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DMT Method Approach for Liquefaction Hazard Vulnerability Mapping in Bantul Regency, Yogyakarta Province, Indonesia

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Abstract - On May 27 2006, an earthquake (Mw 6.2) occurring in Bantul, Yogyakarta Special Province, triggered liquefaction phenomenon such as sand boiling and lateral spreading. Knowledge of the liquefied soil layers is required to mitigate the hazard. The purpose of this research is to determine the depth and thickness of liquefiable soil layers using the flat blade dilatometer test (DMT) method. The horizontal stress index values (K_D) obtained from the DMT were used to calculate the cyclic resistance ratio (CRR), while the PGA (peak ground acceleration) calculated by the software EZ-FRISK 7.52 were employed to determine the cyclic stress ratio (CSR). The DMT-based liquefaction potential analysis shows that the thickness of liquefiable soil layers ranges from 1.8 to 4.0 m. These results show a good agreement with the previous analysis based on CPT (cone penetration test) data. The analysis also indicated that, for the given earthquake magnitude and PGA, the liquefiable soil layers are characterized by a range of maximum K_D value from 2.1 to 3.7.

Keywords: earthquake, flat blade dilatometer, horizontal stress index, liquefaction potential

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Introduction

Background

An earthquake (Mw 6.2) that occurred on May 27, 2006, struck the region of Yogyakarta and its surrounding areas including Bantul, Kulon Progo, Gunung Kidul, Sleman, Solo, Karanganyar, Klaten, and Prambanan. The damaged area in Bantul, including Bantul-Klaten plain extends from Kali Opak to the west Klaten. The study of seismicity by Nurwidyanto *et al*. (2007) indicated that the earthquake source was located at 33 km depth, precisely at 37 km from the south coastline with its epicenter in the Indian Ocean, on the coordinates of 08.26° S and 110.31° E. Another observer (Kuepper, 2006) showed that the earthquake source was located at 17 km depth on the coordinates of 8.007° S and 110.286° E.

That earthquake caused many casualties and huge economic losses, especially in Bantul region due to its close distance to the earthquake source and its geological condition comprising beach alluvial, limestone sediments, and volcanic eruption deposits. This geological condition led to the occurrence of liquefaction phenomenon in the area. Liquefaction can lead to the emergence of sand boiling, settlement of building, and floating of light structure. Soil layers of liquefaction potential are generally formed in the Quaternary geological environment (Soebowo *et al*., 2009).

To address the liquefaction potential, an effective and simple method to evaluate the subsurface condition controlling the liquefaction is required. This method will enable to assist the prediction of areas to liquefaction-prone.

Currently, liquefaction analyses are mainly based on SPT (standard penetration test) and CPT data. Soebowo *et al*. (2009) presented the depth and thickness of soil layers which have liquefaction potential and ground settlement in the area Patalan, Bantul, Yogyakarta using CPT and N-SPT data. Furthermore, Tohari *et al*. (2011) carried out a study of liquefaction potential in Padang City based on CPT/ CPTu and N-SPT. In 2009, Putra *et al*. also used CPT data to evaluate the liquefaction potential in Padang City. On other hand, Monaco *et al*. (2005) showed a result of liquefaction analysis using flat Dilatometer Test (DMT) data.

This paper presents an analysis of the DMT horizontal stress index value (K_D) to calculate the CRR. The CSR and MSF (magnitude scaling factor) values will be correlated with PGA data using EZ-FRISK 7.52 software (Risk Engineering, 2011) to determine the safety factor against liquefaction. The distance data and the magnitude of each DMT location from earthquake hypocentre are obtained using EZ-FRISK 7.52 software and analyzed using Boore-Atkinson *et al*. (2008) attenuation function. This attenuation function is used to analyze the shallow crustal zones and it has a lower standard error (Malau *et al*., 2008). Finally, threshold of K_D is decided by compiling safety factor against liquefaction with K_D value. The purpose of this research is to determine the soil layers which have a potential liquefaction due to earthquakes using Dilatometer Test (DMT) approach. The results obtained will be compared with a CPT approach (Soebowo *et al*., 2009).

Research Location

The research area is located in Bantul area, Yogyakarta Special Province, at the coordinates of 110.290° S - 110.445° S and 8.032° E - 7.823° E. This area consists of low plains and hills stretching from south to north as shown in Figure 1.

Figure 2 shows the geological characteristics of the research area that are composed of alluvial and Merapi laharic deposits (Rahardjo *et al*., 1995). The oldest unit is Semilir Formation comprising Oligo-Miocene interbedded tuff-breccia, pumice breccia, dacitic tuff, andesitic tuffs, and tuffaceous claystone. Then, Nglanggran Formation deposited unconformably on top of the Semilir Formation consisting of volcanic breccia, flow breccia, agglomerate, lava, and tuff of Early-Middle Miocene in age. In turn, the Nglanggaran Formation underlies the Sambipitu Formation comprising tuff, shale, siltstone, sandstone, and conglomerate. The Wonosari Formation composed of reef limestone, calcarenite, and tuffaceous calcarenite overlies conformably the Sambipitu Formation. In turn, the Sambipitu Formation underlies conformably the Sentolo Formation consisting of limestone and marly sandstones. Young Merapi volcanic products overlying unconformably the Tertiary units, consists of undifferentiated tuff, ash, breccia, agglomerate, and lava flows. The youngest unit is Alluvial Deposits of Quaternary in age, made up of gravel, sand, silt, and clay, deposited along larger streams and coastal plain. The occurrence of liquefaction on loose sand deposits of the Merapi Volcano is shown in Figure 2.

One of the geological structures developed in Bantul is a strike slip fault known as the Opak Fault in southeast-northwest direction of approximately N 235° E/80°, where the east block relatively moves towards the north and the west block towards the south (Figure 2). The width of the fault zone is estimated to 2.5 km. Another fault zone is recognized to the north east- south east of N 325° E/70° towards the Gantiwarno Area (Sarah and Soebowo, 2013).

Methods

Field investigation including the geotechnical drilling at five locations with a maximum depth of 22.5 m with SPT at intervals of 1.5 m, CPT test at six points with a maximum depth of 17 m, and DMT test on nine points with maximum depth of 10 m are scattered around the study area. In this paper, DMT data were used to identify liquefaction susceptibility hazard. DMT apparatuses

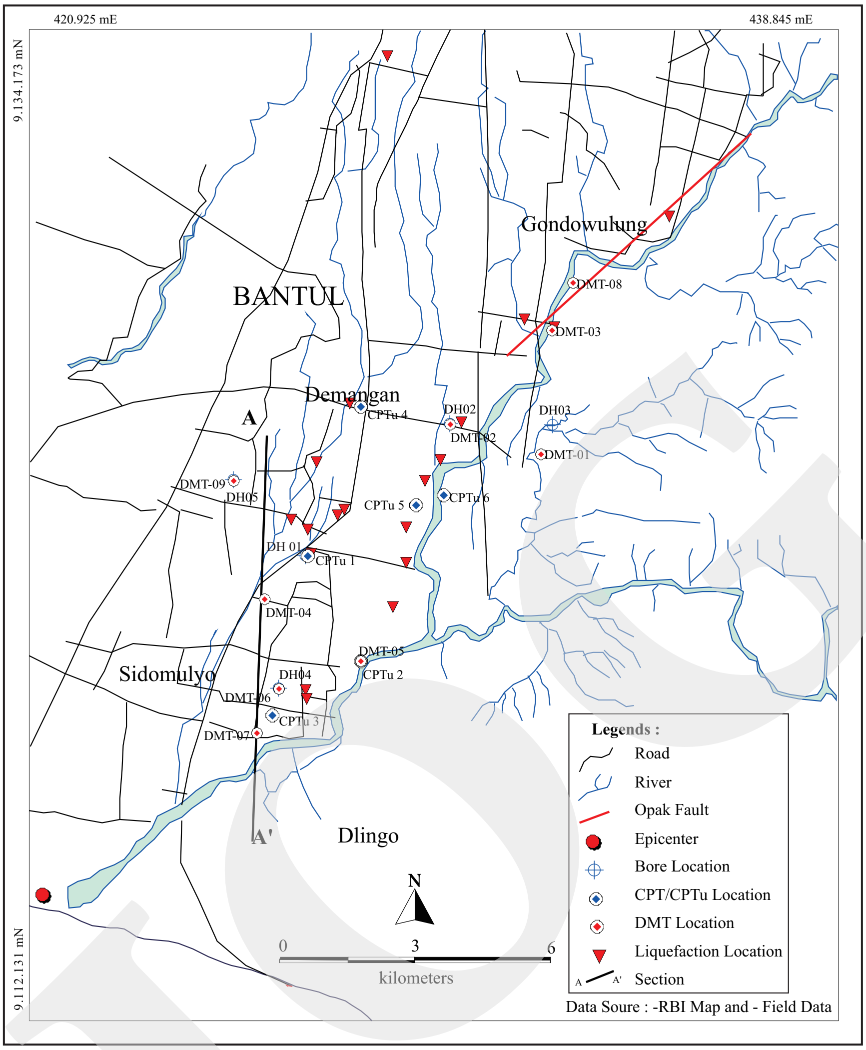

Figure 1. Locality map of research area.

consist of a steel blade having a thin, expandable, circular steel membrane mounted on one face. The blade is connected, by an electro-pneumatic tube, running through the insertion rods, to a control unit on the surface. The test starts by inserting the dilatometer into the ground. By using a control unit with a pressure regulator, a gauge and audio signals, the operator determines, in about 1 minute, the p_o-pressure required to just begin to move the membrane and the p_1-pressure required to inflate its center by 1.1 mm into the soil. The blade is then advanced into the ground of one depth increment, typically 20 cm, using a basic principle of pressure value needed to make a thin membrane on the blade inflated by 1.1 mm from the center, and can be returned to the flat position with the blade (Figure 3).

K_D values obtained by using DMT test are described in the following equations :

$$K_D = (P_0 - U_0)/(\sigma^1 vo) \text{ ....(1)}$$

Where:

$$P_0 = 1.05(A - Z_M + \Delta A - 0.05(B - Z_M - \Delta B) \text{ .....(2)}$$

$$P_1 = B - Z_M - \Delta B \text{ ....(3)}$$

where K_D = horisontal stress index, p_o = correct first reading, p_1 = correct second reading, $Z_{M\,=}$ Gage reading when vented to atm. If ΔA and ΔB are measured with the same gage used for current readings A dan B, set $Z_M = 0$ (Z_M is compensated). $U_{o\,=}$ pre-insertion pore pressure and $\sigma^1_{vo\,=}$ pre-insertion overburden stress.

The cyclic stress ratio (CSR) value data will be proceeded with the data calculated by

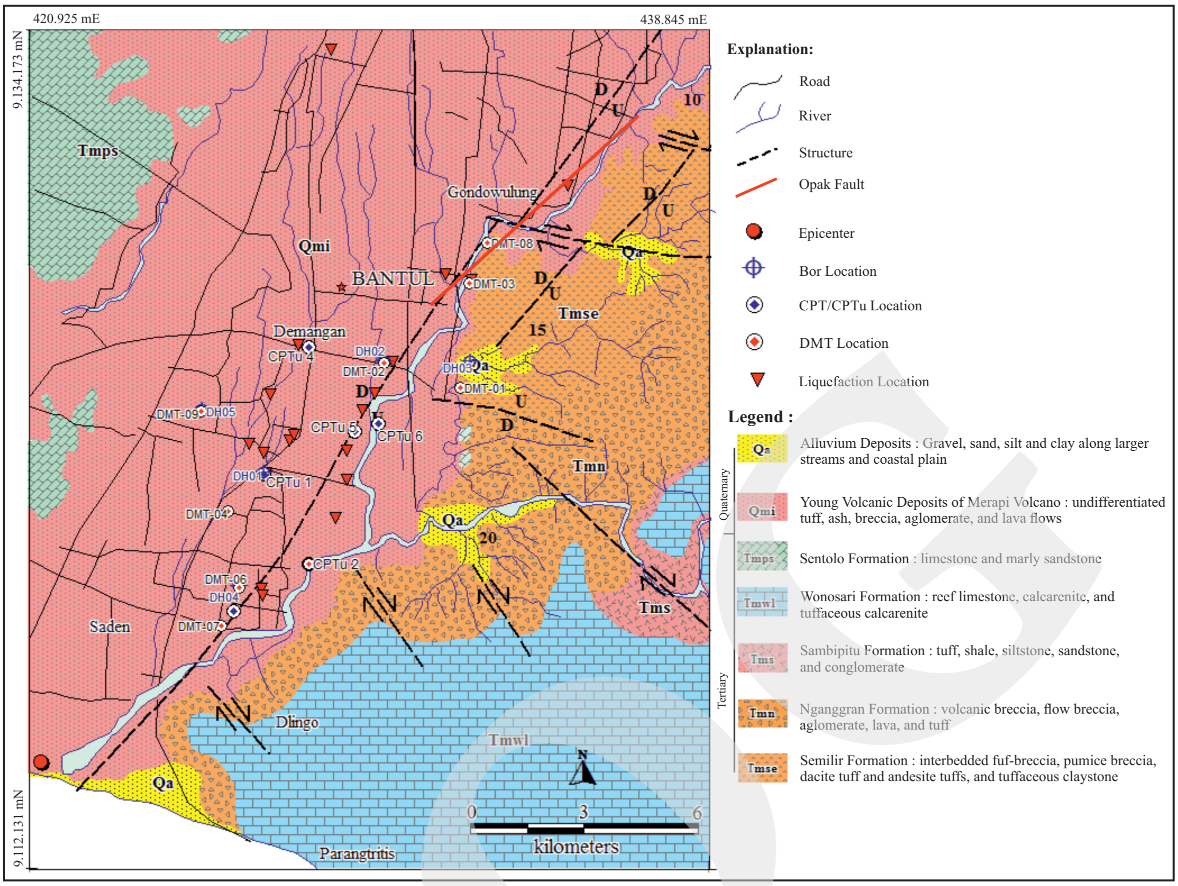

Figure 2. Geological map of Bantul region, Yogyakarta (modified from Rahardjo *et al*., 1995).

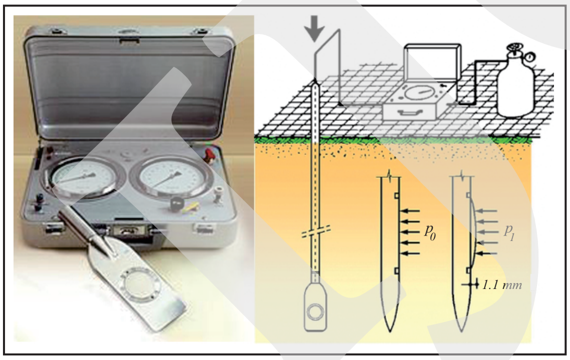

Figure 3. Apparatuses of DMT test.

software EZ-FRISK 7.52. Meanwhile, cyclic resistance ratio (CRR) will be calculated using K_D parameter. MSF (magnitude scaling factor) used in this study has a function to accommodate magnitude earthquake difference from previous chart of K_D and CRR correlation, *i.e* 7.5 Mw. Monaco *et al*. (2005) showed results that DMT can interpret CRR from relationship of K_D values.

The LSF (liquefaction safety factor) is the capacity of soil to resist liquefaction, that is the ratio between CRR and CSR. If CSR is greater than CRR so liquefaction can occur. The cyclic stress ratio (CSR) is calculated by the following equation (Seed and Idriss, 1971) :

$$LSF = \frac{CRR}{CSR} = \left(\frac{CRR_{7.5}}{CSR}\right) MSF \qquad \text{.........................(4)}$$

$$CSR = \frac{\tau_{average}}{\sigma' vo} = 0.65 \frac{a_{\max s}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} rd \qquad \text{......................(5)}$$

where *rd* is calculated using equation (6), and MSF is calculated using equation (7) or (8) , Following Idriss and Boulanger (2004), the factor *rd* in Equation 5. is calculated by equation 6:

$$rd = \exp\left[\left(-1.012-1.126\sin\left(\frac{z}{11.73}+5.133\right)\right) + \left(0.106+0.118\sin\left(\frac{z}{11.28}+5.142\right)\right)Mw\right] \qquad \text{.................(6)}$$

$$MSF = 6.9\exp\left(\frac{-\mathrm{Mw}}{4}\right) - 0.058 \qquad \text{........................(7)}$$

$MSF \leq 1.8$ ....(8)

CRR is calculated using equation (9) proposed by Monaco *et al*. (2005):

$$CRR = 0.0107K_D^3 - 0.0741K_D^2 + 0.2169K_D - 0.1306 \quad ...(9)$$

where LSF = liquefaction safety factor, CSR = The cyclic stress ratio, CRR = cyclic resistance ratio, *MSF* = the magnitude scaling factor, Mw = magnitude, K_D = horizontal stress index value, $\tau_{average}$ = average cyclic shear stress, a_{max} = peak horizontal acceleration at ground surface generated by the earthquake, g = acceleration of gravity, σ_{vo} and σ'_{vo} = total and effective overburden stress, and *rd* = stress reduction coefficient dependent stress on depth, generally in the range of ~ 0.8 to 1.

The result of calculated threshold K_D which susceptible to liquefaction will be compared with the K_D classification based on TC16 (2001) in Monaco *et al*. (2005), as shown in Table 1.

Site selection was based on the location from Kuepper (2006) which produced a peak acceleration in the bedrock similar to the peak acceleration at the bedrock in Indonesian Earthquake Hazard Map 2010 (Irsyam *et al*., 2010).

Table 1. K_D threshold Values against Liquefaction Susceptibility with Mw=7.5 (Monaco *et al*., 2005)

Area Criteria	PGA value (g)	K_D value
No Vulnerabilities	0,00	> 1,7
Low Seismicity	0,00 - 0,15	> 4,2
Medium Seismicity	> 0,15 - 0,25	> 5,0
High Seismicity	> 0,25 - 0,35	> 5,5
Very High Seismicity	> 0,35	N/A

Hypocentrum distance was obtained based on Bantul earthquake source to the DMT points. Attenuation equation of Boore-Atkinson *et al*. (2008) was used to obtain the spectral response of each point of DMT. The results of the calculation for each DMT location can be seen in Table 2. PGA on bedrock is developed from spectral matching of spectral response to time histories shown in Table 2.

Results and Discussion

Based on PGA value at bedrock and K_D value of each DMT location, CSR and CRR were calculated to obtain LSF and K_D threshold. Figure 4 shows the correlation between LSF and K_D threshold for each DMT location**.** Soil layers that are potentially susceptible to liquefaction have a total thickness of: 2.6 m, 2.0 m, 3.1 m, 2.0 m, 0.2 m, 1.9 m, 3.9 m, 3.5 m, and 1.8 m for DMT-01, DMT-02, DMT-03, DMT-04, DMT-05, DMT-06, DMT-07, DMT-08 and DMT-09, respectively (Table 3). The result of thickness liquefiable soil layers based on DMT data shows a good agreement with those of CPT data (Soebowo *et al*., 2009).

The threshold of K_D in each DMT location is summarized in Table 4. The liquefaction potential soil layers, for DMT-01, DMT-02, DMT-03, DMT-04, DMT-05, DMT-06, DMT-07, DMT-08, and

Table 2. Distance (R) of the Earthquake Hypocentrum and PGA at Bedrock of DMT Coordinates

Test Code	UTM Coordinates (49M)		R epicenter (Rjb)	h (depth)	R (hypocenter)	PGA
	X	Y	(km)	(km)	(km)	
DMT-01	432244	9124712	14.8	17	22.6	0.24
DMT-02	430232	9125354	13.8	17	22	0.26
DMT-03	432478	9127454	16.9	17	24	0.22
DMT-04	426115	9121466	8.2	17	18.9	0.29
DMT-05	428258	9120088	9	17	19.2	0.28
DMT-06	426428	9119466	7	17	18.4	0.30
DMT-07	425944	9118482	6	17	18.1	0.33
DMT-08	432942	9128518	18	17	24.8	0.21
DMT-09	425414	9124098	10	17	19.9	0.27

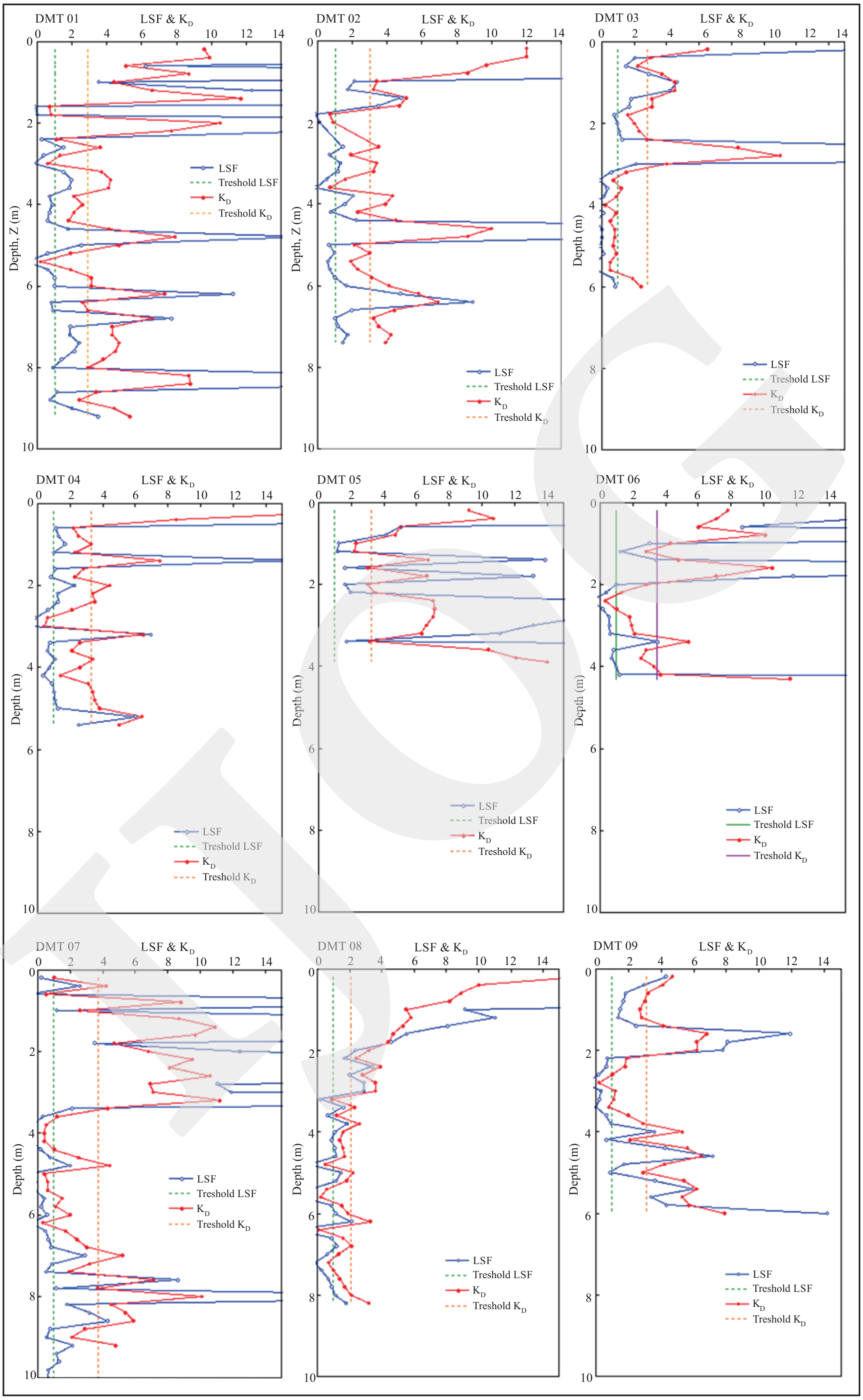

Figure 4. Horizontal stress index value (K_D) threshold of each test site.

Table 3. Results of DMT Data Processing Analysis at Layers that is Potentially Susceptible to Liquefaction

DMT	**DMT01**	**DMT02**	**DMT03**	**DMT04**	**DMT05**	**DMT06**	**DMT07**	**DMT08**	**DMT09**
Depth (m)	1.6-1.8 2.4-2.5 2.7-3.1 3.8-4.5 5.2-6.8 6.4-6.6 8.0-8.1 8.6-8.8	1.7-2.4 3.3-3.7 4.1-4.2 5.0-5.8	1.8-2.3 3.4-6.0	1.6-1.8 2.5-3.0 3.3-3.6	1.0-1.2	2.0-3.3 3.5-4.1	0.0-0.2 0.5-0.6 3.6-4.6 5.0-6.8 7.2-7.5 8.8-9.0 9.7-10.0	3.4-3.6 4.0-4.9 5.2-6.0 6.4-8.0	2.2-3.8 4.15-4.25 4.95-5.05
Total Thickness (m)	2.60	2.00	3.10	2.00	0.20	1.90	3.90	3.50	1.80
Total thickness (m) (Soebowo, 2009)	2.00-3.00	1.00-2.00	3.00-4.00	2.00-3.00	0.00-1.00	3.00-4.00	3.00-4.00	2.00-3.00	1.00-2.00

Table 4. Maximum Acceleration (PGA) at Bedrock of Bantul area with Mw = 6.2

Test Code	**UTM Coordinates (49M)** X	Y	**$R_{hypocenter}$ (km)**	**PGA at the bedrock**	**K_D Threshold Liquefaction Potential**
DMT01	432244	9124712	22.6	0.24	< 2.9
DMT02	430232	9125354	22	0.26	< 3.0
DMT03	432478	9127454	24	0.22	< 2.8
DMT04	426115	9121466	18.9	0.29	< 3.3
DMT05	428258	9120088	19.2	0.28	< 3.2
DMT06	426428	9119466	18.4	0.3	< 3.5
DMT07	425944	9118482	18.1	0.33	< 3.7
DMT08	432942	9128518	24.8	0.21	< 2.1
DMT09	425414	9124098	19.9	0.27	< 3.1

DMT-09 have K_D threshold liquefaction potential value as follows : < 2.9 m, <3.0 m, < 2.8 m, < 3.3 m, < 3.2 m, < 3.5 m, < 3.7 m, < 2.1 m and < 3.1 m, respectively (Table 4). Threshold of K_D value for the highest PGA is 3.7 for the acceleration of 0.33 g at DMT-07, on other hand, K_D value for the lowest PGA, is 2.1 for the acceleration of 0.21 g at DMT-08. It can be concluded that higher PGA makes higher K_D threshold value for liquefaction susceptibility. Based on Table 1 (Monaco *et al.*, 2005), all of DMT locations fall into a medium- to high seismicity area. However, K_D thresholds are in the range of 2.1 to 3.7 because of the earthquake magnitude is lower than Monaco's classification.

Subsurface geological cross sections presented in Figure 5 shows that the subsurface

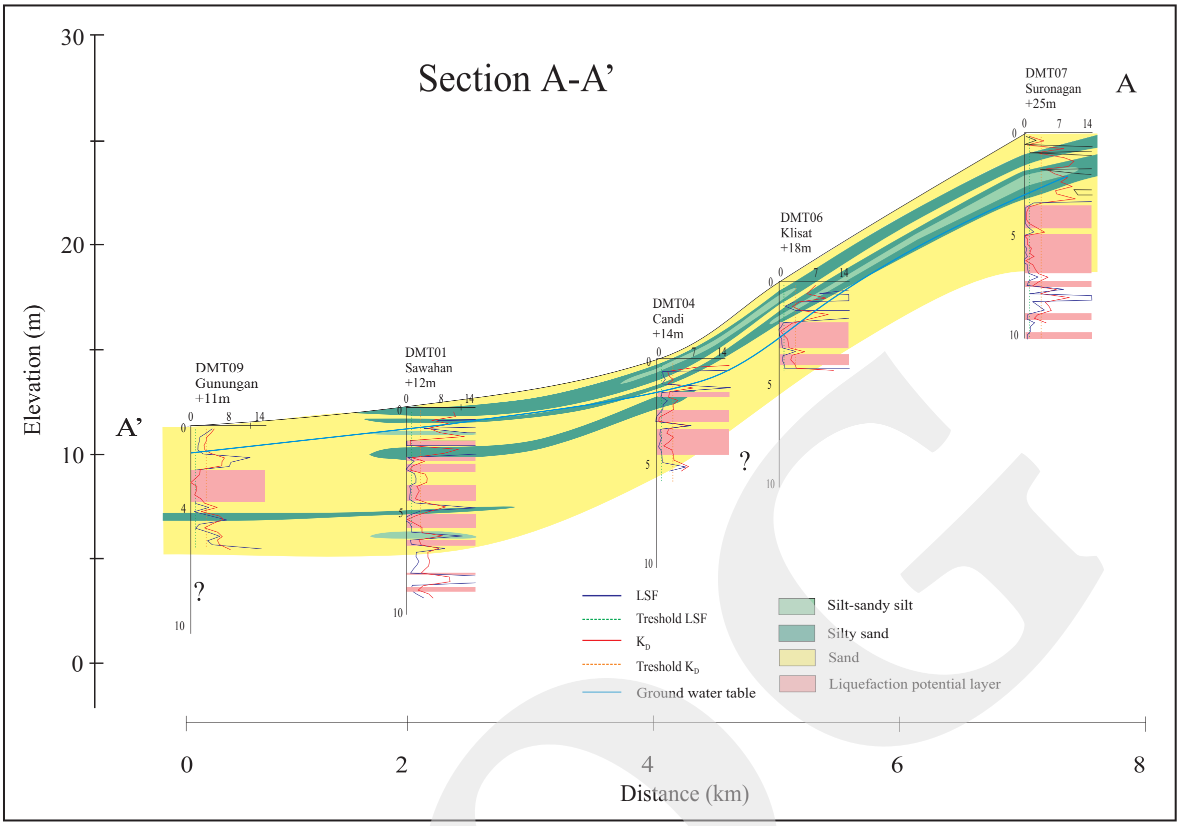

Figure 5. DMT log correlation with the type of soil liquefaction potential zone.

conditions are alluvium deposits consisting of silt, sandy silt, silty sand, and sand layers. Repetition of this layer shows that this area is subjected to a repeated sedimentation process, such as soft to dense sand layer with discontinued silt and silt layers which makes wedge formation at some places. Based on the parameter of material type indexes, liquefaction safety factor, and K_D values, liquefaction potential zones are obtained. It is clear that the potential for liquefaction occurs predominantly in sandy soil layers.

Conclusions

Based on the DMT-based liquefaction analysis, the thicknesses of liquefiable soil layers in Bantul, Yogyakarta for the following DMT locations: DMT-01, DMT-02, DMT-03, DMT-04, DMT-05, DMT-06, DMT-07, DMT-08, and DMT-09 are 2.6 m, 2.0 m, 3.1 m, 2.0 m, 0.2 m, 1.9 m, 3.9 m, 3.5 m and 1.8 m, respectively. In this study, all DMT locations fall into a medium to high seismicity. K_D threshold for Mw=6.2 ranges from 2.1 to 3.7 for the range of PGA values from 0.21 to 0.33g.

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