

Study of Liquefaction Severity-induced Lateral Displacement and Settlement based on SPT Data in Toll Road Project (Case Study: Mungkid and Candimulyo Districts, Central Java, Indonesia)

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Abstract. The common phenomena during liquefaction are the lateral displacement and settlement of saturated soil deposits. These phenomena have the potential damage to the toll road construction where this research is taking place. Toll road projects in Mungkid and Candimulyo Districts, Central Java, Indonesia must be evaluated for lateral displacement and settlement. The study area is located in volcanic deposits originating from Mount Merapi and Merbabu, with shallow groundwater level in some location, and a history big seismicity. PGA value at the research location was calculated using webpage application from Lini Binamarga. This study aims to calculate liquefaction severity using LSI method, lateral spreading using LDI method, and the ground settlement using reconsolidation settlement method with various moment magnitude scenarios. LSI in Candimulyo and Mungkid District are 17.77 (low severity) and 9.68 (very low severity), respectively. Candimulyo and Mungkid Districts experienced the greatest lateral spreading of 3.84 m and 1.87 m. Also, Candimulyo and Mungkid Districts have the largest settlement by 0.42 m in the extensive damage category and 0.15 m in the medium damage category. Based on this assessment, it is necessary to investigate the mitigation required to reduce lateral spreading and settlement caused by liquefaction.

1 Introduction

Ground movement and soil instability in the area hit by earthquake's seismic waves can cause significant damage. Earthquakes frequently cause liquefaction in saturated loose sands. One of the most well-known reasons for earthquake-related ground movement and failure is liquefaction [1]. Following liquefaction during earthquakes, the common geotechnical phenomena are the settlement and lateral spreading of saturated soil deposits [2]. These phenomena lead large soil movement, inflicting extensive damage to underground utilities, vital networks, and a variety of other subsurface and surface infrastructure like buildings, toll roads, bridges, embankments, dams, etc. It will occur due to pore pressure exceeds the confining pressure during seismic loading, resulting in quick loss of soil strength [1].

Severe damage to any kind of structures has resulted from lateral spreading, which occurs when soil liquefies, causing the topsoil move downslope during seismic shaking [3]. Most liquefaction-caused lateral spreading happens on slopes with angles between 0.3 to 3, where the ground formed of loose sand and the water level is close to the surface [4]. The 2018 Palu Earthquake,

which caused damage along canals, buildings, and the area of Gumbasa irrigation, was one of the lateral spreading and flow slide events caused by liquefaction that have occurred in Indonesia [5].

Seismic loading in saturated sand deposits increases pore water pressures and leads the loss of soil strength. The pore water pressures begin to dissipate predominantly towards the ground surface, accompanied by a change in volume of the sand deposits that manifests as settlements on the ground surface. Due to the heterogeneity of the soil deposits, settlements are rarely uniform called as differential settlements. It causes the damage to infrastructure [6].

Evaluation of liquefaction potential has been carried out in Yogyakarta – Bawen Toll Road in Section 1 and Section 2 by [7] and Section 3 by [8]. This study before focused to map liquefaction susceptibility in Yogyakarta – Bawen Toll Road project using LPI method by Iwasaki (1984) and LSI method by [9]. However, no research has been conducted on the severity of liquefaction related to lateral displacement and settlement on the Yogyakarta-Bawen toll road, which runs through the Mungkid and Candimulyo Districts. This research is required to mitigate the effects of damage on toll construction caused by lateral

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displacement and settlement. **Figure 1** shows the map location of this study.

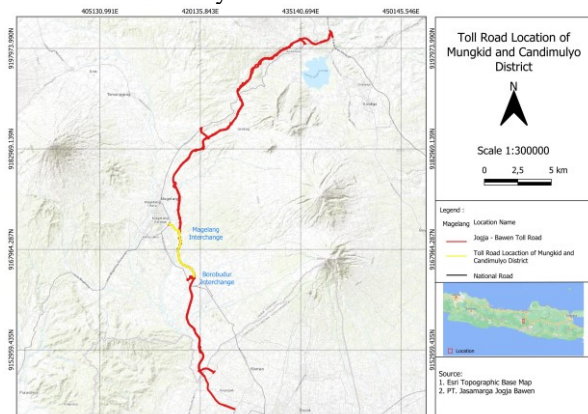


Figure 1. Toll Road Location of Mungkid and Candimulyo District

This study aims to conduct liquefaction severity analysis based on LSI method [9], calculate the lateral spreading based on the method of LDI [10] [11], and estimate the settlement that could occur as a result of liquefaction [6] based on various scenarios of moment magnitude.

2 Research Method

2.1 Research Data

This research focused on using SPT data and laboratory test carried out on toll road projects in Mungkid and Candimulyo Districts. This research was conducted to analyze liquefaction severity induced lateral spreading and settlement caused by reconsolidation. Information about the condition of the soil layer was obtained through drilling data with a minimum depth of 30 m and a maximum depth of 44 m. Research data used are 94 drill holes but they are focused on locations where lateral displacement and settlement might occur. **Figure 2** shows the location of the SPT data.

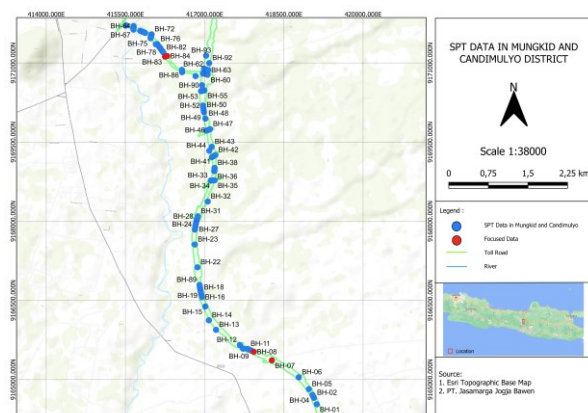


Figure 2. SPT data in Mungkid and Candimulyo District

2.2 Research area condition

Java Island, which located at the northern intersection of two tectonic plates namely Indo-Australian and Eurasian, has several faults tectonic as a stress form

accommodation generated by subduction in the southern Java.

Seismicity in Java Island is dominated by earthquakes related to subduction and faults on mainland. Shear faults and reverse faults dominate Java's active geological features, while normal faults are minor formations. Several known faults in Java are the Cimandiri, Lembang, Semarang, Baribis-Citanduy, Kendeng, Probolinggo, Pasuruan, and Opak faults. The Opak Fault has become the focus of the Jogja and Central Java regions since the 2006 big earthquake; where this fault has a sinistral shear movement and has a southwest-northeast direction [12]. **Figure 3** shows several active faults in Java that might affect on research area.

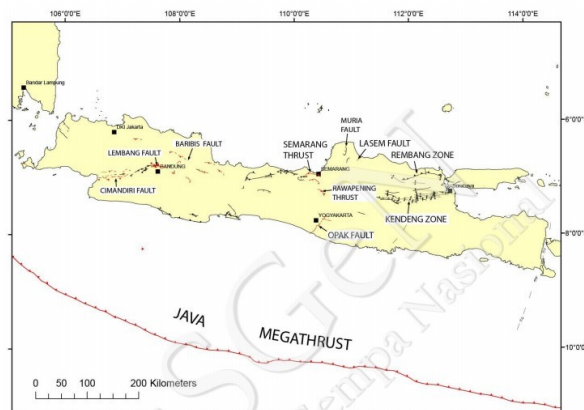


Figure 3. Java fault map [12]

This toll road project is located in Mungkid and Candimulyo Districts. In the geological map of Magelang and Semarang by [13] and the geological map of Yogyakarta by [14], Mungkid and Candimulyo Subdistricts are composed by Young Volcanic Rock Unit of Merapi Volcano (Qmi) and Volcanic Rock Unit of Merbabu Volcano (Qme). The formation of Young Volcanic of Merapi Volcano consists of lava, agglomerates, breccias, tuff, and ash. The formation of Volcanic Deposits of Merbabu Volcano consists of volcano breccia and lava (**Figure 4**). These deposits are predominantly the result of volcanic eruption. Therefore, they are comprised of loose and vulnerable to liquefaction [15].

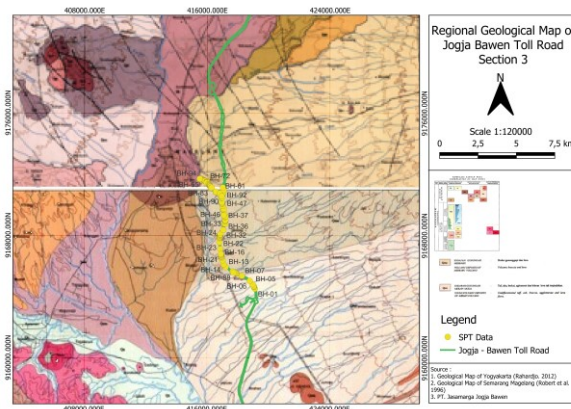


Figure 4. Geological Map of research area (modified from [13] [14])

for the qualitative classification of liquefaction probability, LSI is more specific and divided into six categories (**Table 2**).

Table 2. LSI classification [8]

LSI	Liquefaction Severity
$85 \leq L_s < 100$	Very High
$65 \leq L_s < 85$	High
$35 \leq L_s < 65$	Moderate
$15 \leq L_s < 35$	Low
$0 < L_s < 15$	Very Low
$L_s=0$	No liq

2.6 Lateral Displacement Index (LDI)

LDI can be used to determine the lateral displacement by integrating the γ_{max} value with depth. [10] developed an equation for estimating lateral displacements resulting from liquefaction using SPT and CPT data. This method employs data on liquefaction cases resulting from past earthquakes that also induced lateral displacements.

One crucial aspect in the estimation of lateral spreading displacements involves the consideration of site heterogeneity, particularly in intricate depositional settings or when there is a scarcity of site characterization data. The relationship between the depth-dependent variation of maximum shear strains and their manifestation as lateral spreading displacements at the ground surface is also a significant factor to consider.

LDI can be determined using the equation (11-14) below.

$$\gamma_{lim} = 1.859 \left(1.1 - \sqrt{\frac{(N_1)_{60cs}}{46}} \right)^3 \geq 0 \quad (11)$$

$$F_\alpha = 0.032 + 0.69\sqrt{(N_1)_{60cs}} - 0.13(N_1)_{60cs} \quad (12)$$

$$\gamma_{max} = \min \left(\gamma_{lim}, 0.035(2 - FS_{liq}) \left(\frac{1 - F_\alpha}{FS_{liq} - F_\alpha} \right) \right) \quad (13)$$

$$LDI = \int_0^{Z_{max}} \gamma_{max} \cdot dz \quad (14)$$

Note: Z_{max} = maximum depth below all the potential liquefiable layers with a calculated FS < 2, γ_{max} = maximum shear strain, dz = layer thickness, γ_{lim} = limiting shear strain, F_α = additional parameter of safety, and FS_{liq} = FS against liquefaction. Equation (13) can be used if $2 > FS_{liq} > F_\alpha$, due to $FS_{liq} \geq 2$ then $\gamma_{max} = 0$. Equation (12) can be used if $\gamma_{max} = \gamma_{lim}$.

2.7 Post-Liquefaction Reconsolidation Settlement

Evaluation of post-liquefaction reconsolidation settlement can be determined by converting vertical stress to volumetric strain and integrating over a depth interval [6]. The equation below is used to calculate

liquefaction reconsolidation settlement based on SPT data (15-16).

$$\varepsilon_v = 1.5 \exp(-0.369\sqrt{(N_1)_{60cs}}) \cdot \min(0.08\gamma_{max}) \quad (15)$$

$$S_{v-1D} = \int_0^{Z_{max}} \varepsilon_v \cdot dz \quad (16)$$

Note: S_v = settlement for one dimensional consolidation, ε_v = volumetric strain, γ_{max} = maximum shear strain, and $(N_1)_{60cs} = (NI)_{60}$ value corrected with clean sands. The correlation between damage extent and settlements is classified into 3 categories as shown in **Table 3** below.

Table 3. Correlation between damage and settlements [6]

Settlement (cm)	Extent of damage	Phenomena on ground surface
0 - 10	Light to no damage	Minor cracks
10 - 30	Medium damage	Small cracks, oozing of sand
30 - 70	Extensive damage	Large cracks, large offsets, lateral movement

3 Results dan Discussion

The geotechnical and geological investigation carried out based on SPT data in Mungkid and Candimulyo District reveals predominant soil types in these areas consist of sandt and silty compositions.

In the southern and central part of Mungkid District, the lithology at a depth of 0 – 12 m is dominated by sandy silt with a medium to stiff consistency and at a depth of 13 – 20 m is dominated by silty sand with dense consistency. In the northern and central part of Candimulyo District, the lithology at a depth of 0 – 10 m is dominated by sandy silt and gravelly sand with medium consistency and at a depth of 11 – 20 m is dominated by gravel with high density.

3.1 Result of seismic hazard analysis

As stated in **Table 1**, the estimate of liquefaction potential was conducted utilizing historical magnitudes that have ever occurred in and around Yogyakarta. The PGA determination using webpage application of Lini Binamarga is described in **Table 4**.

Table 4. PGA in the research area

SPT ID	Site Class	PGA	F_{PGA}	PGA_M
BH-07	SD	0.28	1.24	0.35
BH-08	SD	0.28	1.24	0.35
BH-83	SE	0.27	1.36	0.36
BH-84	SE	0.27	1.36	0.36

According to the calculation of PGA, it was found that the maximum PGA value is 0.36 in BH-83 and BH-43 while in BH-07 and BH-08 the PGA value is 0.35.

This is due to the fact that site class on BH-83 and BH-84 is a soft soil (SE) so that the site coefficient is relatively larger.

Based on this evaluation of liquefaction potential, the value of lateral spreading and settlement for these 4 data can be determined due to the calculated value for that lateral spreading and settlement are obtained from the correction of the $(N_1)_{60cs}$ value.

3.2 Safety Factor against Liquefaction

Based on preliminary study and the study that has been carried out before [8], the liquefied layer on BH-07 is at depth of 8 and 12 m with FS value of 0.43 and 0.48. The liquefied layer on BH-08 is at depth 12 to 14 m with FS value of 0.93 and 0.85. The liquefied layer on BH-83 is at depth 8 to 14 m with FS value of 0.5 – 0.71. The liquefied layer on BH-84 is at depth 10 to 14 m with FS value of 0.46 – 0.68. The liquefied layer with FS value less than 1 are dominated by silty sand and contained SPT value less than 20. In the advanced research stage, the author then studied the liquefaction severity, the lateral spreading caused by liquefaction, and the reconsolidation settlement in the research area using various earthquake moment magnitude scenarios, as shown in **Table 1**.

3.3 Result of LSI

LSI value was calculated using equation (7) based on 4 scenarios of the biggest moment magnitude that has ever occurred in the area of Yogyakarta, Central Java, and around research location.

In scenario 1, the highest LSI value is 17.77 on BH-84 in low category and the lowest LSI value is 4.84 on BH-08 in very low category. In scenario 2, the highest LSI value is 17.73 on BH-84 in low category, and the lowest LSI value is 4.26 on BH-08 in very low category. In Scenario 3 and 4, the highest LSI value is 17.63 and 17.46 on BH-84 in low category and the lowest LSI values are 2.96 and 1.82 on BH-08 in very low category. According to the scenario's findings, the severity of the liquefaction is directly proportional to the magnitude value of the earthquake. **Table 5** summarizes the results of LSI value based on four scenarios of moment magnitude.

Table 5. Recapitulation of LSI

Bore ID	LSI			
	Mw 6.3	Mw 6.1	Mw 5.7	Mw 5.2
BH-07	9.68	9.63	9.51	9.30
BH-08	4.84	4.26	2.96	1.82
BH-83	17.77	17.73	17.63	17.46
BH-84	11.73	11.68	11.55	11.32

Figure 6 showed the map of LSI in research area based on [8]

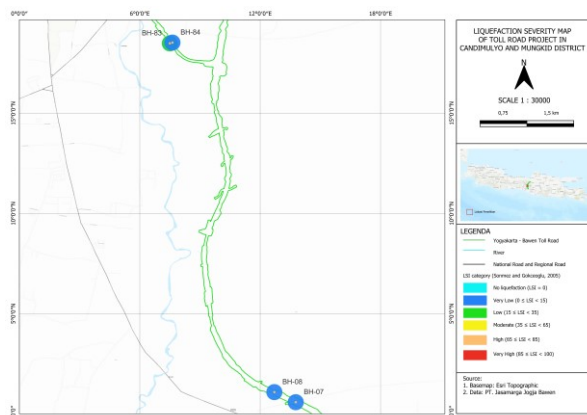


Figure 6. LSI map in research area

3.4 Result of LDI

LDI value was calculated using equation (14). The vertical displacement at BH-08 will increase from 0.09 to 0.38 m along with the increase of Mw scenario value, while the other result of BH-07, BH-83, and BH-84 has no effect due to maximum shear strain obtained from earthquake is less than limiting shear strain. **Table 6** summarizes the results of LDI in four boreholes based on four scenarios of moment magnitude.

Table 6. Recapitulation of LDI

Bore ID	LDI (m)			
	Mw 6.3	Mw 6.1	Mw 5.7	Mw 5.2
BH-07	1.87	1.87	1.87	1.87
BH-08	0.38	0.28	0.18	0.09
BH-83	3.84	3.84	3.84	3.84
BH-84	2.74	2.74	2.74	2.74

3.5 Result of Post-Liquefaction Settlement

Estimation of settlement was calculated using equation (16). The settlement at BH-08 will increase from 0.03 m to 0.1 m along with the increase of Mw scenario value, while the result of BH-07, BH-83, and BH-84 has no effect due to the volumetric strain and shear strain obtained from earthquake is less than limiting shear strain.

The damage category that occurred in BH-07 and BH-84 was medium damage with the phenomena on ground surface in the form small cracks and oozing of sand. The damage category that occurred in BH-08 was light to damage with the phenomena on ground surface in the form minor cracks. Also, the damage category that occurred in BH-83 was extensive damage with the phenomena on ground surface in the form of large cracks, lateral offsets, and lateral movement. **Table 7** summarizes the results of settlement in four boreholes based on four scenarios of moment magnitude.

Table 7. Recapitulation of *Settlement*

Bore ID	<i>Settlement (m)</i>			
	<i>Mw 6.3</i>	<i>Mw 6.1</i>	<i>Mw 5.7</i>	<i>Mw 5.2</i>
BH-07	0.15	0.15	0.15	0.15
BH-08	0.10	0.08	0.05	0.03
BH-83	0.42	0.42	0.42	0.42
BH-84	0.28	0.28	0.28	0.28

Figure 7 showed the map of damage related to settlement based on [6].

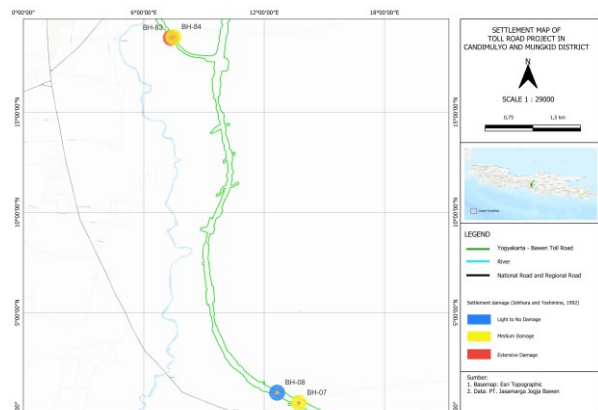


Figure 7. Settlement map in research area

4 Conclusions

The toll road projects in Mungkid and Candimulyo Districts experienced liquefaction severity at several location. This is due to the condition of research area contain volcanic rock material which classify as sandy and silty soil, some locations and borehole depths have N-SPT values < 20, ground water level is shallower than 10 m, and has the history of big seismicity with *Mw* 6.3, *Mw* 6.1, *Mw* 5.7, and *Mw* 5.2

Based on the evaluation of liquefaction severity, there are 3 boreholes that have a very low LSI category located in Candimulyo and Mungkid District and 1 borehole that has a low LSI category located in Candimulyo District. Peak ground acceleration used in this locations are 0.35 and 0.36 g. Candimulyo District experienced the greatest lateral spreading of 3.84 m in BH-83. Candimulyo District also seemed to have the largest settlement by 0.42 m in the extensive damage category. Mungkid District experienced the greatest lateral spreading of 1.87 m in BH-07. And, also Mungkid District seemed to have the largest settlement by 0.15 m in the medium damage category.

To establish the impact of lateral spreading and settlement on the structural stability of the toll road construction, additional research is required. Then, to secure the safety of toll road building, it is necessary to evaluate the most suitable mitigation approach.

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