Journal of the Civil Engineering Forum, January 2024, 10(1):39-48
DOI 10.22146/jcef.7002
Available Online at https://jurnal.ugm.ac.id/v3/jcef/issue/archive

The Correlation of Liquefaction Potential with Excess Pore Water Pressure in Kretek 2 Bridge Area using Empirical and Numerical Methods

Ali Zakariya[1,2], Ahmad Rifa'i[2,*], Sito Ismanti[2]
[1]Directorate of Bridge Construction, Directorate General of Highways, Ministry of Public Works and Housing, 12110, Jakarta, INDONESIA
[2]Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Yogyakarta, INDONESIA
Jalan Grafika No. 2 Sleman
*Corresponding author: ahmad.rifai@ugm.ac.id

SUBMITTED 17 February 2023 **REVISED** 2 November 2023 **ACCEPTED** 3 November 2023

ABSTRACT Liquefaction is soil condition associated with the drastic increase in pore water pressure of uniform sandy soil due to an enormous earthquake. Therefore, this study aimed to investigate the correlation of liquefaction potential with excess pore water pressure ratio in nine boreholes located at Kretek 2 Bridge area using empirical and numerical methods. Liquefaction potential was estimated based on a semi-empirical method simplified by Idriss and Boulanger (2008), and safety factor (SF) value of $\leq$1.0 was used to represent the existence of its potential. The result showed that liquefaction potential was dominant at depths of 1.5 to 6.0 m, with the exception of BH-9 with 16.5 m and BH-4. Furthermore, the excess pore water pressure ratio was estimated using empirical method developed by Yegian and Vitelli (1981) as well as Serafini and Perlea (2010). Numerical analysis was also conducted for comparison purposes and the process focused on using Deepsoil v7.0 to generate excess pore water pressure by considering soil conditions and dominant seismic sources in Kretek 2 Bridge area. The result showed that the ratio of excess pore water pressure was greater or equaled 0.8. Both empirical and numerical methods produced similar values for BH-1, BH-2, BH-8, and BH-9 at a depth of 1.5–3.0 m, 3–4.5 m, 3.0 m, and 16.5 m, respectively. This showed a correlation between excess pore water pressure ratio and liquefaction potential values at the same depth. However, numerical method tended to overestimate the r_u value, necessitating the use of empirical method to obtain a more reliable result.

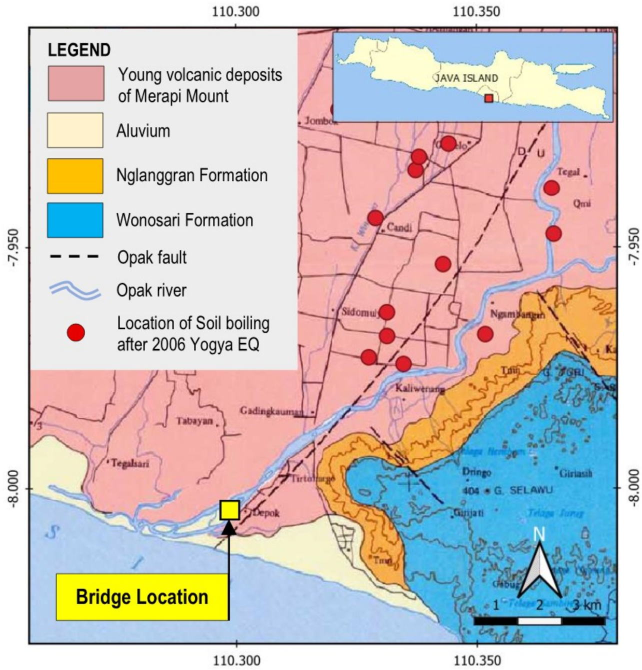
KEYWORDS Simplified Procedure; Safety Factor; Excess Pore Water Pressure Ratio; Deepsoil v7.0; Seismic Source.

1 INTRODUCTION

Indonesia is situated on four tectonic plates, namely the Indo-Australian, Eurasian, Pacific, and Filipina, making the country an archipelagic state. The geographic placement leads to highly susceptibility to recurrent seismic activity, including earthquakes. On May 27th, 2006, a significant earthquake with a magnitude of 6.2 Mw struck Yogyakarta Special Region Province and led to 5,716 deaths, 37,927 injuries, and damages to 202,031 houses with 156,662 destroyed (BAPPENAS, 2006). This devastation was caused by a shallow earthquake with a long seismic duration of 52 seconds that shocked the ground. In the occurrence of this event, Bantul and Klaten Regencies were mostly affected by the earthquake. Another study by Buana and Agung (2015) reported that the 2006 earthquake caused liquefaction in Bantul. Mase (2017*a*) also reported liquefaction effects, including boiling in some places, as shown in Figure 1a. Soil in the area was classified as a quaternary deposit sourced by Merapi Mount Volcanic. Furthermore, the geological map of Yogyakarta in Figure 1b showed that the geological formation of Bantul was dominantly on the young Merapi volcanic mount (Qmi) (Rahardjo et al., 1977). Youd and Perkins (1978) classified the susceptibility of soil deposit susceptibility to liquefaction during a strong seismic, and the result showed that the location was in the “moderate” to “high” category. This was due to the presence of a quaternary soil deposit with a 20 m depth of non-cemented material.

This study was conducted in Opak river estuary, Bantul Regency, Yogyakarta Special Region, characterized by sandy soil with loose sand density at the top layer. Moreover, Kretek 2 Bridge, which crosses Opak river estuary, was constructed betwe-

(a)



(b)

Figure 1 (a) Sand boiling at the well of a resident in Yogyakarta Special Region (Mase, 2017*a*), (b) Modified geological map of Yogyakarta (Rahardjo et al., 1977; Soebowo et al., 2009)

en 2021 and 2022. It was observed to be situated in close proximity to Opak fault, which served as the epicenter of the 2006 Bantul earthquake. The foundation of the bridge was constructed using a bored pile of 32 to 34 m depth classified as a deep category. According to Zakariya et al. (2022*b*), Kretek 2 Bridge area had a low to high liquefaction severity index. The background information led to the adoption of empirical and numerical methods to assess the correlation between liquefaction potential and the ratio of excess pore water pressure in the area. This study was considered important due to the ability of excess pore water pressure to decrease the effective soil stress with subsequent effect on the bearing capacity of the bridge foundation.

2 METHODS

A simplified procedure was proposed by Seed and Idriss (1970) to estimate liquefaction potential with due consideration for laboratory examinations and field observations. The result showed that the potential could be determined by soil deposit type, initial stresses, and the seismic. Moreover, an earthquake normally induces cyclic stress on soil, which can be determined through cyclic stress ratio (CSR). CSR was estimated in the equation shown in Figure 2 using peak ground acceleration maximum (a_{max}), effective soil stress (σ'_{vc}), total soil stress (σ_{vc}), and stress reduction coefficient (r_d). This equation was updated by Idriss (1999) through the multiplication of the magnitude scale factor (MSF) with CSR value. On the other hand, Idriss and Boulanger (2004) suggested multiplying the overburden correction factor with CSR value. During the occurrence of the earthquake, soil resistance or countermeasure value was measured against CSR through the concept of cyclic resistance ratio (CRR) (Idriss and Boulanger, 2008). CRR value was determined by SPT-N corrected ($(N_1)_{60cs}$) using soil drilling equipment, effective overburden pressure correction, and fine soil contents. The two variables, namely CRR and CSR, could be divided to determine safety factor (SF). The flow chart applied to estimate SF against liquefaction is described in the following Figure 2.

This study aimed to investigate the correlation between liquefaction potential based on the simplified procedure and excess pore water pressure determined using empirical and numerical methods. Numerical aspect considered soil type and the dominant earthquake source at Kretek 2 Bridge. This is justified by the global occurrence of liquefaction phenomena, which is triggered by strong

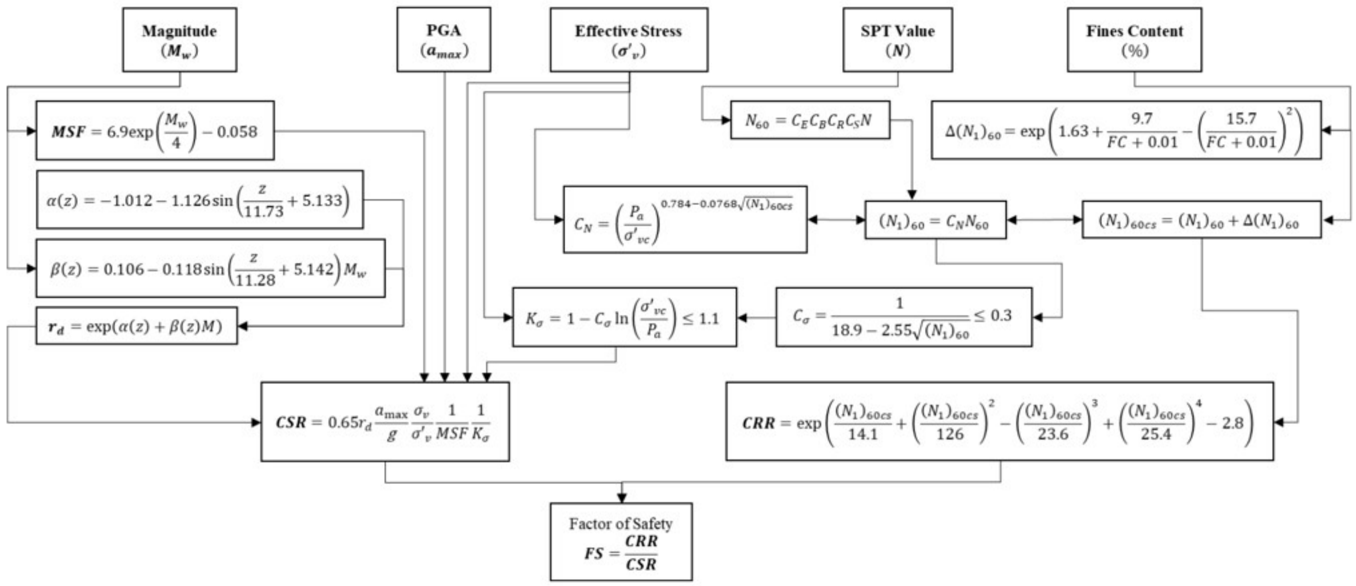


Figure 2 Flow chart to estimate liquefaction potential through the simplified procedure (Idriss and Boulanger, 2008)

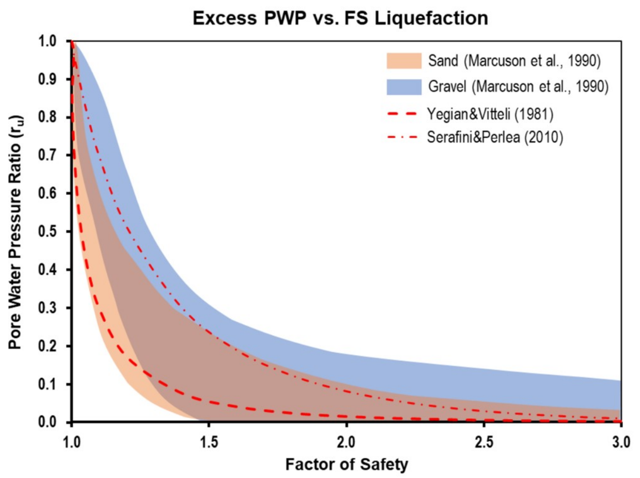


Figure 3 The correlations between SF against liquefaction and excess pore pressure ratio (Marcuson and Hynes, 1990; Serafini and Perlea, 2010; Yegian and Vitelli, 1981)

seismic activities leading to an increased pore water pressure. In addition, a pore water pressure ratio with values greater than 0.9 or close to 1.0 could separate particles of sandy soil to cause liquefaction (Prakoso et al., 2022). Excess pore water pressure ratio can be predicted using the following Equation 1. Where, r_u is excess pore water pressure ratio, Δu is the increased pore water pressure (kPa), and σ'_0 is the initial effective stress.

$$r_u = \left(\frac{\Delta u}{\sigma' o}\right) \quad (1)$$

The increment in the value and approaching the initial effective stress value leads to a reduction of the effective stress in soil, eventually tending to zero (Port and Harbour Research Institute, 1997). Yegian and Vitelli (1981) conducted a study to predict r_u using SF variable based on the following empirical method in Equation 2. Where SF is safety factor against liquefaction, α is a constant set at 0.7, and β is 0.19.

$$r_u = \frac{2}{\pi} arcsin\left(\frac{1}{SF}\right)^{\frac{1}{2\alpha\beta}} \quad (2)$$

Marcuson and Hynes (1990) also plotted a relationship between SF and residual excess pore pressure in sand and gravel soil types. Serafini and Perlea (2010) proposed an equation for the relationship between r_u and SF. Furthermore, a line graph was formed approaching the upper bound limits of the chart by Marcuson and Hynes (1990), specifically for sandy soil types, as shown in Figure 3. Serafini and Perlea (2010) also used numerical method by FLAC software and UBCS and material to produce the following Equations 3 and 4:

$$r_u = SF^X (for SF < 3.0) \quad (3)$$

$$x = -\left(SF + \frac{1.9}{SF} + \frac{0.95}{SF^{0.5}}\right) \quad (4)$$

Numerical method was also applied to analyze the nonlinear site response to pore water pressure using Deepsoil v7.0 by Jalil et al. (2021). Empirical method was used by Yegian and Vitelli (1981), as well as Serafini and Perlea (2010) to generalize the r_u values produced using only one variable, namely SF. Therefore, numerical method was compared with empirical results due to the ability to generate r_u values based on the characteristics of the local soil condition and earthquake load dominantly affecting the area.

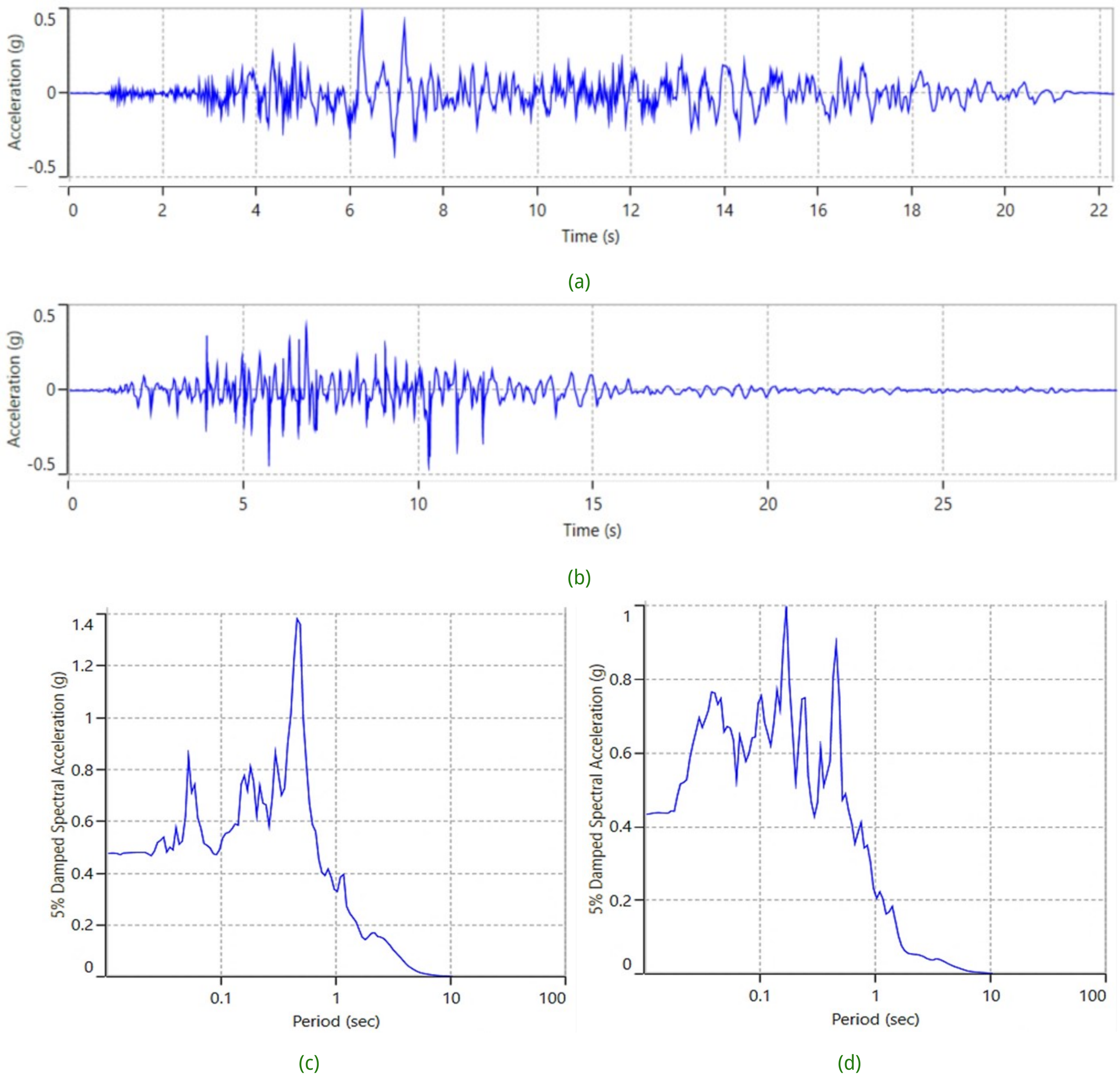


Figure 4 Ground motion and Spectral acceleration of (a)(c) The 1987 Superstition Hills earthquake, and (b)(d) The 1980 Mammoth Lake earthquake, respectively

Table 1. Seismic loads used to represent the 2006 Bantul earthquake

Description	Earthquake		
	Bantul	Superstition Hills	Mammoth Lake
Year	2006	1987	1980
Location	Indonesia	USA	USA
Magnitude scale (Mw)	6.2	6.54	6.06
Depth (km)	17.2	11.16	15.46
Mechanism	Strike-slip	Strike-slip	Normal Oblique

Deepsoil v7.0 is a tool used for numerical analysis, specifically in generating the r_u value for one-dimensional site response analysis based on different parametric soil conditions. This tool was developed by Hashash et al. (2020) to analyze the linear frequency domain, linear time and frequency domain, and nonlinear time domain with or without the generation of pore water pressure. Jalil et al. (2021) applied this method to determine liquefaction potential using the model option of pore water pressure generation and the r_u was found to be more than 0.8 (Hazirbaba, 2005). Another study showed that the limit for the increasing liquefaction in pore water pressure ratio was 0.7 to 1.0. Meanwhile, Mase et al. (2022) reported an increase of 0.9 to 0.95 in the maximum ratio of pore water pressure. The results of previous studies showed that earthquake data was im-

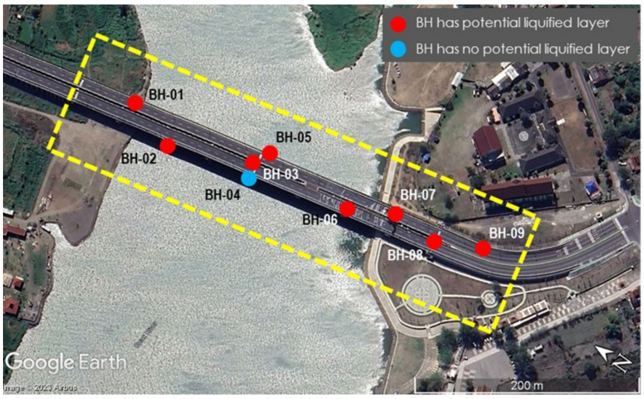


Figure 5 Boreholes location (Google Earth, 2023)

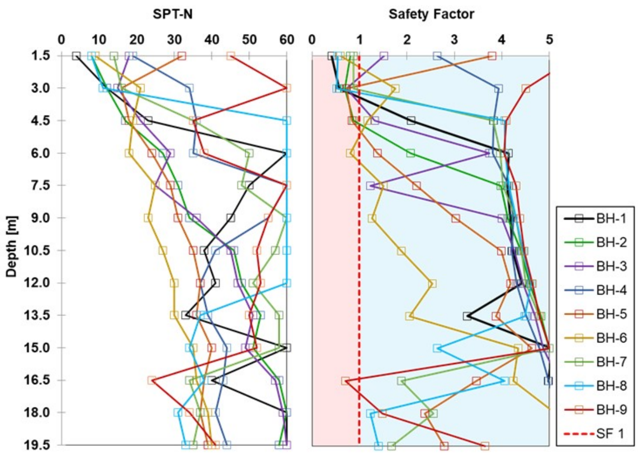


Figure 6 Analysis of SF against liquefaction for nine boreholes

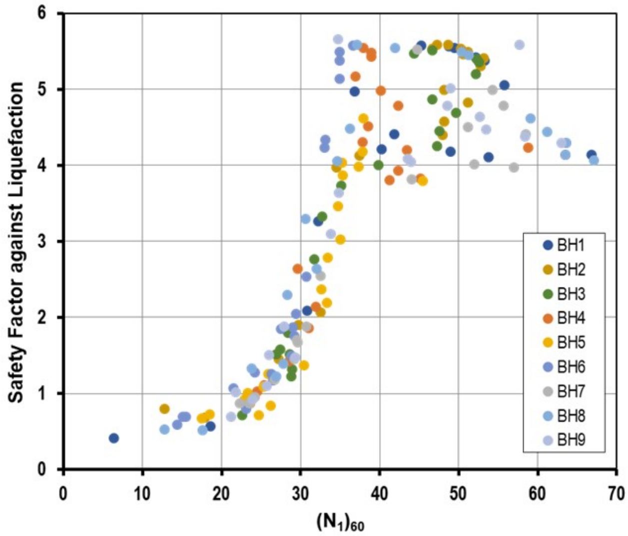


Figure 7 Correlation $(N_1)_{60}$ with SF against liquefaction

portant to the generation of r_u in soil. For example, Pramaditya and Fathani (2020) conducted physical modeling on uniform soil types and found the r_u to be 1.0 at 10 seconds due to the increase in the acceleration of the 1995 Kobe earthquake load. The studies showed that liquefaction events were expected to be found in the r_u range of 0.7 to 1.0, depending on the type of non-cohesive soil and SPT-N value.

The seismic load input in this study includes earthquakes with similar mechanisms as 2006 Bantul (Supartoyo, 2006). This include the Superstition Hills of 1987 and the Mammoth Lake of 1980, as shown in Table 1 and Figure 4. The application of other ground motions in the globe was due to the shortage of relevant data in Indonesia.

3 RESULTS

Soil from nine boreholes was investigated using the standard penetration test data (SPT-N) and grain size distribution from sieve analysis. Moreover, Look (2007) classified sandy soil into different categories including "very loose", "loose", "medium", "dense", and "very dense" for SPT-N of 0 – 4, 4 – 10, 10 – 30, 30 – 50, and >50, respectively. Kretek 2 Bridge area was observed to be dominated by medium to very dense sandy soil. Simplified procedure analysis showed that liquefaction potential was less than 1.0 in most of soil layers at different depths of 1.5 – 6.0 m in each borehole. The exception was BH-9 where the potential occurred at a depth of 16.5 m with a thickness of 1.5 m as well as BH-4 where none was observed in all soil layers, as shown in Figure 5 and Figure 6. Clay soil was specifically obtained from BH-1, BH-2, and BH-7 at 27 to 39 m, 36 to 39 m, and 28.5 to 30 m depth, without any effect of liquefaction. The results were similar to the "very low" to "medium" density soil discovered in a previous study conducted using Settle 3 on the surface layer from 0 to 6.0 m (Zakariya et al, 2022*a*). The result also showed that the maximum value of SPT-N corrected through the effective overburden stress and soil boring equipment or $(N_1)_{60}$ 27 for SF <1.0 (Figure 7).

Numerical method was implemented through Deepsoil v7.0 using soil model with an option of a general quadratic or hyperbolic model and pore water pressure. This model can generate r_u in all soil layers using seismic loads as input. The generation of r_u resulted in a proportional increase in line with the seismic duration. Moreover, Deepsoil v7.0 reported a significant increase in pore water pressure in < 15 seconds, and the r_u reached 0.8, showing liquefaction of soil as presented in Figure 8. The application of a shaking table test in

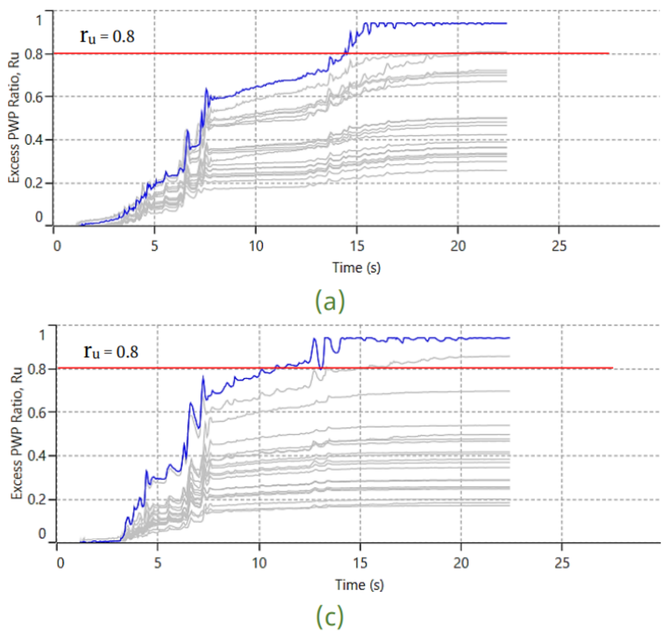


Figure 8 Excess pore water pressure ratio at (a) (b) BH-2 at 3-4.5 m depth (for Superstition Hills and Mammoth Lake earthquakes), and (c) (d) BH-6 at 25.5-27 m depth (for Superstition Hills and Mammoth Lake earthquakes)

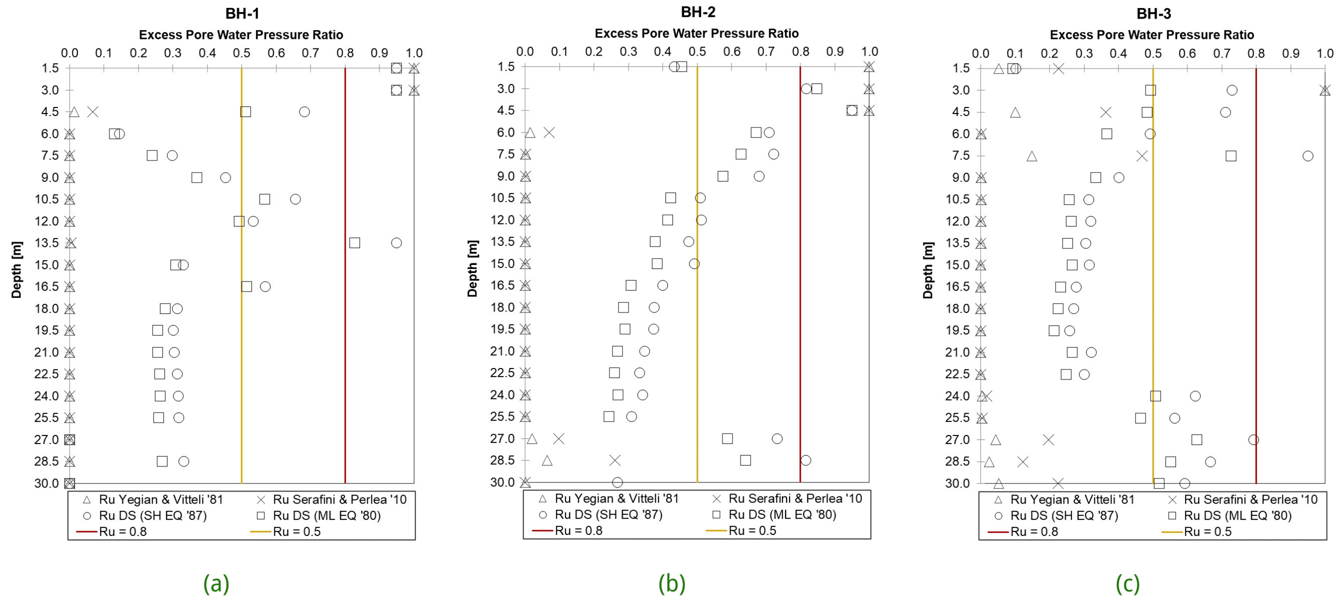
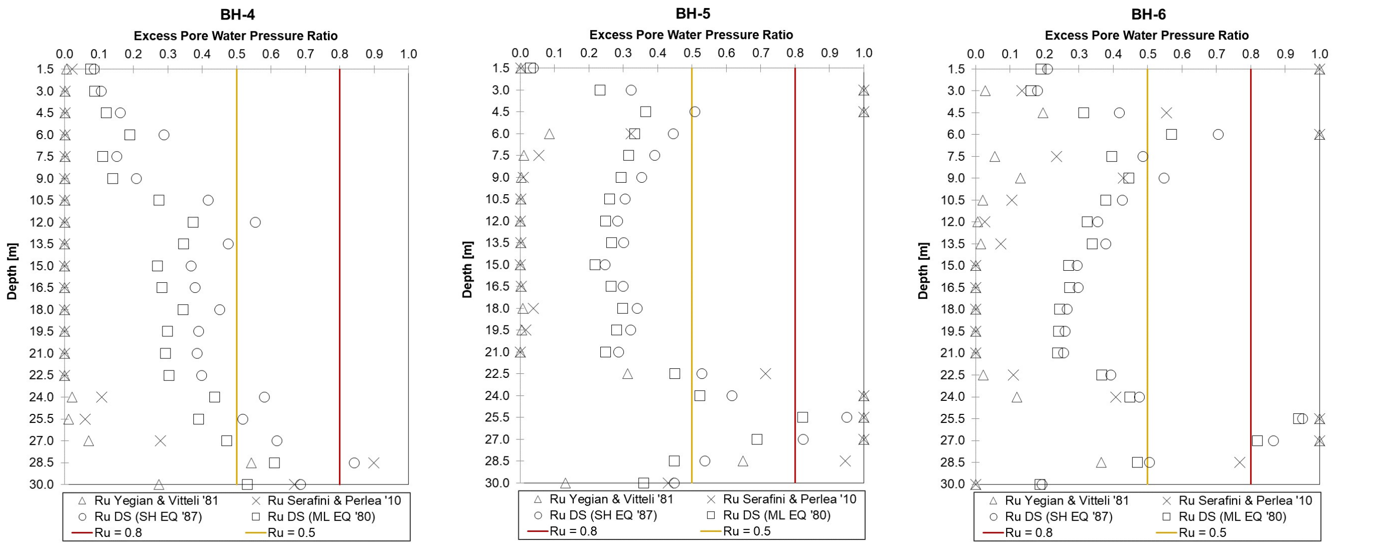


Figure 9 Excess pore water pressure ratio from empirical and numerical analysis a) BH1, b) BH2, and c) BH3

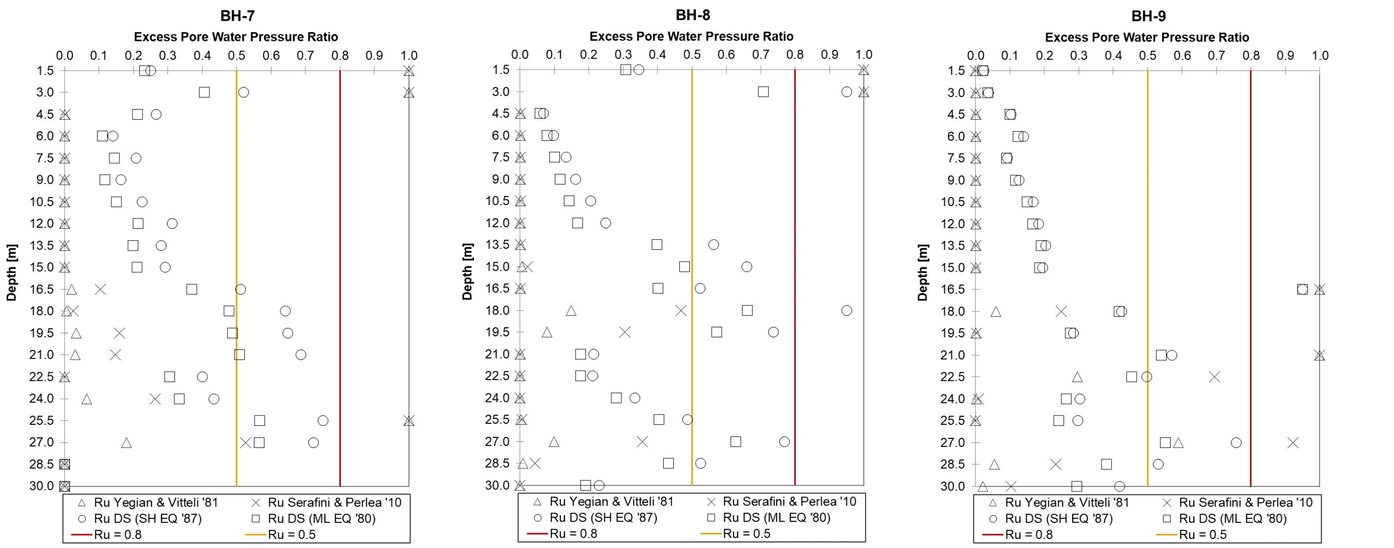
a previous study generated a maximum r_u at > 5 seconds (Mase et al., 2021). Another study conducted using numerical method showed that the time required to generate maximum r_u was dependent on the seismic load and soil characteristics (Mase, 2017*b*; Prakoso et al., 2022). In this study, the time varied based on soil type, seismic load, and method applied. For example, the r_u value was higher than 0.8 in layer 3 – 4.5 m depth at BH-2 and 25.5 – 27 m at BH-6, as shown in Figure 8.

A comparison was made between empirical and numerical analyses applied through Deepsoil v7.0 to every borehole and the results were plotted in the graphs, as shown in Figure 9, Figure 10 and Figure 11 (Yegian and Vitelli, 1981; Serafini and Perlea, 2010). The result showed a partial agreement on the data distribution of excess pore water pressure ratio for the boreholes in both analyses, as shown by SF < 1.0 and $r_u \geqslant 0.8$. These values were recorded at depth of 1.5 – 3.0 m in BH-1, 3.0 – 4.5 m in BH-2, 25.5 – 27.0 m in BH-5 and BH-6, 3.0 m in BH-8, and 16.5 m in BH-9. Meanwhile, r_u was empirically found to be > 0.8 and numerically $0.5 \leqslant r_u < 0.8$ at 4.5 and 24.0 m in BH-5, 6.0 m in BH-6, 3.0 and 25.5 m in BH-7, as well as 21.0 and 27.0



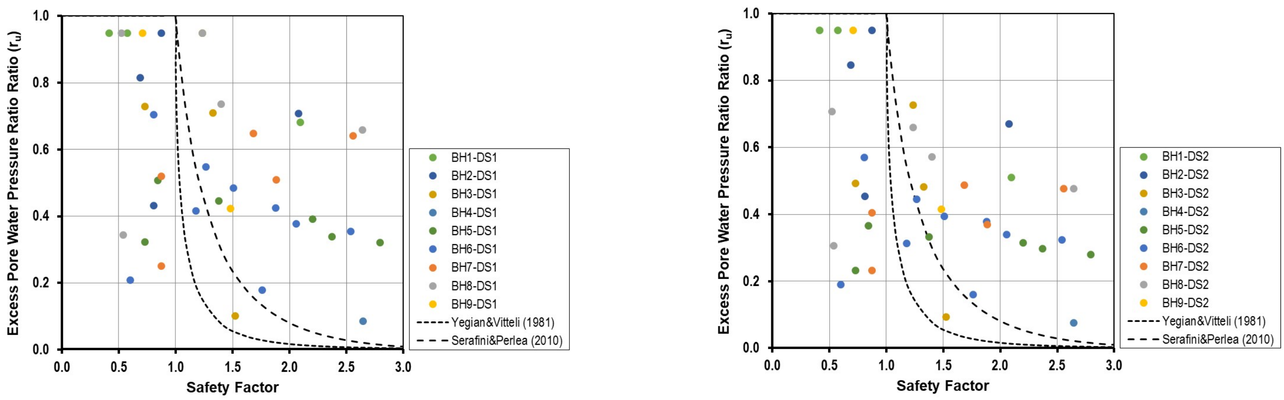
(a) (b) (c)

Figure 10 Excess pore water pressure ratio from empirical and numerical analyses a) BH4, b) BH5, and c) BH6



(a) (b) (c)

Figure 11 Excess pore water pressure ratio from empirical and numerical analyses a) BH7, b) BH8, and c) BH9



(a) (b)

Figure 12 SF vs. Excess pore water pressure ratio based on empirical and numerical methods using seismic source. (a) The 1987 Superstition Hills earthquake and (b) The 1980 Mammoth Lake earthquake

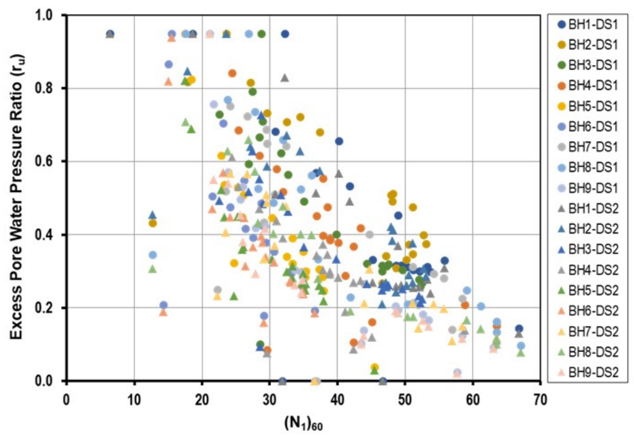


Figure 13 Correlation $(N_1)_{60}$ with excess pore water pressure ratio

m in BH-9 occur. Empirical results showed that SF value was > 1.5 in non-potential liquefaction layer, leading to an r_u of < 0.25. On the other hand, numerical analysis showed a larger value at the same depth, with 0.95 as the maximum recorded value of r_u using numerical method.

4 DISCUSSION

A simplified procedure analysis was conducted to estimate SF against liquefaction. The results showed that liquefaction potential (SF < 1) was dominantly distributed on the surface of soil layer at depths of 1.5 – 6.0 m due to the presence of excess pore water pressure. Furthermore, a threshold of ru ⩾ 0.8 was used to define the limit for liquefaction occurrence. The non-potential liquefaction layer analyzed numerically using Deepsoil v7.0 produced overestimated values compared to empirical method. This was confirmed in Figure 12 where soil layers with SF value > 1.5 had r_u = 0.2-0.7. Empirical results showed that SF value > 1.5 tended to have r_u < 0.25, suggesting an insufficient excess pore water pressure to induce soil liquefaction. Therefore, the application of numerical analysis to determine the r_u value in each soil layer required the controlling effect of empirical method. The r_u values obtained numerically on the left side of empirical line stated by Yegian and Vitelli (1981) and Serafini and Perlea (2010) were more convincing for use in subsequent analytical studies. The selection of the seismic source for numerical analysis was important due to its influence on the r_u value. This was confirmed in Figure 12 where the r_u generated with the 1987 Superstition Hills earthquake was slightly higher than the 1980 Mammoth Lake earthquake.

The relationship between $(N_1)_{60}$ and r_u in Figure 13 shows that smaller $(N_1)_{60}$ has higher r_u. This result is consistent with previous liquefaction potential examined using the simplified procedure showing that smaller $(N_1)_{60}$ produced low SF value. However, Iwasaki et al. (1981) reported the occurrence of liquefaction behavior only at depths < 20 m, showing that the r_u values obtained at > 20 m could be neglected.

5 CONCLUSION

In conclusion, liquefaction potential studied using the simplified procedure showed that all boreholes in the area were vulnerable, with the exception of BH-4. This was confirmed by SF < 1.0 and r_u ⩾ 0.8 recorded at depth of 1.5 – 3.0 m, 3.0 – 4.5 m, 25.5 – 27.0 m, 3.0 m, and 16.5 m in BH-1, BH-2, BH-5 and BH-6, BH-8, and BH-9, respectively. Empirical results showed r_u > 0.8, while numerical analysis reported 0.5 ⩽ r_u < 0.8 at 4.5 and 24.0 m in BH-5, 6.0 m in BH-6, 3.0 and 25.5 m in BH-7, as well as 21.0 and 27.0 m in BH-9. Furthermore, empirical method was used to predict the ratio of excess pore water pressure using SF against liquefaction. Numerical method using Deepsoil v7.0 was used to generate the ratio of excess pore water pressure with attention to the local soil conditions and seismic load considered dominant on the site. The r_u values generated numerically partially was consistent with empirical method but tended to be overestimated. Further investigation was required to determine the r_u limit value for liquefaction and the ⩾ 0.8 used tended to coincide with SF value < 1.0. This showed that liquefaction potential could be determined by considering r_u generated through numerical method using Deepsoil v7.0 but required verification using empirical method to ensure high reliability. The examination of excess pore water pressure ratio in regions vulnerable to liquefaction was important because the condition could lead to a rapid deterioration of the low-bearing capacity of building foundations, as evidenced by the r_u values approaching 1.0. However, studies could be conducted to accurately estimate the excess pore water pressure ratio using other methods, such as the application of soil laboratory tests or in-situ pore pressure measurements.

DISCLAIMER

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

The authors are grateful to the Ministry of Public Works and Housing as well as the University of Gadjah Mada for funding this study. The authors are also grateful to the Unit Work of National Road Implementation, Yogyakarta Special Region Province, and the Directorate General of Highways for data support.

REFERENCES

BAPPENAS (2006), 'Preliminary damage and loss assessment yogyakarta and central java natural disaster'.

Buana, T. and Agung, M. (2015), Liquefaction characteristic based on ground response linier equivalent analysis and cyclic stress concept on young merapi volcanic deposit in bantul, *in* '10th Asian Regional Conference of IAEG', pp. 1–5.

Google Earth (2023), 'Citra satelit google earth - titik bor penyelidikan tanah jembatan kretek 2'. https://earth.google.com/web/.

Hashash, Y., Musgrove, M., Harmon, J., Ilhan, O., Xing, G., Numanoglu, O., Groholski, D., Phillips, C. and Park, D. (2020), *DeepSOIL V 7.0-User Manual*, Board of Trustees of the University of Illinois at Urbana-Champaign, Urbana, IL.

Hazirbaba, K. (2005), Pore Pressure Generation Characteristics of Sands and Silty Sands: A Strain Approach, Ph.d. dissertation.

Idriss, I. (1999), An update of the seed-idriss simplified procedure for evaluating liquefaction potential, *in* 'Transportation Research Board '99 Workshop New Approaches to Liquefaction Analysis', Washington, DC, pp. 37–52.

Idriss, I. and Boulanger, R. (2004), 'Evaluating the potential for liquefaction or cyclic failure of silts and clays', *Neurosci. Lett.* **339**, 123–126.

Idriss, I. and Boulanger, R. (2008), 'Soil liquefaction during earthquakes', *Mach. Prod. Eng.* **160**, 43.

Iwasaki, T., Tokida, K. and Tatsuoka, F. (1981), Soil liquefaction potential evaluation with use of the simplified procedure, *in* 'International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics', Vol. 12, pp. 209–214.

Jalil, A., Fathani, T., Satyarno, I. and Wilopo, W. (2021), Nonlinear site response analysis approach to investigate the effect of pore water pressure on liquefaction in palu, *in* 'IOP Conference Series: Earth and Environmental Science'.

Look, B. (2007), *Handbook of Geotechnical Investigation and Design Tables*, Taylor & Francis Group, London.

Marcuson, W. and Hynes, M. (1990), *Stability of Slopes and Embankments during Earthquakes*.

Mase, L. (2017*a*), 'Experimental liquefaction study of southern yogyakarta using shaking table', *J. Tek. Sipil ITB* **24**, 11–18.

Mase, L. (2017*b*), 'Liquefaction potential analysis along coastal area of bengkulu province due to the 2007 mw 8.6 bengkulu earthquake', *J. Eng. Technol. Sci.* **49**, 721–736.

Mase, L., Fathani, T. and Adi, A. (2021), 'A simple shaking table test to measure the liquefaction potential of prambanan area, yogyakarta, indonesia', *ASEAN Eng. J.* **11**, 89–108. https://doi.org/10.11113/AEJ.V11.16874.

Mase, L., Tanapalungkorn, W., Likitlersuang, S., Ueda, K. and Tobita, T. (2022), 'Liquefaction analysis of izumio sands under variation of ground motions during a strong earthquake in osaka, japan', *Soils Found.* **62**, 101218. https://doi.org/10.1016/j.sandf.2022.101218.

Port and Harbour Research Institute (1997), *Handbook on Liquefaction Remediation of Reclaimed Land*, A.A. Balkema, Rotterdam.

Prakoso, W., Mazaya, D. and Kartika, R. (2022), 'Pore pressure responses of liquefied numerical sand columns', *J. Civ. Eng. Forum* **8**, 225–236. https://doi.org/10.22146/jcef.3395.

Pramaditya, A. and Fathani, T. (2020), 'Physical modelling of earthquake-induced liquefaction on uniform soil deposit and settlement of earth structures', *J. Civ. Eng. Forum* **1000**, 85–96. https://doi.org/10.22146/jcef.59467.

Rahardjo, W., Sukandarrumidi and Rosidi, H. (1977), Geologic map of the yogyakarta quadrangle, java, Technical report, Direktorat Geologi, Departemen Pertambangan, Republik Indonesia, Bandung.

Seed, H. and Idriss, I. (1970), A simplified procedure for evaluating soil liquefaction potential, Technical report, University of California, California.

Serafini, D. and Perlea, V. (2010), Comparison of liquefaction triggering analysis approaches for an embankment dam and foundation, *in* 'The 5th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics', Missouri University of Science and Technology, San Diego, California.

Soebowo, E., Tohari, A. and Sarah, D. (2009), 'Potensi likuifaksi akibat gempabumi berdasarkan data cpt dan n-spt di daerah patalan bantul, yogyakarta', *J. Ris. Geol. dan Pertamb.* **19**, 85. https://doi.org/10.14203/risetgeotam2009.v19.25.

Supartoyo (2006), 'Gempabumi yogyakarta tanggal 27 mei 2006', *Bul. Berk. Merapi* **3**, 36–55.

Yegian, M. and Vitelli, B. (1981), Analysis for liquefaction: Empirical approach, *in* 'Int. Conf. Recent Adv. Geotech. Earthq. Eng. Soil Dyn.', pp. 1–6.

Youd, T. and Perkins, D. (1978), 'Mapping liquefaction-induced ground failure potential', *ASCE J Geotech Eng Div* **104**, 433–446. https://doi.org/10.1061/ajgeb6.0000612.

Zakariya et al (2022*a*), Ground motion and liquefaction study at opak river estuary bantul, *in* '5th International Conference on Earthquake Engineering and Disaster Mitigation', Universitas Gadjah Mada, Yogyakarta. https://doi.org/10.1088/1755-1315/1244/1/012032.

Zakariya et al. (2022*b*), 'Quantitative and qualitative analysis of liquefaction potential in medium-dense sandy soil area near opak fault', *J. Jalan-Jembatan* **39**, 74–87.