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Liquefaction-Induced Lateral Displacement and Settlement Mapping for Yogyakarta-Bawen Toll Road Section I & II, Indonesia

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Abstract: The liquefaction-induced ground displacement (the lateral displacement and ground settlement) study in the Yogyakarta-Bawen toll road, Indonesia, is not yet conducted as the importance of this project, the project needs to be mapped. In this study, the mapping is conducted using two methods for lateral displacement, Gillins & Bartlett's method and Zhang et al.'s method, while the mapping of ground settlement using Tokimatsu & Seed's method and Yoshimine's method. For Gillins & Bartlett's method, the lateral displacement map in Yogyakarta-Bawen is dominated by moderate to high categories in section I but relatively low in section II. Meanwhile, Zhang et al.'s map in the I & II sections of the toll road is relatively dominated by the moderate category. Furthermore, the ground settlement map in I & II sections with Tokimatsu & Seed is mostly categorized as very high meanwhile Yoshimine's map is predominately classified as low to moderate.

Keywords: Liquefaction; lateral displacement; ground settlement; IDW.

Introduction

Based on the liquefaction susceptibility map [1] as shown in Figure 1, the Yogyakarta-Bawen toll road in Yogyakarta-Banyurejo Section (the first section), Indonesia, is built on a moderately susceptible liquefaction zone, but in the Banyurejo-Borobudur (the second section) is not susceptible to liquefaction. This fact is supported by the existence of shallow groundwater (<10 m) and the geological condition of the project which is located above the undifferentiated volcanic rocks. Moreover, based on the preliminary study [2], the toll road location is dominated by the existence of sand, silty sand, and gravel as a result of Merapi volcanic activity.

The previous study conducted in this location mostly discusses liquefaction potential that is indicated by the liquefaction potential index (LPI) and liquefaction severity index (LSI). The preliminary study on the Yogyakarta-Bawen Toll Road indicated that based on Sonmez's liquefaction potential index, the Yogyakarta-Banyurejo section is mostly classified as high category meanwhile in the Banyurejo-Borobudur section is dominated by moderate category [2]. Although the study illustrates liquefaction potential in this area, the scope of this study is limited to 1D SPT-based LPI and LSI analysis only.

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Due to the project's importance, mapping liquefaction-induced ground displacement (lateral displacement and settlement) can navigate the potential hazard and its mitigation.

Analysis Methodology

The analysis methodology for liquefaction-induced lateral displacement and settlement mapping is performed in several steps: (i) Collection of geological, geotechnical, spatial, and seismic data, (ii) Liquefaction-induced ground displacement (lateral spreading and ground settlement) analysis based on SPT and boring data, (iii) Inverse Distance Weighted (IDW) analysis for liquefaction-induced lateral displacement and settlement mapping.

The liquefaction-induced ground displacement takes account of earthquake load, geometry, and N-SPT. The analysis considers earthquake load design that complies with Indonesian National Standard criteria for the conventional bridge with a 1000-year returning period, 75 years design life, and 7% probability of exceedance. The amplified PGA is obtained from the LINI application [3] and calculated based on SNI 2833:2016 [4]. The liquefaction safety factor is measured using Idriss & Boulanger's formula [5]. Furthermore, as slope plays a significant role in lateral displacement, the slope data are obtained from processed Digital Elevation Model (DEM) using DEMNAS data [6]. Elevation data from DEM are collected and analyzed in the geographical information system (GIS) to become slope data. Those data are used as input in Gillins & Bartlett [7] and Zhang et al. [8] formulas.

The liquefaction-induced ground displacement is measured with several methods as shown in Figure 2.

Figure 1. Liquefaction Susceptibility Map in the I & II Section of the Yogyakarta-Bawen Toll Road (Modified from [1])

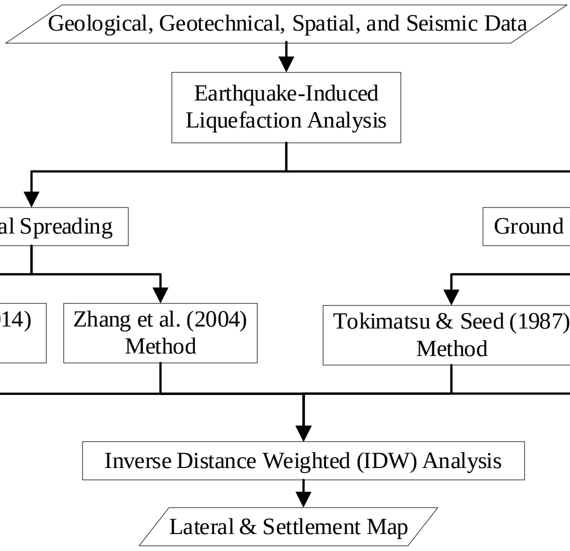

Figure 2. Liquefaction-induced Ground Displacement Analysis Flow Chart

Liquefaction-Induced Lateral Displacement Analysis Method

The liquefaction-induced ground displacement analysis is performed using two methods for lateral spreading and ground settlement. For lateral spreading, analysis is conducted based on Gillins & Bartlett [7] and Zhang et al. [8] formulas. The estimation of lateral displacement is solved with Equations (1) and (2) for Gillins & Bartlett's method.

$$\text{Log } D_H = -8.208 - 0.344\alpha + 1.318M - 1.073\text{Log}R^* - 0.016R + 0.445\text{Log}W + 0.337\text{Log}S + 0.592\text{Log}T_{15} - 0.683x_1 - 1.2x_2 + 0.252x_3 - 0.04x_4 - 0.535x_5 \quad (1)$$

$$R^* = R + 10^{0.89M - 5.64} \quad (2)$$

Where D_H is estimated lateral ground displacement (m); $\alpha = 0$ for ground-sloping conditions, 1 for free-face conditions; M is the moment magnitude of the earthquake; R* is a nonlinear magnitude distance; R is the nearest distance from the seismic energy source (km); W is the ratio of the height to the horizontal base distance of free face (%); S is the ground slope (%); T_{15} is the cumulative thickness liquefiable saturated soils (m); x_i = thickness of the liquefiable layers divided by total cumulative thickness T_{15}.

While the procedure is shown in Figure 3 for Zhang et al.'s. The procedure initially calculates the relative density of the soil layer and it determines the maximum shear strain of soil layers. Furthermore, the LDI is an accumulation of maximum shear strain as a function of layer thickness. Next step, the lateral displacement (LD) formula is determined by slope percentage which is divided into gently ground sloping and free face.

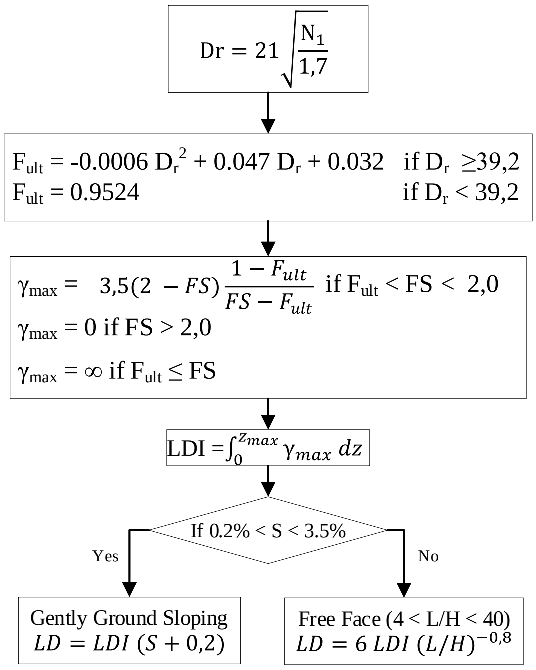

Figure 3. Lateral Displacement [8]

Where Dr is the relative density (%); γ_{max} is the maximum shear strain (%); FS is the safety factor for liquefaction; LDI is the liquefaction displacement index; LD is the lateral ground displacement.

Liquefaction-Induced Ground Settlement Analysis Method

Liquefaction-induced ground settlement in Yoshimine et al.'s method requires maximum shear strain (γ_{max}) and relative density ($D_{r,\ ini}$) to obtain the volumetric strain [9]. Then, the volumetric strain can be calculated using Equations 3a and 3b or using a graph as shown in Figure 4.

$$\varepsilon_v = 1.5[\exp(-0.025\ D_{r,\ ini})]\gamma_{max} \quad \text{if } \gamma_{max} \leq 8\% \tag{3a}$$

$$\varepsilon_v = 12\exp(-0.025D_{r,\ ini}) \quad \text{if } \gamma_{max} > 8\% \tag{3b}$$

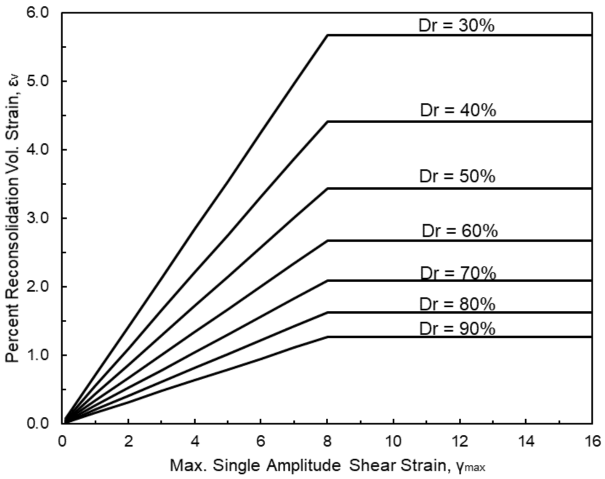

Figure 4. Reconsolidation Volume Change vs. Maximum Shear Strain during Cyclic Loading [9]

The estimated settlement is analyzed by the cumulative liquefiable soil layer thickness times the estimated volumetric strain which is shown in Equation 4.

$$\Delta S_Y = \sum_{i=1}^{n} t_i \times \varepsilon_{v,i} \tag{4}$$

Tokimatsu & Seed's method [10] has a relatively similar procedure to Yoshimine et al.'s, but the difference is how to obtain the volumetric strain which uses cyclic stress ratio (CSR) and $(N_1)_{60}$ instead of maximum shear strain. The relationship between CSR, $(N_1)_{60}$, and the volumetric Strain is shown in Figure 5.

The Tokimatsu & Seed's settlement formula calculates the cumulative thickness of the liquefiable layer times volumetric strain which is the volumetric strain obtained from Figure 5 using $(N_1)_{60}$ and cyclic stress ratio. The formula of ground settlement with Tokimatsu & Seed's method is shown in Equation (5).

$$\Delta S_{TS} = \sum_{i=1}^{n} t_i \times \varepsilon_{vo,i} \tag{5}$$

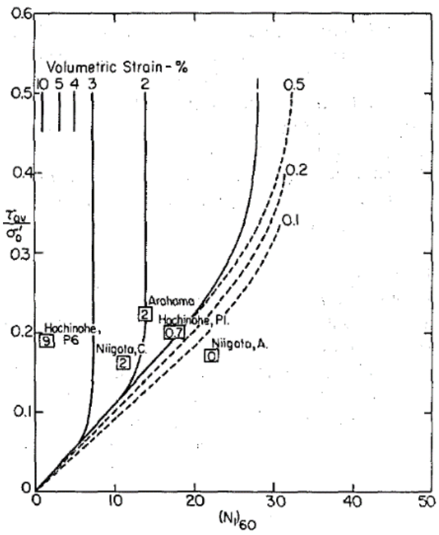

Figure 5. Relationship between Cyclic Stress Ratio, $(N_1)_{60}$, and Volumetric Strain for Saturated Clean Sands [10]

Results

Based on the previous study, the liquefaction potential index (LPI) using Sonmez's method study indicate that the majority of the first section is located in the area of high category meanwhile the second section mostly varied from moderate to low category as shown in Figure 6.

Liquefaction-Induced Lateral Displacement

This result has shown that the majority of bridges in the Yogyakarta-Banyurejo section are prone to liquefaction as they are categorized as high in LPI. To analyze the lateral displacement, the slope data is obtained from slope mapping using digital elevation model data. Based on the slope data, the observed location is dominated by flat (0-8%) and sloping (8-15%) characteristics as shown in Figure 6. In lateral displacement analysis, slope data S (%) is limited to ≤ 6% for Gillins & Bartlett's method and 0.2%<S<3.5% for Zhang et al.'s method to be considered as ground slope condition and for > 6% for Gillins & Bartlett's method and > 3.5% for Zhang et al.'s method is considered as a free-face condition. The slope map is shown in Figure 7.

By applying the scenario of PGA 1000 years returning period and 7% probability of exceedance for Gillins & Bartlett's formula, the lateral displacement in the bridge section (STA 73+100-74+625) is mostly identified as high (0.3-0.5 m) meanwhile the other part of the Yogyakarta-Banyurejo section is mostly classified as moderate (0.1-0.3 m) and low (0-0.1 m). Although some spots identified as high (0.5-1.0 m) are a high category in LPI, lateral displacement with Gillins & Bartlett's method is mostly determined by geometry, seismic energy source, and soil properties.

In the Banyurejo-Borobudur section, the lateral spreading in that area is in a low category (0-0.1 m) due to Gillins & Bartlett's formula characteristic as an empirical formula that is heavily influenced by the proximity of seismic energy source. The estimation of lateral displacement with Gillins & Bartlett in the observed location is shown in Figure 8.

To obtain Zhang et al.'s estimated lateral displacement, the lateral displacement index (LDI) analysis needs to be conducted and the result of LDI is illustrated in Figure 9. The lateral displacement is calculated using LDI and considers the geometry as shown in Figure 3. The lateral displacement map with Zhang et al.'s method is shown in Figure 10.

Zhang et al.'s method is different from Gillins & Bartlett's since the distance of the seismic energy source is not considered in Zhang et al.'s method. Therefore, in this project, Zhang et al.'s result shows a different result from Gillins & Bartlett's that the Banyurejo-Borobudur section is mostly dominated by the moderate category (0.1-0.3 m). However, the most of Yogyakarta-Banyurejo section has relatively similar to Gillins & Bartlett's result which is dominated by moderate (0.1-0.3 m) with fewer high (0.3-0.5 m) categories.

As mentioned earlier, the lateral displacement for Gillins & Bartlett's method is significantly influenced by proximity to the seismic source, as shown in Table 1. The closest section to Opak Fault, the Yogyakarta-Banyurejo section, has the highest lateral displacement and its average difference compared to other parts. Meanwhile, the lateral displacement in the Banyurejo-Borobudur section with Zhang et al's method is higher than that of Gillins & Bartlett's method as it does not consider the proximity to the seismic energy source directly in its equation.

Figure 6. Liquefaction Potential Index using Sonmez's Method in the Observed Location [2]

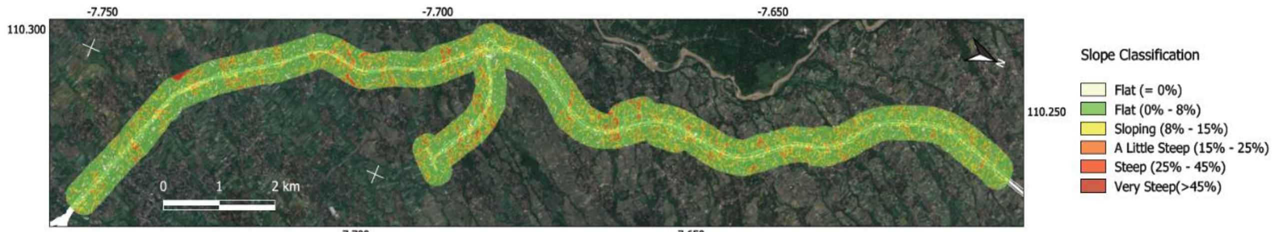

Figure 7. Slope Classification Map Based on Van Zuidam's Classification

Figure 8. Prediction of Lateral Displacement with Gillins & Bartlett's Method in the Project

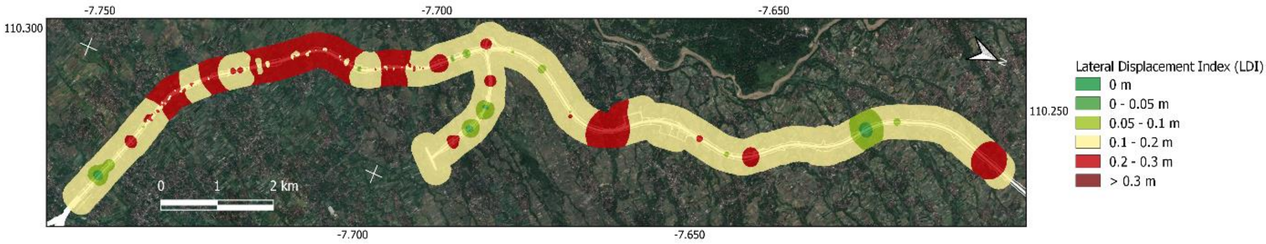

Figure 9. Lateral Displacement Index in the Project

Figure 10. Prediction of Lateral Displacement with Zhang et al.'s Method in the Project

Table 1. Comparison of $LD_{G\&B}$ and LD_Z at Each Borehole

	Yogyakarta-Banyurejo Section	Banyurejo Intersection	Banyurejo-Borobudur Section
Average Difference, m	0.152	0.027	0.030
Maximum Difference, m	0.489	0.121	0.080
Number Boreholes where $LD_{G\&B} > LD_Z$	142	11	3
Number Boreholes where $LD_Z > LD_{G\&B}$	52	12	15

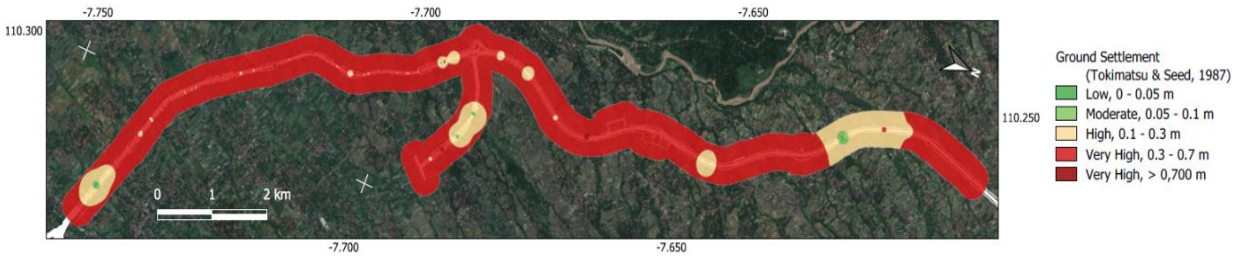

Figure 11. Prediction of Ground Settlement with Tokimatsu & Seed's Method in the Project

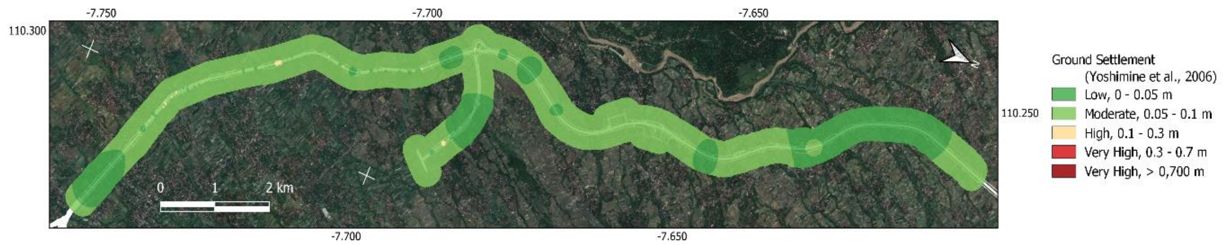

Figure 12. Prediction of Ground Settlement with Yoshimine et al.'s Method in the Project

Liquefaction-Induced Settlement

The Tokimatsu & Seed's ground settlement using PGA 1000 years returning period and 7% probability of exceedance scenario is higher than that of Yoshimine's method as shown in Figures 10 and 11. The higher liquefaction-induced ground settlement is caused by higher volumetric strain ε_v in Tokimatsu & Seed's method compare to Yoshimine et al's method. This has been presented in Figures 4 and 5 that the Tokimatsu & Seed's method has a volumetric strain of up to 10% meanwhile Yoshimine's is less than 6%. Therefore, Tokimatsu & Seed's method produces a more conservative estimation than Yoshimine's.

The ground settlement calculated using Tokimatsu & Seed's method in the majority of the Yogyakarta-Banyurejo and Banyurejo-Borobudur sections is classified as very high (0.3-0.7 m). The area classified as high only in part of the Banyurejo-Borobudur section (STA 59+150–STA 60+825), part of the Yogyakarta-Banyurejo section (STA 75+375–STA 76+175), and several spots in the Banyurejo intersection. The ground settlement map using this method is shown in Figure 11.

Using Yoshimine's method, the ground settlement in the project is mostly classified as moderate (0.05-0.1 m) and low (0-0.05 m). With Yoshimine's method, almost all of the Yogyakarta-Banyurejo and Banyurejo-Borobudur Sections categorize as moderate (0.05-0.1 m), meanwhile, low category is found in part of the Banyurejo-Borobudur section (STA 58+425-STA 61+475), part of the Yogyakarta-Banyurejo section (STA 75+187.5-STA 76+300), and some spots in the Banyurejo Intersection. This condition is illustrated in Figure 12.

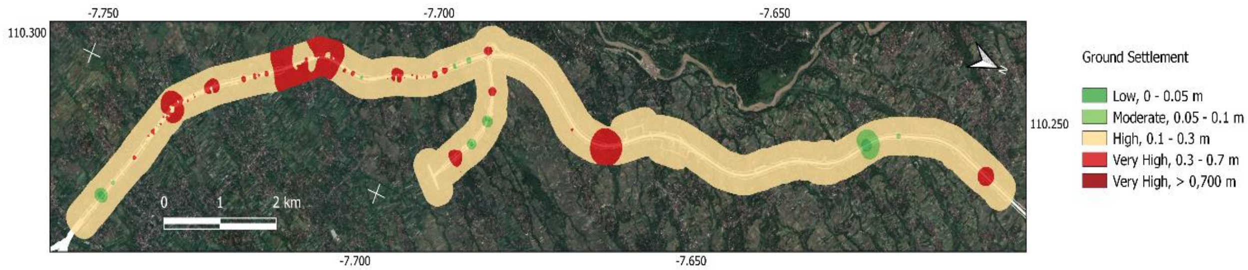

Figure 13. The Average of the Two Methods Results in Ground Settlement

Table 2. Comparison of ΔS_{TS} and ΔS_Y at Each Borehole

	Yogyakarta-Banyurejo Section	Banyurejo Intersection	Banyurejo-Borobudur Section
Average Difference, m	0.417	0.353	0.302
Maximum Difference, m	0.816	0.742	0.618
Number Boreholes where $\Delta_{TS} > \Delta_Y$	194	23	18
Number Boreholes where $\Delta_Y > \Delta_{TS}$	0	0	0

The observed ground settlement has similar trend to Hinckley's study [11] where Tokimatsu & Seed's method produces higher settlement than Yoshimine et al.'s method. The significant differences exist between Yoshimine's method and Tokimatsu & Seed's method are the relative density ($D_{r,\ ini}$) and $\gamma_{c,max}$ in Yoshimine's method generating relatively low volumetric strain compared to Tokimatsu & Seed's (with cyclic stress ratio and $(N_1)_{60}$ as input).

The average of the two method's ground settlements is illustrated in Figure 13 where the majority of the toll road is classified as high (0.1-0.3 m). The very high (0.3-0.7 m) category is only identified in several spots in the Yogyakarta-Banyurejo section and Banyurejo interchange.

The different result between Tokimatsu & Seed's and Yoshimine's method is illustrated in Table 2. There is no Yoshimine's ground settlement exceeding Tokimatsu & Seed's.

Assumptions and Limitations

The description from bore logs becomes a reference to classify the soil category for Gillins & Bartlett's formula because of the lack of fine-content data that is only available in several boreholes.

In the free-face condition, it is assumed that distance from the base of the free face to the analyzed point is 100 m with the height of the slope equal to a percentage of slope multiplied by 100 m as the geometry data is limited.

Conclusion

The liquefaction-induced lateral displacement mapping for Yogyakarta-Bawen Toll Road, Indonesia, Section I & II study suggests that the hazard of lateral displacement is varied from low to high category depending on the formula being used. Moreover, the liquefaction-induced ground settlement for this location also suggests that the ground settlement range from low to high category.

By applying the 1000 years returning period, 75 years design life, and 7% probability of exceedance earthquake scenario, the lateral displacement of Gillins & Bartlett's method is significantly influenced by proximity to seismic source as the Yogyakarta-Banyurejo section is dominated by moderate (0.1-0.3 m) and high (0.3-0.5 m), meanwhile in the Banyurejo-Borobudur section is relatively low (0-0.1 m) as it is farther from Opak Fault. However, Zhang et al.'s method generates moderate lateral displacement in both sections and some areas of low because its formula characteristic which does not consider the proximity of seismic energy to the analyzed location. For ground settlement, Tokimatsu & Seed's formula produces a conservative result than Yoshimine's because Tokimatsu & Seed's formula generates a higher volumetric strain than its counterpart. Almost all sections categorize as very high (0.3-0.7 m) in Tokimatsu & Seed's map. On the other hand, the ground settlement with Yoshimine's method in the project is mostly classified as moderate (0.05-0.1 m) and low (0-0.05 m). As all of the ground displacement's formula (lateral spreading or ground settlement) is based on empirical study, the selection of formula needs to consider the characteristic formula as each formula may have significant differences in result.

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