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

KHORI SUGIANTI, ANGGUN MAYANG SARI, and ARIFAN JAYA SYAHBANA

Research Centre for Geotechnology LIPI, Kompleks LIPI, Jln. Sangkuriang, Bandung

Corresponding author: khorisugianti@gmail.com

Manuscript received: October 8, 2014, revised: January 12, 2015, approved: April 29, 2015.

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

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 Aluvial 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...
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 \( p_0 \)-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).

\[
K_D = \left( \frac{p_0 - U_0}{\sigma'_{vo}} \right) \quad \text{.........................(1)}
\]

Where:

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

\[
P_1 = B - Z_M - \Delta B \quad \text{.............................................(3)}
\]

where \( K_D \) = horisontal stress index, \( p_0 = \) correct first reading, \( p_1 = \) correct second reading, \( Z_M = \) Gage reading when vented to atm. If \( \Delta A \) and \( \Delta B \) are measured with the same gage used for current readings A dan B, set \( Z_M = 0 \) (\( Z_M \) is compensated).

\( U_0 = \) pre-insertion pore pressure and \( \sigma'_{vo} = \) pre-insertion overburden stress.

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

$$ \text{LSF} = \frac{\text{CRR}}{\text{CSR}} = \left( \frac{\text{CRR}}{\text{CSR}} \right)^{\text{MSF}} \quad \text{......................}(4) $$

$$ \text{CSR} = \frac{\tau_{\text{ave}}}{\sigma_{\text{vo}}} = 0.65 \frac{\sigma_{\text{max}}}{g} \sigma_{\text{vo}} \quad \text{rd} \quad \text{......................}(5) $$

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:

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

$$ \text{MSF} = 6.9 \exp \left( -\frac{\text{Mw}}{4} \right) - 0.058 \quad \text{......................}(7) $$
DMT Method Approach for Liquefaction Hazard Vulnerability Mapping in Bantul Regency, Yogyakarta Province, Indonesia (K. Sugianti et al.)

\[ MSF \leq 1.8 \] .................................(8)

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

\[ CRR = 0.0107K_d^3 - 0.0741K_d^2 + 0.2169K_d - 0.1306 \]  ...(9)

where LSF = liquefaction safety factor, CSR = The cyclic stress ratio, CRR = cyclic resistance ratio, \( MSF \) = the magnitude scaling factor, \( M_w \) = magnitude, \( K_d \) = horizontal stress index value, \( \tau_{av} \) = average cyclic shear stress, \( a_{max} \) = peak horizontal acceleration at ground surface generated by the earthquake, \( g \) = acceleration of gravity, \( \sigma_{vo} \) and \( \sigma'_{vo} \) = 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).

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

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### Table 1. \( K_d \) threshold Values against Liquefaction Susceptibility with \( M_w=7.5 \) (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             |

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

| Test Code | UTM Coordinates (49M) | R epicenter (Rjb) (km) | \( h \) (depth) (km) | R (hypocenter) (km) | PGA |
|-----------|------------------------|------------------------|---------------------|---------------------|-----|
| 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

| Test Code | UTM Coordinates (49M) | Hypocenter (km) | PGA at the bedrock | K_D Threshold Liquefaction Potential |
|-----------|------------------------|-----------------|--------------------|-------------------------------------|
| DMT01     | X = 432244, Y = 9124712| 22.6            | 0.24               | < 2.9                               |
| DMT02     | X = 430232, Y = 9125354| 22.0            | 0.26               | < 3.0                               |
| DMT03     | X = 432478, Y = 9127454| 24.0            | 0.22               | < 2.8                               |
| DMT04     | X = 426115, Y = 9121466| 18.9            | 0.29               | < 3.3                               |
| DMT05     | X = 428258, Y = 9120088| 19.2            | 0.28               | < 3.2                               |
| DMT06     | X = 426428, Y = 9119466| 18.4            | 0.32               | < 3.5                               |
| DMT07     | X = 425944, Y = 9118482| 18.1            | 0.33               | < 3.7                               |
| DMT08     | X = 432942, Y = 9128518| 24.8            | 0.21               | < 2.1                               |
| DMT09     | X = 425414, Y = 9124098| 19.9            | 0.27               | < 3.1                               |

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

| Test Code | UTM Coordinates (49M) | Hypocenter (km) | PGA at the bedrock | K_D Threshold Liquefaction Potential |
|-----------|------------------------|-----------------|--------------------|-------------------------------------|
| DMT01     | X = 432244, Y = 9124712| 22.6            | 0.24               | < 2.9                               |
| DMT02     | X = 430232, Y = 9125354| 22.0            | 0.26               | < 3.0                               |
| DMT03     | X = 432478, Y = 9127454| 24.0            | 0.22               | < 2.8                               |
| DMT04     | X = 426115, Y = 9121466| 18.9            | 0.29               | < 3.3                               |
| DMT05     | X = 428258, Y = 9120088| 19.2            | 0.28               | < 3.2                               |
| DMT06     | X = 426428, Y = 9119466| 18.4            | 0.32               | < 3.5                               |
| DMT07     | X = 425944, Y = 9118482| 18.1            | 0.33               | < 3.7                               |
| DMT08     | X = 432942, Y = 9128518| 24.8            | 0.21               | < 2.1                               |
| DMT09     | X = 425414, Y = 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...
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 $M_w=6.2$ ranges from 2.1 to 3.7 for the range of PGA values from 0.21 to 0.33g.

**Acknowledgements**

The authors would like to thank the editor of Indonesian Journal on Geoscience who has offered an opportunity for authors to publish this manuscript. Thank to Dr. Adrin Tohari who helped to discuss about idea in this research. Thanks to research team who helped in data collection and preparing thin section at the laboratory.

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