Liquefaction potential analysis on Gumbasa Irrigation Area in Central Sulawesi Province after 2018 earthquake

A Pratama1,2,*, T F Fathani1,3, I Satyarno1,3

1Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
2Directorate Irrigation and Lowland, Directorate General Water Resources, Ministry of Public Works and Housing, Republic of Indonesia
3Center for Disaster Mitigation and Technological Innovation (GAMA-InaTEK), Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

*Corresponding author: adyansahpratama@mail.ugm.ac.id

Abstract. On September 28, 2018, a 7.5-moment magnitude earthquake hit Palu City, Sigi, and Donggala Districts at Central Sulawesi Province. It triggered liquefaction which was followed by flow-slide. Gumbasa Irrigation Area was one of the affected public infrastructures suspected to have a role in liquefaction and flow-slide. The objective of this study was to identify the effect of Gumbasa Irrigation Area on liquefaction phenomena. Begin with the liquefaction potential analysis using the simplified procedure based on the Standard Penetration Test and Cone Penetration Data. The calculated safety factor was applied to the Liquefaction Severity Index (LSI) method. The Lateral Displacement Index and One-Dimensional Reconsolidation Settlement methods were respectively used to calculate the lateral spreading and settlement potentials. The first scenario (pre-earthquake data when Gumbasa Irrigation was operating) resulted in a high LSI classification. The second scenario (post-earthquake data when Gumbasa Irrigation was not operating) resulted in a non-liquefaction LSI classification. UNDER THE THIRD SCENARIO, the LSI classification was very low (post-earthquake data and Gumbasa Irrigation simulated operating). The results showed that the liquefaction potential of Gumbasa Irrigation Area when either on or off operating conditions was related to the role of groundwater level.

Keywords: Irrigation area, simplified method, cyclic resistance ratio, cyclic stress ratio, the factor of safety

1. Introduction

As a country between three major tectonic plates (the Indo-Australian, Eurasian and Pacific plates), Indonesia is prone to natural disasters. One of the rare phenomena that may be the only one in the world is the earthquake that triggers tsunami and liquefaction followed by flow-slide. It has become one of the interesting phenomena, and it had never occurred in any area in Indonesia. Such a condition occurred on September 28, 2018, when a 7.5-moment magnitude (Mw) earthquake, caused by super-shear rupture mechanism on Palu Koro Fault hit Palu City, Sigi, and Donggala Districts [1], [2]. The liquefaction
followed by flow-slide had caused infrastructure damages in Palu City and Sigi District. Liquefaction is a term used to describe the loss of soil strength and/or stiffness due to the generation of pore water pressure in saturated soil subjected to rapid loading [3]. The area affected by the liquefaction included Balaroa, Petobo, Lolu, Jono Oge, and Sibalaya [4], as shown in Figure 1. Based on post-earthquake reconnaissance, it could be concluded that soil liquefaction initiated flow-slide movement [5].

One of the damaged public infrastructures due to the earthquake and liquefaction was the Gumbasa Irrigation Area. It is one of the infrastructures of water resource utilization in Central Sulawesi Province that provides 8.180 hectares of irrigation area. In 2016, rehabilitation activities were done and scheduled for completion in 2019. However, on September 28, 2018, the 7.5 $M_w$ earthquake had led the canal rehabilitation to be discontinued. The damaged condition of the rehabilitated canal is presented in Figure 2. Minor to major damages of Gumbasa Irrigation Area occurred in almost all canal and irrigation structures.

![Figure 1. The liquefaction area on Palu City and Sigi District.](image1.png)

![Figure 2. The damage on Gumbasa Irrigation Canal (Ministry of Public Works and Housing Republic of Indonesia, 2018).](image2.png)

Four out of five liquefaction and flow-slides were located in the Gumbasa Irrigation Area. The mechanical heterogeneity and liquefaction susceptibility are enhanced by irrigation water. It triggered failure during the earthquake [6]. Increment groundwater level and saturated sandy alluvial soils caused
by rice cultivation supported by irrigation systems, especially inundation systems, can trigger liquefaction when hit by strong ground shaking [7].

This study was conducted in the Gumbasa Irrigation Area, especially in the Jono Oge liquefaction area. The objective of this study was to identify the effect of Gumbasa Irrigation Area against liquefaction. The potential liquefaction analysis in this study is expected to be useful consideration in preparing a reconstruction plan for the Gumbasa Irrigation Area.

2. Material and Methods

This study used geotechnical investigation data conducted by (JICA, 2019) after the 7.5 $M_w$ earthquake. Another geotechnical investigation was collected from (Ministry of Public Works and the Housing Republic of Indonesia, 2015) compiled three years before the 7.5 $M_w$ earthquake. It proposed to observe the geotechnical condition of Gumbasa Irrigation Area before the earthquake.

The liquefaction potential analysis used the Idris-Boulanger simplified method based on the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data, resulting in a safety factor against liquefaction [8]. This method is the closest approach to the liquefaction events found in the field [9], [10]. The irrigation infrastructures were significantly affected by elevation, so the potential for such settlement must be considered. The lateral spreading and settlement potential were analyzed using the Lateral Displacement Index and the One-Dimensional Reconsolidation Settlement method [11], [12]. The Liquefaction Severity Index ($LSI$) method developed by Sonmez and Gokceoglu [13] was used to analyze the liquefaction severity. The Liquefaction Severity Index result was used to create interpretation maps of the liquefaction severity potential.

The calculation of liquefaction potential analysis was performed under the following scenarios: (1) using before earthquake data; (2) using post-earthquake data; and (3) using post-earthquake data with groundwater table that simulated the Gumbasa Irrigation Area on-operating condition.

2.1 Geological and geotechnical condition

Geologic is one of the criteria used to identify the liquefaction susceptibility [14]. The geologic map of Gumbasa Irrigation Area is shown in Figure 3. The area is mainly located on Alluvium and Pakuli Formation, and both are classified as new deposits/quaternary sediment (Holocene). Alluvium Formation is composed of clay, sand, and gravel and Pakuli Formation is composed of conglomerates, sandstones, and carbonaceous claystone. Quaternary deposits are generally loose, decomposed, soft, and less compact. Newly deposited soils tend to be more susceptible to liquefaction than older deposited soil [15].

The distribution of the boreholes is presented in Figure 4. The BH1 and BH7 were used for the first scenario of liquefaction potential analysis. The BH1 and BH7 are the boreholes data collected by (Ministry of Public Works and Housing Republic of Indonesia, 2015) compiled three years before the 7.5 $M_w$ earthquake. The BH2, BH3, BH4, BH5, and BH6 were used for the second and third scenarios of liquefaction potential analysis. The BH2 to BH6 is boreholes data collected by (JICA, 2019) after the 7.5 $M_w$ earthquake. Figure 5 shows the cross-section profile of BH2 to BH6. The profiling was done by classifying the soil layers based on the Unified Soil Classification System (USCS) and drilling log data.

Based on the cross-section profiles of BH2 to BH6, it revealed that the area was dominated by sandy soil. Based on the field observations, BH6 was located downstream of the liquefaction area boundary and did not experience liquefaction or flow-slide. On BH2 experienced liquefaction where settlement and lateral spreading occurred. The BH3, BH4, and BH5 were located in the area that experienced liquefaction and flow-slides. Figure 5 describes BH3 to BH4 to have a layer of clay and silt between the sand layers called the interlayer water film theory. It follows a statement by Hazarika, et al.; that low permeable layers (silt and clay) over loosely deposited sandy and sandy gravel layers suggest the complex mechanism of the long-distance flow-slide for Jono Oge [16].

In refer to the case history in Christchurch City, some earthquakes had caused extensive damage to the lifelines and residential houses and adjacent areas for over nine months period due to the widespread
liquefaction and re-liquefaction in the areas close to major streams, rivers, and wetlands with shallow groundwater level [17]. Thus, to identify this area, a liquefaction potential analysis was required.

Figure 3. Geological condition of Gumbasa Irrigation Area (modified from [18], [19]).

Figure 4. Boreholes data distribution.
2.2 Determination of site modified peak ground acceleration ($PGA_M$) and moment magnitude ($M_w$)

Peak ground acceleration (PGA) for each borehole was determined in refer to the webpage of Desain Spektra Indonesia, 2021 [20]. The webpage requires inputting the longitude and magnitude coordinates for each borehole, as shown in Table 1. The PGA is the value in bedrock. Referring to Indonesia National Standard SNI 1726:2019, PGA value should be multiplied by the site coefficient [21]. The site coefficient depends on the site-class classification by finding the average of $N$-SPT in each borehole. The borehole BH1 and BH7 were CPT data; it was required to assume their site-class classification as medium soil (SD). Table 1 presents the obtained $PGA_M$ and groundwater level.

| Borehole | GWL (m) | Long | Lat  | PGA (g) | $F_{PGA}$ | $PGA_M$ (g) |
|----------|---------|------|------|---------|-----------|-------------|
| BH1      | -3.50   | 119.924 | -0.976 | 0.34    | 1.2       | 0.408       |
| BH2      | -14.08  | 119.927 | -0.983 | 0.331   | 1.3       | 0.430       |
| BH3      | -6.50   | 119.925 | -0.983 | 0.329   | 1.3       | 0.428       |
| BH4      | -3.20   | 119.921 | -0.986 | 0.330   | 1.6       | 0.528       |
| BH5      | -0.70   | 119.909 | -0.989 | 0.331   | 1.3       | 0.430       |
| BH6      | -1.23   | 119.898 | -0.981 | 0.335   | 1.3       | 0.435       |
| BH7      | -3.50   | 119.895 | -0.981 | 0.341   | 1.3       | 0.443       |

The main earthquake recorded on September 28, 2018, 7.5 Mw [5], was used to determine the first earthquake moment magnitude for liquefaction potential analysis. As shown in Figure 6, the second-moment magnitude was 7.9 $M_w$ based on the 2017 Map of Earthquake Sources in Indonesia for the Palu Koro Fault [22].
2.3 Liquefaction potential analysis

The potential liquefaction analysis applied the Idris-Boulanger simplified method based on the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data. This method compares the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR). Following are the equations used in the Idriss-Boulanger method [8]. CSR is the cyclic stress produced by the earthquake load, as described below.

\[
CSR_{M=7.5, \sigma'_{vc}=1} = 0.65 \frac{a_{\text{max}}}{g \sigma_{vc} MSFR_g} \tag{1}
\]

where \(a_{\text{max}}\) is maximum peak ground acceleration or site modified peak ground acceleration (m/s²), \(g\) is the gravitational acceleration constant (m/s²), \(\sigma_{vc}\) is total vertical stress (kN/m²), \(\sigma'_{vc}\) is effective vertical stress (kN/m²), \(r_d\) is shear stress reduction coefficient, \(MSF\) is magnitude scaling factor, \(K_\sigma\) is an overburden correction factor.

CRR is the ratio describing the soil resistance under dynamic load. The CRR equation based on SPT is expressed in equation 2, and the equation based on CPT data is expressed in equation 3.

\[
CRR_{M=7.5, \sigma'_{vc}=1} = \exp \left( \frac{(N_1)_{60cs}}{14.1} + \left( \frac{(N_1)_{60cs}}{126} \right)^2 - \left( \frac{(N_1)_{60cs}}{23.6} \right)^3 + \left( \frac{(N_1)_{60cs}}{25.4} \right)^4 - 2.8 \right) \tag{2}
\]

\[
CRR_{M=7.5, \sigma'_{vc}=1} = \exp \left( \frac{q_{c1NCs}}{540} + \left( \frac{q_{c1NCs}}{67} \right)^2 - \left( \frac{q_{c1NCs}}{80} \right)^3 + \left( \frac{q_{c1NCs}}{114} \right)^4 - 3 \right) \tag{3}
\]

where \((N_1)_{60cs}\) is corrected penetration resistance and \(q_{c1NCs}\) is corrected cone tip resistance. Based on the previous equations, the Safety Factor against liquefaction (FS) is computed by using the following equation:

\[
FS = \frac{CRR}{CSR} \tag{4}
\]

The results of the calculation FS indicate that safety factor against liquefaction where \((FS < 1)\), indicates liquefaction potentially to occur, and \(FS > 1\), indicates no potential for liquefaction to occur. The FS represents the value of the safety number against liquefaction of each soil thickness. The next step that must be done is to obtain the value of liquefaction severity that will occur at that point. The liquefaction severity is calculated using the Liquefaction Severity Index (LSI) method developed by Sonmez and Gokceoglu [13]. This method is an extension of the Liquefaction Potential Index method developed by Iwasaki (1982). The following equation is used to calculate LSI.

\[
L_S = \int_0^{z_0} P_L (z) \cdot W(z) \cdot dz \tag{5}
\]

\[
P_L (z) = \frac{1}{FS + \left( \frac{0.96}{FS} \right)^{1+6}} \text{for } FS < 1.411 \tag{6}
\]

\[
P_L (z) = 0 \text{for } FS \geq 1.411 \tag{7}
\]
\[ W(z) = 10 - 0.5z \text{ for } 0 \leq z \leq 20m \]  
\[ W(z) = 0 \text{ for } z > 20m \]

where \( P_L(z) \) is liquefaction probability value based on depth function and \( W(z) \) is weight factor of soil depth (m). Value of liquefaction events can be classified into six classes as described in Table 2. The LSI calculations were used to create an interpretation map of the liquefaction potential severity by applying ArcGIS.

Based on the field observations, the Gumbasa Irrigation Canal in Jono Oge segment was unlined. The damage was dominated by cracks and settlements as well as lateral displacement on the canal bank. At the same time, some irrigation structures in the segment suffered from structural failure. This study calculated the lateral displacement and settlements potentials caused by liquefaction based on the damage. Zhang [11] developed the lateral displacement index (LDI) method to calculate the lateral displacement potential, using the following equation:

\[ LDI = \int_0^{z_{\text{max}}} \gamma_{\text{max}} \, dz \]  

where \( \gamma_{\text{max}} \) is maximum shear strain and \( z_{\text{max}} \) is maximum depth (m). The calculation of the settlement potential uses the 1-D Reconsolidation Settlement method developed by Yoshimine et al. [12], in the following equation:

\[ S_{v-1D} = \int_0^{z_{\text{max}}} \varepsilon_v \, dz \]  

where \( \varepsilon_v \) is vertical strain and \( z_{\text{max}} \) is maximum depth (m).

Table 2. Liquefaction Severity Index classification [13].

| No. | \( L_S \) | Description     |
|-----|---------|----------------|
| 1   | 85 \( \leq L_S < 100 \) | Very high       |
| 2   | 65 \( \leq L_S < 85 \)  | High            |
| 3   | 35 \( \leq L_S < 65 \)  | Moderate        |
| 4   | 15 \( \leq L_S < 35 \)  | Low             |
| 5   | 0 \( \leq L_S < 15 \)  | Very low        |
| 6   | 0 \( L_S < 0 \)        | Non-liquefied   |

Figure 7. Results of the liquefaction safety factor for BH1 and BH7 under the first scenario (before the earthquake).
3. Results and discussion
CPT data from boreholes BH1 and BH7 (Ministry of Public Works and Housing Republic of Indonesia, 2015), with groundwater level of -3.5 m used for the first scenario of liquefaction potential analysis. The Idriss-Boulanger method requires the Fines Content (FC) value to calculate the clean-sand equivalent value of the corrected tip resistance ($q_{1N_{cs}}$). The geotechnical investigation of BH1 and BH7 did not sieve analysis test to obtain FC. The FC for BH1 and BH7 approach was conducted by observing the correlation between fines contents and soil behavior index ($I_c$) [23]. A comparison of the liquefaction safety factor results for BH1 and BH7 is shown in Figure 7. Table 3 shows the liquefaction severity, the lateral spreading and settlement potentials on BH1 and BH7 boreholes.

| Borehole | $M_w = 7.5$ | | | $M_w = 7.9$ | | |
|----------|--------------|--------------|--------------|--------------|--------------|--------------|
|          | $L_S$ | LDI | S | $L_S$ | LDI | S |
| BH1      | 80.4 | High | 0.572 | 0.067 | 85.1 | Very High | 0.592 | 0.069 |
| BH7      | 82.8 | High | 0.568 | 0.060 | 87.7 | Very High | 0.576 | 0.062 |

Based on the severity index under the first scenario, BH1 and BH7 are classified as high LSI classification. Onsite verification at BH1 showed that both the canal bed and bank were damaged. Figure 8a. shown the condition of the irrigation canal before the earthquake. The settlement and lateral spreading had caused the canal shape to become not as straight as before the earthquake shown in Figure 8b. Meanwhile, the BH7 did not experience liquefaction. The verification results of BH1 proved the relationship between the analysis results of lateral spreading and settlement potential that could predict the damage.

Figure 8. The condition of irrigation canal on borehole BH1: (a) before earthquake (Ministry of Public Works and Housing Republic of Indonesia, 2015); (b) after earthquake.

Under the second scenario, the liquefaction potential analysis used the after earthquake conditions. This scenario aimed to determine the liquefaction potential when the Gumbasa Irrigation Area had not yet operated. The SPT data on BH2, BH3, BH4, BH5, and BH6 represented the upper to the lower sides liquefaction area boundary, with the Gumbasa Irrigation Canal being on the upper side of the liquefaction area. The groundwater level data was used based on Table 1 that gathered the elevation data during the geotechnical investigation (JICA, 2019). A comparison of the liquefaction safety factor results for BH2, BH3, BH4, BH5, and BH6 is shown in Figure 9. Furthermore, Table 4 presents the liquefaction severity index and the lateral spreading and settlement potentials under the second scenario.
Figure 9. The results of liquefaction safety factor for BH2, BH3, BH4, BH5, and BH6 under the second scenario (after the earthquake).

Table 4. The Summary of second scenario (after the earthquake).

| Borehole | $M_w = 7.5$ | $M_w = 7.9$ |
|----------|-------------|-------------|
|          | $L_S$ | LDI | S | $L_S$ | LDI | S |
| BH2      | 0.0 | Non-liquefied | 0.007 | 0.001 | 0.0 | Non-liquefied | 0.019 | 0.004 |
| BH3      | 37.2 | Moderate | 2.222 | 0.251 | 38.5 | Moderate | 2.282 | 0.261 |
| BH4      | 8.6 | Very Low | 0.365 | 0.043 | 11.3 | Very Low | 0.404 | 0.051 |
| BH5      | 44.5 | Moderate | 1.708 | 0.277 | 46.5 | Moderate | 1.754 | 0.285 |
| BH6      | 0.0 | Non-liquefied | 0.000 | 0.000 | 0.0 | Non-liquefied | 0.000 | 0.000 |

Based on the severity index under the second scenario, two boreholes (BH2 and BH6) were classified as non-liquefied. The remaining boreholes (BH3, BH4, BH5) were very low to moderate on the liquefaction area. The lateral displacement and settlement potentials of two boreholes were classified as non-liquefied to almost zero. Borehole BH3 indicated the highest value of lateral displacement and settlement potential.

Under the third scenario, the liquefaction potential analysis used the post-earthquake conditions with the increased groundwater level to simulate Gumbasa Irrigation Area operation. The groundwater level of two boreholes (BH2 and BH3) increased to -3.5 m, referring to the geotechnical investigation report (MPWH, 2015) regarding the groundwater level when Gumbasa Irrigation Area operated. At the same time, other boreholes (BH4, BH5, and BH6) with an elevation of above -3.5 m were used as the elevation recorded in Table 1. A comparison of the results of the liquefaction safety factor of all boreholes is shown in Figure 10. Furthermore, Table 5 shows the liquefaction severity index and

Based on the severity index under the third scenario, only 1 point (BH6) was classified as non-liquefied. The field observations showed that point BH6 was located on the bridge abutment area with quite a high N-SPT value; thus, it did not indicate liquefaction, lateral spreading, and settlement potentials. The BH2, formerly non-liquefied, changed to low classification as the lateral spreading and settlement potentials increased. The other three points (BH3, BH4, and BH5) located on the liquefaction area indicated the same severity index, low to moderate classification. However, point BH3 showed increasing lateral spreading and settlement potentials. Map of liquefaction severity index under the second and third scenarios is shown in Figure 11.
Figure 10. Results of the liquefaction safety factor of BH2, BH3, BH4, BH5, and BH6 under the third scenario (after the earthquake).

Table 5. The Summary of third scenario (after the earthquake).

| Borehole | $M_w=7.5$ | | | $M_w=7.9$ | | |
|----------|-----------|---|---|-----------|---|---|
|          | $L_S$     | LDI | S  | $L_S$     | LDI | S  |
| BH2      | 25.9      | Low | 0.668 | 0.100 | 28.2 | Low | 0.706 | 0.109 |
| BH3      | 60.0      | Moderate | 2.856 | 0.326 | 61.4 | Moderate | 2.888 | 0.333 |
| BH4      | 8.6       | Very Low | 0.365 | 0.043 | 11.3 | Very Low | 0.404 | 0.051 |
| BH5      | 44.5      | Moderate | 1.708 | 0.277 | 46.5 | Moderate | 1.754 | 0.285 |
| BH6      | 0.0       | Non-liquefied | 0.000 | 0.000 | 0.0 | Non-liquefied | 0.000 | 0.000 |

Figure 11. Liquefaction susceptible area based on Liquefaction Severity Index ($LSI$).
Based on the map of severity index, borehole BH6 consistently showed a good green color under the second and third scenarios. Borehole BH2 showed good green color under the second scenario but changed into bright green under the third scenario. Borehole BH3 indicated yellow color under the second scenario and changed into orange color under the third scenario. BH4 and BH5 showed a tendency of constant color under the second and third scenarios.

4. Conclusions
Gumbasa Irrigation Area, located on Alluvium and Pakuli Formation, is classified as new deposits/quaternary sediment (Holocene). The results of the soil profile investigation indicate that it is also dominated by sandy soil. Based on geological and geotechnical criteria, Gumbasa Irrigation Area is susceptible to liquefaction.

The potential liquefaction analysis based on geotechnical investigation data collected before the earthquake revealed an indication of liquefaction potential in Gumbasa Irrigation Area, especially Jono Oge segment. Under the first scenario, BH1, located on Gumbasa Irrigation Canal, resulted in 80.4 liquefaction severity values and was categorized into high LSI classification. The irrigation canal on BH1 showed that the canal bed and bank were damaged after the 7.5 $M_w$ earthquake on September 28, 2018.

Under the second scenario, BH2, located on Gumbasa Irrigation Canal, resulted in a liquefaction severity value of 0 and was categorized into non-liquefied LSI classification. Both 7.5 $M_w$ and 7.9 $M_w$ earthquakes constantly indicated non-liquefied LSI classification for BH2. The highest liquefaction severity value was shown on BH5 with a liquefaction severity value of 44.5 in 7.5 $M_w$ earthquake and categorized into moderate LSI classification. The liquefaction severity value increased to 46.5 in 7.9 $M_w$ earthquake and was categorized into constantly moderate LSI classification.

Under the third scenario, some increments of liquefaction severity value and LSI classification were identified. The initial BH2 liquefaction severity value was 0 and increased to 25.9, affecting the LSI classification to change into low. The highest value of liquefaction severity value was shown on BH3. In 7.5 $M_w$, BH3 resulted in a liquefaction severity value of 60 and was categorized into moderate LSI classification. The liquefaction severity value increased to 61.4 on 7.9 $M_w$, and the LSI classification was constantly moderate. The increments were affected by the groundwater level. Meanwhile, the BH5 liquefaction severity value and LSI classification were constant.

Based on the analysis of the second and third scenarios of liquefaction potential, it was indicated that the results were affected by the earthquake moment magnitude and groundwater level. The increment of liquefaction severity values was identified on borehole BH2, BH3, BH4, and BH5 and followed with lateral spreading and settlement potentials. The liquefaction potential occurred when the Gumbasa Irrigation Area was either on or off operating conditions related to the role of groundwater level. Thus, research on the mitigation plan against liquefaction for Gumbasa Irrigation Area is required.

Acknowledgement
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.

References
[1] Bao H, Ampuero J P, Meng L, Fielding E J, Liang C, Milliner C W D, Feng T and Huang H 2019 Early and persistent supershear rupture of the 2018 magnitude 7.5 Palu earthquake Nat. Geosci. 12 200–5
[2] Socquet A, Hollingsworth J, Pathier E and Bouchon M 2019 Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy Nat. Geosci. 12 192–9
[3] Kramer S L 2013 Encyclopedia of Earth Sciences Series: Encyclopedia of Natural Hazards 594–601
[4] PUSGEN 2018 Gempa Palu Provinsi Sulawesi Tengah 28 September 2018 (M7.4) (Pusat
Penelitian dan Pengembangan Perumahan dan Permukiman Badan Penelitian dan Pengembangan Kementerian Pekerjaan Umum dan Perumahan Rakyat)

[5] Mason H B, Montgomery J, Gallant A P, Hutabarat D, Reed A N, Wartman J, Irsyam M, Simatupang P T, Alatas I M, Prakoso W A, Djarwadi D, Hanifa R, Rahardjo P, Faizal L, Harnanto D S, Kawanda A, Himawan A and Yasin W 2021 East Palu Valley flowslides induced by the 2018 Mw 7.5 Palu-Donggala earthquake Geomorphology 373

[6] Watkinson I M and Hall R 2019 Impact of communal irrigation on the 2018 Palu earthquake-triggered landslides Nat. Geosci. 12 940–5

[7] Bradley K, Mallick R, Andikagumi H, Hubbard J, Meilianda E, Switzer A, Du N, Brocard G, Alfian D, Benazir B, Feng G, Yun S H, Majewski J, Wei S and Hill E M 2019 Earthquake-triggered 2018 Palu Valley landslides enabled by wet rice cultivation Nat. Geosci. 12 935–9

[8] Idriss I M and Boulanger. R W 2008 Soil liquefaction during earthquakes Earthq. Eng. Res. Inst. 160 43

[9] Mase L Z 2018 Studi Kehandalan Metode Analisis Likuifaksi Menggunakan SPT Akibat Gempa 8,6 Mw, 12 September 2007 di Area Pesisir Kota Bengkulu J. Tek. Sipil 25 53

[10] Jalil A, Fathani T F, Satyarno I and Wilopo W 2020 A study on the liquefaction potential in banda aceh city after the 2004 sumatera earthquake Int. J. GEOMATE 18 147–55

[11] Zhang G, Robertson P K and Brachman R W I 2004 Estimating Liquefaction-Induced Lateral Displacements Using the Standard Penetration Test or Cone Penetration Test J. Geotech. Geoenvironmental Eng. 130 861–71

[12] Yoshimine M, Nishizaki H, Amano K and Hosono Y 2006 Flow deformation of liquefied sand under constant shear load and its application to analysis of flow slide of infinite slope Soil Dyn. Earthq. Eng. 26 253–64

[13] Sonmez H and Gokceoglu C 2005 A liquefaction severity index suggested for engineering practice Environ. Geol. 48 81–91

[14] Kramer S L 1996 Geotechnical Earthquake Engineering (Pearson Education India)

[15] Day R W 2012 Geotechnical earthquake engineering handbook: with the 2012 International building code (McGraw-Hill Education)

[16] Hazarika H, Rohit D, Pasha S M K, Maeda T, Masyhur I, Arsyad A and Nurdin S 2021 Large distance flow-slide at Jono-Oge due to the 2018 Sulawesi Earthquake, Indonesia Soils Found. 61 239–55

[17] Orense R P, Pender M J and Wotherspoon L M 2012 Analysis of soil liquefaction during the recent canterbury (New Zealand) earthquakes Geotech. Eng. 43 8–17

[18] Sukamto R 1973 Peta Geologi Tinjau Lembar Palu, Sulawesi (Bandung: Pusat Penelitian dan Pengembangan Geologi)

[19] Sukido, Sukarna D and Sutisna K 1993 Peta Geologi Lembar Pasangkayu, Sulawesi (Bandung: Pusat Penelitian dan Pengembangan Geologi)

[20] PUSGEN 2021 Aplikasi Spektrum Respons Desain Indonesia 2021 Ditjen Cipta Karya, Kementerian PUPR [online] Available at: http://rsa.ciptakarya.pu.go.id/2021/ [Accessed 27 June 2021]

[21] Badan Standardisasi Nasional 2019 SNI 1726-2019 Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung dan Non Gedung

[22] PUSGEN 2017 Peta Sumber Dan Bahaya Gempa Indonesia Tahun 2017

[23] Yi F 2014 Estimating soil fines contents from CPT data Proc. 3rd International Symposium on Cone Penetration Testing, Huntington Beach, Las Vegas, Nevada, USA pp 949–955