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EXAMINATION OF EXISTING DMT-BASED LIQUEFACTION EVALUATION METHODS BY SIDE-BY-SIDE DMT AND CPT TESTS

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ABSTRACT

This study employed the field measurements of flat dilatometer test (DMT) and cone penetration test (CPT) presented by a recent study (Tsai et al. 2009) and additional DMT and CPT data conducted in this present study to examine the existing DMT-based liquefaction evaluation methods. Specifically, the DMT and CPT were conducted side-by-side at each of six in-situ sites and thus it is feasible to incorporate those test results into validating the existing DMT-based methods such as Grasso and Maugeri (2006), Monaco et al. (2005), and Rena and Chameau (1991). The DMT parameter, horizontal stress index (K_D), is used as an indicator for assessing liquefaction resistance of soils. The analysis results revealed that the existing K_D-based liquefaction evaluation methods would overestimate CRR of soils, which leads to overestimate the factor of safety against liquefaction. Also, the estimation of DMT-K_D values by using the CPT-q_c as well as the correlation between DMT-K_D and CPT-q_c proposed by the previous studies would be significantly less than field measurements of DMT-K_D. However, it should be noted that it is desirable to incorporate more field measurements to further verify this finding.

INTRODUCTION

A tremendous earthquake occurred near urban areas usually causes various severe disasters and enormous loss of life and economy. Of various disasters, part of earthquake-induced building damage resulted from liquefaction of soil. Figure 1 shows the liquefaction characteristics on the ground surface and liquefaction-induced building damage in the 1999 Chi-Chi earthquake located in central Taiwan. Based on the comprehensive investigation completed immediately after the 1999 Chi-Chi earthquake, the liquefaction of soils has been triggered in many areas located in various counties during the earthquake.

The earthquake-induced liquefaction has received much attention from the geotechnical engineer. At present, the SPT- and CPT-based methods for evaluating earthquake-induced liquefaction are commonly used in practical design. Over the past two decades, the flat dilatometer test (DMT) has been gradually adopted by the geotechnical engineer to investigate characteristics of in-situ soils, especially the lateral properties of soils. Although only few DMT-based methods for evaluating liquefaction resistance caused by earthquake have been developed, any improvement to the existing DMT-based methods for liquefaction resistance evaluation should be of interest to geotechnical engineers.

Fig. 1. Liquefaction phenomenon and induced damage in 1999 Chi-Chi earthquake

Essentially, DMT has the potential to be a useful tool for liquefaction evaluation. Before a large number of DMT data on liquefaction are available, it would be, intuitively, a feasible means to correlate the DMT data with CPT and/or SPT data for developing a DMT-based method for liquefaction evaluation. In fact, the existing DMT-based methods for evaluating liquefaction resistance such as Monaco et al. (2005) and Grasso and Maugeri (2006) were developed based on this point of view. A recent study conducted a series of side-by-side field DMT and CPT tests to develop a DMT-based method for liquefaction evaluation through directly correlation between the parameters of DMT and CPT (Tsai et al. 2009). In addition, Robertson (2009) attempted to correlate main DMT parameters with CPT parameters and evaluate the correlation using published records and existing links to various other parameters as well as comparison profiles

As shown in Fig. 2, the DMT-based CRR curves presented by Tsai et al. (2009) significantly differs from the ones suggested by the previous studies (Monaco et al. 2005; Grasso and Maugeri 2006). Such difference could confuse geotechnical engineers when selecting a DMT-based CRR curve to practically evaluate the liquefaction potential of soils. It would be desirable to further examine the applicability of the existing DMT-based CRR curves in the liquefaction evaluation. To this end, this study incorporated the side-by-side DMT and CPT data presented by Tsai et al. (2009) and conducted in this study to examine the existing DMT-based CRR curves.

DMT-BASED LIQUEFACTION ANALYSIS METHODS

The DMT-based methods for evaluating liquefaction resistance (CRR) include those by Marchetti (1982), Robertson and Campanella (1986), Reyna and Chameau (1991), Monaco et al. (2005), Grasso and Maugeri (2006), Monaco and Marchetti (2007), and Tsai et al. (2009). The more recent development of CRR curves by Monaco et al. (2005), Grasso and Maugeri (2006) and Tsai et al. (2009) are briefly introduced herein.

Monaco et al. (2005) proposed a CRR curve based on a study of the correlations between cone tip resistance (q_c) and relative density (D_r) and between DMT horizontal stress index (K_D) and D_r. Their DMT-based model is expressed as follows:

$$CRR_{7.5} = 0.0107K_D^3 - 0.0741K_D^2 + 0.2169K_D - 0.1306 \quad (1)$$

Specifically, the relationship between q_c and D_r proposed by Jamiolkowski et al., (1985) was adopted by Monaco et al. (2005) to formulate the CRR curve. This relationship is expressed as:

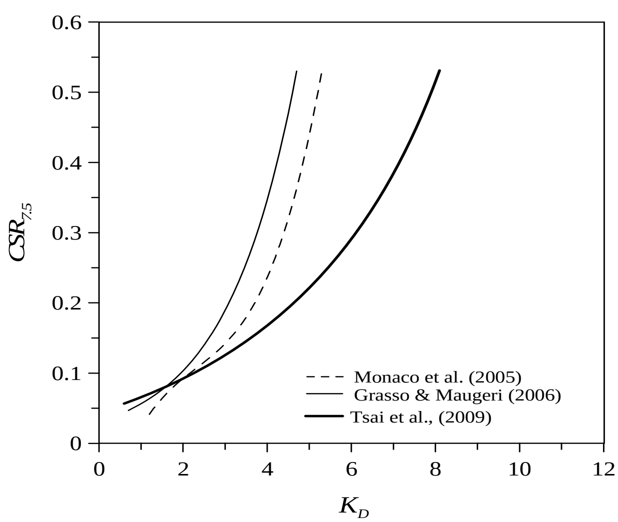


Fig. 2. Existing DMT-based CRR curves

$$q_c = C_0 \, . \, \exp(D_r \, . \, C_1) \, . \, (\sigma'_{v0})^{C2} \quad (2)$$

where D_r is relative density as fraction of unity; σ'_{v0} is effective overburden stress (kgf/cm^2); C_0, C_1, and C_2 is experimental coefficients (C_0=11.79; C_1=2.93; C_2=0.72). In addition, the relationship between K_D and D_r used by Monaco et al. (2005) can be referred to Fig. 3.

Grasso and Maugeri (2006) also followed the methodology to use relationships between q_c and D_r and between K_D and D_r to develop the CRR curve. They further updated the CRR model by Monaco et al. (2005) into:

$$CRR_{7.5} = 0.0308e^{0.6054K_D} \quad (3)$$

Where *e* denotes the void ratio of soil.

Tsai et al. (2009) employed results of in-situ tests to study the correlation between CPT-q_c and DMT-K_D rather than the conventional q_c–D_r–K_D and N–D_r–K_D relationships used in the development of existing DMT-based methods for evaluating the CRR. A total of five sites were selected to conduct the in-situ side-by-side CPT and DMT. The regression analysis was performed to directly establish the relationship between the corrected cone resistance ($q_{c1N,cs}$) and K_D, which can be expressed as:

$$q_{c1N,cs} = 0.4K_D^3 - 7.7K_D^2 + 56K_D - 20 \quad (4)$$

Once the $q_{c1N,cs}$-K_D relationship is available, the K_D-based CRR curve can be easily obtained by incorporating the existing CPT-based CRR curve. The CRR curve proposed by Tsai et al. (2009) is expressed as:

$$CRR_{7.5} = \exp[(K_D/8.8)^3 - (K_D/6.5)^2 + (K_D/2.5) - 3.1] \quad (5)$$

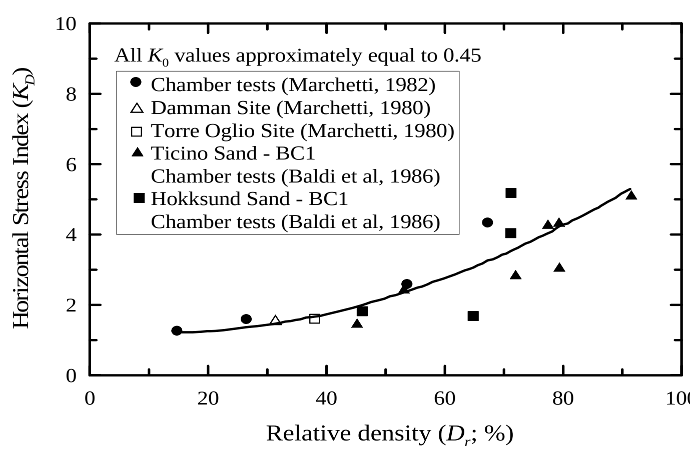
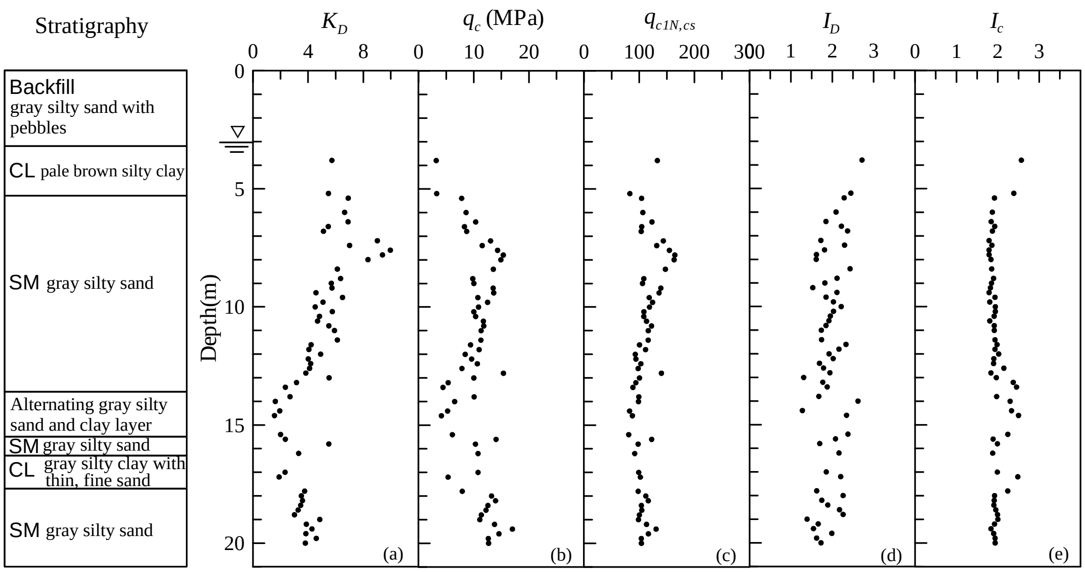


Fig. 3. Relationship between horizontal stress index (K_D) and relative density (D_r)

Note that the above K_D-based CRR curve presented by Tsai et al. (2009) was established based on the widely accepted SPT- and CPT-based CRR models and the correlations between various parameters (q_c-K_D and N-K_D). Detailed information can be referred to their paper.

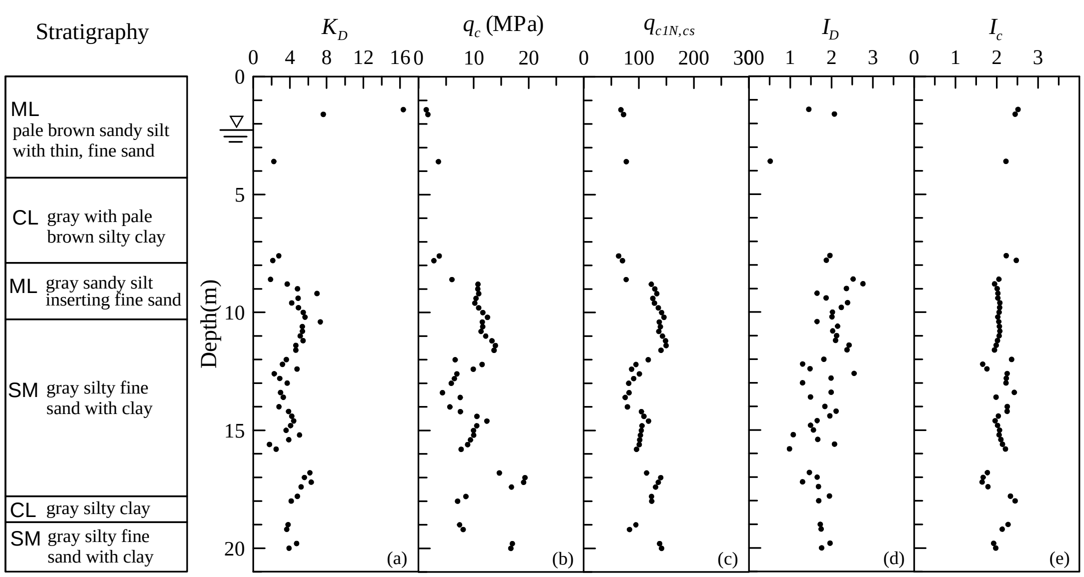
SIDE-BY-SIDE CPT AND DMT TESTS

Two types of in situ tests (CPT and DMT) were performed side by side at each of six sites in Tainan area of Taiwan. Of the six sites, five sites (site 1 to site 5) were performed by Tsai et al. (2009) and one site (site 6) was conducted in this study. Figures 4 through 9 shows the test results of DMT and CPT, including stratigraphy, horizontal stress index (K_D), cone tip resistance (q_c), clean-sand equivalence of normalized cone penetration resistance ($q_{c1N,cs}$), material index (I_D), and soil behavior type index (I_c). Of these parameters, K_D and I_D were calculated from DMT and others were obtained by CPT. For each of six sites, K_D and $q_{c1N,cs}$ of a soil at the same depth are available. As such, use of those data to examine the existing methods becomes feasible. Therefore, the test results were collectively employed to examine the difference of the existing DMT-K_D-based liquefaction evaluation methods between Monaco et al. (2005), Grasso and Maugeri (2006), and Tsai et al. (2009), as shown in Fig. 2.



Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 4. Results of CPT and DMT tests on site 1



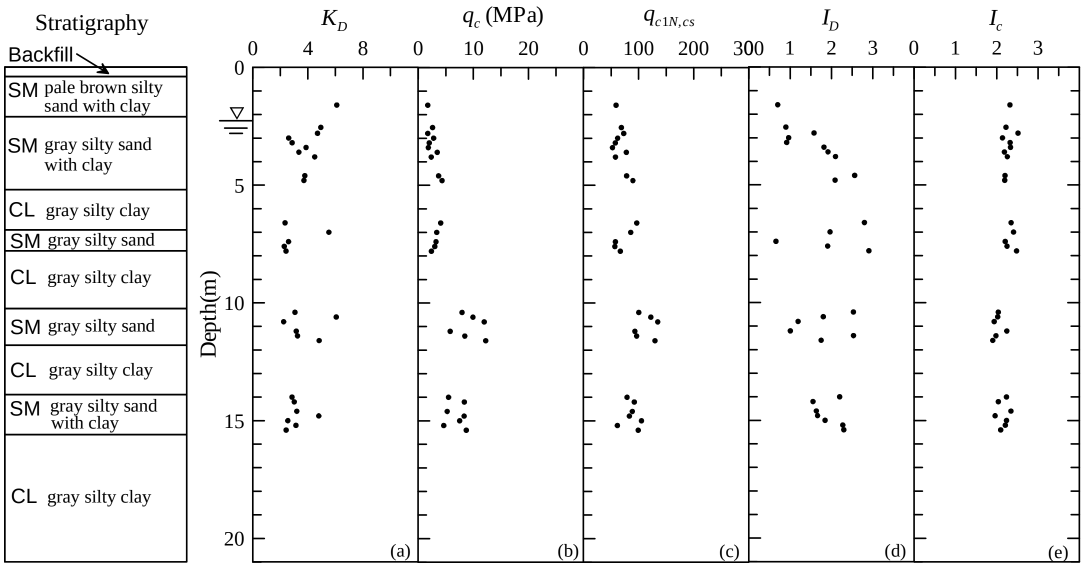
Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 5. Results of CPT and DMT tests on site 2

EXAMINING EXISTING DMT-K_D LIQUEFACTION EVALUATION METHODS

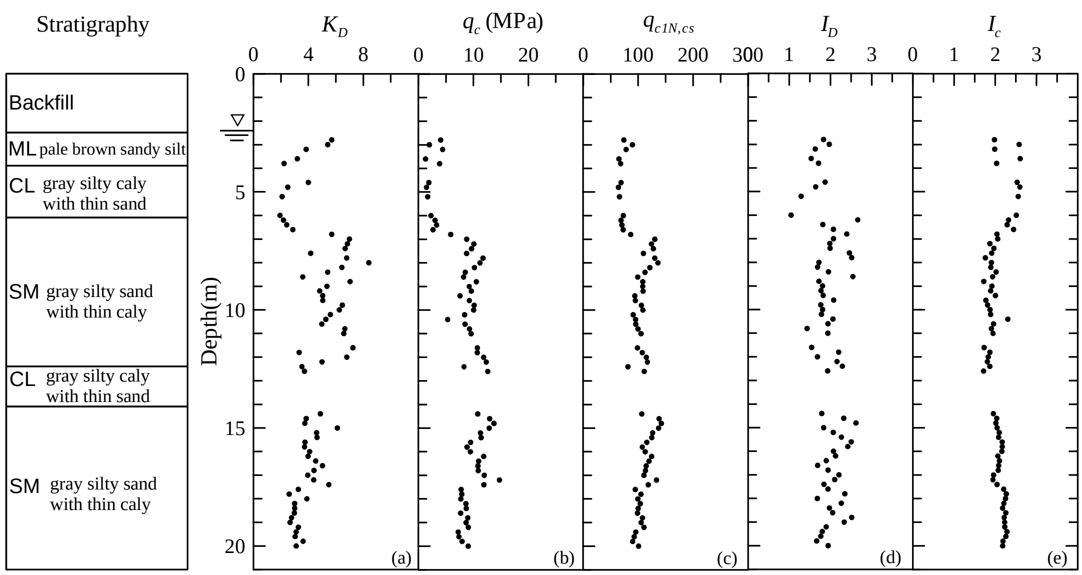
It should be emphasized that the SPT-based liquefaction evaluation methods are excluded in this study due to the fact that CPT and DMT can capture more complete characteristics of stratigraphy. As mentioned previously, all the existing DMT-K_D liquefaction evaluation methods (Monaco et al. 2005; Grasso and Maugeri 2006; Tsai et al. 2009) are developed based on the CPT- or SPT-based CRR as well as the correlation between DMT-K_D and CPT-q_c or between DMT-K_D and SPT-N. As a result, the goal to examine these existing DMT-K_D methods can be achieved through examining the correlation between CPT-q_c and DMT-K_D using the results of side-by-side DMT and CPT tests presented in this study.

Figures 10 through 15 compared K_D values measured by DMT with those computed from CPT-q_c values and q_c-K_D correlations. Note that only the data points of K_D measurements at depths of 0-20m are compared since the liquefaction potential of soil at larger depth is considered relatively low. As shown in Fig. 2, the method by Monaco et al. (2005) is not included in the comparison because the q_c-K_D correlation is not clearly given in their paper. Therefore, only the methods by Tsai et al. (2009) and Grasso and Maugeri (2006) are selected to further study the intended issue.



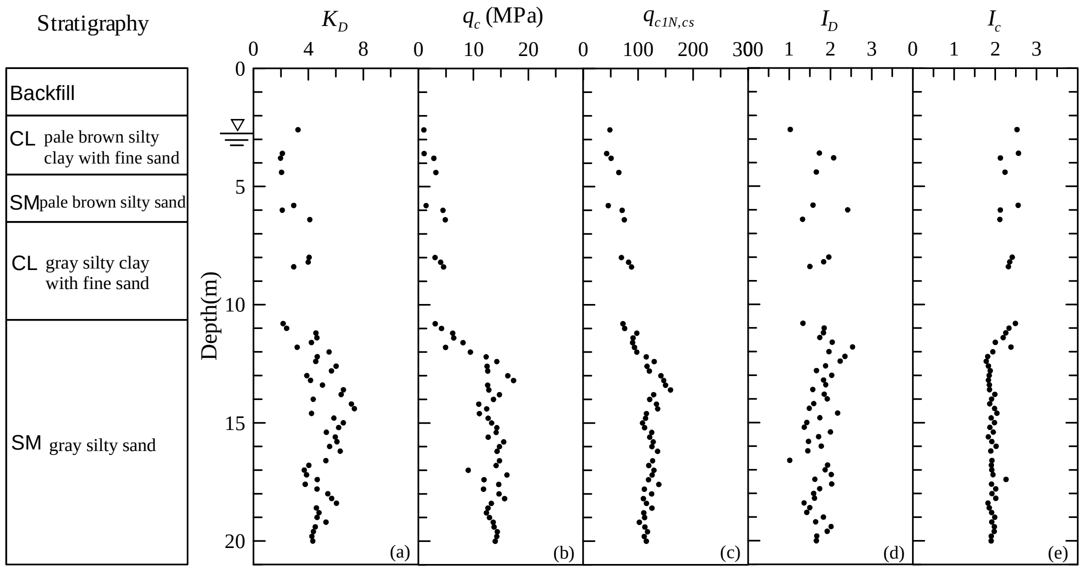
Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 6. Results of CPT and DMT tests on site 3



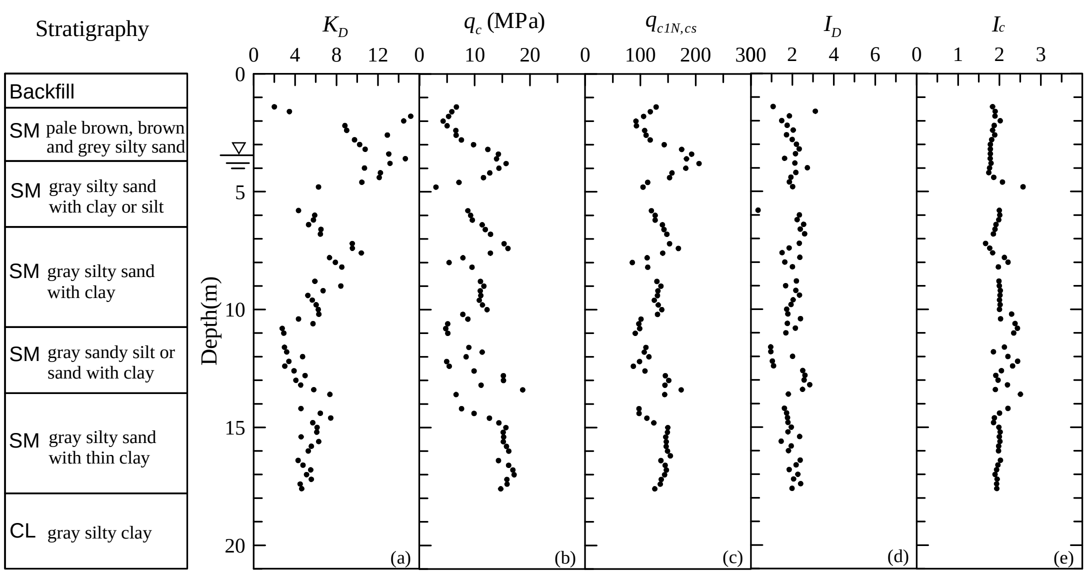
Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 7. Results of CPT and DMT tests on site 4



Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 8. Results of CPT and DMT tests on site 5



Note: Data points in (c) are calculated using Youd et al. (2001)

Fig. 9. Results of CPT and DMT tests on site 6

Figure 10 displays the comparison of K_D at depths within 0-20m on site 1. The black points represent the DMT-K_D measurements at various depths on this site. The dotted line denotes the DMT-K_D values estimated by Tsai et al. (2009) using equation 4, while the solid line represents the DMT-K_D values estimated by Grasso and Maugeri (2006) using equation 2 and Fig. 3. As shown in this figure, the values of K_D of the sandy layer (SM) at depths of 5.3-13.5m are significantly underestimated by Grasso and Maugeri (2006). The estimated K_D is even only equal to a half of the measured at depth of around 8m. The similar results can be obtained in a deeper sandy layer at depths of 15.5-16.5m.

Overall, the results reveal that the method by Tsai et al. (2009) can reasonably estimate the K_D measurements, while the K_D estimated by Grasso and Maugeri (2006) are significantly smaller than the measured. Generally, it is not surprising to learn that the performance of the method by Tsai et al. (2009) is satisfactory because their method was developed directly through regression analysis using the side-by-side CPT and DMT data of site 1 to site 5. Conversely, the performance of the method by Grasso and Maugeri (2006) reflects that much attention should be paid when employing their method to evaluate the liquefaction resistance of soil.

Figure 11 displays the comparison of K_D at depths within 0-20m on site 2. The K_D measured at shallow depths near ground surface obviously increases with the decrease of depth in this site. Both methods by Tsai et al. (2009) and Grasso and Maugeri (2006) can not capture this behavior. For the sandy layer at depths of 10.2-17.8m, the method by Tsai et al. (2009) would overestimates K_D at depths of 10-12m but the estimations at depth of 12-17.8m are satisfactory. The method by Grasso and Maugeri (2006) generally underestimates K_D at this sandy layer although the estimations at few depths are consistent to the measurements.

Figure 12 shows the comparison of K_D on site 3. Similarly, the behavior that K_D measured at shallow depths (0-4m) near ground surface raises with the decrease of depth on site 3 can not be simulated by the two methods. The difference in the accuracy of estimating K_D at various depths between the two methods is rather limited in this case. Generally speaking, the estimations of K_D by Tsai et al. (2009) are greater than those by Grasso and Maugeri (2006) at depths of 4-15m. This characteristic is similar to that obtained on site 1 and site 2.

Figure 13 displays the comparison of K_D at depths within 0-20m on site 4. Similar to sites 2 and 3, the trend that K_D increases with the decrease of depth can not be estimated by Tsai et al. (2009) and Grasso and Maugeri (2006). The measured K_D at depths of 7-9m and 14-18m can be accurately estimated by Tsai et al. (2009). For the depths of 9-12m, both methods obviously underestimate the measured K_D. The K_D estimated by Tsai et al. (2009) is generally greater than that estimated by Grasso and Maugeri (2006).

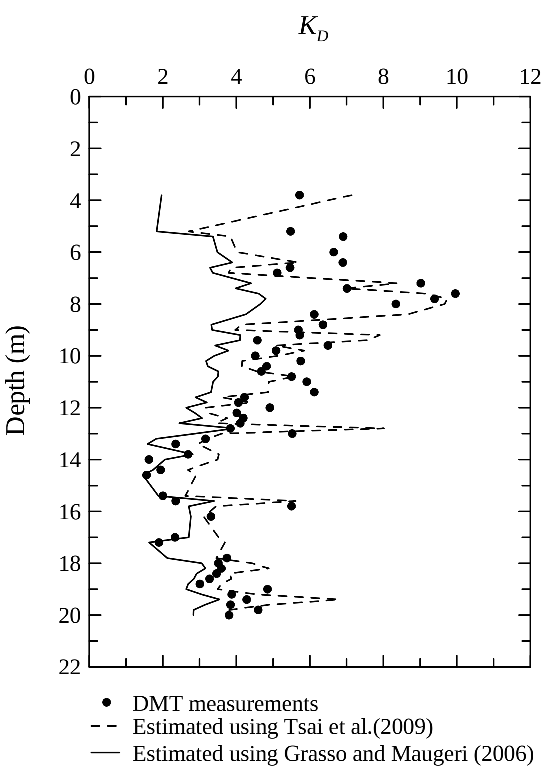


Fig. 10. Comparison of K_D estimated on site 1

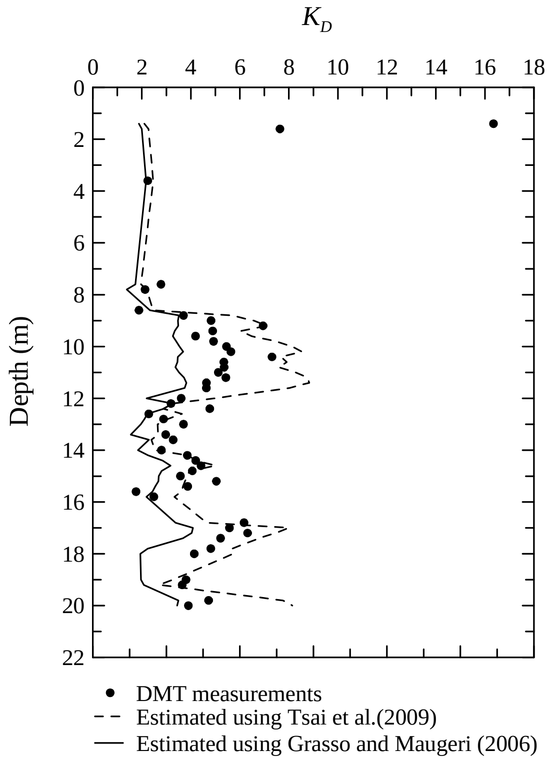


Fig. 11. Comparison of K_D estimated on site 2

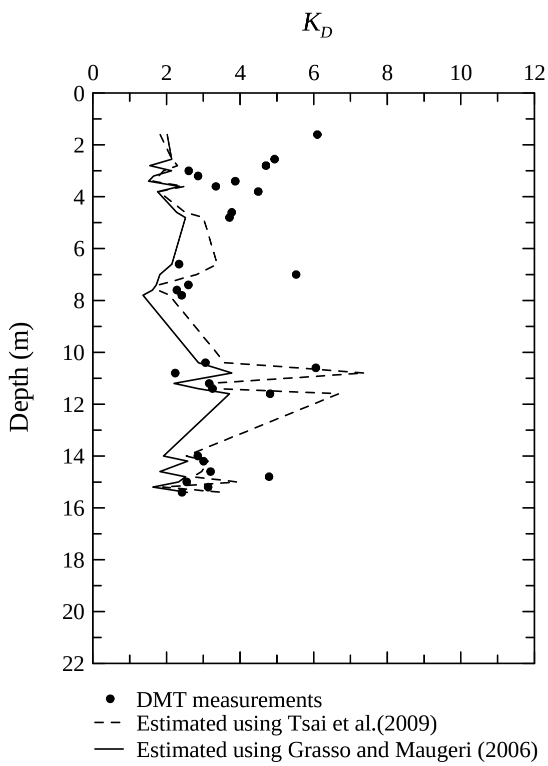


Fig. 12. Comparison of K_D estimated on site 3

The comparison of K_D on site 5 is shown in Fig. 14. The method by Grasso and Maugeri (2006) always underestimates the measured K_D in this case, irrespective of depth. As to the performance of the method by Tsai et al. (2009), the measured K_D is underestimated at shallow depths (2-10m) but can be adequately estimated at greater depths (10-20m).

Figure 15 exhibits the comparison of K_D at depths within 0-20m on site 6. Note that the method by Tsai et al. (2009) was developed based on the CPT and DMT data conducted on site 1 to site 5. That is, the testing data of site 6 are not incorporated into the development of their method. As shown in this figure, the performance of the method by Tsai et al. (2009) on estimating K_D through CPT-q_c is satisfactory. Specifically, the K_D can be reasonably estimated by Tsai et al. (2009) at various depths. Nevertheless, the K_D of sandy layers is significantly underestimated by Grasso and Maugeri (2006) at depths of 0-20m although the variation of K_D profiles estimated by Tsai et al. (2009) and Grasso and Maugeri (2006) with depth is resembling.

DISCUSSIONS

Robertson (2009) indicated that "Although the Cone Penetration Test (CPT) and flat-plat Dilatometer Test (DMT) have been used for over 30 years, relative little has been published regarding comprehensive correlations between the two in-situ tests." In fact, very few DMT-based liquefaction evaluation models have been published in the literature (e.g., Robertson and Campanella 1986; Reyna and Chameau 1991; Monaco et al. 2005; Grasso and Maugeri 2006; Tsai et al. 2009).

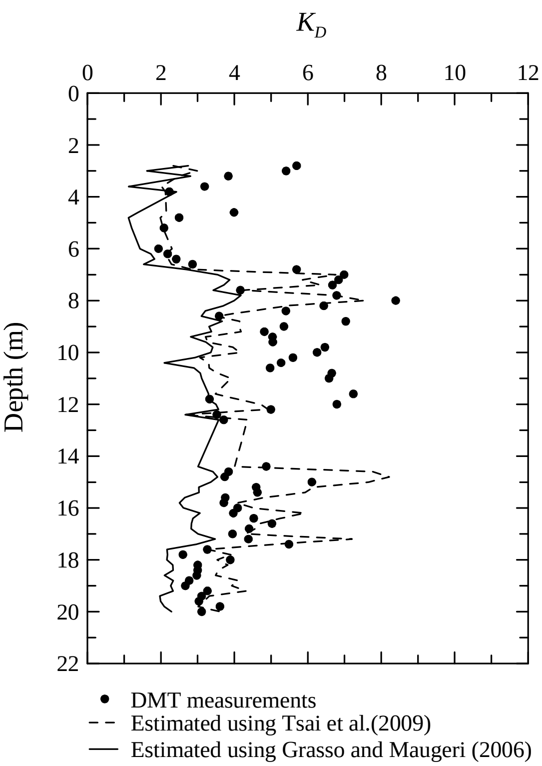


Fig. 13. Comparison of K_D estimated on site 4

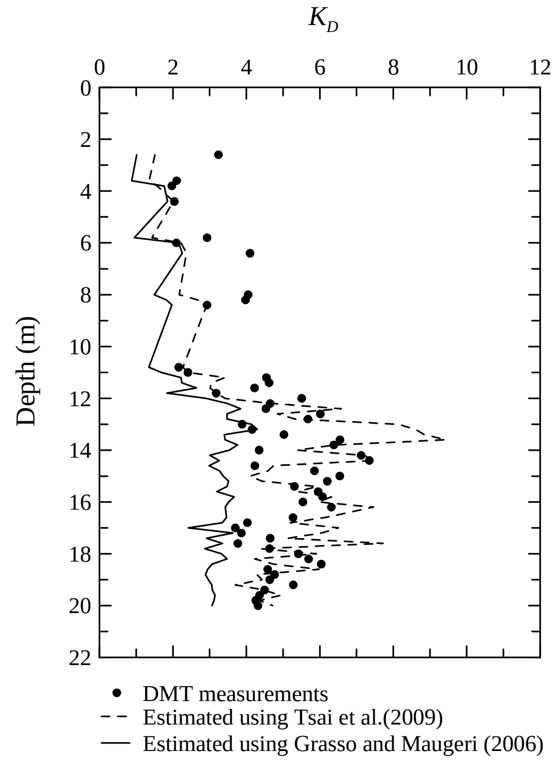


Fig. 14. Comparison of K_D estimated on site 5

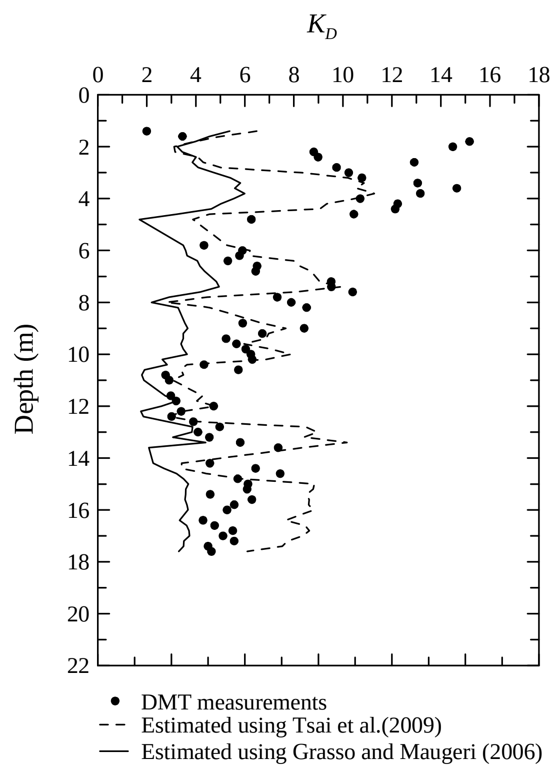


Fig. 15. Comparison of K_D estimated on site 6

The existing DMT-based liquefaction evaluation methods are developed based on the relationship of K_D-D_r-q_c or K_D-D_r-N except the method by Tsai et al. (2009), in which the K_D-q_c relationship is determined through the regression analysis of side-by-side DMT and CPT data. Note that the existing liquefaction evaluation methods (e.g., Reyna and Chameau 1991; Grasso and Maugeri 2006) developed by K_D-D_r-N relationship are not shown in Fig. 2. Basically, their CRR curves are very close to the ones proposed by Monaco et al. (2005) and Grasso and Maugeri (2006). As shown in Fig. 2, the difference between the CRR curve proposed by Tsai et al. (2009) and other existing ones is significant and would be of interest to engineers.

If the CRR curve proposed by Tsai et al. (2009) is correct, the CRR of soils at a certain K_D would be overestimated by other existing CRR equations, which means that the liquefaction potential of soil will be underestimated. As such, it is desirable to investigate this issue for further improving the DMT-based liquefaction evaluation methods. To this end, this paper employs side-by-side testing data of CPT and DMT to study the inconsistency between various methods. The analysis results reveal that, as shown in Figs. 10-15, the method by Grasso and Maugeri (2006) generally underestimates the measured K_D.

For further studying this behavior, all measured data points of K_D as well as those estimated by Tsai et al. (2009) and Grasso and Maugeri (2006) are collectively involved in Fig. 16. The linearly regressed results are also shown in this figure. The slope of the regressed straight line for the method by Tsai et al. (2009) is 0.92, while the slope for the Grasso and Maugeri (2006) is equal to 1.67, which is far away from the 1:1 perfect line. This result could be used to interpret the trend of CRR curves shown in Fig. 2. Based on the preliminary investigation of this study, adopting K_D-D_r-q_c relationship to correlate DMT-K_D with CPT-q_c could result in a significant bias, which causes the fact that the existing DMT-based liquefaction evaluation methods usually overestimate the CRR values of soils.

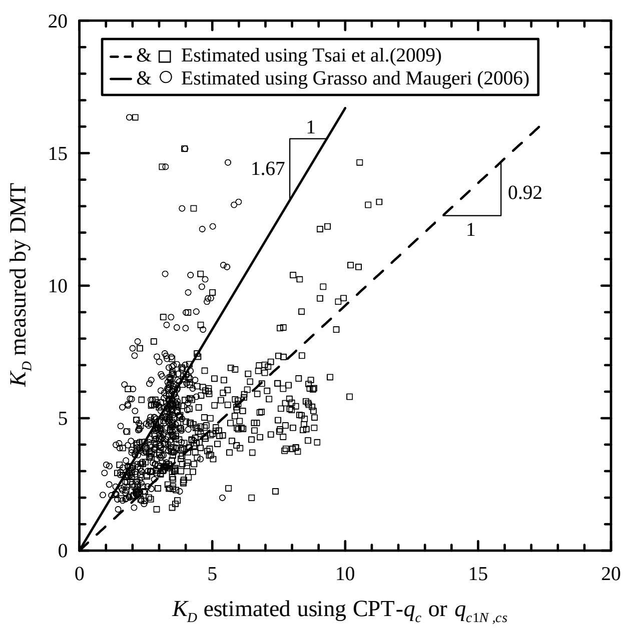


Fig. 16. Performance of various methods on estimating K_D

CONCLUSIONS

Although simplified methods based on SPT, CPT, and Vs are well established, use of DMT for liquefaction resistance evaluation has received a greater attention in recent years. The DMT is capable of measuring horizontal stresses and has an excellent operational repeatability. Thus, any improvement to the existing DMT-based methods for liquefaction resistance evaluation should be of interest to geotechnical engineers. This study collected and conducted the side-by-side DMT and CPT data for examining the existing DMT-based methods for evaluating liquefaction resistance of soils. The results reveal that the method recently developed by Tsai et al. (2009) can improve the bias of existing methods in estimating CRR. Such bias might result from use of D_r to correlate K_D with q_c. However, it is desirable to incorporate more data to calibrate this finding.

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