Potential Study of Liquefication in the Downstream Area of Jono Oge-Paneki River, Central Sulawesi

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Abstract. Liquefaction during an earthquake is likely to occur in the quaternary geological layer of sediment. Based on the geological process, the mainland of Central Sulawesi was initially a sea lifted upward to become land Palu-Koro fault. Therefore, the land is basically of basic alluvium soil formation, sand deposits, and loose rock. The earthquake in Central Sulawesi in September 2018 was the cause of liquefaction, one of which was in the Jono Oge area, where most of the flow entered the Paneki river. This paper analyzed the potential for recurrent liquefaction by considering the soil structure and water level conditions. The authors focused on the downstream areas of the Paneki River, which passes through Langaleso and Kabobona Village. The data used is N-SPT data, followed by examining post-liquefaction settlement and lateral displacement. This study uses several variations of the earthquake magnitude and potential earthquakes that may occur. The results of observations indicate that the soil conditions of the study area are cohesionless soil. The liquefaction analysis shows that most of the research areas have liquefaction, land subsidence, and lateral displacement potential.

Keywords: Palu Koro Fault, post-liquefaction, Paneki river, simplified procedure

1. Introduction

Soil characteristics have an essential role in infrastructure development planning. Soil mechanics investigations have the main objective of understanding the physical and geotechnical properties of the soil. One of the main risks in low-density sandy soils, shallow groundwater, and external forces such as earthquakes is liquefaction [1]. The phenomenon of the loss of soil strength due to earthquake vibrations. Then, the soil layer turns into the slurry so that it cannot support the load of the building; this is called liquefaction [2]. Several important factors influence the process of liquefaction according to [3], namely: 1) The magnitude and duration of the earthquake, 2) the elevation of the groundwater level, 3) the type of soil, 4) the relative density of the soil, 6) Conditions of placement or environment of deposition, 7) Conditions of drainage, 8) Confined pressure in the soil, 9) Shape of soil particles, 10) Aging and cementation of soil, 11) History of location and environment, 12) Load of buildings. A typical subsurface soil condition susceptible to liquefaction is newly deposited cohesive sand, with the groundwater table close to the soil surface.

The liquefication that occurred in the Jono Oge area was one of the aftershocks of the post-earthquake in Central Sulawesi. With a magnitude of 7.7, which shook 26 km north of Donggala-Central Sulawesi.
on Friday (28/9/2018) at 17:02:44 WIB with a depth of 10 km, which was later updated to magnitude 7.4 at 17:02:45 WIB [4]. Based on the Macroseismic Intensity Map from the USGS [5], the earthquake has an intensity scale ranging from VII-VIII MMI, with extreme to severe shocks and moderate to moderate/heavy damage seen in Figure 1. The liquefaction flow in approximately 1.35 square kilometers makes Jono Oge the area most affected by the earthquake. The landslide length reached 2 kilometers which flowed from the top site after the irrigation channel until it stopped settling at the downstream area of the landslide. The landslide caused the cut-off of the Palu-Palolo axis road, damaging agricultural areas and housing settlements. [6]

![Figure 1. Macroseismic Intensity Map USGS from Palu Earthquake [7]](image)

The reliquefaction phenomenon due to earthquake vibrations is known to occur in the same place if the geological conditions and groundwater levels are unchanged. This condition is shown by the example of Japan, the USA, and Greece [8]. The Authors conducted this research to determine the reliquefaction potential along the Jono Oge channel to the Paneki River, passing through Langaleso village and Kabobona village until it ended up the Palu River. The reliquefaction potential results can use to estimate the potential and probability for liquefaction, subsidence, and lateral displacement. The post-disaster N-SPT data tested and the latest N-SPT data will be tested using a simplified procedure.

## 2. Materials and Methods

### 2.1. Research Area

Palu city name comes from Topalu'e (ground lifted) because this area was once the ocean. Palu-Koro Fault is a significant transformation zone at the junction of three major tectonic plates with relatively high movement in eastern Indonesia. The Australian and Philippine plates collide at speeds as high as 7.5 and 9 cm per year, respectively, with the Eurasian plate or the Southeast Asian block [9]. The geological map shows that the Sigi District (study area) generally has alluvial rock formations, sand, gravelly sand, coral limestone, and mud formed through the river [10]. This formation is the minimus sediments in the Central Sulawesi region at Holocene age, as seen in Figure 2.

The study location is downstream from Jono Oge village, namely Langaleso village and Kabobona village. At the September 2018 earthquake, these two villages were affected by liquefaction flow from the Jono Oge area. Implementation of the study began with a ground investigation data collection to...
determine parameters such as physical strength and soil properties. Then, soil investigation was carried out by N-SPT (Standard Penetration Test) data [10][11][12] and soil sampling downstream of the Paneki river. These soil properties and parameters will later become input parameters in the simulation of liquefaction potential analysis. The type and soil profiles based on data N-SPT bore log and relative density can be seen in Figure 4.

Generally, the six boreholes are dominated by sand and gravelly sand soil types. Sections AB10 and J-3 are areas where liquefaction occurred in 2018. There were silty sand and clayey sand soil types covering the top resulting from soil flow from previous liquefaction. Sections J-4 to BR-3 were areas not affected by the last liquefaction flows. It can be seen that most of the soil types have cohesionless sand and gravel sand. The depth of the groundwater table was below 3 m from the ground level. It shows that the downstream area of the Paneki river has liquefaction potential. It has an aspect of vulnerability to liquefaction in terms of soil type and depth groundwater table. Determine this potential; the authors focused on a region that has not occurred liquefaction in the location of J-4 until BR-1.

![Figure 2. Geological Map Reviewing Palu City and Sigi Regency, Sulawesi (13) with modification](image)

![Figure 3. Gradations of liquifiable soils](image)

2.2. Liquefaction Assessment using Grain Size Distribution Test

Evaluation of the grain size distribution used to provide an overview of the soil composition. Therefore, this test was conducted to determine the distribution of soil particle size.
Soil samples from the boreholes at Paneki River were tested mechanically. The distribution of soil grains can be used in conducting initial hypotheses on the analysis of the liquefaction vulnerability of the soil according to [14] and the analysis guide graph seen in Figure 3.

2.3. Liquefaction Potential Analysis using SPT Data
The liquefaction potential analysis aims to determine the value of an area's safety factor (FS) against the liquefaction. To performed this research, the authors using the simplified method proposed by [15] and corrected [16].

| Condition    | N-SPT Value | Symbol |
|--------------|-------------|--------|
| Very Loose   | < 4         | VL     |
| Loose        | 4 – 10      | L      |
| Moderate     | 10 - 30     | M      |
| Dense        | 30 – 50     | D      |
| Very Dense   | > 50        | VD     |

Figure 4. Data Collection Locations (QGIS) and Soil Stratigraphy

2.3.1. Calculation of Cyclic Stress Ratio (CSR)
A simplified procedure is given by equation (1) to estimate the CSR values.
\[ CSR = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_{v0}}{\sigma'_{v0}} \right) r_d \frac{1}{MSF K_{\sigma}} \]  

Where \( \sigma_{v0} \) and \( \sigma'_{v0} \) is the total and effective stress, \( a_{\text{max}} \) is the peak horizontal acceleration on the ground surface which is determined by the class site, \( g \) is the acceleration due to gravity, \( r_d \) is the stress reduction factor of the soil, \( MSF \) is the magnitude scaling factor of each earthquake magnitude design and \( K_{\sigma} \) is an overburden correction factor. The following formula is used to get those parameters;

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

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

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

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

\[ K_{\sigma} = 1 - C_{\sigma} \ln \left( \frac{\sigma_{vc}}{Pa} \right) \leq 1.1 \]  

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

In which \( z \) is depth in meters, \( M \) is moment magnitude, \( \sigma_{vc} \) is total vertical stress, \( C_{\sigma} \) is coefficient for \( K_{\sigma} \) calculated, \( (N_1)_{60} \) is SPT blow count corrected and \( Pa \) is atmospheric pressure.

2.3.2. Calculation of Cyclic Resistance Ratio (CRR)

Several researchers have used the Cyclic resistance ratio for the liquefaction potential estimation using SPT-N data. The equation used for CRR calculation is given in equation (8)-(13)

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

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

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

\[ (N_1)_{60} = C_N (N_{60}) \]  

\[ C_N = \left( \frac{P_n}{\sigma_{vc}} \right)^{0.784 - 0.0768 \sqrt{(N_1)_{60}}} \leq 1.7 \]  

\[ N_{60} = C_E C_B C_R C_S N_M \]  

Where \( (N_1)_{60cs} \) values are the value of \( (N_1)_{60} \) to an equivalent sand value, \( \Delta(N_1)_{60} \) is the correction of fineness content, \( C_N \) is SPT or CPT overburden correction factor, \( N_{60} \) is corrected from N value blow count for an energy ratio of 60% in which \( C_E, C_B, C_R, C_S \) is correction factor of the tools used and \( N_M \) is measured blow count.

2.3.3. Calculation Factor of safety against Liquefaction (FS)

The FS can define the liquefaction potential by using the following equation:
\[ FS = \frac{CRR}{CSR} \]  

Liquefaction will occur if the value is less than 1 (FS<1)  

2.3.4. Liquefaction Probability  
The Liquefaction Probability \( P_L \) the method from [17] can be used to describe where is the layer that probable to liquefy by following equation (15)  

\[ P_L = \frac{1}{1 + \exp \left[ -\left( \beta_0 + \beta_1 \ln \ln (CSR) + \beta_2 (N_1)_{60} \right) \right]} \]  

Where the parameters of \( \beta_0 \), \( \beta_1 \) and \( \beta_2 \) methods from [17]  

2.3.5. Post Liquefaction Lateral Spreading Estimation  
The lateral spreading displacement that calculated by integrating maximum shear strains versus depth represents a measure of the total potential displacement, for which [18] suggested the term "lateral displacement index" (LDI) then computed as equation (16)-(19)  

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

\[ \gamma_{max} = \min \left( \gamma_{lim} \cdot 0.035 \left( 2 - \frac{FS_{liq}}{F_{\alpha}} \right) \left( 1 - \frac{F_{\alpha}}{FS_{liq} - F_{\alpha}} \right) \right) \]  

\[ \gamma_{lim} = 1.859 \left( 1.1 - \frac{(N_1)_{60cs}}{46} \right) \geq 0 \]  

\[ F_{\alpha} = 0.032 + 0.69 \sqrt{(N_1)_{60cs}} - 0.13(N_1)_{60cs} \]  

Where in (16) \( z_{max} \) is maximum depth, \( \gamma_{max} \) is maximum shear strain and \( dz \) is thick of a layer. Equation (17) used if \( 2 > FS_{liq} > F_{\alpha} \), due to \( FS_{liq} \geq 2 \) then \( \gamma_{max} = 0 \). And for equation (19) \( \gamma_{max} = \gamma_{lim} \) if \( FS_{liq} \leq F_{\alpha} \), where \( \gamma_{lim} \) is limiting shear strain, \( F_{\alpha} \) is an additional parameter factor of safety and \( FS_{liq} \) is the FS against triggering of liquefaction. A large number of lateral spreading occurs is the sum of each layer that occurs spreading in meters.  

2.3.6. Post Liquefaction Reconsolidation Settlement Estimation  
This study only defines settlement caused by consolidation. Another method used to determine reconsolidation settlement is to consider shear deformation. According to [19], the recommended relationships can be reasonably approximated by using this equation (20) (21)  

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

\[ \varepsilon_v = 1.5 \cdot \exp \left( -0.369 \sqrt{(N_1)_{60cs}} \right) \cdot \min(0.08, \gamma_{max}) \]  

Where \( S_{v-1D} \) is ground surface settlement for one-dimensional consolidation and \( \varepsilon_v \) is volumetric strain. The one-dimensional post-liquefaction reconsolidation settlement calculation depends on the spatial distribution of the liquefation zone and the type of structure being evaluated.
3. Results and Discussion

3.1. Grain Size Analysis

The grain size curve divides into two criteria which have uniform graded and well graded. Using the grain size distribution as seen in Figure 5, the four boreholes are generally dominated by sandy soil. In borehole J-4, the distribution of soil grain size by type is evenly distributed and categorized as well graded soil. Meanwhile, boreholes DB-1, DB-2, and BR-1 can be classified as uniformly graded soils because a few sizes generally dominate the distribution of grain size gradations. In terms of liquefaction potential, the grain size gradation distribution at the borehole location J-4 has liquefaction resistance compared to others.

According to [20], uniform graded soils are generally more susceptible to liquefaction than well-graded soils. In well-graded soils, smaller particles fill the voids between larger particles to reduce the potential for volume changes due to shaking. Although the fineness soil content is relatively at location J-4 is high (above 20%), it still is tested using a simplified procedure to overview the potential for liquefaction from the four locations.

3.2. Liquefaction Potential Analysis using SPT Data results

Peak Ground Acceleration (PGA) can be determined by reviewing based on the peak acceleration map in the bedrock (SB) listed [21]. In this map, there are several variations of probability that will be exceeded and the period. To determine the Peak Ground Acceleration Max (PGA_max), PGA values obtained must first be multiplied by the coefficient value-based site [22].

![Figure 5. Grain Size Distribution for each boreholes using [14] method](image-url)
Table 1. Results of Liquefaction Potential

| Bore Hole Point | Groundwater Table (m) | PGA$_M$ (g) | Liquefaction Potential | $M_w=5$ | $M_w=6$ | $M_w=7$ | $M_w=7.4$ | $M_w=7.9$ |
|-----------------|------------------------|-------------|-------------------------|--------|--------|--------|--------|--------|
| J-4 (Langaleso) | 1.5                    | 0.390       | Non-Liquified           | Non-Liquified | Non-Liquified | Non-Liquified | Non-Liquified | Non-Liquified |
| DB-1 (Kabobona) | 0.5                    | 0.390       | Liquified               | Liquified | Liquified | Liquified | Liquified | Liquified |
| DB-2 (Kabobona) | 0.5                    | 0.390       | Liquified               | Liquified | Liquified | Liquified | Liquified | Liquified |
| BR-1 (Palu River)| 0.5                    | 0.390       | Liquified               | Liquified | Liquified | Liquified | Liquified | Liquified |

The authors used several variations of the earthquake magnitude in the study; the lower scale was $M_w = 5.0$, and an enormous scale was $M_w = 7.9$. This most considerable scale is obtained from the potential of the Palukoro Fault, which has the potential for an earthquake to reach 7.9 $M_w$. By using formulas (1)-(14), the results of calculating the Factor of Safety (FS) values for the $M_w = 5.0$ up to $M_w = 7.9$ Earthquakes can be seen in Table 1 and Figure 6.

Using the results of the potential liquefaction analysis, with variations in the $M_w = 5.0$ to $M_w = 7.9$ earthquakes, only the J-4 borehole has no liquefaction potential. In an earthquake measuring $M_w = 5.0$, point DB-1 has the potential for liquefaction in layers with a depth of 1 and 5 m, point DB-2 at 2 m, and point BR-1 at 2 and 5 m.

Whereas in the $M_w = 7.9$ earthquakes, point DB-1 has the potential for liquefaction at a depth of 1,3 and 7 m, point DB-2 of 2 and 4 m, and point BR-1 of 1 - 7 m. This result stated that liquefaction potential would increase with the increasing intensity of the earthquake and the shock duration. Along with the rising power of the earthquake magnitude, the potential depth of the affected area will also increase.

Figure 6. The liquefaction safety factor of each hole with variations in earthquake magnitude
Using the formula (15) is used to obtain the liquefaction probability of 4 boreholes as follows in Table 2. Based on the results of liquefaction probability calculations for several variations of earthquake magnitude, it can be stated that the J-4 borehole is a point that does not have the potential for liquefaction to occur. Meanwhile, in another site, the probability of liquefaction varies with the magnitude of the earthquake and the depth of the affected layer, as shown in Figure 7.

| Bore Hole Point | Layer to Liquefy (m) | Probability of Liquefaction (%) |
|-----------------|----------------------|---------------------------------|
| J-4             | Non Liquified        | 0                               |
| DB-1            | 1-7                  | 0.85                            |
| DB-2            | 2-4                  | 0.88                            |
| BR-1            | 1-7                  | 0.93                            |

Having analyzed that liquefaction occurs, authors can estimate Post Lateral Spreading Liquefaction (LDI) with the (16)-(19) formula and calculation results in the following Table 3. Based on the calculation results of Post Liquefaction Lateral Spreading on several variations of earthquake magnitude, because the J-4 borehole is a point that does not have the potential for liquefaction to occur, lateral spreading does not occur. However, as for the other matters with potential liquefaction, lateral spreading increases with increasing magnitude quake.

In addition to the Lateral Spreading Estimation, the authors also calculated the Post Liquefaction Reconsolidation Settlement Estimation \( S_{v-1D} \) using (20) (21) formulas with the following results as seen in Table 4. Based on the results of the Post Liquefaction Reconsolidation Settlement calculation on several variations of earthquake magnitude, it is the same as the calculation of lateral spreading because the J-4 borehole is a point that does not have the potential for liquefaction to occur, so there is no reconsolidation of settlement. Meanwhile, another potential site for liquefaction and lateral spreading is also a reconsolidation settlement that increases along with the increase in the earthquake magnitude.

**Figure 7.** The liquefaction probability maps of the downstream area of the Jono Oge-Paneki River

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### Table 3. Post liquefaction lateral spreading results for four boreholes

| Bore Hole Point | Dominant Soil | $M_w=5$ | $M_w=6$ | $M_w=7$ | $M_w=7.4$ | $M_w=7.9$ |
|-----------------|---------------|---------|---------|---------|---------|---------|
| J-4             | Sand          | 0       | 0       | 0       | 0       | 0       |
| DB-1            | Gravelly Sand | 0.462   | 0.682   | 0.826   | 0.862   | 0.916   |
| DB-2            | Gravelly Sand | 0.310   | 0.339   | 0.401   | 0.448   | 0.510   |
| BR-1            | Sand          | 0.864   | 1.032   | 1.099   | 1.117   | 1.137   |

### Table 4. Post liquefaction reconsolidation settlement results for four boreholes

| Bore Hole Point | Dominant Soil | $M_w=5$ | $M_w=6$ | $M_w=7$ | $M_w=7.4$ | $M_w=7.9$ |
|-----------------|---------------|---------|---------|---------|---------|---------|
| J-4             | Sand          | 0       | 0       | 0       | 0       | 0       |
| DB-1            | Gravelly Sand | 0.072   | 0.088   | 0.106   | 0.114   | 0.121   |
| DB-2            | Gravelly Sand | 0.036   | 0.043   | 0.057   | 0.064   | 0.073   |
| BR-1            | Sand          | 0.123   | 0.137   | 0.146   | 0.150   | 0.153   |

### 4. Conclusion

According to soil profile investigation and grain size analysis, the downstream area of Jono Oge has a soil condition profile dominated by cohesionless soil (sand) and gravel sand. Although some of them have a well-graded classification, the downstream part of this area is dominated by sandy soil with a uniform-graded category. Areas with cohesive soil conditions and uniformly graded soil types are the areas that have high liquefaction potential, so specific methods are needed for handling them [23]. Furthermore, the groundwater level in this area is also relatively shallow, which is below 3 m from the ground surface. It is indicated that liquefaction can repeatedly occur in the downstream region of Jono Oge because it has aspects of vulnerability to liquefaction.

According to the analysis with varying earthquake magnitudes, most of the downstream site of Jono Oge has liquefaction potential. Likewise, the analysis of reconsolidation settlement and lateral spreading post liquefaction. Therefore, mitigation efforts against the liquefaction potential, especially in the downstream part of Jono Oge, need to be carried out to prevent or reduce disaster risk. In addition, these areas are in direct contact with the housing and local infrastructure.

To reduce the potential liquefaction, it is proposed to lowering the groundwater level. The water level is lowered by making deep longitudinal excavations intersecting layers indicated to be liquefied [24]. In addition, a retaining wall with a geotextile layer can be used for channel reinforcement, and a weep hole pipe installed for the groundwater outlet at the rear of the structure.

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### References

[1] Araujo W, Palinginis J and Ruiz G 2018 Prediction methods of liquefaction phenomenon and mitigation strategies *Proceedings of the 16th LACCEI International Multi-Conference for Engineering, Education, and Technology: “Innovation in Education and Inclusion”* vol 2018-July (Latin American and Caribbean Consortium of Engineering Institutions)

[2] Towhata I 2008 *Geotechnical Earthquake Engineering* (Berlin, Heidelberg: Springer Berlin Heidelberg)
[3] Day R W 2002 Geotechnical Earthquake Engineering Handbook (Mc Graw Hill)
[4] BMKG 2018 Ulasan Guncangan Tanah Akibat Gempa Bumi Donggala 28 September 2018
[5] USGS 2018 M7.5 Palu, Indonesia Earthquake of September 28, 2018
[6] 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 2020 East Palu Valley flowslides induced by the 2018 M 7.5 Palu-Donggala earthquake Geomorphology 373 107482
[7] Sugawara E and Nikaido H 2014 Properties of AdeABC and AdeIJK Efflux Systems of Acinetobacter baumannii Compared with Those of the AcrAB-TolC System of Escherichia coli Antimicrob. Agents Chemother. 58 7250–7
[8] Wakamatsu K 2012 Recurrence of Liquefaction at The Same Site Induced by the 2011 Great East Japan Earthquake Compared with Previous Earthquakes Proc. 15th world Conf. Earthq. Eng. 24 28
[9] Walpersdorf A, Vigny C, Subarya C and Manurung P 1998 Monitoring of The Palu-Koro Fault (Sulawesi) by GPS Geophys. Res. Lett. 25 2313–6
[10] JICA 2019 Boring Survey For Basic Response For Central Sulawesi Earthquake (Phase I) (Central Sulawesi)
[11] Corporation Dee. ltd 2021 Geotechnical Report Of River Improvement And Sediment Control In Paneki River, Central Sulawesi
[12] Buana Raya P B 2015 Laporan Geologi dan Mekanika Tanah - Studi Penanggulangan Sedimentasi dan Pengaturan Penambangan Di Sungai Palu
[13] Sukamto R 1973 Peta Geologi Tinjau Lembar Palu, Sulawesi Skala 1 : 250.000 Pus. Penelit. dan Pengemb. Geol. Bandung
[14] Tsuchida T and Koester J P 1988 Earthquake-Induced Liquefaction of Fine-Grained Soils - Considerations From Japanese Research 1–51
[15] Seed H B and Idriss I M 1970 A Simplified Procedure For Evaluating Soil Liquefaction Potential (University of California)
[16] Idriss I M and Boulanger R 2008 Soil Liquefaction During Earthquakes vol 3 (Earthquake Engineering Research Institute)
[17] Liao S C, Veneziano D and Whitman R V. 1988 Regression Models For Evaluating Liquefaction Probability J. Geotech. Eng. 114 389–411
[18] 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
[19] Naik S P, Gwon O, Park K and Kim Y-S 2020 Land Damage Mapping and Liquefaction Potential Analysis of Soils from the Epicentral Region of 2017 Pohang Mw 5.4 Earthquake, South Korea Sustainability 12 1234
[20] Kramer S L 1996 Geotechnical Earthquake Engineering (Prentice-Hall, International Series)
[21] Pusat Studi Gempa Nasional T 2017 Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017 (Kementerian Pekerjaan Umum dan Perumahan Rakyat)
[22] Nasional B S 2019 SNI 1726:2019-Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung dan Nongedung
[23] Pramadiyta A and Fathani T F 2020 Physical Modelling of Earthquake-induced Liquefaction on Uniform Soil Deposit and Settlement of Earth Structures J. Civ. Eng. Forum 07 85–96
[24] Pratama A P, Hardyatmo H C and Faris F 2020 Parametric Study of the Effect of Ground Anchor on Deep Excavation Stability J. Civ. Eng. Forum 6 19