Analysis of liquefaction potential in Lolu Village, Palu using SPT method and laboratory test of grain size distribution

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Abstract. Liquefaction is known to be a natural phenomenon where granular soil material from its solid to liquid form. One of its impacts is from an earthquake that occurred in Palu in September 2018. This research will conduct an analysis based on field test data of Standard Penetration Test (SPT) and laboratory test data of Grain Size Distribution. Samples were taken from five different boreholes. The analysis will use the Idriss and Boulanger method, referring to the soil safety factor's value to evaluate the liquefaction potential. For grain size analysis, evaluation of liquefaction potential is carried out referencing liquefaction based on grain grading of Tsuchida, the coefficient of uniformity, and the curvature of the liquefied soil.

The results showed that liquefaction potential was found from 1 m depth to 20 m with N-SPT value ranging from 3 – 54 blows. On the other hand, analysis using a grain distribution test showed that soil at the location is dominated by sandy soil with fine-grained contents that can experience liquefaction.

1. Introduction

Liquefaction is transforming granular material from its solid-state to liquid state due to increasing pore pressure and loss of significant stress [1]. One of the liquefaction events that have a massive effect is the Palu earthquake, which occurred on 28 September 2019 with a magnitude of 7.4 Mw. The earthquake epicenter itself is located 26 km north of Donggala, Central Sulawesi, and 80 km northwest of Palu City with a 10 km depth. Some of the severe impacts can be seen in Sigi District, precisely in Baloroa, Petobo, Jono Oge, Lolu, and Sibalaya.

Palu itself was known to be an area with immense potential for earthquakes due to its high seismicity. The location has a liquefaction potential due to an earthquake supported by its geological conditions dominated by fluviatile and alluvium deposits. When liquefaction occurs, the soil's strength and bearing capacity to withstand the load will decrease, causing other subsidence or ground movement problems. Furthermore, it would cause damage to ground surfaces, such as the collapse of building structures.

This paper will discuss the liquefaction in one of the affected areas, namely the Lolu village, Sigi District, Palu city, which experienced land movement up to 70 m as an impact due to liquefaction at the Palu-Koro fault (seen in Figure 1).
This research evaluates the liquefaction potential of the zone based on the field test data of Standard Penetration Test (SPT), carried out at points BH-9, BH-6, BH-4, BH-3, and BH-2 as seen in Figure 1. In addition to the field test, this research also reviews a grain size distribution test in the laboratory. Overall, this research aims to analyze the potential for liquefaction based on the safety factor value of SPT and grain size distribution analysis from Lolu village to help disaster mitigation in similar cases.

2. Research Methodology

In general, this research studies the liquefaction potential in two ways: field tests and laboratory tests. Five SPT points and two deep borings of BH-4 and BH-2 will be analyzed with the sampling locations seen in Figure 1.

2.1. Standard Penetration Test

The field test carried out in this study is the Standard Penetration Test (SPT), which is conducted referring to ASTM D1452 [2] and SNI 4153:2008 [3]. SPT is a test method carried out simultaneously with drilling to determine both the dynamic resistance of the soil and the disturbed sampling using impact techniques [3]. The test is carried out up to a depth of 20 m with readings for every 1 m. The results are N-SPT values, which are corrected to the corrected N-SPT value, which is used for further liquefaction analysis using Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR). The overall research steps can be seen in Figure 2.

Cyclic Stress Ratio (CSR) is calculated using the Seed and Idriss method. The cyclic stress is generated in a sand layer, and a certain amount is derived from cyclic stress distributed according to

Figure 1. Liquefaction zone in Lolu Village, Sigi District, Palu City, Central Sulawesi

Figure 2. Research steps based on Standard Penetration Test
time. The shear stress that causes liquefaction can then be calculated from the cyclic shear stress \( \tau_{av} \) generated at each point in the soil layer, expressed by equation (1).

\[
\tau_{av} = 0.65 \cdot \gamma \cdot z \cdot \frac{\sigma_{max}}{g} \cdot r_d
\]

Where \( a_{max} \) is the acceleration of the horizontal peak on the ground caused by an earthquake; which in this case, Palu earthquake has a maximum acceleration of 335 gals in the vertical direction and 333 gals in the horizontal direction. \( g \) is the value of the acceleration due to gravity, \( \gamma \) is the total density of the soil, \( z \) is the depth below the ground, and \( r_d \) is the depth reduction factor. A factor of 0.65 is used in this research since the assumption was that the equivalent uniform shear stress \( (\tau_{av}) \) is 65% of the absolute maximum shear stress generated by the earthquake. The value was chosen since it is still used from the start of developing the liquefaction evaluation procedure in 1996 until now.

The value of \( r_d \) (depth reduction factor) can be obtained from equation (2), (3), and (4) using the Idriss-Boulanger method using depth and magnitude of the earthquake that occurred.

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

\[
\alpha(z) = -1.012 - 1.126 \sin \left( \frac{z}{11.73} + 5.133 \right)
\]

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

Where \( z \) is the considered depth from the ground elevation, and \( M \) is the earthquake's magnitude. Thus, Seed and Idriss in 1971 formulated an equation for calculating CSR's value using equation (5) below [4].

\[
CSR = \left( \frac{\tau_{av}}{\sigma'_{vo}} \right) = 0.65 \cdot \left( \frac{\sigma_{max}}{g} \right) \cdot \left( \sigma_{vo} / \sigma'_{vo} \right) \cdot r_d
\]

Where \( \sigma'_{vo} \) and \( \sigma'_{vo} \) are vertical overburden stresses and significant vertical overburden stresses at the location, a variable needs to be interpreted in an equation that defines soil capacity as liquefaction resistance. The soil's ability to withstand liquefaction is called the cyclic resistance shear stress, which is described by the Cyclic Resistance Ratio (CRR) variable [5]. One of the ways to obtain CRR value is using a standard penetration test (SPT); however, a correction from the N-SPT needed to be done according to equation (6) below.

\[
(N_1)_{60} = N_m C_n C_E C_B C_S C_S
\]

Where \( N_m \) is the field SPT value, \( C_n \) is the correction factor for the effective overburden pressure, \( C_E \) is the correction factor for the SPT hammer energy ratio, \( C_B \) is the correction factor for the SPT borehole diameter, \( C_K \) is the correction factor for the length of the SPT rod, and \( C_S \) is the correction factor. Other correction factors related to the sampling method can be seen in SNI 4153:2008 [3]. Lastly, the correction factor for the effective overburden stress \( C_n \) is needed because increased overburden stress is due to increased N-SPT value obtained from the Liao-Whitman [6] equation (7) below.

\[
C_n = \frac{2.2}{\left(1.2 + \frac{\sigma'_{vo}}{P_a} \right)}
\]

Where \( \sigma'_{vo} \) is the effective overburden pressure, and \( P_a \) is the atmospheric pressure, which is 1 atm or 100 kPa. \( C_n \) value cannot be greater than 1.7. Thus, the value of CRR at the 7.5 Mw magnitude can be calculated using the Idriss-Boulanger method in equation (8) below.

\[
CRR_{7,5} = \exp \left( \frac{(N_1)_{60} C_S}{14.1} \right) + \left( \frac{(N_1)_{60} C_B}{126} \right)^2 - \left( \frac{(N_1)_{60} C_S}{23.6} \right)^3 + \left( \frac{(N_1)_{60} C_S}{25.4} \right)^4 - 2.8
\]

For earthquake magnitude other than 7.5, the CRR value is calculated according to equation (9), (10), (11), and (12).

\[
CRR = CRR_{7,5} \cdot K_g \cdot MSF
\]
\[ K_\sigma = \left( \frac{\sigma_{vo}}{P_a} \right)^f \]  
\[ f = 0.831 - \frac{(N_1)_{60\text{cs}}}{160} \]  
\[ MSF = 6.9 \exp \left( -\frac{M}{4} \right) - 0.058 \]

As for the Idriss-Boulanger method, the following equation (13) and (14) is used.

\[ K_\sigma = 1 - C_\sigma \ln \left( \frac{\sigma_{vo}}{P_a} \right) \leq 1.1 \]  
\[ C_\sigma = \frac{1}{18.9 - 2.55 \sqrt{(N_1)_{60\text{cs}}}} \]

Where, from equation (8) to equation (14), CRR\text{7.5} is the CRR value in the 7.5 earthquakes on the Richter Scale, K\sigma is the overburden correction factor, MSF or Magnitude Scaling Factor is the earthquake scale factor first proposed by Seed and Idriss in 1982 [7], and f is the relative soil density factor.

Lastly, to determine whether the soil layer from the SPT analysis has a liquefaction potential or not, a safety factor (SF) can be calculated according to equation (15) below.

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

If the SF is less than 1, the soil has liquefaction potential. If the SF equals to 1, the soil is known to be in critical condition. Whereas if the SF is higher than 1, then liquefaction would not occur.

2.2. Grain Size Distribution Test

The grain size distribution test is carried out to determine the soil grains’ distribution size, which ranges from 4.76 mm to 0.074 mm. The grain size distribution analysis is needed to give a close representation of a wide variety of soil composition. Soil samples from Lolu village, Palu city, were tested mechanically for every 1 m depth to determine soil grains distribution in detail. The results would be able to describe the original conditions in the field. The test is carried out according to ASTM D 6913-04 [8]. For soil passing the No. 200 sieve or smaller than 0.074 mm in diameter, the hydrometer test was used referring to ASTM D 421 [9], ASTM D 422 [10], AASHTO T 88 [11], and SNI 3424:2008 [12].

According to Tsuchida [13], soil grains distribution can be used as an analysis of the potential for soil liquefaction. The guide was presented in a soil grain distribution chart that describes the susceptibility criteria of a soil susceptible to liquefaction potential. The analysis guide graph can be seen in Figure 3, where the potential level of liquefaction can be determined based on the grading distribution of the constituent material grains.

![Figure 3. Liquefaction potential level based on grain gradation [13]](image-url)
3. Result and Discussion

3.1. Standard Penetration Test Results

From the field Standard Penetration test (SPT) results, the N-SPT value obtained was corrected and used to determine the CRR and CSR value, as shown in Figure 4.

The CRR value is relatively uniform from the five boreholes, dominated by a range of 0.1 to 0.2. The component of CRR is determined by the type of soil and N-SPT value on each layer. The denser the soil, the higher the N-SPT value, the higher the CRR value obtained. It was also found that the value of CRR soared in a depth of 9 m at BH-2. The significant value was due to the rock, which is found during the testing. It can also be verified that the type of soil found in the form was gravelly sand.

As seen in Figure 4, the CSR value was relatively stagnant at each borehole and depth. The behavior is due to several earthquake components, such as acceleration and magnitude; both are the same value for all layers at the five boreholes. The CSR value is also affected by the vertical overburden stress, which is influenced by soil type. It was known that the soil found in each layer was mostly dominated by silty to gravelly sand. From its characteristics, it is widely known that sand has a low shear strength due to the total pore space, which affected the CSR value as calculated.

From the value of CRR and CSR, the safety factor (SF) can be calculated. The results indicated that the SF ranges from 0.3 to 1. Only a few layers which do not have any liquefaction potential. In detail, it can be seen that in BH-2, the liquefaction potential was found at depth 0 – 8 m, 10 – 15 m, and 19 m, where the N-SPT value ranges from 3 to 24 blows and resulting in SF less than 1. From BH-4, it can be seen that liquefaction potential is found at a depth of 0 - 5 m, 7 - 9 m, 11 - 14 m, and 16 - 20 m, where the N-SPT value ranges from 0 to 21 blows. From BH-6, the liquefaction potential can be seen at a depth of 0 - 12 m and 16-19 m, where the N-SPT value ranges from 0 blows to 23 blows. Lastly, from BH-9, the liquefaction potential can be seen at depths of 0 - 2 m, 4 - 10 m, 12 - 13 m, and 19 m, where the N-SPT value ranges from 0 blows to 24 blows.

3.2. Grain Size Distribution Results
The grain size distribution results are reviewed based on the liquefaction potential graph shown in Figure 3. Two boreholes are considered BH-2 and BH-4 for the grain size distribution analysis, and the results can be seen in Figure 5 to Figure 8.
Figure 5. Analysis of grain size distribution test for BH-2 of depth 0 – 10 m

Figure 6. Analysis of grain size distribution test for BH-2 of depth 10 – 20 m

Figure 7. Analysis of grain size distribution test for BH-4 of depth 0 – 10 m

Figure 8. Analysis of grain size distribution test for BH-4 of depth 10 – 20 m
From the grain size distribution results, it was known that for soil from BH-2 and BH-4, both are dominated by sand. In detail, BH-2 composition at depth 0 – 6 m are 3 – 13% gravel, 69 – 87% sand, 5 – 18% silt, and 2 – 6% clay. Whereas for BH-4 composition at depth 0 – 6 m are 6 – 18% gravel, 56 – 82% sand, 15 – 41% silt, and 3 – 6% clay.

The graph of grain size distribution, coupled with the boundaries from Tsuchida [13] for BH-2, can be seen in Figure 5 and Figure 6. It can be seen that for Figure 5, at a depth of 0 – 10 m, the soil is at the border of the substantial possibility of liquefaction to happen. Whereas from Figure 6, at a depth of 11 – 20 m, the grain grains graph has a reasonably steep graph and shows that the soil distribution can be classified as having a possibility of liquefaction. The results confirmed the analysis of liquefaction potential from the calculated SF from the SPT results where the potential liquefaction was found at a depth of 0 – 19 m based on the Idriss and Boulanger method.

On the other hand, the graph of the grain size distribution of BH-4 can be seen with Tsuchida's boundaries [13] in Figure 7 and Figure 8. It was known that a different behavior between the SPT and grain size distribution results could be seen in BH-4. The N-SPT value for BH-4 was relatively high, but the grain size distribution results indicated that the soil has liquefaction potential instead. This behavior is probably due to the fine contents that affect the SF of depth 1 – 5 m, categorized in a substantial liquefaction possibility. At a depth of 7 – 10 m, the soil becomes having a possibility of liquefaction. The results are in line with the calculation of liquefaction potential using the Idriss-Boulanger method, which shows that at a depth of 0 – 5 m and 7 – 9 m, liquefaction potential can be found. Figure 8 shows that at a depth of 11 – 15 m, the zone becomes having a substantial possibility of liquefaction to happen again. Whereas at a depth of 16 – 20 m, the grain size distribution spreads closer to the border of having the possibility of liquefaction indicator instead. Lastly, the results for a depth of 16 – 20 m can also be seen as having accordance with the Idriss-Boulanger method calculation from the SPT.

4. Conclusion
From the results, some conclusions can be made from the liquefaction research at Lolu village. First, it is known that from the five boreholes of SPT, the liquefaction potential can be found at a depth range of 0 – 19 m and N-SPT value range of 0 – 25 blows which generate safety factor values less than 1. Second, it can be seen that sandy soil is the typical type to have the potential for liquefaction, which is shown by the grain size distribution data consisting of more than 55% sandy soil results. Third, based on the chart from Tsuchida [13], the soil at shallow depths has a higher potential to experience liquefaction than the deeper depths. Lastly, as this research shows that liquefied soil still can experience liquefaction in the future, the results can be useful for liquefaction mitigation in areas with similar characteristics.

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References
[1] Marcuson W F 1978 Definition of terms related to liquefaction J. Geotech. Eng. 104 9 pp 1197-1200
[2] Annual Book of ASTM Standards 2005 ASTM D 1452 Standard Practice for Soil Investigation and Sampling by Auger Borings (ASTM International)
[3] Badan Standardisasi Nasional 2008 SNI 4153:2008 Test Field Penetration with SPT (Badan Standardisasi Nasional)
[4] Seed H B and Idriss I M 1971 Simplified procedure for evaluating soil liquefaction potential J. Soil Mech. Found. Div. 97 9 pp 1249-1273
[5] Youd T L and Idriss I M 1997 NCEER Workshop on evaluation of liquefaction resistance of soils *Nat. Ctr. for Earthquake Engrg Res.*

[6] Liao S S C and Whitman R V 1986 Overburden correction factors for SPT in sand *J. Geotech. Eng.* 112 3 pp 373-377

[7] Seed H B and Idriss I M 1982 *Ground Motions and Soil Liquefaction during Earthquakes* (Earthquake Engineering Research Institute Monograph)

[8] Annual Book of ASTM Standards 2005 ASTM D 6913 *Standard Test Method for Particle Size Distribution (Gradation) of Soils Using Sieve Analysis* (ASTM International)

[9] Annual Book of ASTM Standards 2007 ASTM D 421 *Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants* (ASTM International)

[10] Annual Book of ASTM Standards 1999 ASTM D 422 *Standard Test Method for Particle-Size Analysis of Soils* (ASTM International)

[11] American Association of State Highway and Transportation Officials 2019 AASHTO T 88 *Standard Method of Test for Particle Size Analysis of Soils* (AASHTO)

[12] Badan Standardisasi Nasional 2008 SNI 3423: 2008 *Soil Size Analysis Test Method* Jakarta: Badan Standardisasi Nasional

[13] Tsuchida H 1970 Prediction and countermeasure against liquefaction in sand *Depots Sem. of the Port and Harbor Research Institute*