the Lolu village condition four days after the earthquake using the satellite images showed that two areas experience different movements. These areas are divided as the zone that experiences massive lateral movement as far as 150 m and the zone that experiences small lateral movement as far as 1 m to 2 m (seen in Figure 4).
In connection with the potential for liquefaction that may occur in Indonesia's territory, this study aims to analyze the potential for liquefaction based on the safety factor value indicator calculated from the results of field tests and laboratory tests so that it can help in proper mitigation in similar cases.

2. Research Methodology

In this study, the liquefaction potential will be analyzed in two ways: field tests and laboratory tests. Eight cone penetration test (CPT) points and two deep borings (BH) points were carried out in a zone that experienced lateral movement as far as 150 m in Lolu village with the placement of the test points can be seen in Figure 5 below.

![Figure 5. Distribution of CPT and BH tests in Lolu Village](image)

From the CPT data, an evaluation was done according to the method developed by Idriss and Boulanger [6]. The determination of liquefaction potential is based on the end resistance strength ($q_c$) and blanket friction ($f_s$) from the CPT results, which are then transformed into two liquefaction indicators using empirical equations. The two indicators are the ratio between the soil's resistance in facing liquefaction, known as the Cyclic Resistance Ratio (CRR), and the earthquake that occurred, known as Earthquake-induced Cyclic Stress Ratio (CSR), both at the normalized magnitude of 7.4.
Mw. Afterward, the liquefaction potential is obtained from the value of the safety factor obtained from the components’ ratio.

The Cyclic Stress Ratio (CSR) used in assessing the liquefaction potential is calculated through the empirical equations of (1), (2), (3), and (4) below.

\[
CSR = 0.65 \frac{a_{\text{max}}}{g} \frac{\sigma_0}{\sigma_0'} r_d
\]

\[
 r_d = \frac{(1-0.4113z^{0.5}+0.4052z+0.001732z^{1.5})}{(1-0.4177z^{0.5}+0.0572z+0.0062z^{1.5}+0.00121z^2)}
\]

\[
MSF = 6.9 \left( \frac{M}{4} \right) - 0.058 \leq 1.8
\]

\[
(CSR)_{7.5} = \frac{CSR}{MSF}
\]

From the equations, \(\sigma_0'\) is effective soil shear stress (kN/m\(^2\)), \(\sigma_0\) is total soil stress (kN/m\(^2\)), \(a_{\text{max}}\) is the maximum acceleration of the earthquake that occurred (gal), \(g\) is the earth’s gravitational acceleration (m/s\(^2\)), \(r_d\) is ground stress reduction factor, \(z\) is the depth that was reviewed (m), MSF is the Magnitude Scaling Factor, and \(M\) is the magnitude of the earthquake (Mw).

The Cyclic Resistance Ratio (CRR) is calculated using the CPT method, where the CRR is the force that can hold the soil in the face of cyclic stress. The following equations of (5), (6), (7), and (8) are used to calculate the CRR that occurs.

\[
C_Q = \left( \frac{P_a}{\sigma_0'} \right)^n
\]

\[
q_{c1N} = C_Q \left( \frac{q_c}{P_a} \right)
\]

\[
Q = \left[ \frac{(q_c-\sigma_0)}{P_a} \right] \left( \frac{P_a}{\sigma_0'} \right)^n = \left[ \frac{(q_c-\sigma_0)}{\sigma_0'} \right]
\]

\[
F = \left( \frac{f_s}{(q_c-\sigma_0)} \right) \times 100\%
\]

From the equation, \(P_a\) is the pressure at 1 atm (kN/m\(^2\)), \(\sigma_0'\) is effective soil shear stress (kN/m\(^2\)), \(C_Q\) is the normalization of cone tip resistance, \(q_c\) is CPT cone tip resistance value (kN/m\(^2\)), \(n\) is the exponential value of the soil type, and \(f_s\) is the friction value on the cone blanket (kN/m\(^2\)). From the four equations, the value \(n\) can be determined by the type based on the value of the tip resistance and the value of resistance, which can be seen in Figure 6 below.

Figure 6. Exponential value of soil types based on SBT [7]
Afterward, the following equations of (9), (10), and (11) are used to calculate the value of CRR at the magnitude of 7.4 Mw.

\[ I_c = [(3.47 - \log Q)^2 + (1.22 + \log F)^2]^{0.5} \]  

(9)

If \( I_c < 1.64 \), then \( K_c = 1 \), but if \( I_c > 1.64 \), then \( K_c = -0.403I_c^4 + 5.581I_c^3 - 21.63I_c^2 + 33.75I_c - 17.88 \). Thus, \( (q_{c1N})_{cs} \) can be calculated as:

\[ (q_{c1N})_{cs} = K_c \times q_{c1N} \]  

(10)

Then, to calculate the CRR value, if \( q_{c1N} < 211 \), then \( CRR_{7.5} \) can be calculated as:

\[ CRR_{7.5} = \exp\left(\frac{(q_{c1N})_{cs}}{540} + \left(\frac{(q_{c1N})_{cs}}{67}\right)^2 - \left(\frac{(q_{c1N})_{cs}}{80}\right)^3 + \left(\frac{(q_{c1N})_{cs}}{114}\right)^4\right) - 3 \]  

(11)

But, if \( q_{c1N} > 211 \), then \( CRR_{7.5} = 2 \). Whereas, from the equations, \( q_{c1N} \) is corrected end resistance value (kN/m^2), \( (q_{c1N})_{cs} \) is the clean-sand normalization equivalent value, and \( K_c \) is correction factor for given characteristics. The calculation of safety factor (SF) from the liquefaction can used the equation (12) below.

\[ SF = \frac{CRR_{7.5}}{CRR_{7.5}} \]  

(12)

Where liquefaction is known to happen if the SF is under 1, to be in critical conditions if SF equals to 1, and no liquefaction happens when SF is more than 1.

In addition to the field data, laboratory tests were also used in soil analysis at a depth of 6 meters. The laboratory test conducted was grain size distribution of hydrometer and sieve analysis test, referring to ASTM D6913 [8] and ASTM D 422 [9]. Afterward, the classification system for the results uses the United Soil Classification System (USCS). The soil sample's depth refers to [10], where liquefaction in Lolu village occurs up to this depth. Furthermore, an analysis of the potential level of liquefaction is carried out based on the grain grading, as shown in Figure 7 below.

![Figure 7. Graph of liquefaction potential level based on grain gradation [11]](image-url)

3. Results and Discussion

From the CPT results, the safety factor (SF) pattern of the location in Lolu village is divided into two types of soil, namely Type-A and Type-B.
3.1 CPT Results
The CPT results are differentiated into two types of soils and can be seen in Figure 8 (Type-A) and Figure 9 (Type-B).

**Figure 8.** Liquefaction potential analysis for CPT S-6, S-9, and S-14 for Type-A soils

**Figure 9.** Liquefaction potential analysis for CPT S-7, S-10, S-11, S-12, and S-13 for Type-B soils

From the CPT results, it can be seen that the soil which has high density, indicated by the high CRR value, is seen in shallow depths for Type-A soil, whereas for Type-B are found at deeper depths. For Type-A soils, the high-density soil is found at 6.6 m for S-6, 6.2 m at S-9, and 6.4 m at S-14. Next, for Type-B soils, the high-density soil is found at 9 m for S-7, 10 m for S-10, 9.4 m for S-12, 9.8 m for S-11, and 10.4 m for S-13.

It can also be inferred that the range of CSR values of the Type-A soils is 0.21 – 0.25, and Type-B soils are 0.21 – 0.32. According to the CRR value, Type-A typically has a high CRR value near the hard soil stratum for S-6 and S-9 but is limited to the depth of 3 - 5 m for S-14. The same high CRR value behaviour can be seen in Type-B soil, where it is found near the hard stratum. However, the CRR value increases drastically at a depth of 2 - 3 m. Furthermore, SF value's different behaviour shows that the high-density soil can be found at a shallower depth for S-11 at a depth of 6.6 - 8.4 m and S-13 at a depth of 3.4 - 5.4 m.
From the CPT result, the SF value can also map the potential of liquefaction for each soil type. The categorization of the potential of liquefaction can be seen in Table 1 below.

### Table 1. Liquefaction potential for the three soil types

| Soil Type | CPT-Name | With Liquefaction Potential | No Liquefaction Potential |
|-----------|----------|-----------------------------|---------------------------|
|           |          | q_c (kg/cm²) | FR (%) | Soil Type | q_c (kg/cm²) | FR (%) | Soil Type |
| Type-A    | S-6      | 0 - 70 | 0 - 9.1 | clay, clay silt, and sandy silt | 65 - 200 | 1.1 - 7.9 | sandy silt |
|           | S-9      | 0 - 55 | 0 - 4.6 | clay, clay silt, and sandy silt | 86 - 200 | 0.4 - 1.4 | sand |
|           | S-14     | 0 - 60 | 0 - 4.6 | clay, clay silt, and sandy silt | 50 - 200 | 0.5 - 3.8 | sandy silt |
| Type-B    | S-7      | 0 - 80 | 0 - 7.3 | clay, clay silt, and sandy silt | 96 - 200 | 0.7 - 5.5 | sandy silt |
|           | S-10     | 0 - 80 | 0 - 27.3 | clay, clay silt, and sandy silt | 60 - 200 | 0.7 - 4.9 | sandy silt |
|           | S-12     | 0 - 80 | 0 - 4.6 | clay, clay silt, and sandy silt | 70 - 200 | 1 - 3.6 | sandy silt |
|           | S-11     | 0 - 85 | 0 - 6.9 | clay, clay silt, and sandy silt | 120 - 176 | 0.7 - 4.4 | sandy silt |
|           | S-13     | 0 - 145 | 0 - 6.1 | clay, clay silt, and sandy silt | 60 - 200 | 0.7 - 2.1 | sandy silt |

3.2 **Laboratory Results**

The grain size analysis results are used to verify the results obtained from CPT. The samples are taken from the deep, boring hole (BH) of BH-3 and BH-06. For BH-03 with the depth of 0 – 6 m, the grain size analysis: 7% - 63% gravel, 36% - 72% sand, 1% - 15% silt, and 0% - 9% clay. Whereas for BH-06 with the depth of 0 – 6 m, the grain size analysis: 6% - 61% gravel, 38% - 85% sand, 1% - 15% silt, and 0% - 7% clay. Both BH-03 and BH-06 grain size distribution for liquefaction analysis can be seen for each 1 m depth in Figure 11 and Figure 12 below.

![Analysis of Grain Size Distribution BH-3](image.png)

**Figure 10.** Graph of BH-03 liquefaction analysis
Figure 1 shows that for BH-03, the sloping line of 0 – 1 m and 2 – 6 m is in the range of high possibility of liquefaction, whereas 1 – 2 m has a steep line and has a possibility of liquefaction. On the other hand, from Figure 12, it can be seen that for BH-06, the gradient line at a depth of 0 – 2 m and 5 – 6 m have a gentle line, whereas the depth of 2 – 5 m has a steep line and has a possibility of liquefaction.

Based on the fine-grained percentage for both BH-03 and BH-06, the soil is considered susceptible to liquefaction due to the finer content < 15% [12], meaning that this fine-grained soil needs further laboratory tests. As a result, there is a high gravel content at several depths. Further observation is needed due to its effect on liquefaction when conditions are not drained, and the presence of an impermeable layer hampers the dissipation of pore water pressure. Lastly, it can be seen that the content of sand is greater than 50%, which means that the location is susceptible to liquefaction.

4. Conclusion
From the results, some conclusions can be made from the liquefaction research at Lolu village. First, it is known from the CPT data that there is a potential of liquefaction at the depth range of 5 – 10 m, where the soil has a tip resistance of 0 – 80 kg/cm². Second, the grain size analysis gradation shows that more than 50% of the soil is loose sand based on Tsuchida chart [11]. Thus it can be concluded that most of the soil has a high potential of liquefaction. Lastly, as this study is only limited to Lolu village, a further study can be used as a benchmark for other areas which has similar characteristics and considerable earthquake potential.

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