Liquefaction potential analysis in Palu Bay area

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Abstract. Sulawesi Island has a Palu Koro Fault that actively moves with a high displacement magnitude but low seismicity. On 28 September 2018, at 18:02 local time, an earthquake occurred in Palu Koro Shear Fault. The field investigations along the Palu coast revealed new evidence regarding the extensive liquefaction in these areas, both inland and coastal land. The research command area was located in the Palu Bay coastal area, the Province of Central Sulawesi. The data used was in the form of the Standard Penetration Test of the area, and the potential liquefaction analysis was carried out using the simplified procedure method. Furthermore, to determine the level of liquefaction potential, Liquefaction Potential Index was applied. Geological observations showed that the soil condition in the Palu Bay area was dominated by non-cohesive soil (sand). Based on the liquefaction potential analysis, it was indicated that most of the eastern region of the Palu Bay area showed no liquefaction potential. On the contrary, the western and southern parts were indicated to have liquefaction potentials. The Liquefaction Potential Index analysis results showed that the western and southern areas were dominated with extremely high liquefaction potentials. Meanwhile, in the eastern area, it was extremely low.

Keywords: Coastal area, potential liquefaction index, Palu Koro Fault, simplified procedure

1. Introduction
Indonesia is located on the confluence of three major tectonic plates, namely the Eurasian Plate, the Australian Plate, and the Pacific Plate. Such conditions lead to earthquakes on the plate borders, such as in the Sulawesi Island, which is composed of a complex tectonic arrangement [1]. The structures identified in Sulawesi are still actively moving and often produce earthquakes in various magnitudes [2]. In the central part of Sulawesi Island, the Palu Koro Fault is actively moving with geodetic and geological shifts of 41-45 mm/year [3] and 29 mm/year [4], respectively. The Palu basin is interpreted as a full extension of the fault displacement to the sinistral [5]. Such sinistral displacement was observed from the river offsets along the fault. The geometry of the Palu Basin was 7 km wide in north-south directions, with a steep triangular aspect of 60 m high and the alluvial fan being truncated on the west.
side. The fault moves slowly on the east side, approximately 20 km from Palu Bay to the north and the Gumbasa Valley to the south. Therefore, Palu Koro Fault is classified as a fault with high displacement magnitude and low seismicity [4].

On 28 September 2018, at 18:02 local time, a 7.5 $M_w$ earthquake occurred in the Palu Koro Shear Fault, which traversed north-south and extended through Palu City as well as other areas in the Province of Central Sulawesi, Indonesia. Figure 1 shows the epicenter of the earthquake, located about 10 km depth and 72 km north of Palu City. According to the United States Geological Survey (USGS) [6], the geodetic evidence showed the fault shift reached 150 km. The earthquake caused a landslide event to the sediments under the sea of Palu Bay. The landslide caused a tsunami that hit Palu City and its surroundings [7]. The field investigations along the Palu coast revealed new evidence regarding the extensive liquefaction on inland and coastal land areas [8].

Liquefaction is a phenomenon where the soil loses a lot of strength or rigidity only in a short time, but enough to cause damage, deaths, and financial losses [9]. Liquefaction results in soil damage, ground instability, settlement, sand boils, and changes in ground motion [10], [11].

This research was conducted to determine the potential for liquefaction in the Palu Bay area. The potential liquefaction analysis was carried out using the simplified procedure method proposed by the Seed-Idriss equation [13] and corrected using the Idriss-Boulanger [14]. Furthermore, to determine the level of liquefaction potential, Liquefaction Potential Index ($LPI$) was applied. It is a method introduced by Iwasaki et al. [15] and corrected by Juang et al. [16], used to predict the level of liquefaction potential. Its value is equivalent to the liquefied soil thickness, depth, and safety factor.

2. Material and Methods

2.1 Geological condition of Palu Bay

Knowledge about the geology of the local site is essential for characterizing the nature and possibility of land area at a particular site that is prone to liquefaction. The level or degree of liquefaction depends on the distribution of non-cohesion sediments (gravel, sand, and silt plasticity) in the deposits. It requires adequate groundwater levels to become largely saturated sediments. The most vulnerable sediments include filled and alluvial, fluvial, marine, deltaic, and windblown sediments [14].

![Figure 1. Locations of major earthquakes and aftershocks (modified from [12]).](image-url)
The soil types in the southern and eastern parts of the Palu Bay area are alluvium and coastal sediment. These deposits consist of gravel, sand, silt, and limestone formed in rivers, delta, and shallow marine environments. These deposits are the youngest sediments in this area that may also be entirely Holocene in age.

The soil types in the western part of Palu Bay consisted of shale, sandstone, conglomerate, volcanic rock, limestone, and chert, including filite, slate, and quartzite near intrusions (primarily volcanic rock). The soil type on the northwest part of the Palu Bay also consisted of conglomerate, sandstone, mudstone, limestone coral, and marl [17]. Figure 2 shows a more detailed description of Palu Bay soil conditions.

This research was conducted in the Palu Bay coastal area, Central Sulawesi Province. Data used included N-SPT (Standard Penetration Test) of Palu Bay area taken from 22 points. Figure 2 shows a cross-section area based on the N-SPT data collection. Rockworks software was applied to compose soil profiling. Soil type profile based on N-SPT data is presented in Figure 3.

The field and laboratory investigations of the 22 drill points in the Palu Bay area showed that the soil layer was dominated by non-cohesive soil (sand), which was a layered mix between gravel or silt. Cohesive soil only existed at BAY-1, BAY-2, BAY-3, BAY-12, BAY-19, BAY-22, and BAY-23. The groundwater level position in the Palu Bay area varies between 0.09 m and 4.48 m below the ground level.

Figure 3 shows that the cross-section A-A’ profile on the top and bottom consisted of gravely sand and sandy silt, respectively. Cross-section B-B’ profile consisted of gravelly sand, sand and gravel, and sandy gravel. Cross-section C-C’ shows various soil profiles. However, cross-section C-C’ was dominated by clayey silt and gravelly sand. Cross-section D-D’ profile consisted of clayey silt, silty sand, gravely sand, and a small area of sandy gravel. Cross-section E-E’ consisted of gravelly sand and silty sand. Case histories indicate that soil types prone to liquefaction consist of loose sand, silty sands/sandy silts containing mostly nonplastic silt, and gravel. It is rare for clays, except sensitive clays, to experience a loss of strength [18]. The area around Palu Bay indicates liquefaction potential due to its aspects of susceptibility to liquefaction.

Figure 2. The geological map of Palu Sheet, Sulawesi (modified from [17]) and the cross-section based on core drilling points.
2.2 Liquefaction potential analysis

2.2.1 Liquefaction potential analysis based on N-SPT data

The liquefaction potential in the Palu Bay area was conducted following the soil investigation. Based on the soil characteristic, it was indicated that the area was prone to liquefaction. SPT is one of the sampling methods to show the density and strength of the soil. Sampling was carried out by obtaining 100% core drilling in unconsolidated rock and deposits with a core sample diameter of not less than 50 mm.

After the N-SPT data is obtained, a potential liquefaction analysis can be carried out. The analysis was performed by applying the simplified procedure method proposed by the Seed-Idriss equation [13] and corrected by Idriss-Boulanger [14]. The analysis of the Safety Factor ($FS$) against liquefaction was carried out by comparing the Cyclic Resistance Ratio ($CRR$) and the Cyclic Stress Ratio ($CSR$) values, as formulated below:

$$ FS = \frac{CRR}{CSR} $$

Seed and Idriss [13] chose to represent the cyclic stresses induced by earthquakes using a representative value (or equivalent uniform value) equal to 65% of the peak cyclic stress. Therefore, the $CSR$ due to the earthquake was appropriately calculated as:

$$ CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} = 0.65r_d\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)\left(\frac{a_{max}}{g}\right)\left(\frac{1}{MSF}\right)\left(\frac{1}{K_o}\right) $$

where $r_d$ is shear stress reduction coefficient, $\sigma_{vo}$ is total vertical stress (kN/m$^2$), $\sigma'_{vo}$ is effective vertical stress (kN/m$^2$), $g$ is the acceleration of gravity (m/s$^2$), $MSF$ is magnitude scaling factor, $K_o$ is overburden
correction factor, and the \( a_{\text{max}} \) is maximum peak ground acceleration (m/s\(^2\)), the \( a_{\text{max}} \) value is obtained from the spectrum response design issued by the Indonesia 2021 Design Response Spectrum Application, Ministry of Public Works and Public Housing of the Republic of Indonesia [19].

\( CRR \) can be defined as the soil’s ability to resist liquefaction. One of the geotechnical in situ tests used to analyze soil capability is SPT [20]. \( CRR \) is calculated as:

\[
CRR = \exp \left( \frac{(N_1)_{\text{60cs}}}{14.1} + \left( \frac{(N_1)_{\text{60cs}}}{126} \right)^2 - \left( \frac{(N_1)_{\text{60cs}}}{23.6} \right)^3 + \left( \frac{(N_1)_{\text{60cs}}}{25.4} \right)^4 - 2.8 \right) 
\]

(3)

where \((N_1)_{\text{60cs}}\) is corrected penetration resistance.

2.2.2 Liquefaction Potential Index (LPI)

Liquefaction Potential Index (LPI) is a method introduced by Iwasaki et al. [15] to predict the rate of liquefaction potential. The LPI value is equivalent to the thickness of the liquefied soil, the depth of liquefied soil layer, and the safety factor. The \( LPI \) method was corrected by Juang et al. [16] because Iwasaki et al. [15] method cannot be used for universal use. Juang et al. [16] proposed the \( LPI \) formula as:

\[
LPI = \int_{0}^{20} F(z)w(z)dz 
\]

(4)

\[
F(z) = PL - 0.35 \quad \text{for} \quad PL \geq 0.35 
\]

(5)

\[
F(z) = 0 \quad \text{for} \quad PL < 0.35 
\]

(6)

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

(7)

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

(8)

where the \( F(z) \) value is the level of damage of a layer in the liquefaction analysis, while \( w(z) \) is the weight factor of the depth. The \( P_L \) value is the liquefaction probability which is determined under the following equation:

\[
P_L = \frac{1}{1 + e^{-3.64+5.37F_S}} 
\]

(9)

The deeper the liquefied layer, the smaller the effect on the soil surface damage. Therefore, the next step is to calibrate the obtained \( LPI \) value by using the equation below:

\[
P_G = \frac{1}{1 + e^{6.75-0.57(LPI)}} 
\]

(10)

where \( P_G \) is the probability of surface manifestation. The \( LPI \) value classification is shown in Table 1.

**Table 1.** Potential liquefaction category based on \( LPI \) [16].

| \( P_G \) | Liquefaction Potential |
|-----------|-----------------------|
| 0.0 – 0.1 | Extremely Low         |
| 0.1 – 0.3 | Low                   |
| 0.3 – 0.7 | Medium                |
| 0.7 – 0.9 | High                  |
| 0.9 – 1.0 | Extremely High        |

3. Results and discussion

According to USGS, the historical earthquake data used in this study was the 7.5 \( M_w \) Palu-Donggala earthquake on 28 September 2018. **Figure 4** shows a map of earthquake sources in Indonesia, especially in the Palu Koro Fault area. The earthquake potential of this area was up to 7.9 \( M_w \) [2]. Such magnitude
requires analysis of its potential liquefaction to provide insight and mitigation measures against potential disaster liquefaction. The calculation results of the Safety Factor (FS) values for the 7.5 $M_w$ and 7.9 $M_w$ earthquakes are presented in Table 2.

Table 2. The safety factor (FS) of Palu Bay area on 7.5 $M_w$ and 7.9 $M_w$ earthquake magnitudes.

| Drilling Point | Ground Water Level (m) | Dominant Soil    | Peak Ground Acceleration (PGA) (g) | Liquefaction Potential (7.5 $M_w$) | Liquefaction Potential (7.9 $M_w$) |
|----------------|-----------------------|------------------|-------------------------------------|-----------------------------------|-----------------------------------|
| BAY-1          | 0.80                  | Sand             | 0.68                                | Liquified                         | Liquified                         |
| BAY-2          | 0.67                  | Silt             | 0.69                                | Liquified                         | Liquified                         |
| BAY-3          | 0.87                  | Gravely Sand     | 0.68                                | Liquified                         | Liquified                         |
| BAY-4          | 2.99                  | Gravely Sand     | 1.03                                | Liquified                         | Liquified                         |
| BAY-5          | 1.23                  | Silty Sand       | 0.68                                | Liquified                         | Liquified                         |
| BAY-6          | 0.90                  | Silty Sand       | 0.68                                | Liquified                         | Liquified                         |
| BAY-7          | 1.12                  | Gravely Sand     | 1.17                                | Liquified                         | Liquified                         |
| BAY-8          | 4.48                  | Gravely Sand     | 1.00                                | Liquified                         | Liquified                         |
| BAY-9          | 0.09                  | Sandy Gravel     | 0.90                                | Liquified                         | Liquified                         |
| BAY-10         | 2.89                  | Gravely Sand     | 0.77                                | Unliquified                       | Unliquified                       |
| BAY-11         | 1.35                  | Sand and Gravel  | 0.69                                | Liquified                         | Liquified                         |
| BAY-12         | 0.75                  | Silty Sand       | 0.68                                | Liquified                         | Liquified                         |
| BAY-13         | 1.90                  | Sandy Gravel     | 0.70                                | Unliquified                       | Unliquified                       |
| BAY-14         | 2.11                  | Sandy Gravel     | 0.79                                | Unliquified                       | Unliquified                       |
| BAY-15         | 1.25                  | Silty Sand       | 0.56                                | Liquified                         | Liquified                         |
| BAY-16         | 2.76                  | Gravely Sand     | 0.63                                | Unliquified                       | Unliquified                       |
| BAY-17         | 2.75                  | Silty Sand       | 0.68                                | Liquified                         | Liquified                         |
| BAY-18         | 1.22                  | Sandy Silt       | 0.68                                | Liquified                         | Liquified                         |
| BAY-19         | 1.05                  | Clayey Silt      | 0.68                                | Liquified                         | Liquified                         |
| BAY-20         | 2.30                  | Silty Sand       | 0.56                                | Unliquified                       | Unliquified                       |
| BAY-21         | 1.57                  | Gravely Sand     | 0.68                                | Liquified                         | Liquified                         |
| BAY-22         | 1.35                  | Silt             | 0.68                                | Unliquified                       | Unliquified                       |

Based on the analysis results on the 7.5 $M_w$ earthquake, about 6 points in the Palu Bay area were indicated not to have the liquefaction potential. Similar analysis results were obtained for the 7.9 $M_w$ earthquake. The analysis results were then plotted on the map using the QGIS software, as seen in Figure 5.

Based on the observations, Figure 5 describes that most of the eastern region of the Palu Bay area showed no liquefaction potential. On the contrary, the western and southern parts were indicated with liquefaction potential. This was due to the Palu Koro fault line on Palu Bay's western and southern regions, which brought more significant hazards and risks than the eastern region. Therefore, mitigation efforts against potential liquefaction, especially in Palu Bay's southern and western regions, are required to prevent or reduce the disaster risks.

The obtained FS value was then further analyzed by using the $LPI$. Table 3 shows the results of $LPI$ calculations of the 7.5 $M_w$ and 7.9 $M_w$ earthquakes. There were only slight result changes between the liquefaction potential of 7.5 $M_w$ and 7.9 $M_w$. The difference occurred at BAY-2 point, in which low liquefaction potential or $LPI$ for 7.5 $M_w$ earthquake magnitude turned into medium liquefaction potential or $LPI$ calculation results for 7.9 $M_w$. Moreover, another difference occurred at the BAY-3 point, which indicated extremely low liquefaction potential in the $LPI$ for the 7.5 $M_w$ earthquake that turned into low liquefaction potential in the $LPI$ calculation results for the 7.9 $M_w$ earthquake. Last differences occurred at BAY-4 point, which medium liquefaction potential or $LPI$ for 7.5 $M_w$ earthquake magnitude turned into extremely high liquefaction potential or $LPI$ calculation results for 7.9 $M_w$. Countermeasure efforts to mitigate the liquefaction, especially at high and extremely high $LPI$ categories, are required.
Figure 4. Map of earthquake sources in Indonesia (modified from [2]).

Figure 5. The map of liquefaction potential of the 7.5 $M_w$ and 7.9 $M_w$ earthquakes.

The $LPI$ analysis that was plotted on the map is presented in Figures 6a and 6b. The analysis results showed that the Palu Bay area dominated extremely high and low liquefaction potentials. Extremely high liquefaction potential areas are distributed in the western and southern regions. On the contrary, the eastern region is dominated by extremely low liquefaction potential.

Site visits were conducted to determine the location of the core drilling points. It aims to evaluate the results of calculations against field conditions. Figure 7 shows the locations of core drilling data. Core drilling data collections are mostly taken from the side of the river and bridge area along the coast. Therefore, the calculation results only represent the potential for liquefaction on the coast of Palu Bay.
Table 3. LPI category for 7.5 $M_w$ and 7.9 $M_w$ earthquake magnitudes.

| Drilling Point | $\sum LPI$ (7.5 $M_w$) | Liquefaction Potential (7.5 $M_w$) | $\sum LPI$ (7.9 $M_w$) | Liquefaction Potential (7.9 $M_w$) |
|----------------|------------------------|-----------------------------------|------------------------|-----------------------------------|
| BAY-1          | 1.29                   | Extremely High                     | 1.97                   | Extremely High                     |
| BAY-2          | 0.23                   | Low                                | 0.36                   | Medium                             |
| BAY-3          | 0.08                   | Extremely Low                      | 0.16                   | Low                                |
| BAY-4          | 0.47                   | Medium                             | 1.86                   | Extremely High                     |
| BAY-5          | 17.51                  | Extremely High                     | 17.56                  | Extremely High                     |
| BAY-6          | 17.60                  | Extremely High                     | 17.64                  | Extremely High                     |
| BAY-7          | 14.10                  | Extremely High                     | 14.13                  | Extremely High                     |
| BAY-8          | 1.95                   | Extremely High                     | 2.96                   | Extremely High                     |
| BAY-9          | 10.89                  | Extremely High                     | 11.18                  | Extremely High                     |
| BAY-10         | 0.02                   | Extremely Low                      | 0.02                   | Extremely Low                      |
| BAY-11         | 3.45                   | Extremely High                     | 6.80                   | Extremely High                     |
| BAY-12         | 18.31                  | Extremely High                     | 18.32                  | Extremely High                     |
| BAY-13         | 0.02                   | Extremely Low                      | 0.03                   | Extremely Low                      |
| BAY-14         | 0.02                   | Extremely Low                      | 0.02                   | Extremely Low                      |
| BAY-15         | 0.18                   | Low                                | 0.18                   | Low                                |
| BAY-16         | 0.02                   | Extremely Low                      | 0.03                   | Extremely Low                      |
| BAY-17         | 3.70                   | Extremely High                     | 4.93                   | Extremely High                     |
| BAY-18         | 13.33                  | Extremely High                     | 14.04                  | Extremely High                     |
| BAY-19         | 12.96                  | Extremely High                     | 13.08                  | Extremely High                     |
| BAY-20         | 0.02                   | Extremely Low                      | 0.02                   | Extremely Low                      |
| BAY-22         | 13.30                  | Extremely High                     | 13.93                  | Extremely High                     |
| BAY-23         | 0.02                   | Extremely Low                      | 0.03                   | Extremely Low                      |

Figure 6. Map of the liquefaction potential level of the Palu Bay area: (a) earthquake magnitude 7.5 $M_w$; and (b) 7.9 $M_w$. 

(a) 
(b)
4. Conclusions
Based on the soil profile investigation results, the soil condition profile of Palu Bay area is dominated by non-cohesive soil (sand). Areas with non-cohesive soil conditions are those with high liquefaction potential. In addition, the groundwater level position in the area varies between 0.09 m and 4.48 m below ground level. These indicate that the Palu Bay area can cause liquefaction due to its aspects of liquefaction vulnerability.

Based on the analysis of the liquefaction potential in Palu Bay, in which the earthquake magnitudes were 7.5 $M_w$ and 7.9 $M_w$, most of its eastern region indicated no liquefaction potential. On the contrary, liquefaction potential was indicated in the western and southern parts. Due to Palu Koro fault line in the area, the earthquake hazards and risks are more significant than in the eastern region. Therefore, countermeasure efforts against potential liquefaction, especially in the southern and western parts of Palu Bay, are required to prevent or reduce the risk of disasters.

Based on the LPI analysis results on the 7.5 $M_w$ and 7.9 $M_w$ earthquakes, the Palu Bay area is dominated by extremely high and low liquefaction potentials. Extremely high liquefaction potential areas are dispersed in the western and southern regions. Meanwhile, the eastern region of the Palu Bay area is dominated by extremely low liquefaction potential. There is only a slight difference between the 7.5 $M_w$ and 7.9 $M_w$ LPI calculation results.

Based on on-site visit results, data collections are mostly taken from the side of the river and bridge area along the coast. Therefore, the calculation results only represent the potential for liquefaction on the coast of Palu Bay. It is suggested to carry out further research, especially on the mitigation efforts for locations with high and extremely high liquefaction potential.
Acknowledgment
The authors would like to express their gratitude for the support given by the Balai Wilayah Sungai Sulawesi III, Directorate General of Water Resources, Ministry of Public Works, and Public Housing, Republic of Indonesia.

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