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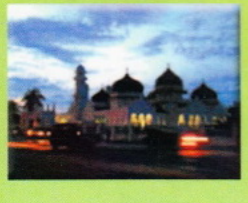

Evaluation of Peak Ground Acceleration Using CPT Data for Liquefaction Potential

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Abstract- The Universitas Muhammadiyah Yogyakarta (UMY) campus was constructed on 28 hectare which mostly rested on a sand deposit. The ground water table was shallow. Theoretically, the site was susceptible to liquefaction during ground-shaking. During earthquake on May 27, 2006, a magnitude 6.3 shocked the provinces of Yogyakarta, among those number of seismic damages were reported. The damages were identified because of liquefaction phenomena during the ground vibration. Reconnaissance study after the earthquake was found some sand boiling sites near the Masjid and Library building. This paper presents a liquefaction evaluation at those two building. The liquefaction analysis based upon force equilibrium concept can not be directly performed in this study, because there are no accelerometers in the hazard areas in this earthquake. Therefore, the accelerations back-calculated by liquefaction analysis are recommended in this article. The analysis was calculated using 475 cone penetration test (CPT) data that collected from 18 testing sites. By using the CPT data and the estimated cyclic stress ratio from Robertson & Campanella (1985), the critical accelerations from 0.23 g to 0.93 g will generate liquefactions in all depth, loose sand layers in hazard areas. In addition, the accelerations from 0.23g to 0.54g will make 50% of top sand layer liquefied. In general, the estimated ground acceleration of 0.36 g to 0.68 g was sufficient to generate liquefaction at the observed hazard area.

Keyword: liquefaction, earthquake intensity, ground acceleration, CPT, loose sand, Yogyakarta.

I. INTRODUCTION

Indonesian was known as archipelago nation that was laid on tectonic and volcanic activities. The Indonesia islands are at the south edge of Eurasian Plate. They are north to the Australian Plate and west to the Philippine Sea Plate. Many faults exist due to the north-east movement of Australian Plate associated with the west-north movement of Philippine Sea Plate. The tectonic setting of the region is dominated by the subduction of the Indo-Australian plate under the Eurasian plate, which causes large deep earthquakes mainly north of Java. It is then one of the seismic sources in this area. High frictional stresses also cause medium earthquakes on the over-riding plate that are observed often within and to the south of the Island. The megathrust region to the west-north west of Java has also caused colossal earthquakes. Therefore, the study region is subjected to three potential earthquakes, medium, large and massive. Return periods cannot be constrained but the region is certainly subjected to high to very high seismic hazard. Many historical and instrumental earthquakes have been previously recorded in the region, both off- and onshore.

Geology of the Yogyakarta area are mostly covered by quaternary young volcanic deposit of Merapi Volcano. These young volcanic deposits are composed of tuff, ash, breccia agglomerate and lava flows [1]. The weathered breccia and loose tuff were the main deposits exposed at most areas. This may have caused some areas in Yogyakarta and its vicinity to geotechnical hazards. Bantul region is precisely situated in a quake's vulnerable path of Opak Fault. This fault is one of the very important geological structures of Java Island, due to which the earthquake relative displacement occurred and from which the seismic waves emanated. Some fault plane solutions point towards a left-lateral strike-slip mechanism. The estimated fault rupture dimensions are 20 km long by 10 km wide. The earthquake of M_w6.3 shaking on May 27, 2006 was captured by a number of seismographs that had certain deficiencies leading to a highly unreliable set of records. The duration of shaking of 60 seconds is unusually long, given the earthquake magnitude.

Fig. 1 Lateral spreading and differential settlement at Main Library building.

Extensive damage to houses concentrated in lowland areas, attempts were made in the present survey to reveal the soft soil conditions in these areas as well as possible effects of liquefaction. Sand boiling evidences was reported by some witnesses. The Universitas Muhammadiyah Yogyakarta is located in 28 hectare loose sand deposit and very shallow ground water table. Theoretically, the area was susceptible to liquefaction hazard. However, the effect was minimal so there was no severe damage for building. Lateral spreading and differential settlement was observed at Main Library building during the seismic vibration (Fig. 1). It is significant to study liquefaction potential in the hazard area to have an understanding about hazard risk and reduction. This paper presents the analysis of liquefaction potential based on cone penetration (CPT) data. The analysis was aimed to evaluate the acceptable peak ground acceleration (PGA) for liquefaction if the data from accelerometer was not available.

II. Method of Analysis

Based on the CPT site investigation report, the campus of UMY is covered by 8 m to 10 m thick sandy soil layers. Loose sand layer generally appears at the depth from 3 m to 10 m. The ground water table is at the depth of 0.5 m to 1.0 m. The particle size distribution curves of sites are presented in Figure 2. The average particle diameter D_{50} of the soil at Masjid building range from 0.07 mm to 0.57 mm (the mean and variance was 0.26 mm and 0.025 mm, respectively), and at Library building, the range of D_{50} was between 0.057 mm – 0.841 mm (the mean and variance value was 0.57 mm and 0.054 mm, respectively). Comparing with curves from other researches [2], i.e. Seed and Idriss (1957), Lee and Fitton (1968) and Kishida (1969), it is obvious that the sandy soils in UMY area fall in the range of sands with high liquefaction potential.

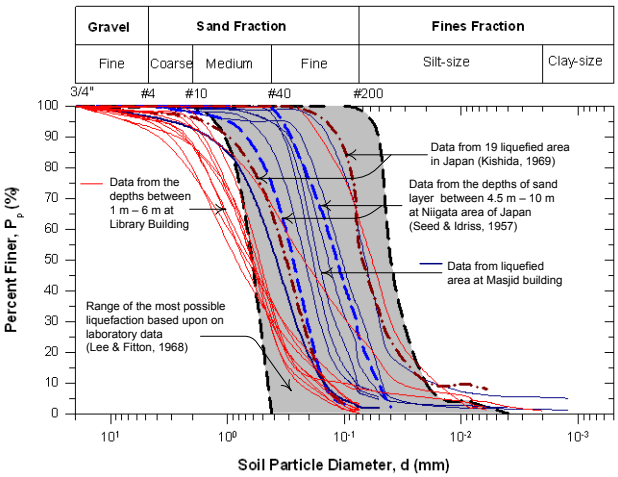

Fig. 2 Particle size distribution curve of the liquefied area.

A. Liquefaction Prediction

Calculation, or estimation, of two variables is required for evaluation of liquefaction resistance of soils: (1) the seismic demand on a soil layer, expressed in terms of cyclic stress ratio (CSR) to generate liquefaction; and (2) the capacity of the soil to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR). The approach requires an estimate of the CSR profile caused by a design earthquake. A simplified method to estimate CSR was also developed by Seed and Idriss [2] based on the peak ground surface acceleration (a_{max}) at the site. This simplified approach can be summarized as follows:

$$CSR = \frac{\tau_{av}}{\sigma'_{vo}} = 0,65\left(\frac{a_{\max}}{g}\right)\cdot\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)\cdot r_d \qquad (1)$$

where τ_{av} is the average cyclic shear stress; a_{max} is the maximum horizontal acceleration at the ground surface; g = 9.81 m/s^2 is the acceleration due to gravity; σ_{vo} and σ'_{vo} are the total and effective vertical overburden stresses, respectively; and r_d is a stress-reduction factor which is dependent on depth. The factor r_d can be estimating using the following bi-linear function, which provides a good fit to the average of the suggested range in r_d originally proposed by Seed and Idriss [2], that is

$$r_d = \begin{cases} 1-0,00765z & ;\text{ if } z<9,15 \text{ m} \\ 1,174-0,0267z & ;\text{ if } 9,15 \le z \le 23 \text{ m} \end{cases} \qquad (2)$$

By using the CPT data, the estimated CRR was calculated from Robertson and Campanella [3]. The flow-chart for calculation is shown in Fig. 3.

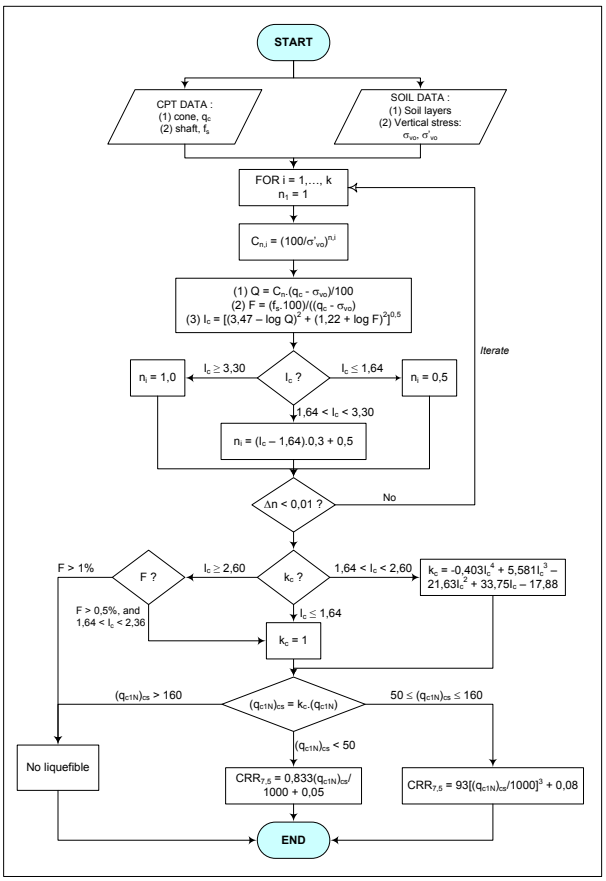

Fig. 3 CRR estimation from CPT (Modified after [3]).

The result of the calculated CRR based upon the flow chart, for the instance at SB1 point of Library area, is shown in Fig. 4.

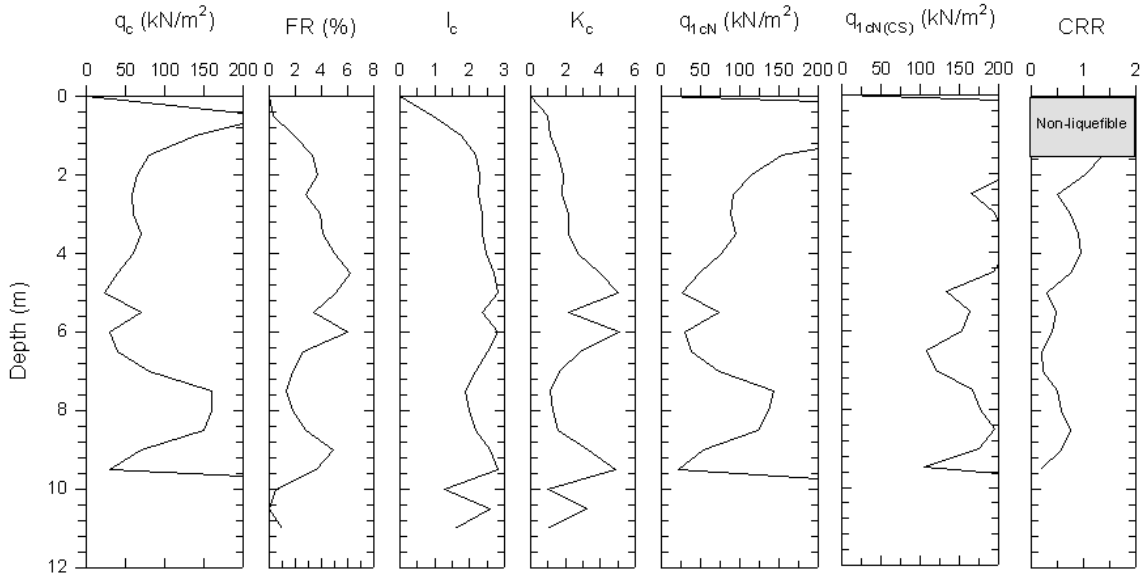

Fig. 4 CPT method for estimating cyclic resistance ratio (CRR) at point SB1 in Library area.

B. Estimation of Seismic Ground Response

Using the principle of force equilibrium, the factor of safely against liquefaction is de-fined as:

$$FS_L = \left(\frac{CRR_{7,5}}{CSR} \right) \cdot MSF \qquad (3)$$

where, where MSF is the Magnitude Scaling Factor to convert the $CRR_{7.5}$ for M = 7.5 to the equivalent CRR for the design earthquake. The recommended MSF are based on the NCEER Workshop in 1996 [4] :

$$MSF = \left(\frac{M_w}{7,5} \right)^{-2,56} \qquad (4)$$

The liquefaction analysis based upon force equilibrium concept can not be directly performed in this study, because accelerometers record was not available in the hazard areas in this earthquake. Therefore, the peak ground accelerations (PGA) or a_{max} were back-calculated using the CPT records at two sites Masjid and Main Library building. The analysis was computed from 475 CPT data that was collected from 18 test point. The a_{max} for given site was iterated numerically such that the FS_L = 1. The variation of the calculated a_{max} for both sites is shown in Fig. 5 and 6.

In this paper, the critical acceleration is defined as the minimum acceleration required causing liquefaction at a depth. One can see from the Fig. 4 that the smallest critical acceleration of Masjid area is 0.23g at the depth of 13 m. The largest critical acceleration is up to 0.9g at the top sand layer and depth up to 20 m. The mean value and deviation standard of all critical accelerations at Masjid area are 0.51 g and 0.16 g, respectively. The critical accelerations from 0.23g to 0.49g will generate liquefactions at the depth of 2.5 m to 15 m in Masjid and its vicinity areas. It indicates that the range of accelerations will make over 50% of top sand layer liquefied. For area in Library building (Fig. 6), the smallest a_{max} is 0.30g which is obtained at the depth of 9.5 m. The mean value and deviation standard of a_{max} is 0.54g and 0.15g respectively. Dense sand layer was found from the depth of 12 m to 13 m. The critical acceleration range from 0.30g to 0.54g will make the loose sand layer above the dense sand layer liquefy during ground shaking.

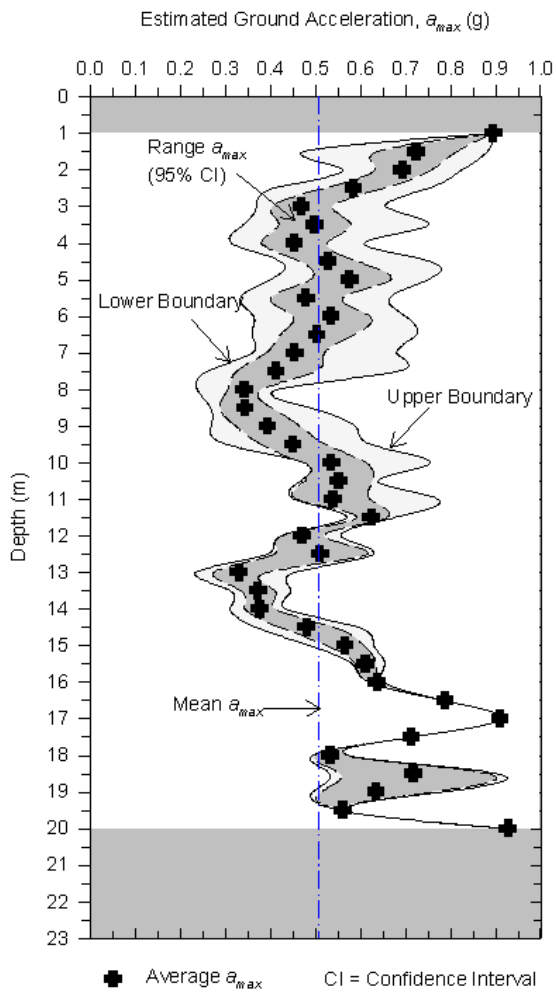

Fig. 5. The estimated PGA at Masjid area and its vicinity.

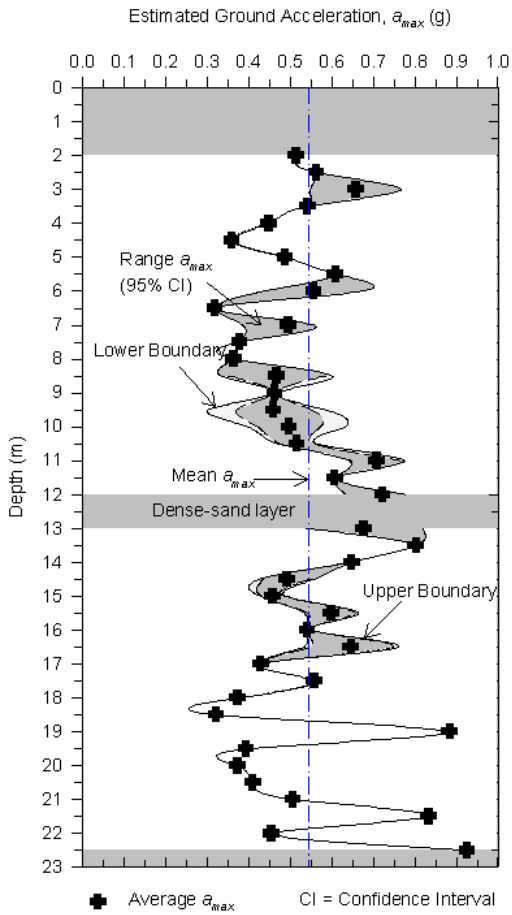

Fig. 6. The estimated PGA at near Library building

III. Discussion

The peak ground acceleration remains the most commonly used ground-motion parameter. In large part this is due to the fact that most earthquake-resistant design is based on the response spectrum of acceleration and PGA corresponds to the spectral ordinate at zero period [5].

The accelerometer data from the sites were not available. Hence, the vertical PGA was estimated from the measured data at BMG Station in Yogyakarta (YOG1 Station). Elnashai et al. [6] estimated for Bantul area that the vertical PGA ranges from 0.183g to 0.303g, and the horizontal PGA was 0.197g to 0.336g. These provide the best available estimates in the absence of more reliable data. It is noted that the PGA value in vicinity of the fault in Bantul area are significantly higher than elsewhere. The maximum PGA is about 0.49g and 0.47g at horizontal and vertical direction respectively. Comparing the results from CPT data, the mean of maximum acceleration at two-observed sites were 0.51g and 0.54g respectively at Masjid and Library area. Consider the deviation standard for each sites, that is mean value ± deviation standard, the maximum ground acceleration range between 0.35g – 0.67g at Masjid area, and 0.34g – 0.69g at Library area. Using the all CPT data from the both area, the mean value and deviation standard are 0.52g and 0.16g respectively. Generally speaking, the maximum ground acceleration at the observed area is between 0.36g – 0.68g. From the field reconnaissance observation, the seismic intensities of this earthquake are about VIII by Modified Mercalli Intensity (MMI) Scale of USA. Using the correlation given by Wald et al. [7], the corresponding PGA was about 0.3g to 0.7g (Fig. 7). Based on this study, the estimated PGA from the CPT is reasonable to be accepted for liquefaction potential analysis at sand deposit in UMY campus area and its vicinity.

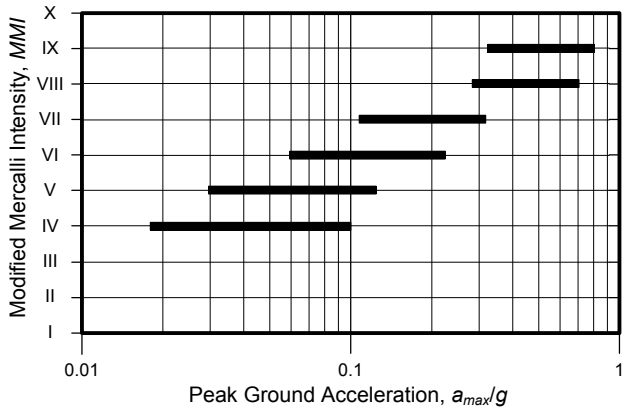

Fig. 7 Earthquake intensity and ground acceleration (Modified after [7]).

IV. Conclusions and Recommendations

Through the physical property test results of sand samples from sand boiling sites and spring wells, the depths of Yogyakarta sands with high liquefaction potential was found. Based upon the field reconnaissance data and back analysis results of liquefied site conditions, the accelerations of about 0.36g to 0.68 g were proposed most possible by this article. The critical accelerations from 0.23g to 0.54g will generate over fifty percents the top sand layer to liquefy during the ground shaking. The estimated PGA from the CPT is reasonable to be accepted for liquefaction potential analysis at sand deposit in UMY campus area and its vicinity.

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