Liquefaction potential evaluation on reconstruction project of irrigation canal in the Jono Oge and Lolu Village

I Made Widyanata[1,2], *Sito* Ismanti[1*], and *Angga Fajar* Setiawan[1]

[1]Department of Civil and Environment Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
[2]Directorate General of Construction Development, The Ministry of Public Works and Housing, South Jakarta 12110, Indonesia

Abstract. In Indonesia's liquefaction history, the province of Central Sulawesi was severely affected in several locations when a 7.5 M_w earthquake occurred in September 2018. This study aims to evaluate the liquefaction potential and generate the liquefaction hazard map in the reconstruction project of the Gumbasa Irrigation Canals passed through Jono Oge Village and Lolu Village, closely related to the liquefaction event in the Sigi Regency area. Using the simplified procedure method by Idriss and Boulanger, the Liquefaction Factor of Safety (FOS) was calculated for each layer of soil from thirteen (13) locations of soil investigation test at the end of 2021 by the Ministry of Public Works and Housing. Furthermore, it was followed by calculating the Liquefaction Potential Index (LPI) and Liquefaction Severity Index (LSI). The analysis results show that the construction work area has the liquefaction potential with the observed groundwater level. It is mapped on irrigation canals along the Jono Oge Village and Lolu Village to know the critical segment of the irrigation project. Hereafter, an irrigation canal segment named BGKN-45 to BGKN-46 in Jono Oge required a specific mitigation plan to prevent damage from liquefaction in the future.

1 Introduction

Events involving earthquake-liquefaction can cause harmful deformations in building structures, which can have detrimental effects like structural damage and the possibility of expensive repair expenses. It happened and was documented during the Indonesian earthquake of 7.5 M_w on September 28, 2018, which led to a tsunami and liquefaction in Palu, Central Sulawesi [1]. Massive deaths and property damage resulted from the widespread liquefaction phenomena that struck various regions in Palu, Sigi, and Donggala.

Because of the mortality of earthquake-liquefaction events, post-disaster planning is necessary to reduce potential harm from re-liquefaction. Existing structures and buildings are prone to liquefaction damage and can be strengthened by retrofitting. Also, the soil improvement method through densification, solidification, drainage, reinforcing, and soil replacement prevent liquefaction [2]. Since 2019, the Ministry of Public Works and Housing Indonesia (MPWH) and the JICA (Japan International Cooperation Agency) Team have implemented post-disaster development in Central Sulawesi Province. The Rehabilitation and Reconstruction of the Gumbasa Irrigation System are one of the early 2023 infrastructure development packages to be carried out in the Sigi Regency area of Jono Oge and Lolu, which previously experienced liquefaction.

Several scholars have previously conducted analyses of liquefaction potential in the Jono Oge and Lolu areas, which has a significant value in those locations [3–6]. However, the Potential for liquefaction at the irrigation canal reconstruction site has yet to be specifically discovered, and further studies must be required.

The latest soil investigations in 2021 on Jono Oge and Lolu were taken by the Ministry of Public Works and Housing in the form of the Standard Penetration Test (SPT) and Multichannel Analysis Surface Wave (MASW). Thirteen (13) borehole locations spread along the irrigation canal have yet to be analyzed in the previous study. Evaluation of the possibility for liquefaction along the irrigation canal of Jono Oge and Lolu Village (Fig. 1) is necessary for the irrigation building and canal project design.

This study aims to evaluate the Liquefaction Potential to produce a liquefaction hazard map for the Gumbasa Irrigation Canals reconstruction project that passes through Jono Oge Village and Lolu Village. The value for the liquefaction Factor of safety (FOS) is calculated using a simplified procedure method by Idriss Boulanger [8]. Then it determined the Liquefaction Potential Index (LPI) and Liquefaction Severity Index (LSI) [9–11]. The liquefaction hazard map for the reconstruction project is generated by ArcGIS software with the Inverse Distance Weighting (IDW) method using the LPI value. This research could be used to determine relevant and effective liquefaction mitigation measures for the reconstruction of public facilities.

*Corresponding author: sito.ismanti@ugm.ac.id

Fig. 1. Location of irrigation canal reconstruction project in Jono Oge and Lolu Village (modified from [7]).

2 Theory and background

Geology is one factor used to determine liquefaction vulnerability [12]. Fig. 2 maps the geology formation of Jono Oge and Lolu Area.

According to the regional geological map, there are five types of rock formations in the Sigi Regency and its environs: alluvium and coastal deposits, Celebes molasses, Tinombo formations, complex metamorphism, and granite [14-15]. The primary canal of Gumbasa Irrigation in Jono Oge and Lolu Village is located in the southern part of Palu City, geologically an alluvium and coastal deposit formation. It is categorized as new deposits/quaternary sediment. Typically, newly deposited soils are more prone to liquefaction than older soils [16].

The preliminary investigation on the flow slide in the Jono Oge region indicates that the soil layer in the Jono Oge region comprises low permeability layers atop loosely formed sand and sand gravel layers, which could cause a long-distance flow-slide [17]. The flow slide could be produced by liquefaction in the sand and sand-gravel layers following ground shaking. In addition, the flow slide may have originated from creating a water interlayer beneath the surface layer [18].

2.1 Liquefaction potential analysis

Potential liquefaction analysis aims to determine each soil layer's liquefaction factor of safety (FOS). This investigation utilized the liquefaction trigger procedure based on SPT established by Idriss and Boulanger [8]. The FOS value is determined by comparing the cyclic stress ratio (CSR) to the cyclic resistance ratio (CRR). When the value of CRR divided by CSR is less than 1, liquefaction is possible for the soil layer.

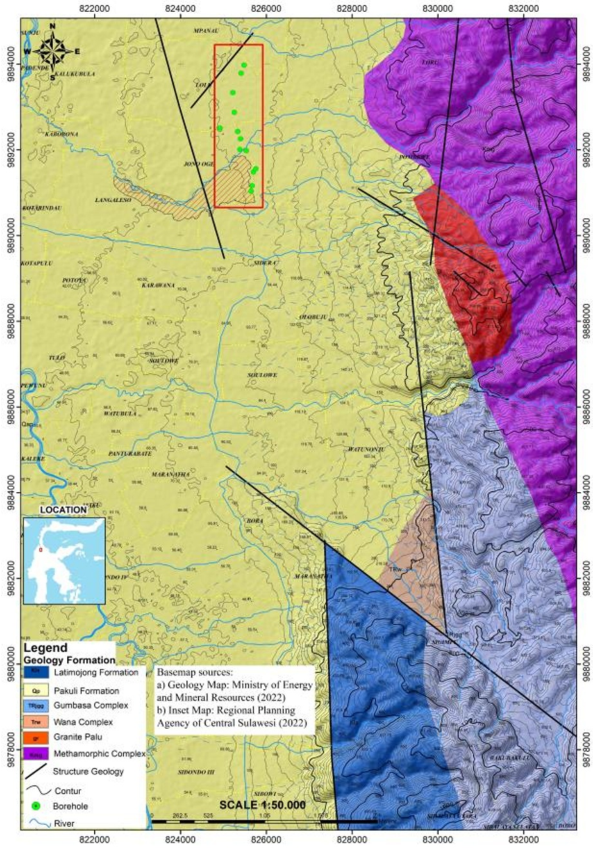

Fig. 2. Geological Condition in Jono Oge and Lolu Village (modified from [13]).

2.1.1 Cyclic stress ratio (CSR)

The cyclic stress ratio (CSR) is derived from the following Equations 1-9.

$$CSR_{M=7.5,\sigma'_v=1} = \frac{CSR_{M,\sigma'_v}}{MSF.K_\sigma} \quad (1)$$

$$CSR_{M,\sigma'_v} = 0.65\frac{\sigma_v}{\sigma'_v}\frac{a_{max}}{g}r_d \quad (2)$$

$$r_d = \exp\left[\alpha(z) + \beta(z).M\right. \quad (3)$$

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right) \quad (4)$$

$$\beta(z) = -0.106 - 0.118\sin\left(\frac{z}{11.28} + 5.142\right) \quad (5)$$

$$K_\sigma = 1 - C_\sigma ln\left(\frac{\sigma'_v}{P_a}\right) \le 1.1 \quad (6)$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60cs}}} \le 0.3 \quad (7)$$

$$MSF = 1 + (MSF_{max} - 1)\left(8{,}64\exp\left(\frac{-M}{4}\right) - 1{,}325\right) \quad (8)$$

$$MSF_{max} = 1{,}09 + \left(\frac{(N_1)_{60cs}}{31{,}5}\right)^2 \le 2{,}2 \quad (9)$$

Where, as MSF is the magnitude correction factor, K_σ It is an overburden correction factor with a maximum value of 1.1, σ_v and σ'_v are total and effective vertical stress at z meters depth, $\frac{a_{max}}{g}$ is the maximum horizontal acceleration at ground level due to earthquakes, r_d is stress reduction coefficient, P_a is overburden pressure of 101 kPa, and $(N_1)_{60cs}$ is penetration resistance in clean sand.

2.1.2 Cyclic resistance ratio (CRR)

The CRR value can be determined under the earthquake magnitude and specific effective stresses using the cyclic resistance ratio derived from the circumstances M = 7.5 and σ'_v= 1 atm by adjusting the N-SPT value with a correction factor and fine-grain correlation $(N_1)_{60cs}$. The following Equations 10-16 describes the CRR based on the SPT:

$$CRR_{M=7.5,\sigma'_v=1atm} = exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.80\right) \quad (10)$$

$$CRR_{M,\sigma'_v} = CSR_{M=7.5,\sigma'_v=1}.MSF.K_\sigma \quad (11)$$

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \quad (12)$$

$$(N_1)_{60} = C_N N_{60} \quad (13)$$

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^m \le 1.7 \quad (14)$$

$$m = 0.784 - 0.0768(\sqrt{(N_1)_{60cs}}) \quad (15)$$

$$\Delta(N1)_{60} = exp\left(1.63 - \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right) \quad (16)$$

In which $(N1)_{60}$ is penetration resistance to the same sand at 1 atm overburden stress if all other attributes are held constant, C_N is overburden correction factor, and FC is soil fines content.

2.1.3 Liquefaction factor of safety (FOS)

The value of the soil safety factor for the risk of liquefaction is the ratio of the CRR and CSR values in equations (2) and (11). The following Equation 17 is used to determine the FOS value.

$$FOS = \frac{CRR_{M,\sigma'_v}}{CSR} \quad (17)$$

If the FOS value is higher than 1, according to equation (17), there is lesser to none of the liquefaction potential in the soil layer. On the other side, when the FOS value is less than 1, it indicates that the land has the possibility to liquefy.

2.2 Liquefaction potential index (LPI)

Liquefaction Potential Index (LPI) Correlation, created by Iwasaki (1981), was used to assess the liquefaction potential. By measuring the association between the safety factor against liquefaction and the depth, the LPI value was utilized to evaluate the liquefaction potential of various sites [9]. The following Equation 18 can be used to determine the LPI and express the potential liquefaction index in the study area.

$$LPI = \int_0^{20} F.W(z)\,dZ \quad (18)$$

Where, F=1–FOS for F < 1.0 and F = 0 if FOS > 1.0, and W(z) = 10-0.5z where z is in meters. The LPI value reflects the level of liquefaction potential in the examined area; the range is updated by Sonmez (2003) and varies from non-liquified to very high if the amount of liquefaction potential is indicated in Table 1.

Table 1. Liquefaction potential index classification [10].

LPI Value	Categories
0	Non-liquefied
0< LPI ≤2	Low
2< LPI ≤5	Moderate
5< LPI ≤15	High
15<LPI	Very High

2.3 Liquefaction severity index (LSI)

The value of the liquefaction severity index is determined using the value of the liquefaction factor of safety (FOS) derived from the potential liquefaction study at a depth between 0 and 20 m [11]. Sonmez and Gokceoglu (2005) developed the equation of Iwasaki et al. (1981) with the following Equations 19-22.

$$L_S = \int_0^{20} P_L(z).W(z)\,dZ \quad (19)$$

$$P_L(z) = \frac{1}{1+(\frac{FOS}{0.96})^{4.5}} \text{ for FOS} < 1.411 \quad (20)$$

$$P_L(z) = 0 \text{ for FOS} \ge 1.411 \quad (21)$$

$$w(z) = 10 - 0.5z \quad (22)$$

Where w(z) is the soil weight factor, and PL(z) is the liquefaction probability based on the depth function. Table 2 classifies LSI values into six tiers, ranging from non-liquefied to very high, based on their LSI values.

Table 2. Liquefaction severity index classification [11].

LSI Value	Categories
85 < LS < 100	Very high
65 < LS < 85	High
35 < LS < 65	Moderate
15 < LS < 35	Low
0 < LS < 15	Very low
0	Non-liquefied

3 Results and discussion

3.1 Evaluation of the Jono Oge and Lolu liquefaction potential results

The liquefaction potential of 13 (thirteen) boreholes located along the main irrigation canal was evaluated, involving 9 (nine) boreholes in Jono Oge and 4 (four) boreholes in Lolu Village. The position of this borehole is close to the liquefaction event in the Sigi Regency area. Based on the geotechnical investigation report of the Ministry of Public Works and Housing from 2021, soil liquefaction potential in Jono Oge and Lolu Village was assessed. These geotechnical study reports served as the foundational information for rehabilitating and reconstructing the Gumbasa irrigation system.

Fig. 3 depicts the Jono Oge liquefaction-impacted area with the locations of nine boreholes, and the location of four boreholes In Lolu Village is used for the liquefaction analysis.

The location of BH1 and BH2 between the irrigation canal is named BGKN-45 (Fig. 4) and BGKN-46. Those are very close to the liquified area of Jono Oge in 2018. The borehole's Ground Water Level (GWL) ranged between 4 – 11.69 meters. The five boreholes named BH3, BH4, BH6, BH7, and BH12 were found dry based on the standpipe observation on November 30, 2021. During the earthquake, the pore water pressure of potentially liquefiable soil was impacted by the depth of the groundwater level.

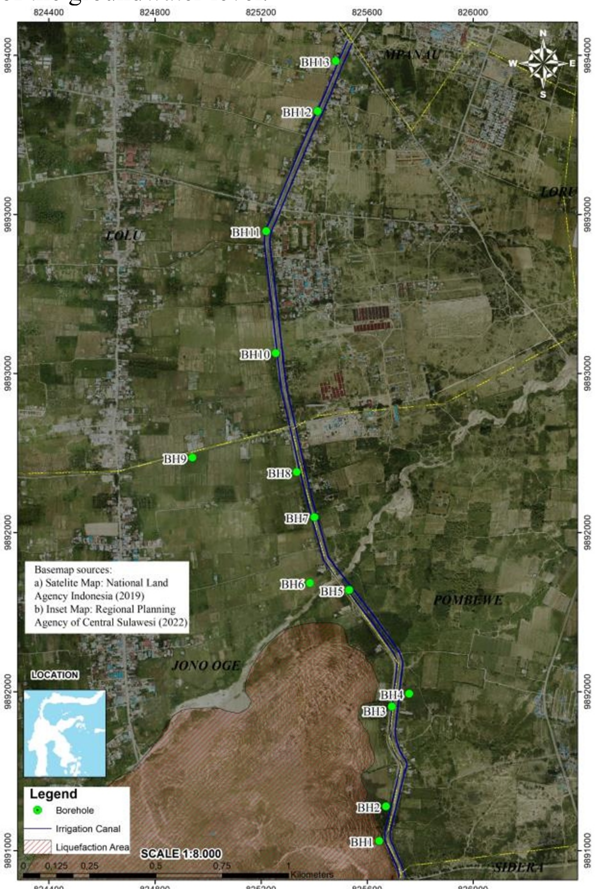

Fig. 3. Location of thirteen boreholes (modified from **[7]**).

Fig. 4. Irrigation canal of BGKN-45 (Source: MPWH 2022).

This study will evaluate the Potential for liquefaction against the influence of the groundwater level using 3 cases. Case one is the groundwater level based on observations on November 30, 2021. The second case assumes that there will be an increase in the groundwater level with a height of up to -3.5 meters below the ground surface based on observations in the Jono Oge irrigation canal in 2015 by the Ministry of Public Works and Housing [4]. The third case assumes the groundwater level can be controlled to -11 meters below the ground surface.

3.1.1 Soil grain size distribution

The soil grain size analysis results can be utilized to conduct a simple preliminary examination of potential liquefaction soils [19]. Sieving was used to determine the soil grain size distribution. In this instance, the grain size distribution of the soil is the proportion of the soil weight in the sieve according to a particular diameter. The boundary curve for most liquefiable and potentially liquefiable soils was developed by Tsuchida (1970).

Several sandy soil samples were collected at each borehole to determine the grain size of the soil in the Jono Oge and Lolu areas for the Irrigation Canal Reconstruction Project. The chart developed by Tsuchida (1970) is then plotted with the grain size analysis data graph for each borehole. Fig. 5-12 illustrate the results of grain size distribution charting.

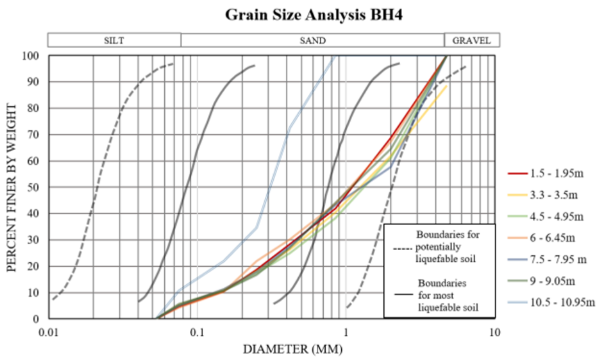

Fig. 5. Grain size analysis for BH4.

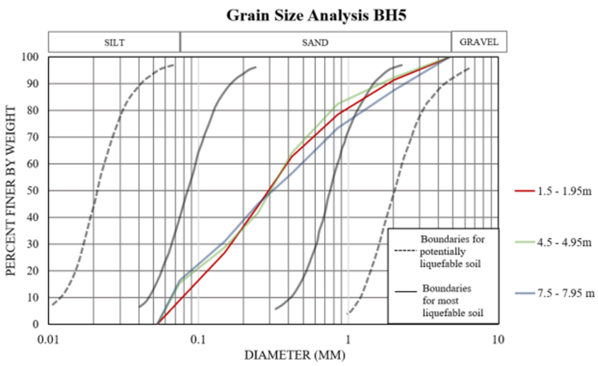

Fig. 6. Grain size analysis for BH5.

According to the analysis results based on Fig. 5-12 and the non-cohesive soil samples obtained from the eight boreholes, the area is dominated by sandy soil with low or uniform gradation. The graphs of soil grain distribution for the remaining five boreholes are not displayed because they lack complete soil grain size analysis data.

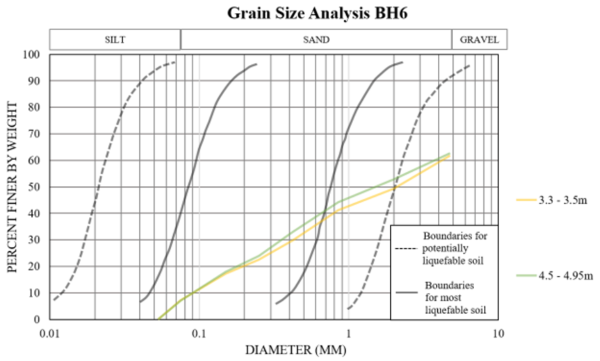

Fig. 7. Grain size analysis for BH6.

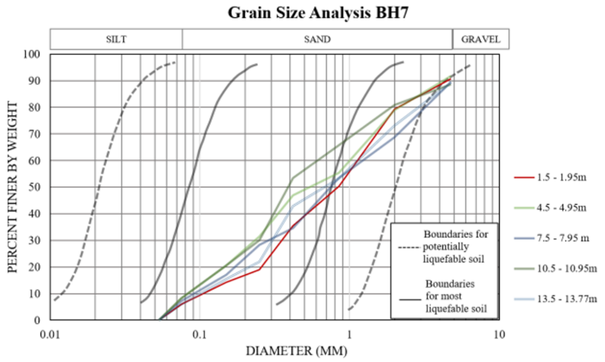

Fig. 8. Grain size analysis for BH7.

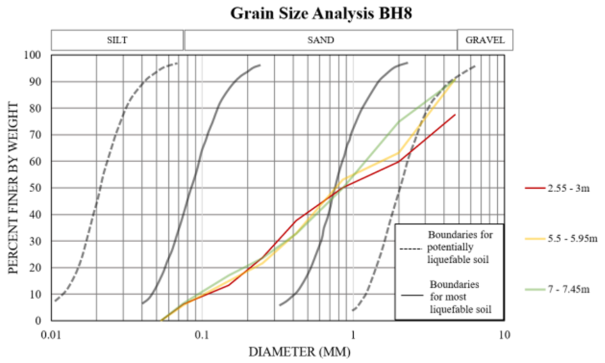

Fig. 9. Grain size analysis for BH8.

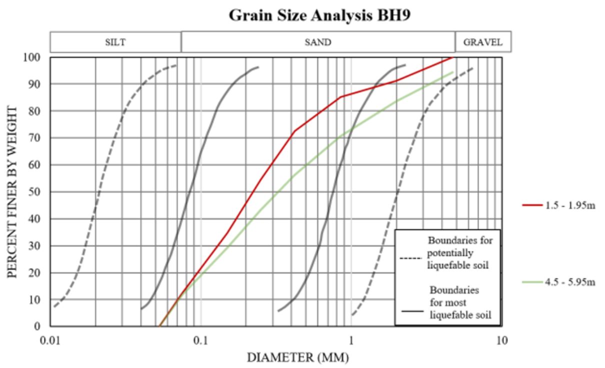

Fig. 10. Grain size analysis for BH9.

However, based on the soil's lithology and the bore log description, it shares the same sandy soil type as the other boreholes. All non-cohesive soil samples evaluated for grain gradation had liquefaction potential.

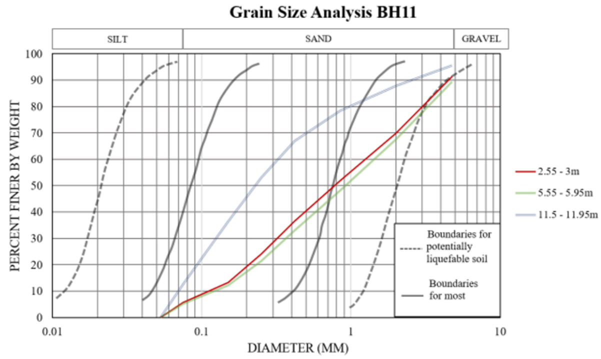

Fig. 11. Grain size analysis for BH11.

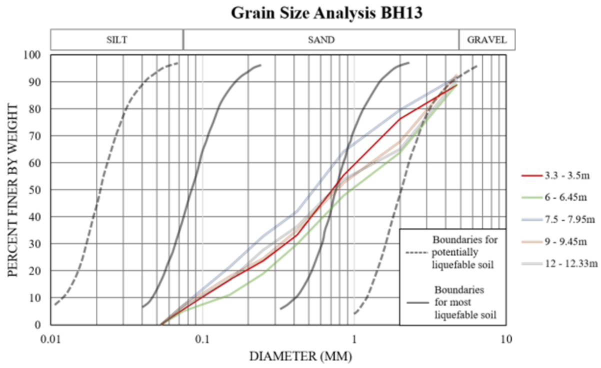

Fig. 12. Grain size analysis for BH13.

3.1.2 Liquefaction factor of safety (FOS) results

This study investigated the liquefaction factor of safety using a simplified procedure method devised by Idriss and Boulanger (2014). The stress-based approach was used to evaluate the potential for liquefaction by comparing the earthquake-induced cyclic stresses to the cyclic resistance of the soil. The soil's cyclic stresses at each depth depend on the earthquake's moment magnitude and peak ground acceleration (PGA).

The PGA value for evaluating liquefaction potential was determined using earthquake magnitude data of 7.5 Mw and a maximum ground acceleration value of 3.2 m/s^2 or 0.33g from a 2018 USGS report for the Palu Valley area. Based on the results of Multichannel Analysis of Surface Wave (MASW) tests, the site class refers to the VS_{30} value, and these locations are designated as site class D. According to SNI 1726:2019, the site coefficient (F_{PGA}) is 1.30 for medium soil [20]. The derived PGA_M value is 0.43g and is used for analysis.

Thirteen boreholes with a maximum depth of 20 meters were analyzed for their liquefaction potential using Equation 17. The analysis is predicated on observations of groundwater level made on November 30, 2021, and there are five dry boreholes. Fig. 13-16 depict the Liquefaction factor of safety graph for the eight boreholes.

The results of the analysis indicate that the six locations of the SPT test points, BH1, BH2, BH5, BH8, BH10, and BH13, in the construction of the Gumbasa irrigation canal in the Jono Oge and Lolu areas contain FOS less than one at various depths of soil layers and are susceptible to liquefaction-related damage. The most

https://doi.org/10.1051/e3sconf/202342904012

vulnerable soil layers are located at 5.50 meters in BH2, while the deepest is at 18 meters in BH10.

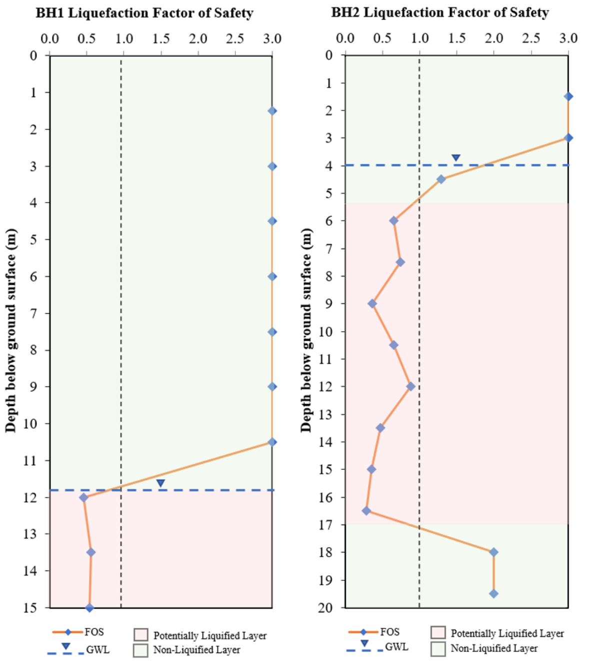

Fig. 13. Liquefaction FOS of BH1 and BH2.

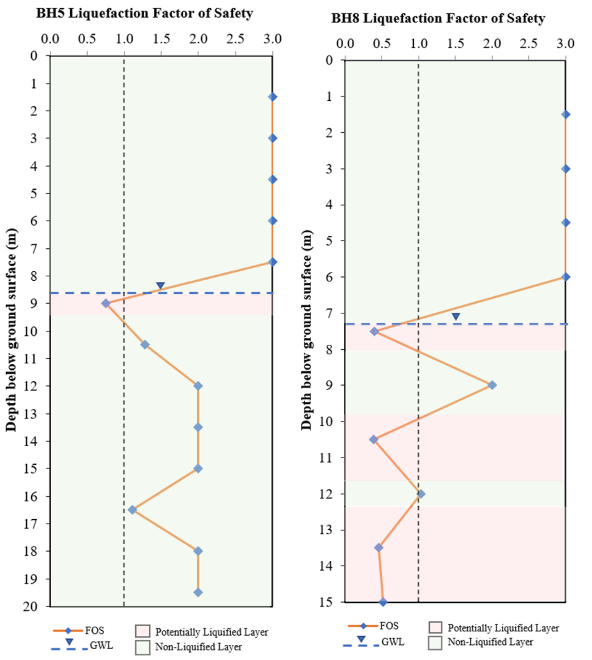

Fig. 14. Liquefaction FOS of BH5 and BH8.

As for the location of BH9 and BH10, their FOS is more significant than 1.1, making them relatively secure. It can occur if the N-SPT number is more than 20. The BH3, BH4, BH6, BH7, and BH12 lack FOS due to a groundwater table's absence.

The findings of the performed liquefaction FOS calculations strengthen the conclusions of the preliminary study of probable liquefaction soils from the Tsuchida chart, particularly for BH8, BH11, and BH13. In addition, GWL and SPT values considerably impact the outcomes of this analysis. Using the results of this FOS, the liquefaction potential index and liquefaction severity index will be calculated in the following section.

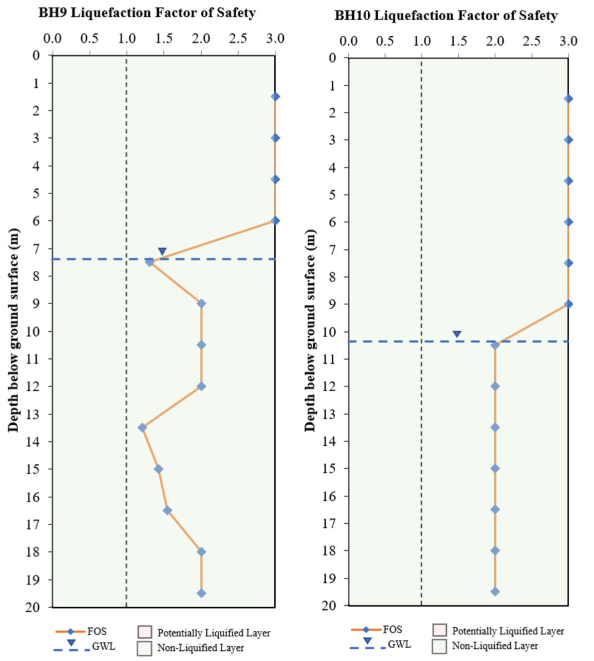

Fig. 15. Liquefaction FOS of BH9 and BH10.

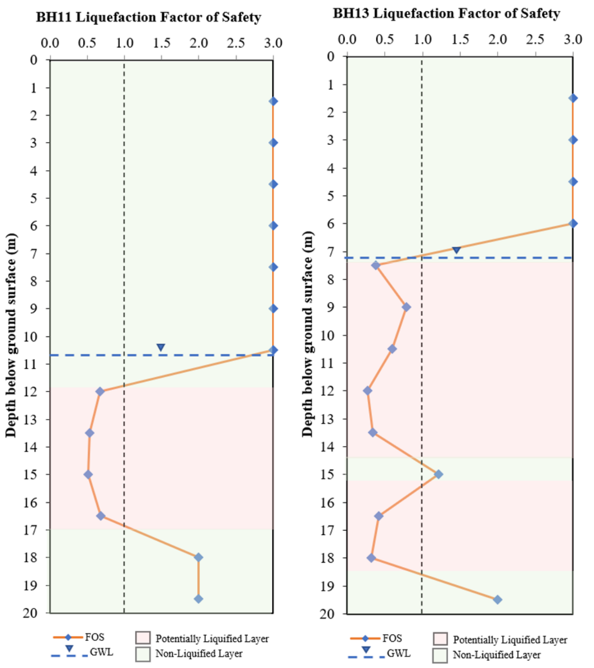

Fig. 16. Liquefaction FOS of BH11 and BH13.

3.2 Liquefaction potential index results and mapping in irrigation canal

The liquefaction potential index value is derived according to equation 18 based on the results of the FOS liquefaction calculation with the GWL observed on November 30, 2021 (case 1). Table 3 summarizes the LPI calculation results. The LPI values of each borehole from Table 3 were then mapped along the reconstruction project using the IDW method in ArcGis, with the results can be seen in Figure 17.

Table 3. LPI for case 1.

Borehole Name	GWL (m)	LPI	Category
BH1	11.69	7.17	High
BH2	4	21.45	Very High
BH3	Dry	0.00	Non-liquefied
BH4	Dry	0.00	Non-liquefied
BH5	8.6	2.09	Moderate
BH6	Dry	0.00	Non-liquefied
BH7	Dry	0.00	Non-liquefied
BH8	7.49	14.53	High
BH9	6.73	0.00	Non-liquefied
BH10	10.38	0.00	Non-liquefied
BH11	10.76	6.95	High
BH12	Dry	0.00	Non-liquefied
BH13	7.12	19.66	Very High

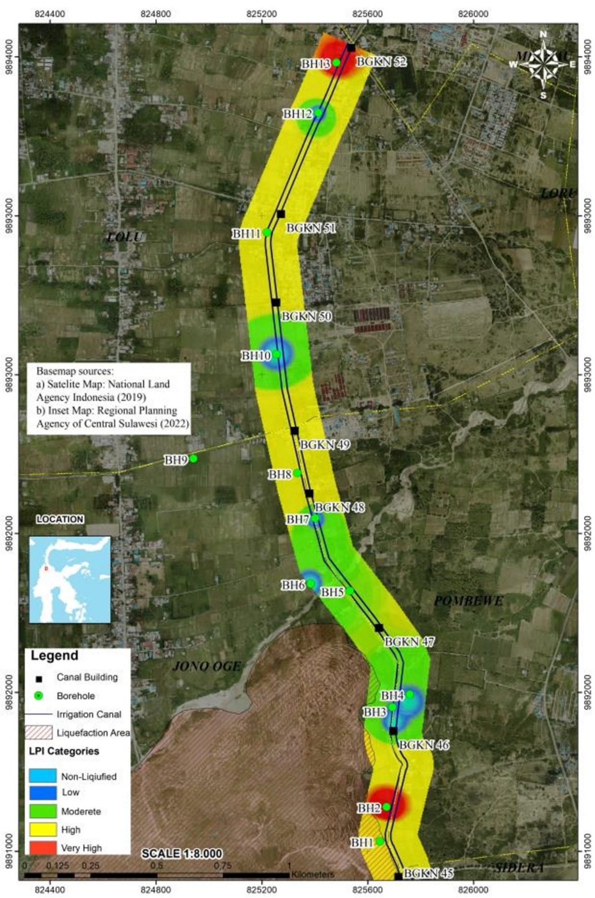

Fig. 17. Liquefaction hazard map with observed GWL on November 30, 2021 (case 1) (modified from [7]).

The potential liquefaction index was also analyzed with cases 2 (GWL -3.5m) and 3 (GWL -11m), with the following results in Table 4. Fig. 18 illustrate the results of LPI hazard mapping on the reconstruction project in case 3.

Table 4. LPI for case 2 and case 3.

Borehole Name	Case 2		Case 3	
	LPI	Category	LPI	Category
BH1	36	Very High	7.17	High
BH2	22.1	Very High	6.89	High
BH3	32.43	Very High	8.17	High
BH4	31.99	Very High	5.02	High
BH5	7.51	High	0	Non-liquefied
BH6	6.88	High	2.11	Moderate
BH7	30.67	Very High	8.45	High
BH8	27.59	Very High	4.14	Moderate
BH9	0	Non-liquefied	0	Non-liquefied
BH10	0	Non-liquefied	0	Non-liquefied
BH11	20.48	Very High	6.95	High
BH12	20.76	Very High	7.21	High
BH13	35.59	Very High	8.62	High

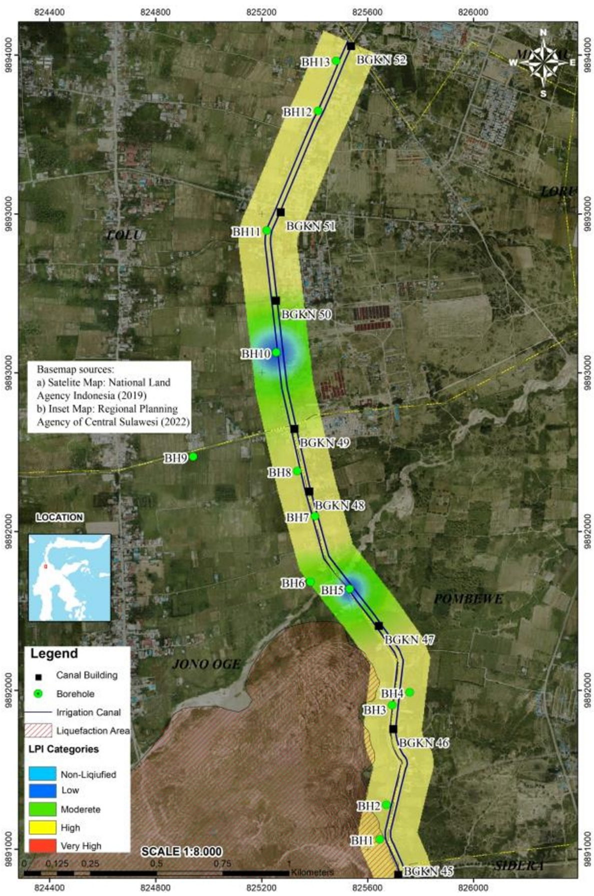

Fig. 18. Liquefaction hazard map if the GWL controlled to -11 meters (case 3) (modified from [7]).

In the last observation of the groundwater table (case 1), segments BGKN-45 and BGKN-46 in Jono Oge and BGKN-52 in Lolu are prone to damage due to the high index of liquefaction potential. Also, Fig. 18 show that the severity can be reduced if the groundwater level is controlled below 11 meters.

3.3 Liquefaction severity index results

Based on the FOS liquefaction calculation findings with the GWL recorded on November 30, 2021 (case 1), the liquefaction severity index value is produced using equation 19. Also, the LSI values for cases 2 and 3 were determined. The calculation results of LSI can be seen in Tables 5-6.

Table 5. LSI for case 1.

Borehole Name	GWL (m)	LSI	Category
BH1	11.69	9.19	Very Low
BH2	4	31.57	Low
BH3	Dry	0.00	Non-liquefied
BH4	Dry	0.00	Non-liquefied
BH5	8.6	5.79	Very Low
BH6	Dry	0.00	Non-liquefied
BH7	Dry	0.00	Non-liquefied
BH8	7.49	17.99	Low
BH9	6.73	2.09	Very Low
BH10	10.38	0	Non-liquefied
BH11	10.76	10.18	Very Low
BH12	Dry	0	Non-liquefied
BH13	7.12	23.91	Low

Table 6. LSI for case 2 and case 3.

Borehole Name	Case 2		Case 3	
	LSI	Category	LSI	Category
BH1	39.95	Moderate	9.19	Very Low
BH2	31.86	Low	9.51	Very Low
BH3	37.42	Moderate	10.49	Very Low
BH4	38.8	Moderate	8.24	Very Low
BH5	15.35	Low	0.63	Very Low
BH6	15.19	Low	5.84	Very Low
BH7	35.62	Moderate	8.84	Very Low
BH8	32.02	Low	7.17	Very Low
BH9	4.23	Very Low	1.74	Very Low
BH10	0	Non-liquefied	0	Non-liquefied
BH11	24.66	Low	10.18	Very Low
BH12	25.58	Low	8.37	Very Low
BH13	38.7	Moderate	9.67	Very Low

In Case 1, the highest value on BH 2 with category low is 31.57, and the lowest is 0 (non-liquified) on BH3, BH4, BH6, BH7, BH10, and BH12. In case 2, the highest value in the moderate category is 39.95 on BH 1, and the lowest value is 0 (non-liquified) on BH 10. The highest value in case 3 is 10.49 on BH 3, with a category very low, and the lowest value on BH10 is 0 (non-liquified).

According to the analysis's findings in Tables 5 and 6, the liquefaction severity index results for Cases 1, 2, and 3 are comparable to those of the liquefaction potential index analysis. The LSI value is ranged from non-liquified to moderate. Buildings in Jono Oge's BGKN-45 through BGKN-46 and Lolu Village's BGKN-52 are particularly vulnerable. As the groundwater level rose to 3.5 meters at BH1, the highest value of LSI was 39.95 in the moderate category. However, when the groundwater level was regulated to -11 meters in cases 1 and 3, this value dropped to 9.19.

3.4 Liquefaction countermeasure plan

The liquefaction mitigation plan for the Gumbasa irrigation canal, especially Jono Oge and Lolu, has been planned in several schemes by the Ministry of Public Works and Housing. The first plan is to control the groundwater level in the area. To stop water seepage, which increases the groundwater level, a 0.75 mm thick waterproof Geomembrane will be used as the lining of the irrigation canals. In addition, it is currently planned to construct a shallow well in the Jono Oge area that aims to release the soil pore water pressure during an earthquake.

The second plan is to strengthen the embankment that supports the irrigation canal building with geotextiles. A 0.8 km stone-filled trenches will be built west of Jono Oge village for irrigation canals from BGKN-45 to BGKN-46. This construction is expected to have two effects: to help reduce excess pore water pressures and to increase the shear resistance of the soil.

4 Conclusion

The 0.8-kilometer-long BGKN-45 and BGKN-46 portions are very susceptible to liquefaction based on the results of a liquefaction potential evaluation, especially when considering the LPI value with groundwater level measurements on November 30, 2021. In addition, the irrigation canal is situated in the Jono Oge flow-slide area. The BGKN-52 segment in Lolu village also needs particular attention, but the location was not damaged as severely as the liquefaction in Jono Oge.

In preventing liquefaction from causing damage to infrastructures, mitigation measures such as impermeable lining, geogrid, shallow wells, and stone-filled trenches have been developed. In subsequent research, the outcomes of modeling, potential scenarios, and the efficacy of the mitigation plan will be examined.

The authors would like to convey their appreciation for the assistance from the River Basin Organization Sulawesi III Palu and the Directorate General of Water Resources.

References

1. European Commission, *Mw 7.5 earthquake in Indonesia, 28 September 2018*, in JRC Emergency Reporting – Activation #021 (2018) https://www.gdacs.org/Public/download.aspx?type=DC&id=75
2. R.P. Orense, Encyclopedia of Earthquake Engineering, 1-13 (2015)

3. A.N. Andiny, F. Faris, A.D. Adi, IOP Conf. Ser.: Earth Environ. Sci. **861**, 052030 (2021) DOI 10.1088/1755-1315/861/5/052030
4. A. Pratama, T.F. Fathani, I. Satyarno, IOP Conf. Ser.: Earth Environ. Sci. **930**, 012093 (2021) DOI 10.1088/1755-1315/930/1/012093
5. W. Rahayu, Nurizkatilah, E. Bahsan, IOP Conf. Ser.: Earth Environ. Sci. **622**, 012016 (2021) DOI 10.1088/1755-1315/622/1/012016
6. A. Widyatmoko, D. Legono, H.C. Hardiyatmo, IOP Conf. Ser.: Earth Environ. Sci. **930**, 012084 (2021) DOI 10.1088/1755-1315/930/1/012084
7. National Land Agency Indonesia, *PASIGALA image in 2019*, in Pasigala Image Documentation (2019)
8. R.W. Boulanger, I.M. Idriss, Report No. UCD/CGM-14/01 (Department of Civil & Environmental Engineering, College of Engineering, University of California, 2014)
9. T. Iwasaki, K. Tokida, F. Tatsuoka, *Soil liquefaction potential evaluation with use of the simplified procedure*, in International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 26 Apr – 3 May, St. Louis, Missouri (1981)
10. H. Sonmez, Env Geol **44**, 862–871 (2003) https://doi.org/10.1007/s00254-003-0831-0
11. H. Sonmez, C. Gokceoglu, Environ Geol **48**, 81-91 (2005) https://doi.org/10.1007/s00254-005-1263-9
12. S.L. Kramer, Geotechnical earthquake engineering (Prentice-Hall, New Jersey, 1996)
13. Ministry of Energy and Mineral Resources, *UpToDate*, Geological map of sigi regency (2022) https://geologi.esdm.go.id/
14. R. Sukamto, Geological map View of Palu Sheet, Sulawesi (PPPG, 1973)
15. Sukido, D. Sukarna, K. Sutisna, Geological map View of Palu Sheet, Sulawesi (PPPG, 1993)
16. R.W. Day, Geotechnical earthquake engineering handbook: with the 2012 international building code, 2nd Edition (McGraw-Hill Education, 2012)
17. H. Hazarika, D. Rohit, S.M.K. Pasha, T. Maeda, I. Masyhur, A. Arsyad, S. Nurdin, Soils and Foundations **61**(1), 239-255 (2021) https://doi.org/10.1016/j.sandf.2020.10.007
18. T. Kiyota, H. Furuichi, R.F. Hidayat, N. Tada, H. Nawir, Soils and Foundations **60**(3), 722-735 (2020) https://doi.org/10.1016/j.sandf.2020.03.015
19. H. Tsuchida, *Prediction and countermeasure against liquefaction in sand Deposits*, in Seminar of the Port and Harbor Research Institute (1970)
20. National Standardization Agency, Procedures for planning earthquake resistance for building and non-building structures (SNI 1726:2019)