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Examination of DMT-based methods for evaluating the liquefaction potential of soils*

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Abstract: The flat dilatometer test (DMT) has the potential to be a useful tool in the evaluation of liquefaction potential of soils. In practice, it is necessary to carefully examine existing DMT-based methods for evaluating liquefaction potential. We conducted the DMT and cone penetration test (CPT) in high liquefaction potential areas to examine the existing DMT-based methods for liquefaction potential evaluation. Specifically, the DMT and CPT were conducted side-by-side at each of six in-situ sites, and thus it is feasible to utilize those test results to validate the existing DMT-based methods. The DMT parameter, horizontal stress index (K_D), is used as an indicator for estimating liquefaction resistance of soils in terms of cyclic resistance ratio (CRR). The analysis results revealed that the existing K_D-based liquefaction evaluation methods would overestimate the CRR of soils, which leads to overestimation of the factor of safety against liquefaction. Also, the estimations 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 smaller than field measurements. The results reflected that further validation of the existing DMT-based methods for liquefaction evaluation is desirable.

Key words: Liquefaction, Flat dilatometer test (DMT), Horizontal stress index, Earthquake
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1 Introduction

When an earthquake occurs near urban areas, part of earthquake-induced building damage results from liquefaction of soil. At present, the standard penetration test (SPT)- and cone penetration test (CPT)-based methods for evaluating earthquake-induced liquefaction are commonly used in practical designs. Over the past two decades, the flat dilatometer test (DMT) has been gradually adopted by geotechnical engineers to investigate characteristics of in-situ soils, especially the lateral properties of soils. As only a few DMT-based methods for evaluating liquefaction resistance caused by earthquake have been developed, improvements to the existing DMT-based methods for liquefaction resistance evaluation are of interest to geotechnical engineers.

Essentially, DMT has the potential to be a useful tool for liquefaction evaluation due to the convenience of testing and data post-processing. When a large number of DMT data are not available to develop a DMT-based method for liquefaction evaluation, it would be, intuitively, a feasible means to correlate the DMT data with CPT and/or SPT data for developing the intended method. In fact, some of 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 approach. A recent study involved a series of side-by-side field DMT and CPT tests to develop DMT-based methods for liquefaction evaluation

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through a direct correlation between the parameters of DMT and CPT (Tsai *et al.*, 2009). In addition, Robertson (2009) has correlated main DMT parameters with CPT parameters and evaluated the correlation using published records and existing links to various other parameters, as well as comparison profiles.

Fig. 1 shows that the DMT-based curve of cyclic resistance ratio (CRR) presented by Tsai *et al.* (2009) significantly differs from the ones proposed by Monaco *et al*. (2005) and Grasso and Maugeri (2006). This difference could confuse geotechnical engineers when attempting to select 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 for liquefaction evaluation. To this end, this study collected five sets of side-by-side DMT and CPT data presented by Tsai *et al.* (2009) and conducted another side-by-side test set to collectively examine the existing DMT-based CRR curves.

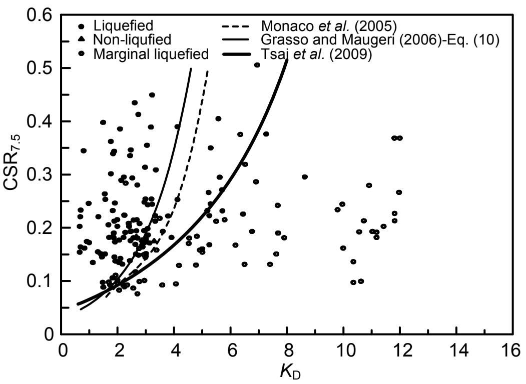

Fig. 1 Existing DMT-based CRR curves considered in this study

$CSR_{7.5}$: cyclic stress ratio at a magnitude of earthquake equal to 7.5

2 DMT-based liquefaction evaluation methods

The DMT-based methods for evaluating liquefaction resistance of soils in terms of CRR have been presented 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 recent development of CRR curves by Monaco *et al.* (2005), Grasso and Maugeri (2006), and Tsai *et al.* (2009) is briefly introduced herein.

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

$$\mathrm{CRR}_{7.5} = 0.0107K_D^3 - 0.0741K_D^2 + 0.2169K_D - 0.1306, \tag{1}$$

where $\mathrm{CRR}_{7.5}$ is the cyclic resistance ratio of soil at a magnitude of earthquake equal to 7.5.

Specifically, the relationship between q_c and D_r adopted by Monaco *et al*. (2005) to formulate the CRR curve may be the one proposed by Jamiolkowski *et al.* (1985a) or Jamiolkowski *et al.* (1985b). Monaco *et al.* (2005) did not clearly indicate which equation was adopted. Subsequently, Grasso and Maugeri (2006) followed the methodology adopted by Monaco *et al.* (2005), in which the relationships between q_c and D_r and between K_D and D_r were used to develop the CRR curve. Note that there were three CRR models proposed by Grasso and Maugeri (2006), of which, only the one developed based on the relationship between q_c and D_r proposed by Jamiolkowski *et al.* (1985b) was used in this study to compare the performance in evaluating the liquefaction potential of soils. The relationship between q_c and D_r proposed by Jamiolkowski *et al.* (1985b) is expressed as

$$q_c = C_0 \exp(D_r \times C_1)(\sigma'_{v0})^{C_2}, \tag{2}$$

where D_r is the relative density as fraction of unity; σ'_{v0} is the effective overburden stress (kg/cm^2); C_0, C_1, and C_2 are the experimental coefficients (C_0=11.79; C_1=2.93; C_2=0.72).

The CRR model presented by Grasso and Maugeri (2006) is expressed as

$$\mathrm{CRR}_{7.5} = 0.0308\mathrm{e}^{0.6054K_D}. \tag{3}$$

Note that Eq. (3) corresponds to Eq. (10) in Grasso and Maugeri (2006). Tsai *et al.* (2009) employed the results of in-situ tests to establish 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 by Monaco *et al.* (2005) and Grasso and Maugeri (2006) to develop the DMT-based method for evaluating the CRR. A total of six sites were selected to conduct the in-situ side-by-side CPT and DMT tests. The regression analysis was then performed to directly establish the relationship between the corrected cone resistance ($q_{\rm c1N,cs}$) and horizontal stress index ($K_{\rm D}$), which can be expressed as

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

Note that $q_{\rm c1N,cs}$ is so-called the clean-sand equivalence of the corrected cone tip resistance according to Robertson and Wride (1998). Once the $q_{\rm c1N,cs}$-$K_{\rm D}$ relationship is available, the $K_{\rm D}$-based CRR curve can be easily established through the existing CPT-based CRR curve. The CRR curve proposed by Tsai *et al.* (2009) is expressed as

$$\text{CRR}_{7.5}=\exp[(K_{\rm D}/8.8)^3-(K_{\rm D}/6.5)^2+(K_{\rm D}/2.5)-3.1]. \quad (5)$$

Note that the above $K_{\rm D}$-based CRR curve was established based on the widely accepted SPT- and CPT-based CRR curves (Robertson and Wride, 1998; Youd *et al.*, 2001; Idriss and Boulanger, 2006) as well as the correlations between $q_{\rm c}$ and $K_{\rm D}$. The CRR curve proposed by Tsai *et al.* (2009) has been additionally validated by Kung *et al.* (2009). More detailed information can be found in their paper.

3 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 City 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. Fig. 2 shows the locations of six sites analyzed in the present study. Figs. 3–8 show the test results of DMT and CPT, including stratigraphy, cone tip resistance ($q_{\rm c}$), sleeve friction ($f_{\rm s}$), soil behavior type index ($I_{\rm c}$), clean-sand equivalence of normalized cone penetration resistance ($q_{\rm c1N,cs}$), material index ($I_{\rm D}$), and horizontal stress index ($K_{\rm D}$). Of these parameters, $q_{\rm c}$, $f_{\rm s}$, $I_{\rm c}$, and $q_{\rm c1N,cs}$ from CPT were calculated according to Youd *et al.* (2001), while K_D and I_D from DMT were calculated according to Marchetti *et al.* (2001). Specifically, $q_{\rm c}$ and $f_{\rm s}$ are directly measured by the CPT. Then, $q_{\rm c1N,cs}$ and $I_{\rm c}$ can be calculated based on Robertson and Wride (1998). In Figs. 3–8, SM represents silty sand, CL denotes low-plasticity silty clay, and ML represents low-plasticity sandy silt. For each of six sites, DMT and CPT tests were conducted at the same depth, which means $K_{\rm D}$ and $q_{\rm c1N,cs}$ of a soil at the same depth are available. In this regard, using those data to examine the existing methods becomes feasible. Therefore, the test results were collectively employed to examine the difference between the existing DMT-$K_{\rm D}$-based liquefaction evaluation methods of Monaco *et al.* (2005), Grasso and Maugeri (2006), and Tsai *et al.* (2009), as shown in Fig. 1.

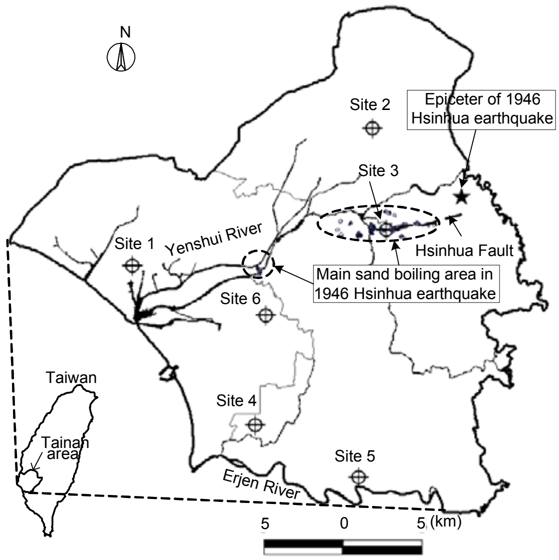

Fig. 2 Layout of six study sites in Tainan

4 Examining existing DMT-$K_{\rm D}$ liquefaction evaluation methods

It should be emphasized that the SPT-based liquefaction evaluation methods are excluded in the present study because CPT and DMT can capture more complete characteristics of stratigraphy. As mentioned previously, all the existing DMT-$K_{\rm D}$ liquefaction evaluation methods considered in this study (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-$K_{\rm D}$ and CPT-$q_{\rm c}$ or between DMT-$K_{\rm D}$ and SPT-*N*. As a result, the goal to examine these existing DMT-$K_{\rm D}$

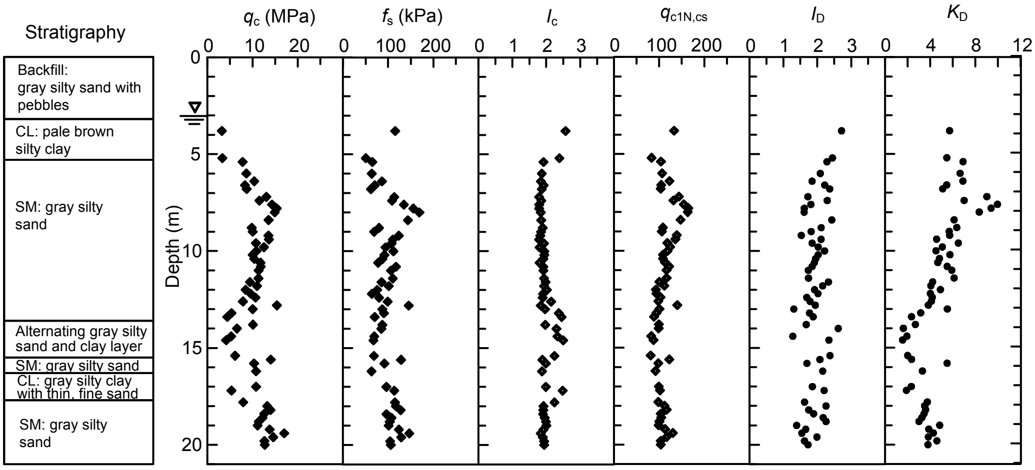

Fig. 3 Results of CPT and DMT test on site 1

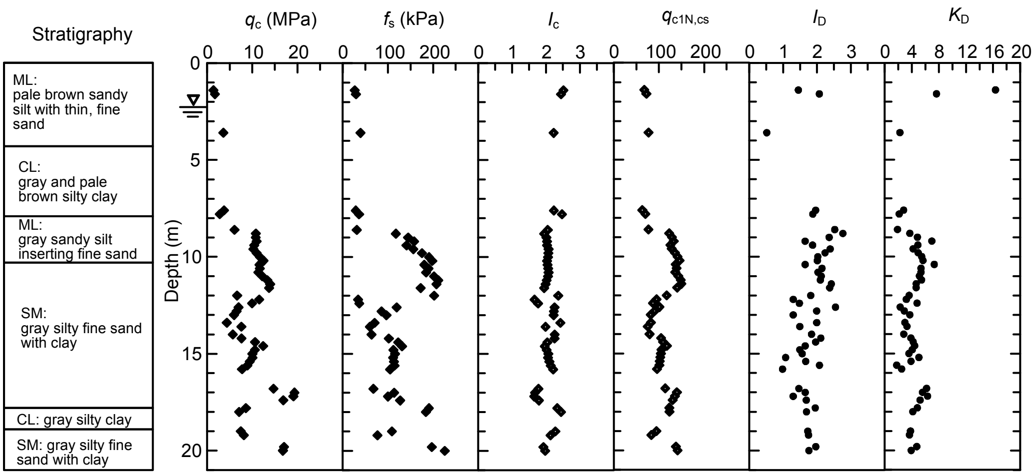

Fig. 4 Results of CPT and DMT test on site 2

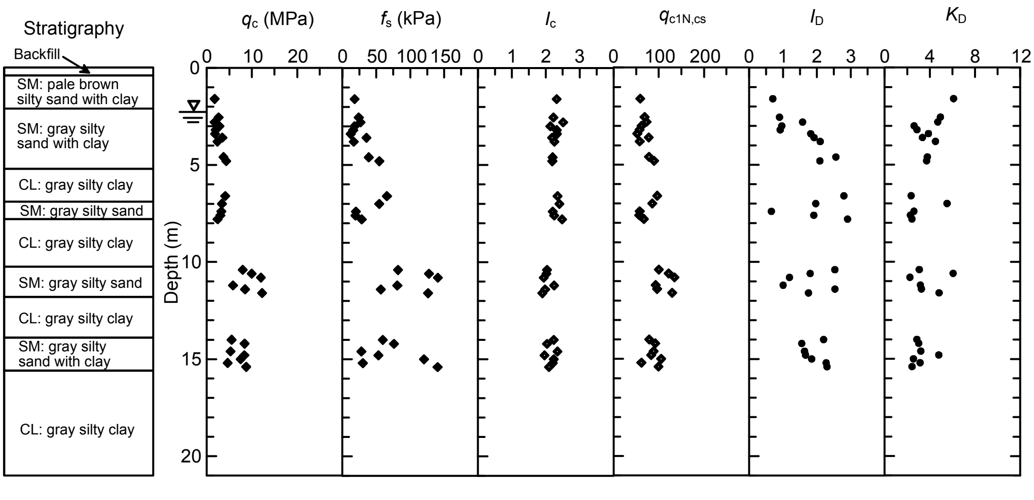

Fig. 5 Results of CPT and DMT test on site 3

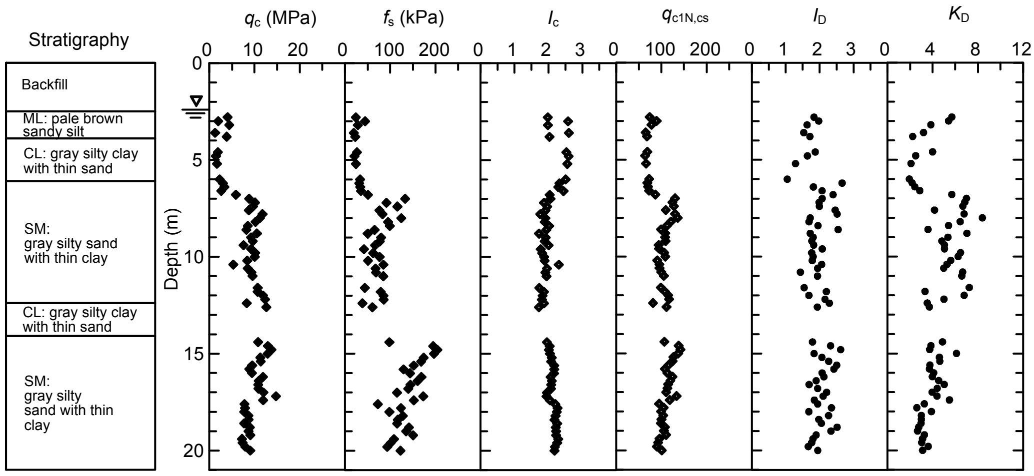

Fig. 6 Results of CPT and DMT test on site 4

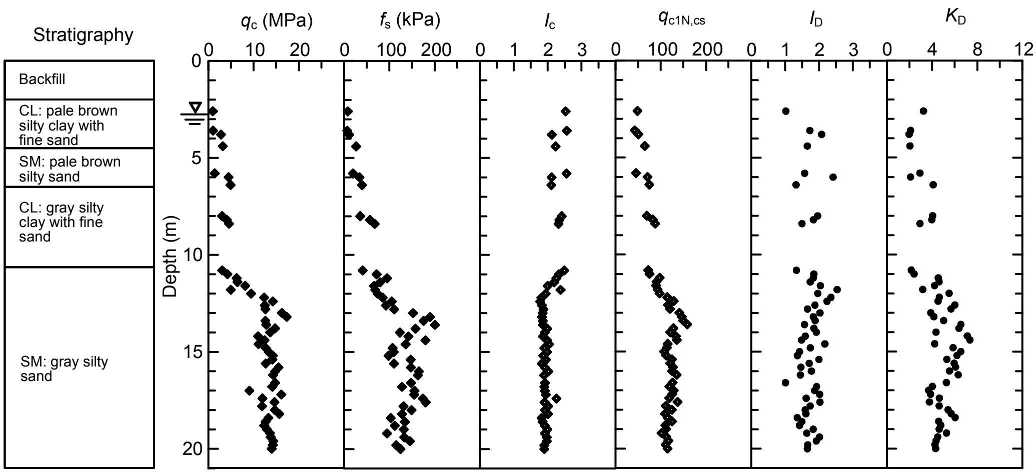

Fig. 7 Results of CPT and DMT test on site 5

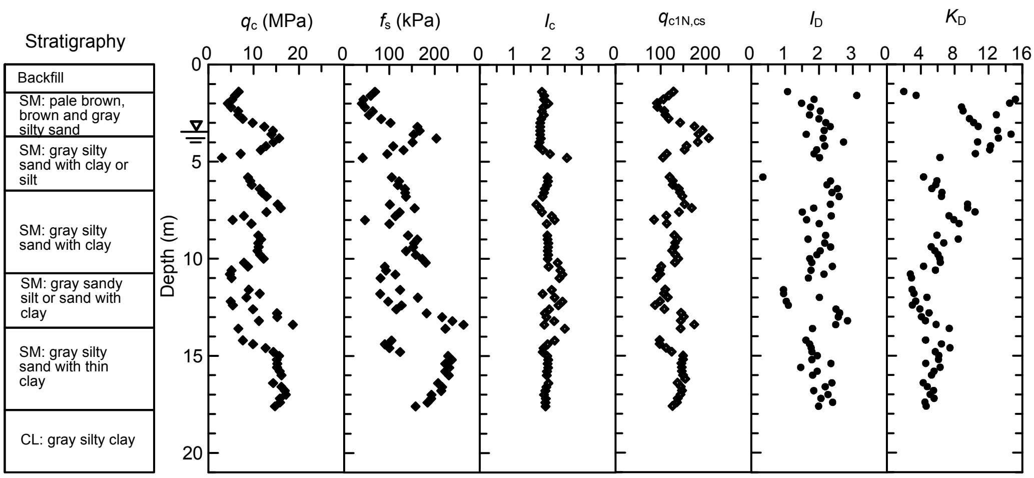

Fig. 8 Results of CPT and DMT test on site 6

methods can be achieved by examining the correlation between CPT-q_c and DMT-K_D using the results of side-by-side DMT and CPT tests (Figs. 3–8).

Figs. 9–14 compare K_D values measured by DMT with those computed based on CPT-q_c values and q_c-K_D correlations. Note that only the data of K_D measurements at depths of 0–20 m are compared since the liquefaction potential of soil at larger depth is considered relatively low. As shown in Fig. 1, 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. As shown in Figs. 9–14, the soil behavior type index I_c from CPT is applied in the present study to filter the test data. Only the data points with $I_c \leq 2.6$, which can be identified as the sandy soil according to Youd *et al.* (2001), are adopted in the comparison (Figs. 9–14).

Fig. 9 displays the comparison of K_D at depths within 0–20 m 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 Eq. (4), while the solid line represents the DMT-K_D values estimated by Grasso and Maugeri (2006) using Eq. (2). As shown in this figure, the K_D values of the sandy layer (SM) at depths of 5.3 to 13.5 m are significantly underestimated by Grasso and Maugeri (2006). The estimated

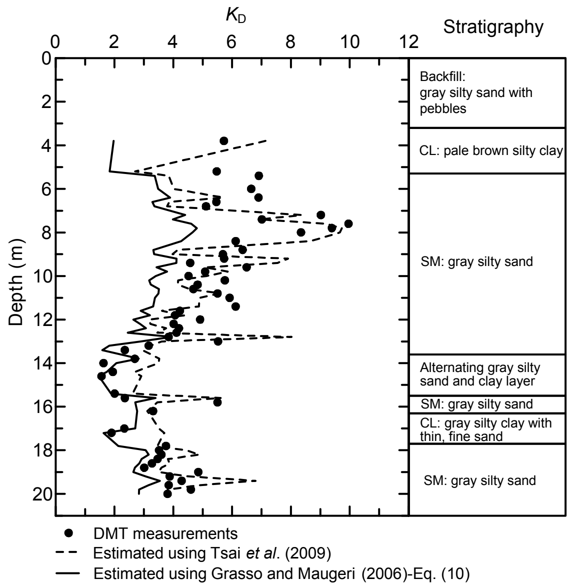

Fig. 9 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 1

K_D is only equal to a half of the measurements at depth of around 8 m. Similar results can be obtained in a deeper sandy layer at depths of 15.5 to 16.5 m.

Fig. 10 displays the comparison of K_D on site 2. The K_D measured at shallow depths near ground surface rapidly increases with the decrease of depth in this site. Both methods from Tsai *et al.* (2009) and Grasso and Maugeri (2006) cannot capture this behavior. For the sandy layer at depths of 10.2 to 17.8 m, the method by Tsai *et al.* (2009) would overestimate K_D at depths of 10 to12 m, but the estimations at depths of 12 to 17.8 m are satisfactory. The method by Grasso and Maugeri (2006) generally underestimates K_D in this sandy layer at depths of 10.2 to 17.8 m.

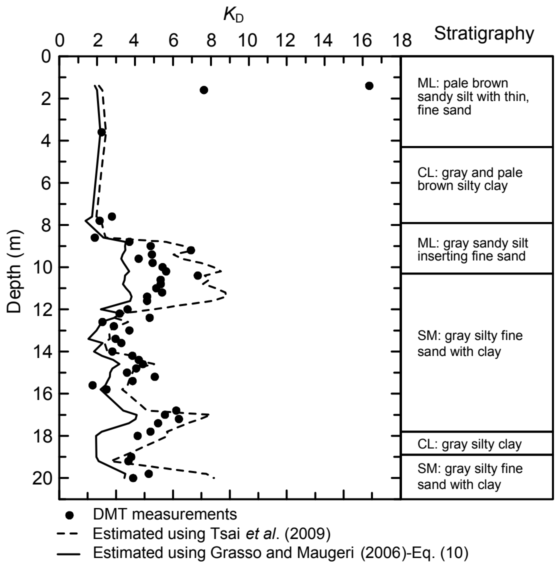

Fig. 10 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 2

Fig. 11 shows the comparison of K_D on site 3. Similarly, the behavior that K_D measured at shallow depths (0–4 m) near ground surface raises with the decrease of depth on this site cannot 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, the estimations of K_D by Tsai *et al.* (2009) are greater than those by Grasso and Maugeri (2006) at depths of 4–15 m. This trend is similar to those obtained on sites 1 and 2.

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

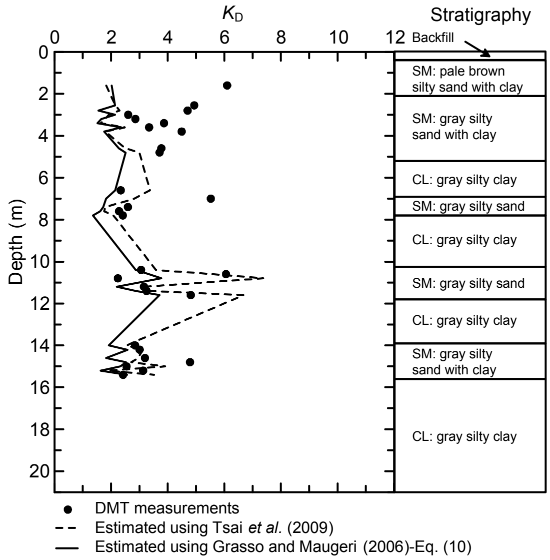

Fig. 11 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 3

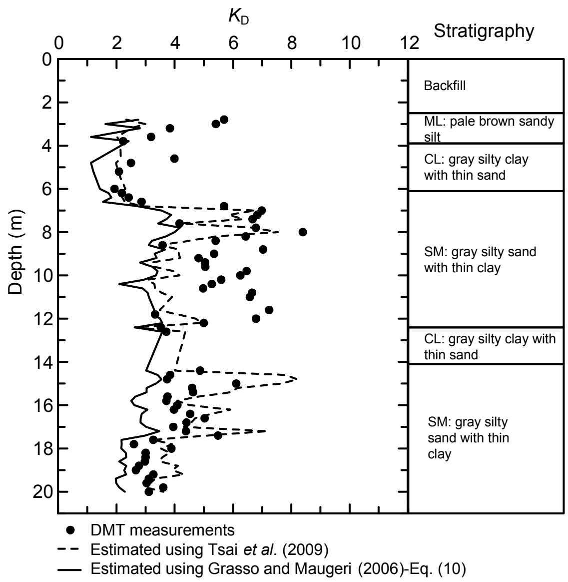

Fig. 12 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 4

The comparison of K_D on site 5 is shown in Fig. 13. The method by Grasso and Maugeri (2006) always underestimates K_D in this case, irrespective of depth. As to the performance of the method by Tsai *et al.* (2009), K_D is underestimated at shallow depths (2 to 10 m), but can be adequately estimated at greater depths (10 to 20 m).

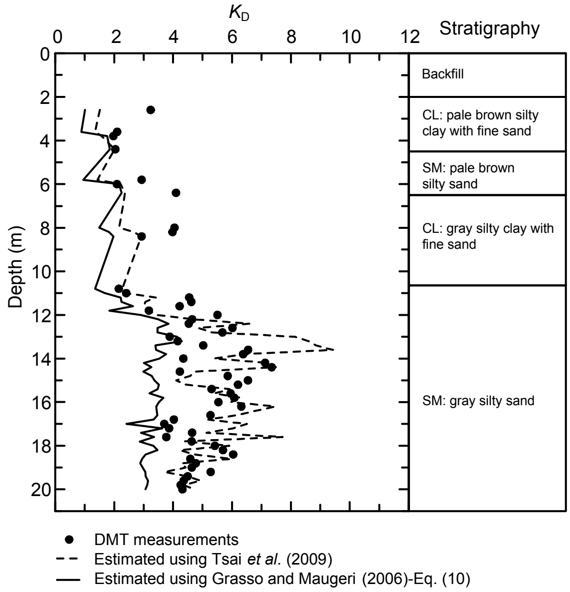

Fig. 13 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 5

Fig. 14 exhibits the comparison of K_D 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. 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, K_D can be reasonably estimated by Tsai *et al.* (2009) at various depths. Nevertheless, K_D of sandy layers is significantly underestimated by Grasso and Maugeri (2006) at depths of 0–20 m although the variation of K_D profiles estimated by Tsai *et al.* (2009) and Grasso and Maugeri (2006) with depth is similar.

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 values. It is not surprising that the performance of the method by Tsai *et al.* (2009) is more 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.

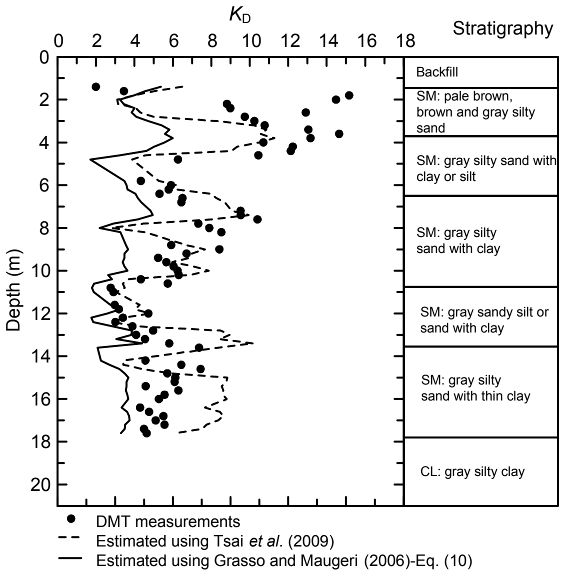

Fig. 14 Comparison of K_D measured by DMT and estimated from q_c-K_D correlations on site 6

Although the CPT and flat-plat DMT have been used for over 30 years, relatively little has been published regarding comprehensive correlations between the two in-situ tests (Robertson, 2009). Only a few DMT-based liquefaction evaluation models have been published (Robertson and Campanella, 1986; Reyna and Chameau, 1991; Monaco *et al.*, 2005; Grasso and Maugeri, 2006; Tsai *et al.*, 2009). The existing DMT-based liquefaction evaluation methods considered in this study were developed based on the relationship of K_D-D_r-q_c or K_D-D_r-N.

According to Figs. 9–14, the analysis results reveal that the method by Grasso and Maugeri (2006) generally underestimates the K_D value. 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. 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 included in Fig. 15. The linear regression 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. 1. 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 usually leads to overestimation of the CRR values of soils of the existing DMT-based liquefaction evaluation methods.

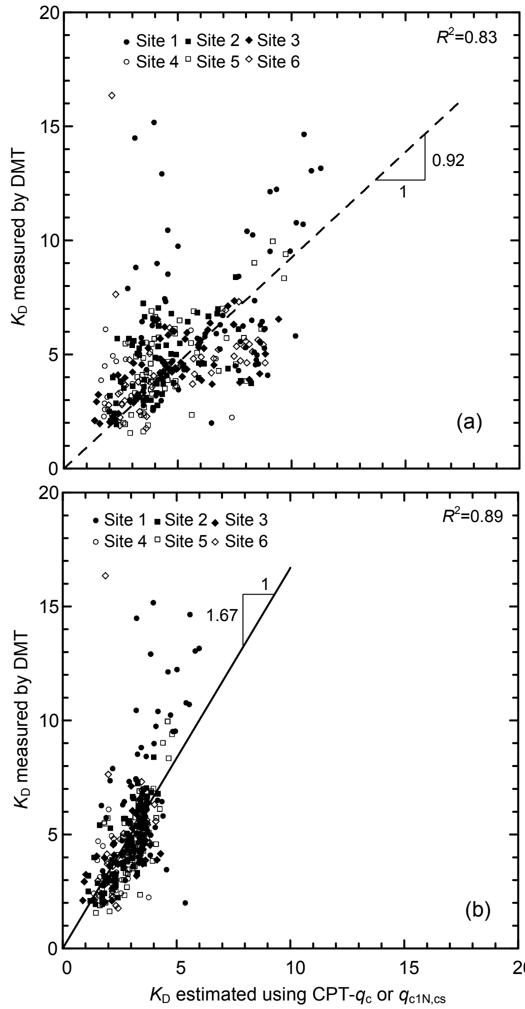

Fig. 15 Comparison of performance of various methods in estimating K_D from CPT-q_c. (a) Tsai *et al.* (2009); (b) Grasso and Maugeri (2006)-Eq. (10)

As shown in Figs. 9–14, there exists an interesting trend in that the value of K_D would increase with the decrease of depth at shallow depths (e.g., <4 m), which is similar to the trend of the overconsolidation ratio (OCR). Further analyses on this point are shown in Figs. 16 and 17. As shown in Fig. 16, the K_D at depths of 0–4 m is underestimated (1:1.37) by Tsai *et al.* (2009), while slight overestimation of K_D can be obtained for depths of 4–20 m (1:0.88). For the scenario shown in Fig. 17, the K_D is significantly underestimated by Grasso and Maugeri (2006) at depths of 0–4 m and 4–20 m simultaneously. In this regard, the capability of the method by Tsai *et al.* (2009) in estimating K_D is more satisfactory. However, it can be concluded that both methods by Tsai *et al.* (2009) and Grasso and Maugeri (2006) are incapable of capturing the characteristics of K_D at shallow depths. In other words, it is not suggested to use those methods to analyze the potential of liquefaction of soils at shallow depths. Indeed, it is desirable to study this interesting research topic further.

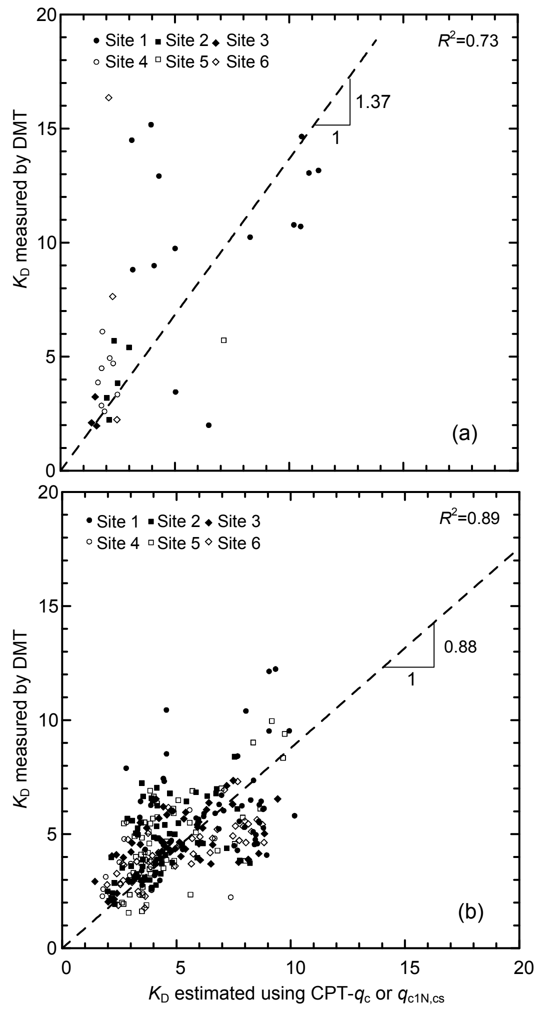

Fig. 16 Performance of the method by Tsai *et al.* (2009) with various depths. (a) 0–4 m; (b) 4–20 m

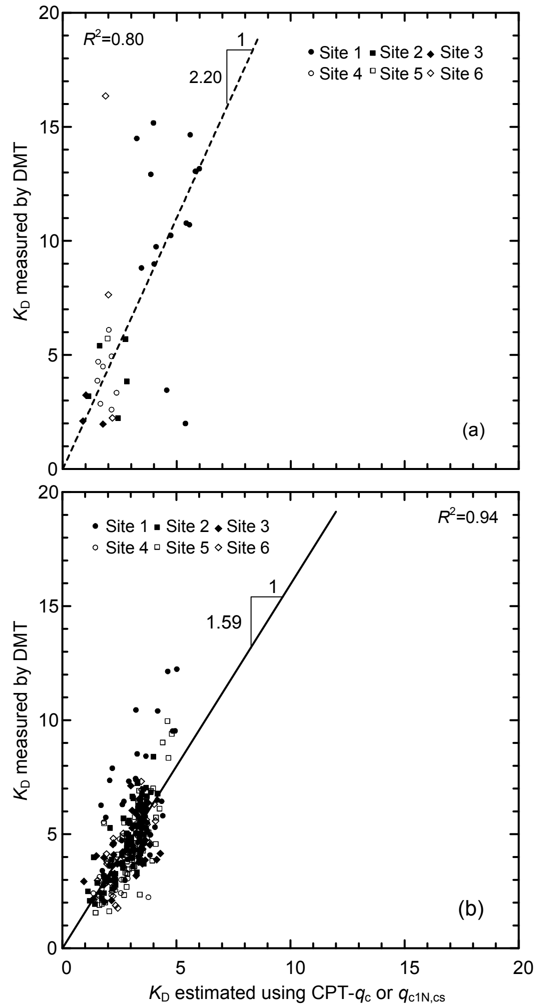

Fig. 17 Performance of the method by Grasso and Maugeri (2006)-Eq. (10) with various depths. (a) 0–4 m; (b) 4–20 m

It may be desirable to examine the performance of the material index criterion for identifying the soil type. Fig. 18 shows the fines content measured by the soil samples taken from each of the six sites and material index measured by the DMT tests. In practice, a soil can be classified as sandy soil with I_D>1.8, silty soil with 0.6<I_D<1.6, and clayey soil with I_D<0.6. Based on the test results conducted in the present study, the upper bound may be slightly adjusted to be 1.6 for more adequately identifying the sandy soil (Fig. 18). However, additional test results are required to further verify this founding.

Finally, this study collects liquefaction case histories, in which the DMT data are available, to examine the accuracy of CRR curves proposed by

Tsai *et al.* (2009) and Grasso and Maugeri (2006). According to the comparison in the previous section of this study, K_D based on CPT data would be significantly underestimated by Grasso and Maugeri (2006), which results in the overestimated CRR curve. This can be effectively verified by a number of data points from actual liquefaction case histories (Fig. 19).

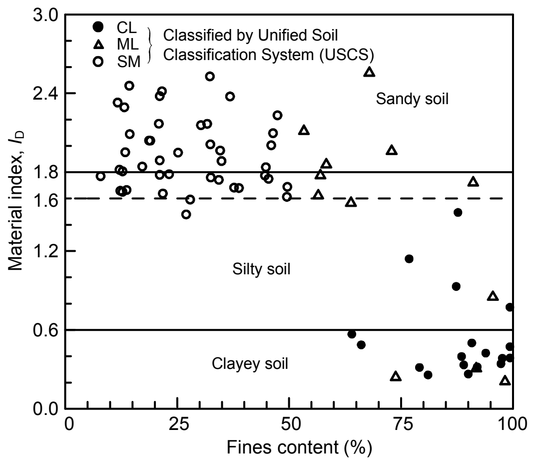

Fig. 18 Examination of material index (I_D) using the test data

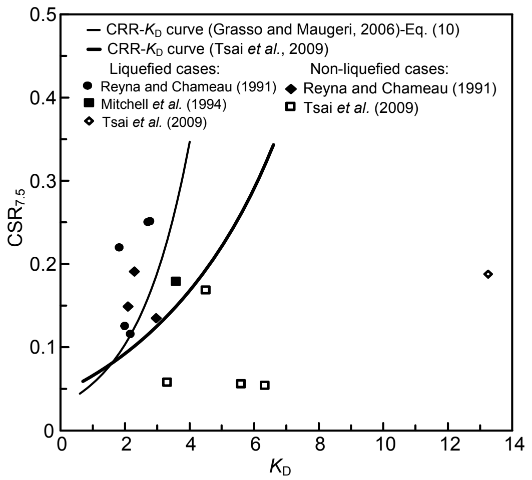

Fig. 19 Performance of existing DMT-based CRR-K_D curves from comparison with published liquefaction case histories

5 Conclusions

Although simplified methods for evaluating liquefaction potential of soils are well established, based on SPT, CPT, and shear wave velocity, use of DMT for liquefaction resistance evaluation has received 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 and used these data to examine the existing DMT-based methods for evaluating liquefaction resistance of soils. Specifically, this study employed the CPT-q_c data and the correlation between CPT-q_c and DMT-K_D to calculate the values of DMT-K_D at various depths, and then the calculated and tested values of DMT-K_D were compared.

The results reveal that the method by Grasso and Maugeri (2006) would significantly underestimate the DMT-K_D of soils. This implies that adopting K_D-D_r-q_c relationship to correlate DMT-K_D with CPT-q_c could result in a significant bias, which leads to overestimation of the CRR values of soils of the existing DMT-based liquefaction evaluation methods. Instead, the simplified method by Tsai *et al.* (2009) can improve the bias of existing DMT-based methods in estimating CRR of soils.

The results also indicate that the behavior of K_D value increasing with the decrease of depth cannot be captured by the methods of Tsai *et al.* (2009) and Grasso and Maugeri (2006). This finding may be due to the effect of the overconsolidation behavior of soil at shallow depths not being reflected by the existing DMT-based methods for liquefaction evaluation. Further study on this aspect is desirable.

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