Civil Engineering Dimension, Vol. 25, No. 1, March 2023, 29-36
ISSN 1410-9530 print / ISSN 1979-570X online
DOI: https://doi.org/10.9744/CED.25.1.29-36

The Preliminary Study of Liquefaction Susceptibility Map in the Yogyakarta-Bawen Toll Road Sections I and II, Indonesia

Kevin, P.[1]* and Muhrozi[1]

Abstract: The parts of Yogyakarta-Bawen Toll Road Indonesia, based on the geological agency's liquefaction susceptibility map are located on moderately susceptible to liquefaction soil. This map can be a preliminary indication of liquefaction as it can roughly indicate liquefaction potential. However, it cannot illustrate the actual condition in detail as its inputs are macro parameters (geological and seismicity factors). The existence of silty sand and sand, earthquake sources, and shallow groundwater increase the liquefaction possibility to occur in this important national project. Therefore, the Liquefaction Severity Index (LSI) and the Liquefaction Potential Index (LPI) using Sonmez's and Iwasaki's analysis methods are conducted with peak ground acceleration (PGA) of 0.322 g for the first section and in the second section 0.298 g. The results of the three types of analysis have relatively similar trends but the differences are in each category. The LSI's categories are very low-moderate in the observed location, meanwhile, the LPI's categories are low-very high.

Keywords: Susceptibility; liquefaction severity index; liquefaction potential index; QGIS.

Introduction

The construction of the Yogyakarta-Bawen Toll Road, Indonesia, will become the new network that connects Central Java and Special Region of Yogyakarta Provinces. This connection is projected to reduce traffic congestion on artery roads, support industrial areas in Ungaran – Bawen, and develop the tourism site in Yogyakarta – Semarang. The presence of the project is important as this connection is one of the national strategic projects as shown in Figure 1.

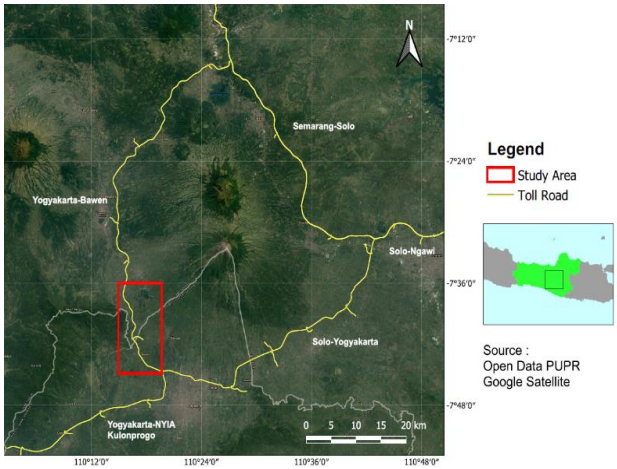

Figure 1. The Toll Road Network in the Central Part of Java

[1] Department of Civil Engineering, Universitas Diponegoro, Jl. Prof. Soedarto SH, Tembalang, Semarang, INDONESIA
*Corresponding author; Email: pauluskevin08@students.undip.ac.id

Note: Discussion is expected before July, 1st 2023, and will be published in the "Civil Engineering Dimension", volume 25, number 2, September 2023.

Received 07 March 2023; revised 17 March 2023; accepted 28 March 2023.

However, the liquefaction susceptibility in the Yogyakarta-Bawen toll road based on the liquefaction susceptibility map [1] varied from low to moderate, due to its proximity to earthquake sources and geological conditions as shown in Figure 2. As this map is used only for preliminary studies purposes, detailed studies are needed to assess the liquefaction potential condition in the toll road project.

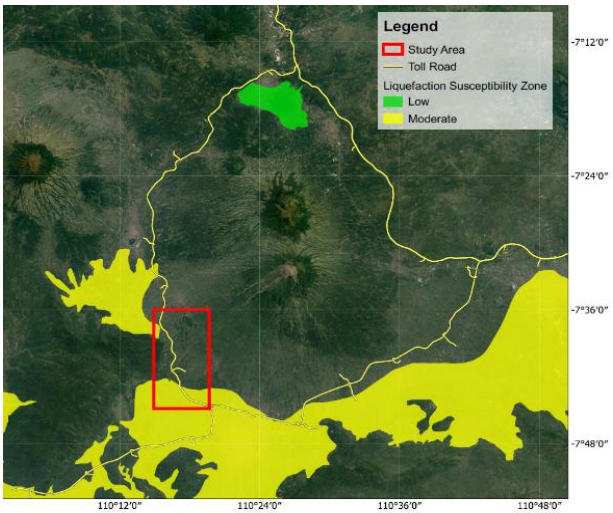

Figure 2 Liquefaction Susceptibility Zone Map in Central Java and Special Region of Yogyakarta

The seismotectonic map is created for the initial assessment of potential earthquake sources in which this map is based on USGS earthquake databases from 1907 to 2022 and the PUSGEN earthquakes map as presented in Figure 3. According to this map, the significant earthquake that mostly occurred in the central part of Java Island (Central Java and Special Region of Yogyakarta) came from the surrounding Opak Fault and the southern part of Java.

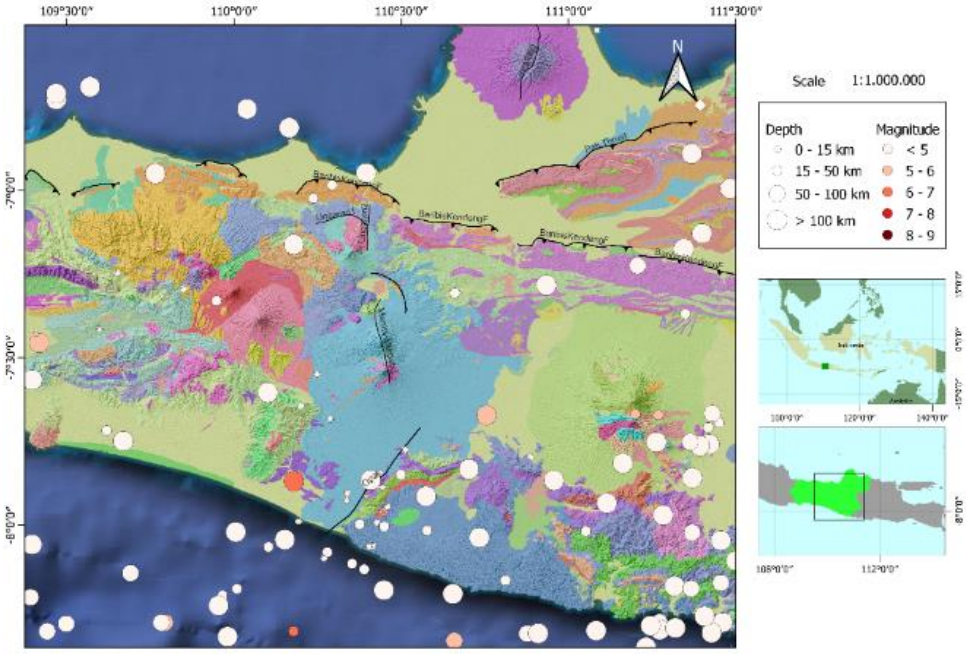

Figure 3. Seismotectonic Map in Central Part of Java

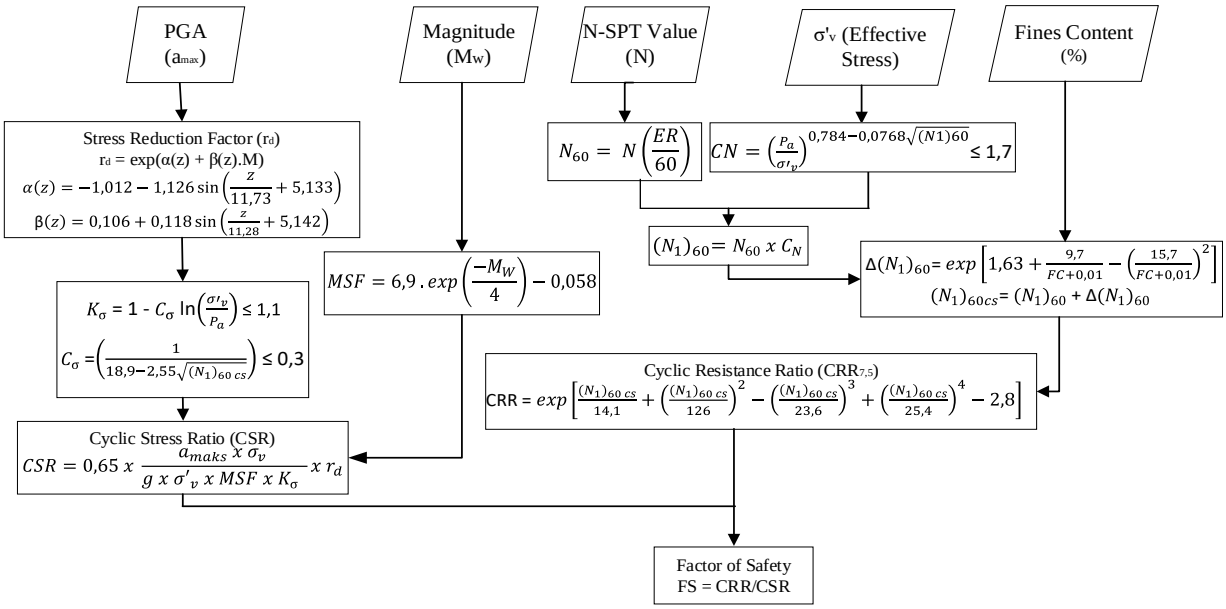

Figure 4. Liquefaction Potential Analysis Procedure

The previous studies were conducted to investigate liquefaction potential in parts of Yogyakarta [2], New Yogyakarta International Airport [3], and the Solo-Yogyakarta toll road. However, the study about potential liquefaction in the Yogyakarta-Bawen toll road project location is currently limited compared to other national strategic projects in Special Region of Yogyakarta. Thus, another specific study about liquefaction is needed to map liquefaction potential in the Yogyakarta-Bawen toll road project due to its importance as one of the national strategic projects in Indonesia.

Analysis Methodology

The analysis for liquefaction potential mapping is conducted in several steps: (i) Collection of geotechnical, geological, and seismic data; (ii) Carrying out Liquefaction Potential Analysis based on SPT and boring data (iii) Preparation of liquefaction susceptibility map based on Liquefaction Potential Index (LPI) [4-5] and Liquefaction Severity Index (LSI) [6].

This study considers peak ground acceleration (PGA) based on Indonesian National Standard Criteria [7,8]

whereby the criteria for a conventional bridge must comply with 75-year design life, a 1000-year returning period, and a 7% probability of exceedance. Then, the surface PGA is calculated from bedrock PGA which is amplified with an amplification factor based on site classification using SPT value. The site class using standard penetration test (SPT) is determined by $\overline{N}$ value which is expressed in Equation 1.

$$\overline{N} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{N_i}} \quad (1)$$

Where N_i = standard penetration resistance, d_i = thickness of soil layer.

The PGA in bedrock value is obtained from the LINI application [9] and SNI 2833:2016 [8]. Meanwhile, the magnitude (M_W) input is based on the nearest fault (shallow crustal) data from the observed location.

The liquefaction safety factor is measured with Idriss & Boulanger's [10] method as shown in Figure 4.

$$LPI = \int_0^{20} F(z)w(z) \quad (2)$$

$$F(z) = 1 - FS \text{ for } FS < 1.0 \quad (3a)$$

$$F(z) = 0 \text{ for } FS \geq 1.0 \quad (3b)$$

$$w(z) = 10\text{-}0.5z \text{ for } z < 20 \text{ m} \quad (4a)$$

$$w(z) = 0 \text{ for } z > 20 \text{ m} \quad (4b)$$

Where FS = safety factor of liquefaction, z = depth from the soil surface (m).

The liquefaction potential categories by Iwasaki et al. [4] consist of only four categories as shown in Table 1. However, those categories have limitations in identifying non-liquefiable and moderate circumstances. Sonmez [5] proposed modifications to equations that also consider the threshold of safety factor between the non-liquefiable and marginally liquefied (1.2 and 0.95). This equation and the categories are shown in Equations 5a and 5b and Table 2 as follows:

$$F(z) = 0 \text{ for } FS \geq 1.2 \quad (5a)$$

$$F(z) = 2 \times 10^{6} e^{-18.427\,FS} \text{ for } 1.2 > FS > 0.95 \quad (5b)$$

Table 1. Liquefaction Potential Categories by Iwasaki [4]

LPI	Liquefaction Potential Category
0	Very low
$0 < LPI \leq 5$	Low
$5 < LPI \leq 15$	High
$LPI > 15$	Very high

Table 2. Liquefaction Potential Classification by Sonmez [5]

LPI	Liquefaction potential category
0	Non-liquefiable (based on $FS \geq 1.2$)
$0 < LPI \leq 2$	Low
$2 < LPI \leq 5$	Moderate
$5 < LPI \leq 15$	High
$LPI > 15$	Very high

In his later studies, Sonmez and Gokceoglu [6] developed a new method to measure liquefaction severity based on probabilities of soil liquefaction where this method calculate liquefaction severity index (LSI) using Equations 6, 7a, and 7b.

$$LSI = \int_0^{20} P_L(z)w(z)dz \quad (6)$$

$$P_L(z) = \frac{1}{1 + \left(\frac{F_L}{0.96}\right)^{4.5}} \text{ for } F_L \leq 1.411 \quad (7a)$$

$P_L(z) = 0$ for $F_L > 1.411$ or the soil layer with $F_L \leq 1.411$ can be considered as a non-liquefiable layer considering Clay Content and Liquid Limit (7b)

Table 3. Liquefaction Severity Classification based on [6]

LSI	Liquefaction potential category
$85 \leq LSI < 100$	Very high
$65 \leq LSI < 85$	High
$35 < LSI \leq 65$	Moderate
$15 < LSI \leq 35$	Low
$0 < LSI \leq 15$	Very Low
$LSI = 0$	Non-liquefied

The spatial analysis was carried out with a geographic information system (GIS) program to create a liquefaction susceptibility and groundwater level map with an inverse distance weighted (IDW) interpolation method. To develop those maps, 235 borehole investigations are conducted in a long section.

Afterward, the plasticity index (PI), liquid limit (LL), and water content (w_c) can be used to predict liquefaction susceptibility [11]. The available data are analyzed and compared to the Idriss & Boulanger method analysis results. Bray & Sancio indicate that if $PI \leq 12$ and $w_c/LL \geq 0.85$, soil can liquefy under cyclic load, meanwhile if $12 < PI \leq 18$ and $w_c/LL \geq 0.8$ the soil can liquefy if a significant number of cyclic loading occur. Otherwise, the soil with $PI > 18$ tends not to liquefy, except in some cases of sensitive soil that can lose strength under cyclic load. Those criteria are illustrated in Figure 5.

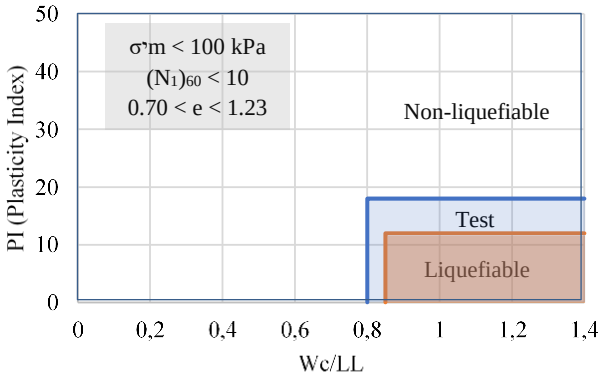

Figure 5. Liquefaction Susceptibility Criteria [11]

Geological and Geotechnical Condition

The Yogyakarta-Bawen Toll Road Section I (Yogyakarta-Banyurejo) and II (Banyurejo-Borobudur) are located above undifferentiated volcanic rocks as shown in Figure 6 which consist of undifferentiated tuff, ash, breccia, agglomerate, and lava flows [12]. Based on the bore log database, the location is dominated by the existence of silty sand, sand, and gravel as a result of volcanic activity.

For amplification analysis, the site class of each borehole is determined by a standard penetration test with a minimum 30 m depth. The borehole is determined as soft soil (SE) if $\overline{N} < 15$ and stiff soil (SD) if $15 \leq \overline{N} \leq 50$. In most of the Yogyakarta-Banyurejo section, the soft soil (SE) site class is located, meanwhile, the Banyurejo-Borobudur section is predominantly categorized as stiff soil (SD). Figure 7 shows the site classification map of the observed area.

Hidrogeological Condition

The groundwater basin area is classified into three categories which are recharge area, transition area, and discharge area. Generally, in higher elevations,

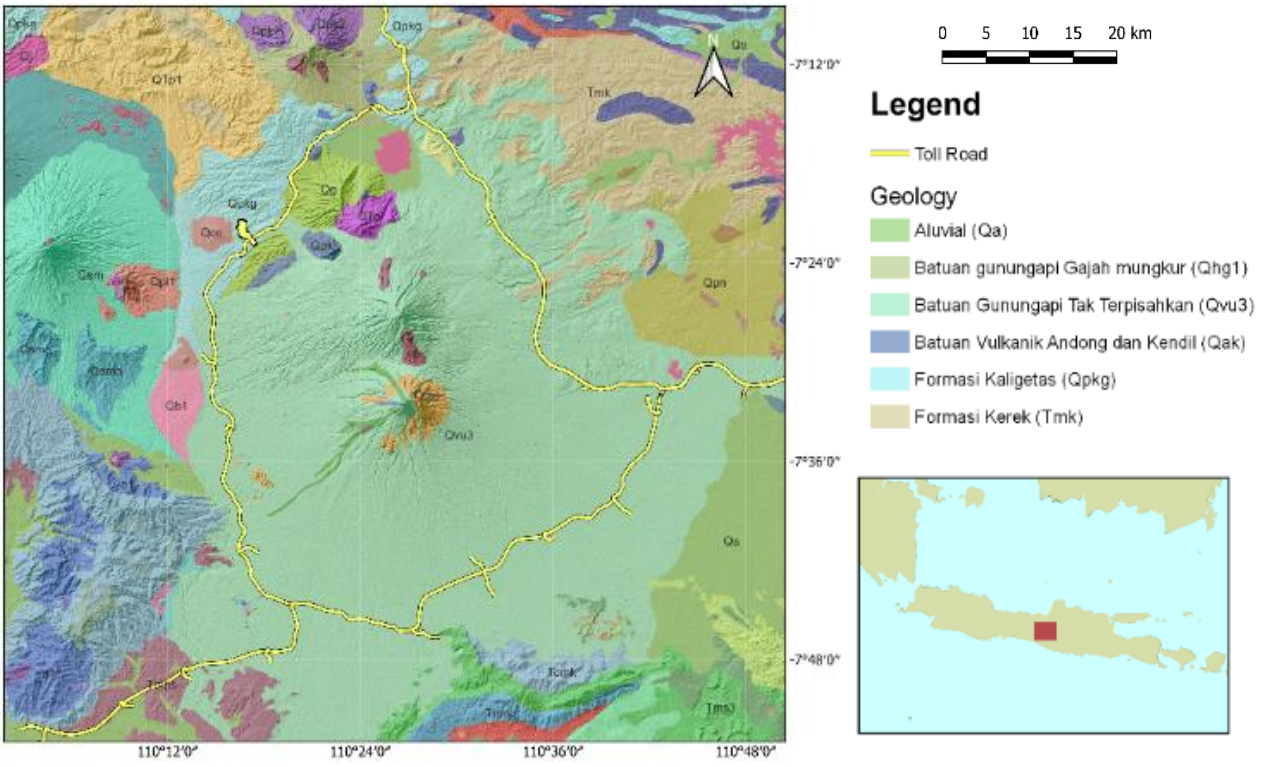

Figure 6. Geological Map

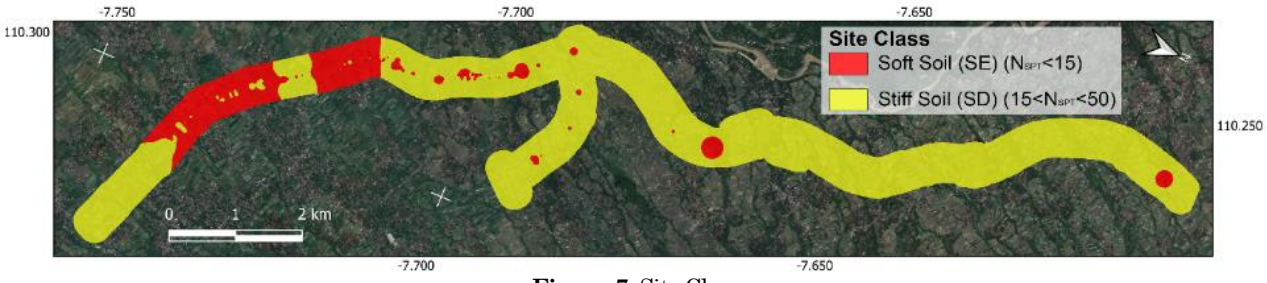

Figure 7. Site Class

this area becomes a recharge area and groundwater far below the surface. Meanwhile, in the discharge area, the groundwater is closer to the ground surface. The Yogyakarta-Bawen Toll Road is above two groundwater basins, Yogyakarta-Sleman and Magelang-Temanggung groundwater basins. The modified map of groundwater basins [13–15] in the Yogyakarta-Bawen Toll Road is shown in Figure 8.

As shown in Figure 7, the first to the fourth section of the toll road is located in a discharge area, this condition allows shallow groundwater to exist across the toll road. Theoretically, shallow groundwater ≤ 10 m can also contribute to earthquake-induced liquefaction [16]. Regarding the water table, the static groundwater level in each borehole is obtained and mapped in Figure 9. It shows the groundwater depth is 0 to 9 m which increases the liquefaction possibility in the project.

Result and Discussion

Based on LINI, the PGA on bedrocks with 1000 years return period and 7% probability of exceedance in the first section is 0.322 g and in the second section is 0.298 g and this PGA amplified based on calculated site class in Figure 3 to obtain a_{max} for liquefaction potential analysis. Moreover, this liquefaction potential analysis considers earthquake magnitude from the nearest fault (Opak Fault) [17] which has a maximum magnitude (M_{max}) of 6.6. The observed location (STA 57+500 – STA 75+300) is shown in Figure 10.

Based on Figure 2, the majority of the Yogyakarta-Banyurejo section (STA 75+300 – STA 70+800) is located on moderately prone to liquefaction, meanwhile in the Banyurejo-Borobudur section, the map indicates that this section is not susceptible to liquefaction.

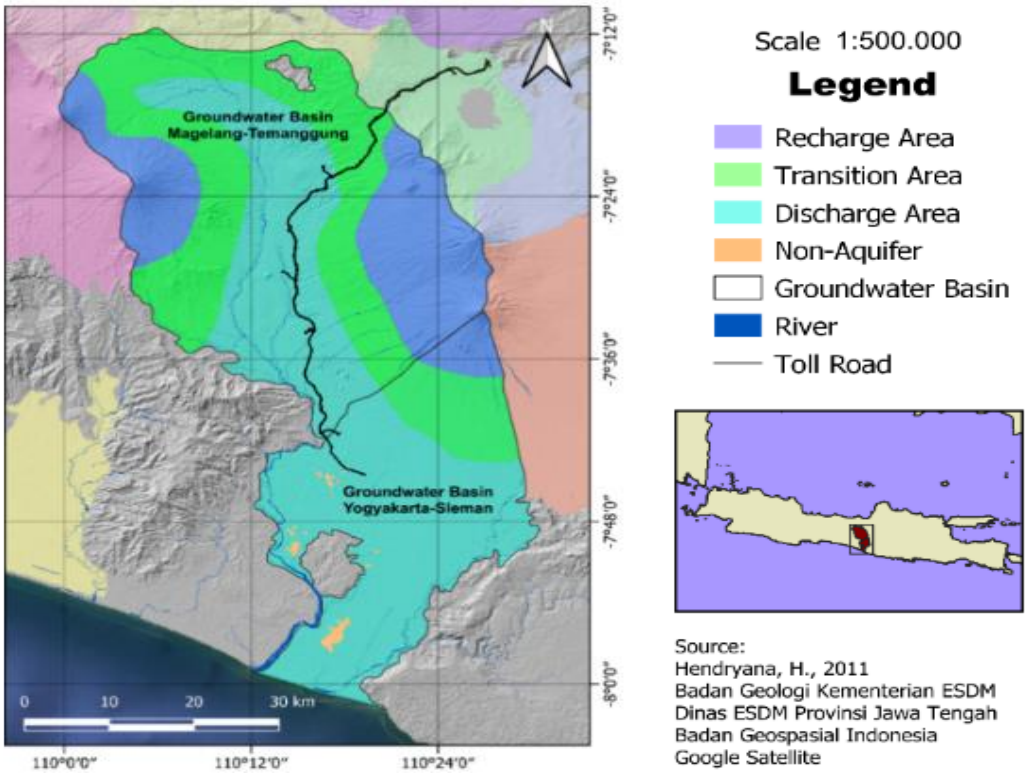

Figure 8. Groundwater Basins in the Yogyakarta-Bawen Toll Road

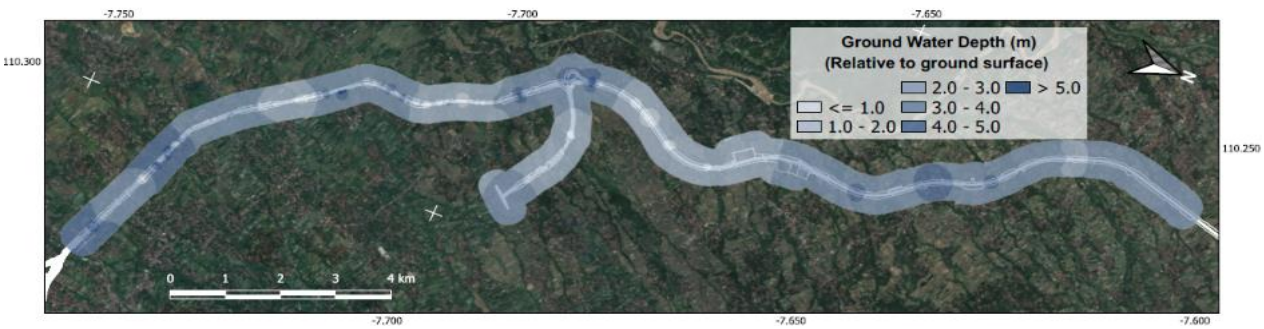

Figure 9. Water Table in the Yogyakarta-Bawen Toll Road 1st and 2nd Section

Based on the analyzed liquefaction severity index (LSI) map in Figure 11, the areas with the very low category are located in the Sleman (STA 75+150 – STA 76+300), most of Banyurejo-Borobudur section (STA 58+400 - STA 64+000), and Banyurejo interchange. In another category, the majority of the Yogyakarta-Banyurejo section and part of the Banyurejo-Borobudur section (STA 64+000 – STA 75+150) have LSI with low level. Furthermore, a moderate level is only identified in 10 spots in the bridge and embankment sections in the Yogyakarta-Banyurejo section. In general, the Yogyakarta-Bawen Toll Road Section I and II is categorized as very low to moderate zone based on Sonmez's liquefaction severity index.

For the Liquefaction Potential Index map using the Sonmez formula, low-moderate categories are located in the majority of the Banyurejo-Borobudur section (STA 58+375 – STA 64+325), and in Sleman (STA 74+475 – STA 76+300), and most of part Banyurejo Interchange. The high category is shown in most of the Yogyakarta-Banyurejo section (STA 68+825 – STA 74+475) and at the start of the Banyurejo-Borobudur section (STA 64+325 - STA 66+725). The very high potencies location nearly matched with 10 spots of moderate level from the LSI map and all of them are located in the Yogyakarta-Banyurejo section. Overall, the Yogyakarta-Bawen toll road I and II sections based on LPI (Sonmez's method) are classified as low to very high. The LPI by Sonmez map in the project is shown in Figure 12.

Despite using the modified formula, LPI (Sonmez) resulting a relatively similar LPI result to the Iwasaki formula. As shown in Figure 13, the difference between the two maps is in low and moderate in Sonmez's map constitute low in Iwasaki's map. However, due to insignificant differences in LPI number, the high and very high categories are relatively similar in both maps. Increasing the threshold for the safety factor to 1.2 and introducing a formula for a safety factor less than 1.2 and more than 0.95 only increases an insignificant number to LPI in this case.

The liquefaction susceptibility map by the Geological Agency and the result of LSI and LPI maps indicate that Geological Agency's map can become a good preliminary indication for liquefaction as it can roughly locate the potential of liquefaction. The most of moderate zone (yellow) in the liquefaction susceptibility zone map overlap with the high (in LPI) or the

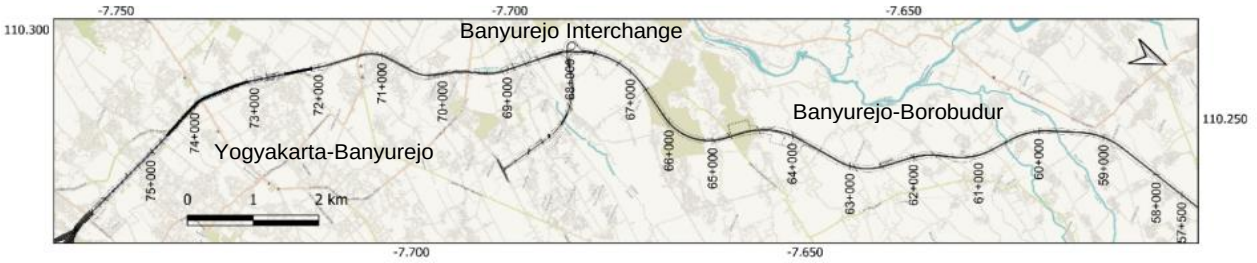

Figure 10. The Observed Location

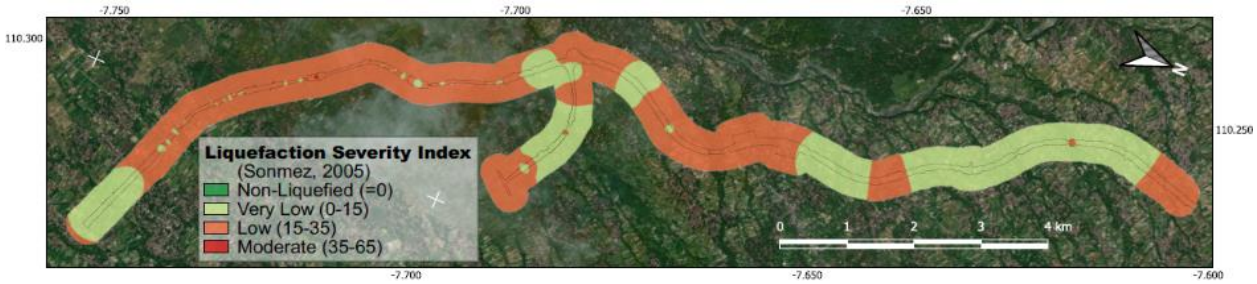

Figure 11. The Liquefaction Severity Index Map in the Yogyakarta-Bawen Toll Road Section I and II

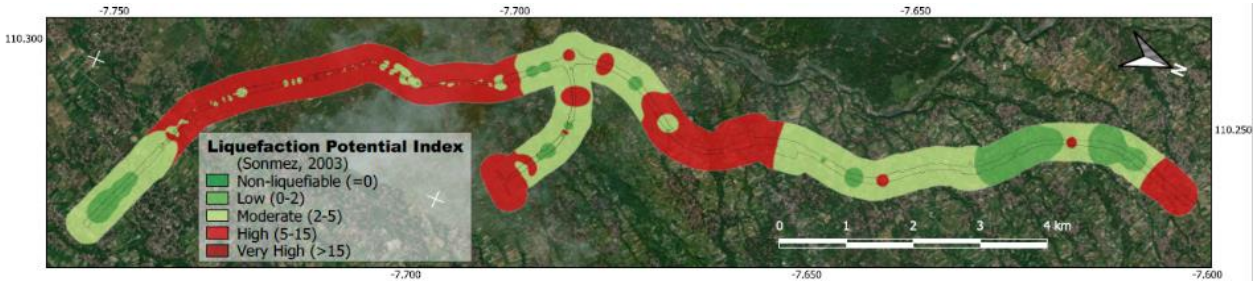

Figure 12. The Liquefaction Potential Index (Sonmez) Map in the Yogyakarta-Bawen Toll Road Section I and II

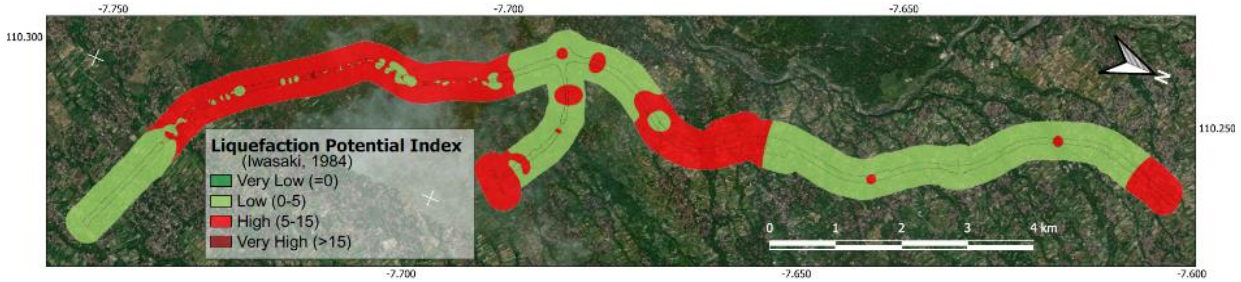

Figure 13. The Liquefaction Potential Index (Iwasaki) Map in the Yogyakarta-Bawen Toll Road Section I and II

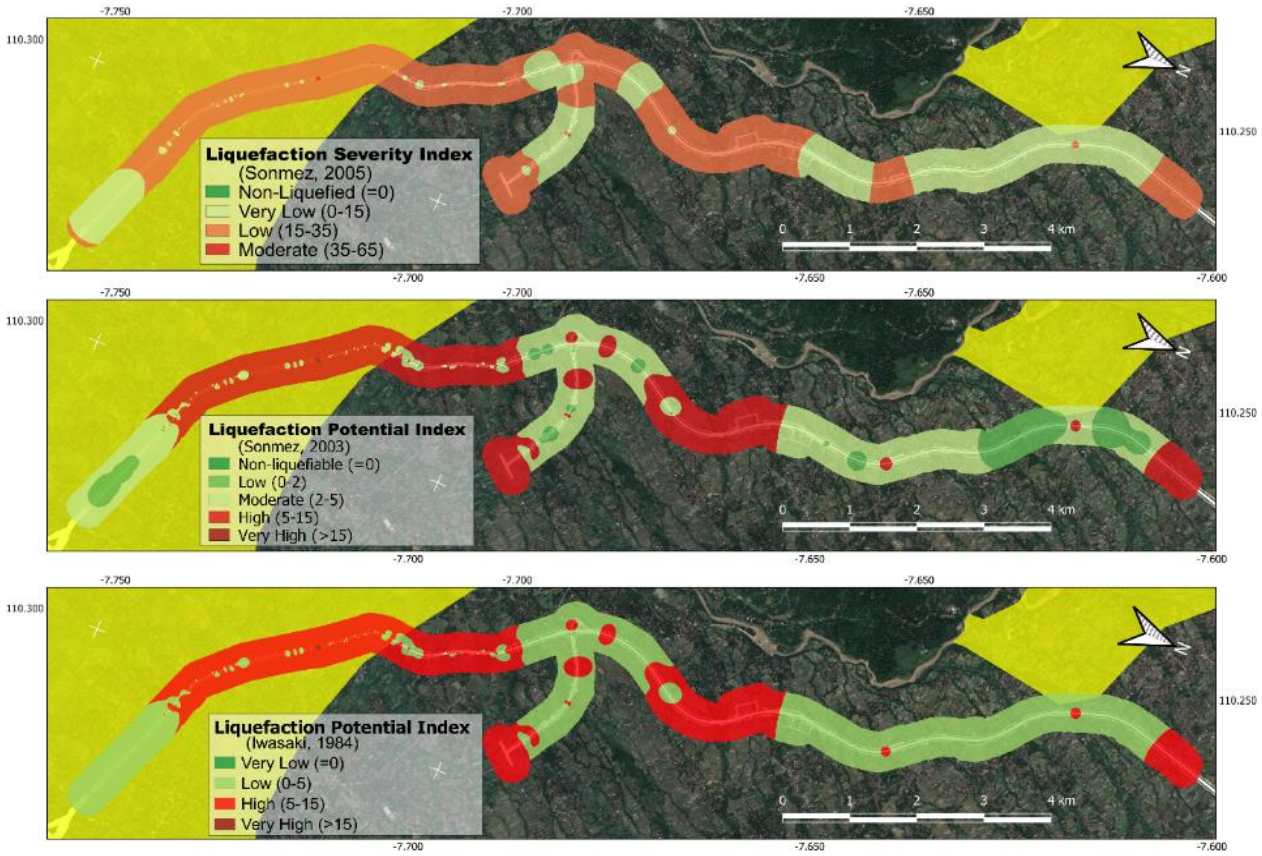

Figure 14. The overlay LPI and LSI with the Liquefaction Susceptibility Map in the Study Area

moderate (in LSI) zone. However, in detail, the liquefaction susceptibility zone map cannot illustrate the actual condition as the inputs of this map are macro parameters such as geological (lithology and hydrogeology) and seismicity factors as illustrated in Figure 14.

Figure 15 shows that the liquefaction criteria [11] may differ from the result of SPT analysis using the Idriss and Boulanger method, but the result is quite limited to draw conclusions due to the availability of data. Further analysis is needed to have a wider perspective on the reliability of the result.

Conclusion

The Yogyakarta-Bawen toll road Section I and II is constructed on soil that is dominated by silty sand, sand, and gravel as it is located above undifferentiated volcanic rocks. The groundwater basin map in the site indicates that most of the toll road is located in the discharge area and it implicates the existence of shallow groundwater (<10 m). Furthermore, the recent seismic activity of the Opak Fault with other soil parameters could be an initial indication of future liquefaction. After a series of analyses, the LSI and LPI value indicates that the liquefaction susceptibility map could be a good preliminary indicator. However, the result may vary due to different methods of analysis.

The LPI value between Iwasaki and Sonmez does not show a significant difference, but the classification of low and moderate in the Sonmez method is low in the Iwasaki method. Moreover, Sonmez's LPI indicates that the majority of the first section and some areas

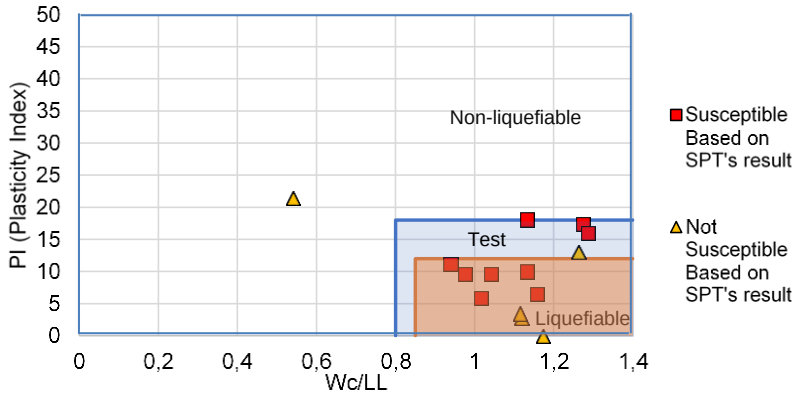

Figure 15. The Sample Comparison of Liquefaction Susceptibility in the Project

in the second section are at a high level. Meanwhile, in the majority of the second section, the Banyurejo intersection, and Sleman (STA 74+475 – STA 76+300) are at low-moderate levels. For Iwasaki's LPI, the map illustrates similarity and the only difference is in the low category (low-moderate in Sonmez's).

LSI's map has a similar trend as LPI's maps but the classification is different. The areas with the very low category are located in the Sleman, the most of Banyurejo-Borobudur section, and the Banyurejo interchange. In the low-level category, the majority of the Yogyakarta-Banyurejo section and part of the Banyurejo-Borobudur section. The moderate category area (In LSI) occupies almost the same as the very high category in LPI.

The Yogyakarta-Bawen Toll Road I and II Section is categorized as very low to moderate category based on the LSI Map. Meanwhile, in the LPI map, the Yogyakarta-Bawen Toll Road I and II Section is classified as low to high zone.

References

1. Badan Geologi, *Peta Zona Kerentanan Likuefaksi Indonesia,* Bandung, 2019.
2. Mase, L.Z., Fathani, T.F., and Adi, A.D., A Simple Shaking Table Test to Measure Liquefaction Potential of Prambanan Area, Yogyakarta, Indonesia, *ASEAN Engineering Journal*, 11(3), 2021, pp. 89–108, doi: 10.11113/AEJ.V11.16874.
3. Hartono, N. and Fathani, T.F., The Using of GIS to Delineate the Liquefaction Susceptibility Zones at Yogyakarta International Airport, *Civil Engineering Dimension*, 24(1), 2022, pp. 62–70, doi: 10.9744/ced. 24.1.62-70.
4. Iwasaki, T., Arakawa, T., and Tokida, K., Simplified Procedures for Assessing Soil Liquefaction During Earthquakes, *International Journal of Soil Dynamics and Earthquake Engineering*, 3(1), 1984, pp. 49–58.
5. Sonmez, H., Modification of the Liquefaction Potential Index and Liquefaction Susceptibility Mapping for a Liquefaction-prone Area (Inegol, Turkey), *Environmental Geology*, 44(7), 2003, pp. 862–871, doi: 10.1007/s00254-003-0831-0.
6. Sonmez, H. and Gokceoglu, C., A Liquefaction Severity Index Suggested for Engineering Practice, *Environmental Geology*, 48(1), pp. 81–91, 2005, doi: 10.1007/s00254-005-1263-9.
7. Badan Standardisasi Nasional, *SNI 8640:2017 Persyaratan Perancangan Geoteknik,* Jakarta, 2017.
8. Badan Standardisasi Nasional, *SNI 2833:2016 Perencanaan Jembatan Terhadap Beban Gempa,* Badan Standardisasi Nasional, Jakarta, 2016.
9. Kementerian Pekerjaan Umum dan Perumahan Rakyat, *Aplikasi LINI*, 2022. https://lini.bina-marga.pu.go.id/.
10. Idriss, I.M. and Boulanger, R.W., *SPT-Based Liquefaction Triggering Procedures (No. UCD/CGM-10/02)*, Davis, 2010.
11. Bray, J.D. and Sancio, R.B., Assessment of the Liquefaction Susceptibility of Fine-grained Soils, *Journal of Geotechnical and Geoenvironmental Engineering*, 132(9), 2006, pp. 1165–1177, doi: 10.1061/(asce)1090-0241(2006) 132:9(1165).
12. Pusat Survei Geologi, *Peta Geologi Indonesia,* Bandung, 2019.
13. Hendrayana, H., *Peta Cekungan Air Tanah Yogyakarta-Sleman,* Yogyakarta, 2011.
14. Badan Geologi, *Peta Cekungan Air Tanah Indonesia,* Jakarta, 2009.
15. Dinas Pertambangan dan Energi Provinsi Jawa Tengah, *Peta Potensi Air Tanah CAT Magelang-Temanggung Provinsi Jawa Tengah,* Semarang, 2004.
16. Japan Road Association, *Design Code and Explanation for Roadway Bridges-Seismic Resistance Design 1995 revision,* Japan Road Association, 1996.
17. PUSGEN (Pusat Studi Gempa Nasional) Pusat Litbang Perumahan dan Permukiman, *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017 (Map of Indonesia Earthquake Sources and Hazards in 2017),* Jakarta, 2017.