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PERFORMANCE OF *DMT*-BASED LIQUEFACTION EVALUATION METHODS ON CASE HISTORIES OF CHI-CHI EARTHQUAKE

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Key words: Liquefaction, Chi-Chi earthquake, Case history, Flat dilatometer test.

ABSTRACT

This study examines two recently-developed *DMT*-based methods, one $CRR_{7.5}$-K_D boundary curve and one $CRR_{7.5}$-E_D boundary curve, for evaluating the liquefaction resistance of soils using in-situ test data. The collected data consist of a number of liquefied and non-liquefied case histories, which were performed shortly after the disastrous Chi-Chi earthquake in 1999. The results of examining the $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D boundary curves showed that both curves are capable of accurately estimating the liquefaction resistance of soils and thus the liquefaction potential of soils. The developed *DMT*-based methods therefore have the potential to be an alternative to the existing procedure of liquefaction evaluation, such as the *SPT* and *CPT* evaluation methods, to practically obtain a more accurate liquefaction resistance of soils.

I. INTRODUCTION

In practice, simplified procedures for evaluating the liquefaction potential of soils generally consist of two components: 1) to evaluate the loading to a soil caused by an earthquake and 2) to evaluate the resistance of a soil to the triggering of liquefaction. The former can be performed through estimating the cyclic stress ratio (*CSR*) such as the *PGA*-based methods proposed by Seed and Idriss [16]. The latter can be accomplished through estimating the cyclic resistance ratio (*CRR*) using the simplified methods, such as *SPT*-based methods [4, 15, 16, 17, 19, 20], *CPT*-based methods [4, 6, 13, 14, 19, 20], or V_s-based methods [1, 19, 20]. It should be noted that the intrinsically uncertain factors of liquefaction potential evaluation need to be clarified when using the existing liquefaction evaluation methods. For instance, the in-situ loose soils may be evaluated as potentially liquefiable before the earthquake, but those were actually not liquefied during the earthquake event.

With use of simplified methods in the liquefaction evaluation, the accuracy of evaluating liquefaction potential of soils may not be effectively assured as only one kind of simplified method is adopted in the evaluation process. In this regard, Youd *et al*. [20] proposed that "Where possible, two or more test procedures should be applied to assure adequate definition of soil stratigraphy and a consistent evaluation of liquefaction resistance." Except the above-mentioned *SPT*-, *CPT*-, and V_s-based simplified methods, a new Flat-dilatometer-test-based (*DMT*-based) simplified method for evaluating $CRR_{7.5}$ of soils was recently developed by Tsai *et al.* [18], in which two *DMT* parameters, the horizontal stress index (K_D) and the dilatometer modulus (E_D), are used as an indicator for assessing the $CRR_{7.5}$ of soils, respectively.

The *DMT*-based methods developed by Tsai *et al.* [18] were preliminarily examined in their study and the results reveal that accuracy of evaluating $CRR_{7.5}$ of soils using the methods was satisfactory. However, it is desirable to further examine the applicability of the methods in liquefaction evaluation. In this study, a number of *SPT* and *CPT* data conducted in the liquefaction areas in central Taiwan caused by the disastrous Chi-Chi earthquake in 1999 were collected and used to examine the *DMT*-based methods through the correlations between K_D (or E_D) and $N_{1,60cs}$ (or $q_{c1N,cs}$) established by Tsai *et al.* [18]. Note that $N_{1,60cs}$ represents the clean sand equivalent penetration resistance for *SPT* and $q_{c1N,cs}$ represents the clean sand equivalent normalized cone penetration resistance for CPT. Those data collected in this study are not adopted to develop or validate the *DMT*-based methods developed by Tsai *et al.* [18]. The results show that the liquefaction resistance of soils can be accurately evaluated by using the *DMT*-based methods.

II. SIMPLIFIED METHODS FOR EVALUATING LIQUEFACTION POTENTIAL OF SOILS

As mentioned previously, the procedure for evaluating liquefaction potential of soils consists of estimations of $CSR_{7.5}$

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and $CRR_{7.5}$. In general, the factor of safety (FS) against occurrence of liquefaction is practically defined as:

$$FS = CRR_{7.5}/CSR_{7.5} \tag{1}$$

The methods for estimating $CSR_{7.5}$ and $CRR_{7.5}$ commonly used in practical liquefaction evaluation are briefly described as follows:

1. Estimation of CSR$_{7.5}$

According to Seed and Idriss [16], Seed [15], Youd *et al.* [20], and Idriss and Boulanger [4], the earthquake-induced maximum ground surface acceleration ($a_{\max}$) may be used to estimate the $CSR_{7.5}$ through:

$$CSR_{7.5} = 0.65(a_{\max}/g)(\sigma_{v0}/\sigma'_{v0})r_d / MSF \tag{2}$$

where σ_{v0} is the total overburden pressure on sand layer under consideration; σ'_{v0} is the initial effective overburden pressure on the same sand layer; g is the acceleration of gravity; r_d is the stress reduction factor; MSF is the magnitude scaling factor, which provides an approximate representation of an effect of shaking duration or equivalent number of stress cycles. MSF is defined as:

$$MSF = CSR_M / CSR_{7.5} \tag{3}$$

where CSR_M represents a CSR value with respect to a specific moment magnitude M. In the present study, the procedures for estimating r_d and MSF proposed by Youd *et al.* [20] and Idriss and Boulanger [4] are employed for estimating $CSR_{7.5}$.

1) Youd et al.:

Youd *et al.* [20] proposed that for a routine practical project, the following equations may be used to estimate the averaged r_d:

$$r_d = 1.0 - 0.00765z \quad \text{for } 0 \le z \le 9.15 \tag{4a}$$
$$r_d = 1.174 - 0.0267z \quad \text{for } 9.15 < z \le 23 \tag{4b}$$

where z is the depth (m) of the sandy layer. MSF may be determined by:

$$MSF = 10^{2.24}/M^{2.56} \tag{5}$$

where M is the moment magnitude of an earthquake.

2) Idriss and Boulanger:

Idriss and Boulanger [4] presented that r_d may be estimated by:

$$\ln(r_d) = \alpha(z) + \beta(z)M \quad \text{for } z \le 34 \tag{6a}$$

where $\alpha(z)$ and $\beta(z)$ can be determined by:

$$\alpha(z) = -1.012 - 1.126\sin((z/11.73) + 5.133) \tag{7a}$$
$$\beta(z) = 0.106 + 0.118\sin((z/11.28) + 5.142) \tag{7b}$$

where z is the depth (m). MSF can be determined by:

$$MSF = 6.9\exp(\frac{-M}{4}) - 0.058 \le 1.8 \tag{8}$$

2. *SPT*- and *CPT*-Based Methods for Estimating CRR$_{7.5}$

The common *SPT*- and *CPT*-based methods for estimating $CRR_{7.5}$ of soils are briefly described as follows:

1) SPT-Based Methods:

Seed *et al.* [17] first established several charts for estimating *SPT*-based $CRR_{7.5}$ using the clean sand equivalent penetration resistance ($N_{1,60cs}$). Due to the limitation of the charts in the computation efficiency and probabilistic analysis, Youd and Idriss [19] formulated the $CRR_{7.5}$ curve established by Seed *et al.* [17]. Later, the $CRR_{7.5}$ curve was further modified as [20]:

$$CRR_{7.5} = \frac{1}{34 - N_{1,60cs}} + \frac{N_{1,60cs}}{135} + \frac{50}{\left(10N_{1,60cs} + 45\right)^2} - \frac{1}{200} \tag{9}$$

Note that (9) is valid only for $N_{1,60cs} < 30$, while the sandy soil is considered unliquefible when $N_{1,60cs}$ is greater than 30.

Idriss and Boulanger [4] indicated that the trend of the $CRR_{7.5}$ curve proposed by Youd and Idriss [19] and Youd *et al.* [20] would sharply increase as the $N_{1,60cs}$ value approaches 30. The $CRR_{7.5}$ value in the case of $N_{1,60cs} \ge 30$ may induce unreasonable results when conducting the probabilistic analysis. Therefore, a new equation for calculating the $CRR_{7.5}$ is proposed and expressed as [4]:

$$CRR_{M=7.5} = Exp\ \left[\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right] \tag{10}$$

Note that the range of $N_{1,60cs}$ value in (10) is not elaborated in their study.

2) CPT-Based Methods:

The *CPT*-based equations for estimating $CRR_{7.5}$ using the clean sand equivalent normalized cone penetration resistance ($q_{c1N,cs}$), proposed by Robertson and Wride [14] and Youd *et al.* [20] are identical and expressed as:

$$CRR_{7.5} = 0.833\left[\frac{q_{c1N,cs}}{1000}\right] + 0.05 \quad \text{for } q_{c1N,cs} < 50 \quad (11a)$$

$$CRR_{7.5} = 93\left[\frac{q_{c1N,cs}}{1000}\right]^3 + 0.08 \quad \text{for } 50 \le q_{c1N,cs} < 160 \quad (11b)$$

where $q_{c1N,cs} = K_c q_{c1N}$, in which K_c = the correction factor for grain characteristics; q_{c1N} = the normalized penetration resistance and can be determined by $q_{c1N} = C_Q\ (q_c/P_a)$ where q_c = the field cone penetration resistance, C_Q = normalizing factor for cone penetration resistance, and P_a = 100 kPa (1 atm) of pressure. Detailed *CPT*-based methods can be referred to Robertson and Wride [14] and Youd *et al.* [20].

However, it should be noted that in the process of $CRR_{7.5}$ evaluation using the *CPT*-based methods [14, 20], the overburden pressure normalizing factor for cone penetration resistance (C_Q) is different as reflected by the exponent n value and the upper limiting value of C_Q:

$$C_Q = \left(\frac{P_a}{\sigma'_{vo}}\right)^n \quad (12)$$

where P_a is 1 atm of pressure in the same unit used for σ'_{vo}. Specifically, n values, 0.75 and 0.7, and upper limiting values of C_Q, 2.0 and 1.7, are proposed by Robertson and Wride [14] and Youd *et al.* [20], respectively.

3. A Recently-Developed *DMT*-Based Method for Estimating $CRR_{7.5}$

Similar to the $N_{1,60cs}$ and $q_{c1N,cs}$ employed as an indicator for estimating the $CRR_{7.5}$ in *SPT*- and *CPT*-based methods, respectively, two indexes K_D and E_D are used to develop *DMT*-based $CRR_{7.5}$ boundary curves. Specifically, two *DMT*-based boundary curves ($CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves) are established following the existing boundary curves ($CRR_{7.5}$-$N_{1,60cs}$ and $CRR_{7.5}$-$q_{c1N,cs}$ curves). Note that the correlations between K_D (or E_D) and the corrected blow count ($N_{1,60cs}$) in the *SPT* or corrected cone tip resistance ($q_{c1N,cs}$) from the *CPT* are the key element in the development of $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D boundary curves. To this end, Tsai *et al.* [18] established these correlations through regression analyses of the results of *SPT*, *CPT*, and *DMT* conducted side-by-side at five sites in Tainan. Then, two *DMT*-based boundary curves ($CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves) can thus be established as follows [18]:

$$CRR_{7.5} = EXP\left[\left(\frac{K_D}{8.8}\right)^3 - \left(\frac{K_D}{6.5}\right)^2 + \left(\frac{K_D}{2.5}\right) - 3.1\right] \quad (13a)$$

$$CRR_{7.5} = EXP\left[\left(\frac{E_D}{49}\right)^3 - \left(\frac{E_D}{36.5}\right)^2 + \left(\frac{E_D}{23}\right) - 2.7\right] \quad (13b)$$

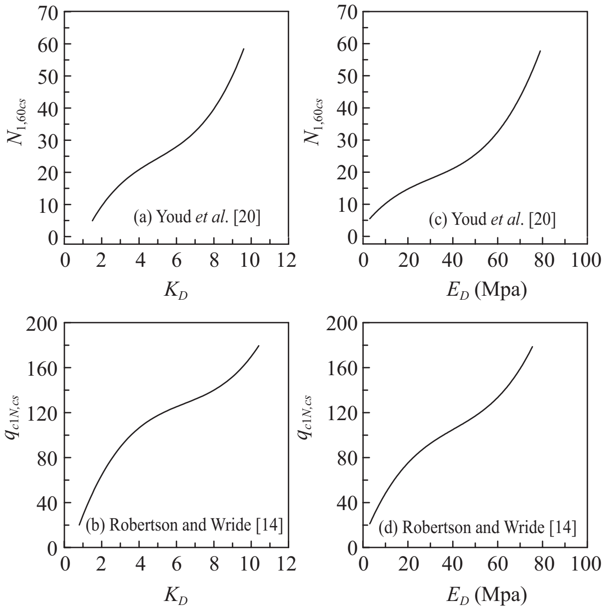


Fig. 1. The proposed correlations between K_D (or E_D) and the blow count (N) in the *SPT* or cone tip resistance (qc) from the *CPT*.

where K_D is the horizontal stress index and E_D is the dilatometer modulus. Note that (13a) and (13b) were established through the combination of the existing *SPT*- and *CPT*-based boundary curves ((9) to (11)) and the correlations between K_D (or E_D) and $N_{1,60cs}$ (or $q_{c1N,cs}$) ((14) and (15)). Specifically, four correlations, K_D-$N_{1,60cs}$, K_D-$q_{c1N,cs}$, E_D-$N_{1,60cs}$, and E_D-$q_{c1N,cs}$, were established by Tsai *et al.* [18].

For the correlations related to K_D (see Figs. 1(a) and 1(b)):

$$N_{1,60cs} = 0.185K_D^3 - 2.75K_D^2 + 17K_D - 15 \quad (14a)$$

$$q_{c1N,cs} = 0.4K_D^3 - 7.7K_D^2 + 56K_D - 20 \quad (14b)$$

For the correlations related to E_D (see Figs. 1(c) and 1(d)):

$$N_{1,60cs} = 0.00022E_D^3 - 0.02E_D^2 + 0.9E_D + 3 \quad (15a)$$

$$q_{c1N,cs} = 0.00078E_D^3 - 0.095E_D^2 + 5E_D + 7 \quad (15b)$$

III. THE CHI-CHI EARTHQUAKE AND IN-SITU TEST DATA COLLECTION

The disastrous 1999 Chi-Chi, Taiwan earthquake caused great destruction to buildings and other facilities. Lessons should be learned in the rare full-scale experimentation in geotechnical engineering. Of particular interest to geotechnical engineers is the phenomenon of soil liquefaction that caused significant damage to buildings and lifelines. Shortly after the earthquake, an extensive field investigation in central

Table 1. Comparison of bit error rates for the simulation.

Area	Test	Number	Triggering of liquefaction	Reference	Seismological station used for liquefaction analysis
Wufeng	*SPT*	9	Yes	MAA [10]	TCU065
		1	No	MAA [10]	
	CPT	3	Yes	MAA [10]	
		2	No	MAA [10]	
		2	Yes	Ku [7]	
Nantou	*SPT*	7	Yes	MAA [10]	TCU076
		1	No	MAA [10]	
	CPT	4	Yes	MAA [10]	
		1	No	MAA [10]	
Yuanlin	*SPT*	8	Yes	MAA [11]	TCU110
		5	No	MAA [11]	
	CPT	6	Yes	MAA [11]	
		6	No	MAA [11]	
Changbin Industrial Park	*CPT*	7	Yes	Ku [7]	TCU117
		4	No	Ku [7]	

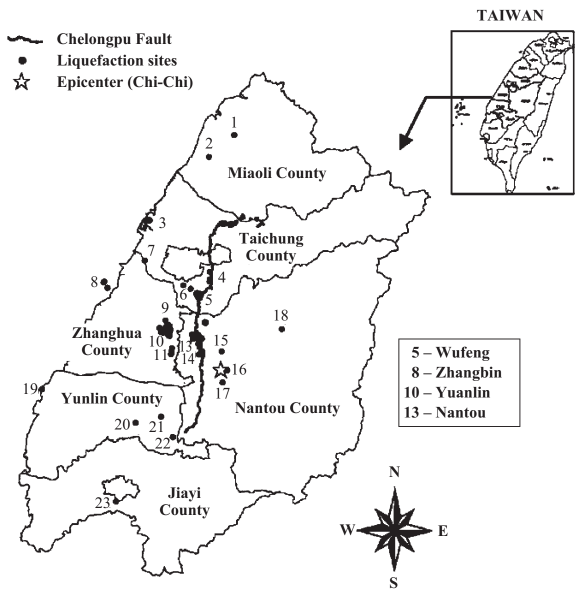


Fig. 2. Distribution of liquefaction sites in the Chi-Chi earthquake [12].

Taiwan was conducted by National Center for Research on Earthquake Engineering [12] and other parties. The in situ *SPT* and *CPT* tests performed along with ground performance observations performed can provide a basis for examining the *DMT*-based simplified methods for evaluating $CRR_{7.5}$ of soils.

1. Chi-Chi Earthquake

On 21 September 1999, a disastrous earthquake ($M_w = 7.6$) hit Taiwan at 1:47 AM local time. According to the records of the Central Weather Bureau (CWB) of Taiwan, the epicenter was located at 23.87°N, 120.81°E, which is near Chi-Chi, a town in Nantou County. The Chi-Chi earthquake with a focal depth of 8.0 km was triggered by reactivation of the Chelungpu fault in central Taiwan. The energy released by the Chelungpu fault resulted in a rupture of the earth surface that extended for almost 100 km. This quake caused over 2400 deaths and injured 8373 people. The total damage, including lost productivity, ranges from US$20 billion to US$30 billion [3]. After this earthquake, sand boiling, serious settlement, and surface ruptures were widely observed in areas of central Taiwan [9].

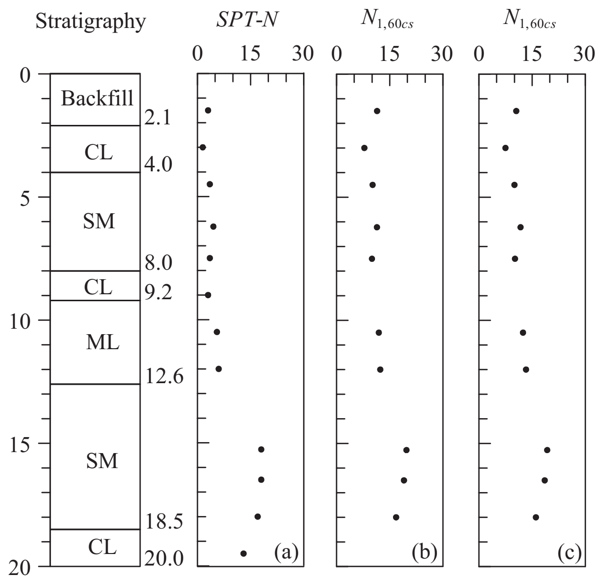
2. Collecting *SPT* and *CPT* Data after the Chi-Chi Earthquake

The synchronization of the earthquake's high intensity with long duration led to severe soil liquefaction damages in several counties. According to the investigation by NCREE [12], the liquefaction sites are primarily located in Nantou county, Taichung county, and Zhanghua county. Figure 2 shows the detailed distribution of liquefaction sites caused by the Chi-Chi earthquake, in which, specifically, the liquefaction hazards primarily occurred in four areas, Wufeng, Zhangbin industrial park, Yuanlin, and Nantou (Nos. 5, 8, 10, and 13 in Fig. 2). The data of in-situ *SPT* and *CPT* tests conducted at the liquefied sites of the four areas shortly after the Chi-Chi earthquake [7, 10, 11] are collected for examining the *DMT*-based methods.

Table 1 shows the collected data of *SPT* and *CPT*, including the liquefied and non-liquefied cases. A total of 31 *SPT* cases, 24 liquefied and 7 non-liquefied, as well as 35 *CPT* cases, 22 liquefied and 13 non-liquefied, are available to be used in the

Table 2. Intensity and PGA magnitude of the Chi-Chi earthquake measured at four stations in central Taiwan.

Station code*	Location	Intensity (scale)	Epicentral distance (km)	PGA (gal)			Coordinate	
				V	N-S	E-W	Longitude (deg.)	Latitude (deg.)
TCU065	Wufeng primary school	7	26.13	257.8	563.2	774.4	120.69	24.06
TCU076	Nantou primary school	7	15.53	275.4	420.0	340.1	120.68	23.91
TCU110	Yuanlin primary school	5	27.63	116.3	187.5	178.2	120.57	23.96
TCU117	Hsienhsi junior high school	5	47.73	90.0	113.5	121.3	120.46	24.13



(b) $N_{1,60cs}$ is estimated using Idriss and Boulanger [4]
(c) $N_{1,60cs}$ is estimated using Youd *et al.* [20]

Fig. 3. Variations of the *SPT-N* raw data and modified N values at one of sites in Yaunlin.

subsequent examination process. For estimating the $CSR_{7.5}$, four seismological stations of the CWB (station codes: TCU065, TCU076, TCU110, and TCU117) adjacent to the corresponding cases collected in this study are used to determine the *PGA* value, which is a necessity in the liquefaction evaluation. The location and coordinate of the four stations and the monitored records of the Chi-Chi earthquake are shown in Table 2. It should be noted that the $a_{\max}$ value required in the liquefaction evaluation of each case in this study is selected to be the maximum of *PGA* values in N-S and E-W directions monitored at each of the four stations.

IV. PERFORMANCE OF *DMT*-BASED METHODS

The procedures of examining the *DMT*-based methods for liquefaction evaluation based on the collected *SPT* and *CPT* data, including liquefied and non-liquefied cases, consist of five steps: 1) to compute the corrected blow count ($N_{1,60cs}$) and corrected cone penetration resistance ($q_{c1N,cs}$) from the *SPT* and *CPT* data, 2) to determine the critical soil layer in each of cases collected, 3) to estimate the $CSR_{7.5}$ of the critical soil layer of each case using (2) to (8), 4) to calculate the values of K_D and E_D at the critical soil layer of each case through (14) and (15), and 5) to determine the $CRR_{7.5}$ value of the critical soil layer in each case by (13). Of the five steps, steps 1, 3, 4, and 5 can be performed following the definite equations proposed by the previous studies. Therefore, only step 2 is further described herein.

1. Determination of the Critical Soil Layer

In this study, the results of previous studies [2, 7, 8, 10, 11], from which the data of *SPT* and *CPT* were reported and/or analyzed, along with the factor of safety against occurrence of liquefaction (see (1)) at each of sandy layers of all cases computed are incorporated together into determining the critical soil layer at each of cases. Figure 3 is an example for illustrating how to determine the critical soil layer of a liquefied case using the *SPT* data. Based on the calculated *SPT*-$N_{1,60cs}$ using existing methods proposed by Youd *et al.* [20] and Idriss and Boulanger [4] as well as the factor of safety against occurrence of liquefaction (Eq. (1)) at each of sandy layers of this case, the layer at depth of 4.0 m to 8.0 m is determined as the critical soil layer, where the liquefaction has most probably been triggered. Figure 4 is another example for showing how to distinguish the critical soil layer of a liquefied case using the *CPT* data. Based on the calculated *CPT*-$q_{c1N,cs}$ using existing methods proposed by Robertson and Wride [14] and Youd *et al.* [20] as well as the factor of safety against occurrence of liquefaction (Eq. (1)) at each of sandy layers of this case, the layer at depth of 1.7 m to 4.5 m is determined as the critical soil layer accordingly. After the critical soil layer of each of liquefied and non-liquefied cases is determined, the liquefaction analysis in each case can be performed at the determined critical soil layer and the results can then be used to examine the *DMT*-based methods for evaluating the liquefaction resistance of soils.

Table 3. Examination of accuracy of proposed *DMT*-based methods for evaluating the liquefaction potential of soils.

Test	Analytical method adopted (reference No.)	Correlation of various indices	$CRR_{7.5}$ adopted	Accuracy of the *DMT*-base method: Liquefaction zone (liquefied points/points in this zone)	Non-liquefaction zone (non-liquefied points/points in this zone)	Overall accuracy	Fig. No.
SPT	[20]	Eq. (14a)	Eq. (13a)	23/26	4/5	27/31	5
		Eq. (15a)	Eq. (13b)	23/25	5/6	28/31	7
	[4]	Eq. (14a)	Eq. (13a)	24/28	3/3	27/31	6
		Eq. (15a)	Eq. (13b)	23/26	4/5	27/31	8
CPT	[14]	Eq. (14b)	Eq. (13a)	22/29	6/6	28/35	9
		Eq. (15b)	Eq. (13b)	18/21	10/14	28/35	11
	[20]	Eq. (14b)	Eq. (13a)	22/29	6/6	28/35	10
		Eq. (15b)	Eq. (13b)	18/20	11/15	29/35	12

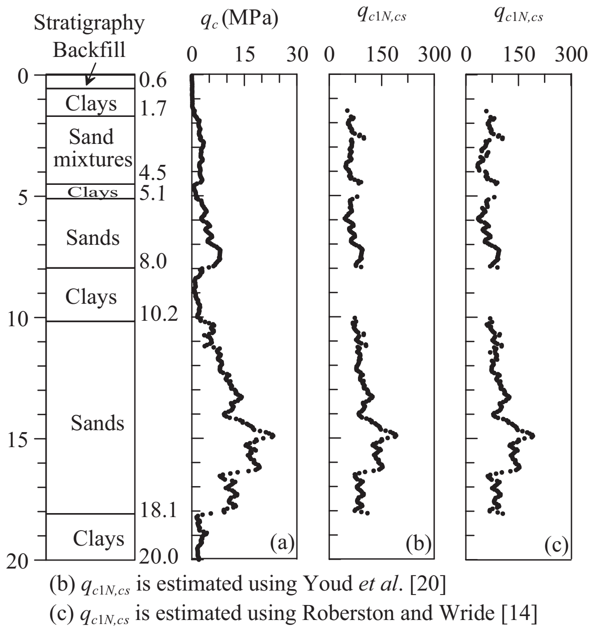


Fig. 4. Variations of the *CPT*-q_c raw data and modified q_c values at one of sites in Yaunlin.

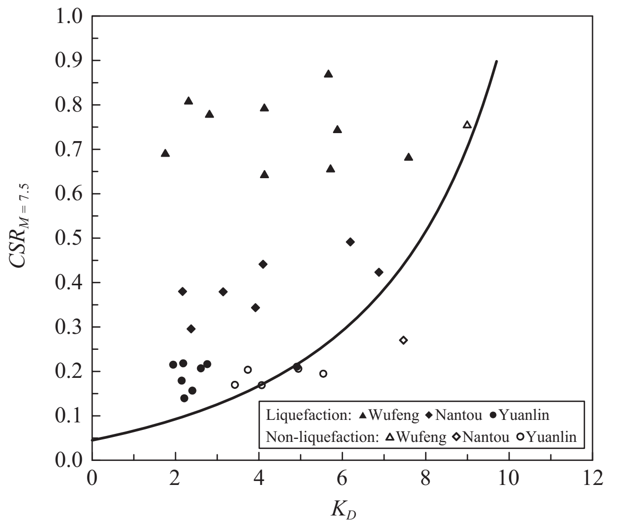


Fig. 5. Examination of the proposed $CRR_{7.5}$-K_D boundary curve for liquefaction evaluation using *SPT-N* data corrected by Youd *et al.* [20].

2. Examination of the Proposed *DMT*-Based Methods Using the *SPT* Data

First of all, this study examined the *DMT*-based $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D boundary curves (Eqs. (13a) and (13b)) using the collected *SPT* data of liquefied and non-liquefied cases performed shortly after the Chi-Chi earthquake in Wufeng, Nantou, and Yuanlin. Figure 5 shows the results of examining the $CRR_{7.5}$-K_D curve (Eq. (13a)). The method proposed by Youd *et al.* [20] for determining the $CSR_{7.5}$ and $N_{1,60cs}$ along with the $N_{1,60cs}$-K_D correlation (Eq. (14a)) established by Tsai *et al.* [18] are employed together herein. Detailed scenarios and results of examining the $CRR_{7.5}$-K_D boundary curve can be referred to Table 3. As shown in Fig. 5, the accuracy of the $CRR_{7.5}$-K_D curve in evaluating the liquefaction resistance of soils is satisfactory as reflected by the fact that, overall, 27 of 31 data points can be accurately estimated (23 of 26 points in the liquefaction zone and 4 of 5 points in the non-liquefaction zone, respectively; see Table 3). Note that the four inaccurate points (one liquefied and three non-liquefied) are located very close to the $CRR_{7.5}$-K_D curve. As such, the applicability of this boundary curve in evaluating liquefaction resistance of soils is considered appropriate.

By substituting the method by Idriss and Boulanger [4] for that by Youd *et al.* [20], results of examining the $CRR_{7.5}$-K_D curve, as shown in Fig. 6, are satisfactory and essentially much similar to those in Fig. 5. Overall, 27 of 31 data points can be accurately estimated (24 of 28 points in the liquefaction zone and 3 of 3 points in the non-liquefaction zone, respectively; see Table 3).

Similar to Figs. 5 and 6, Figs. 7 and 8 reveal the results of examining the $CRR_{7.5}$-E_D curve (Eq. (13b)) using the same

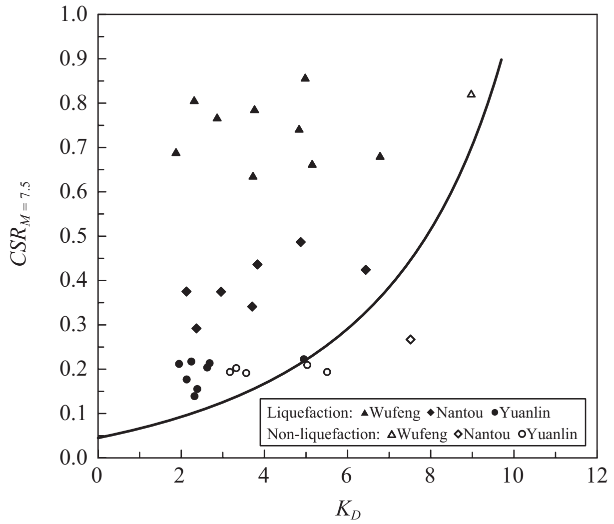


Fig. 6. Examination of the proposed $CRR_{7.5}$-K_D boundary curve for liquefaction evaluation using *SPT-N* data corrected by Idriss and Boulanger [4].

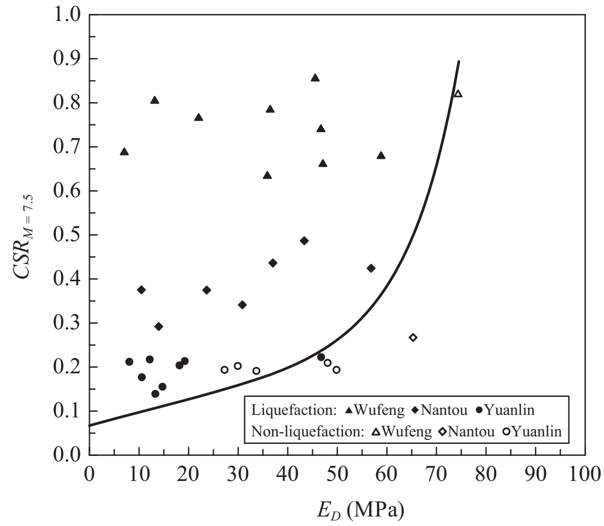


Fig. 8. Examination of the proposed $CRR_{7.5}$-E_D boundary curve for liquefaction evaluation using *SPT-N* data corrected by Idriss and Boulanger [4].

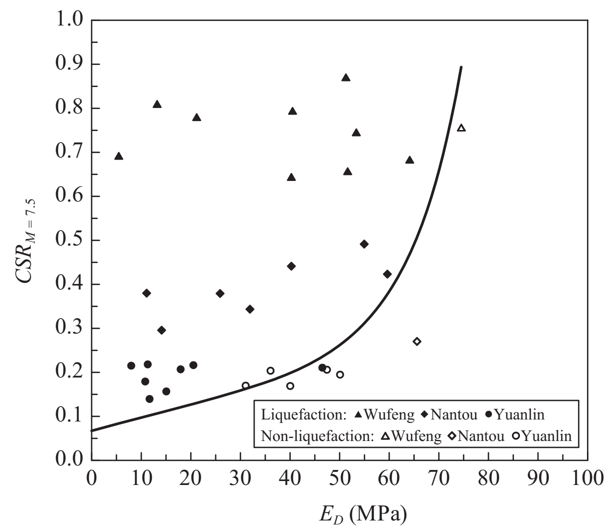


Fig. 7. Examination of the proposed $CRR_{7.5}$-E_D boundary curve for liquefaction evaluation using *SPT-N* data corrected by Youd *et al.* [20].

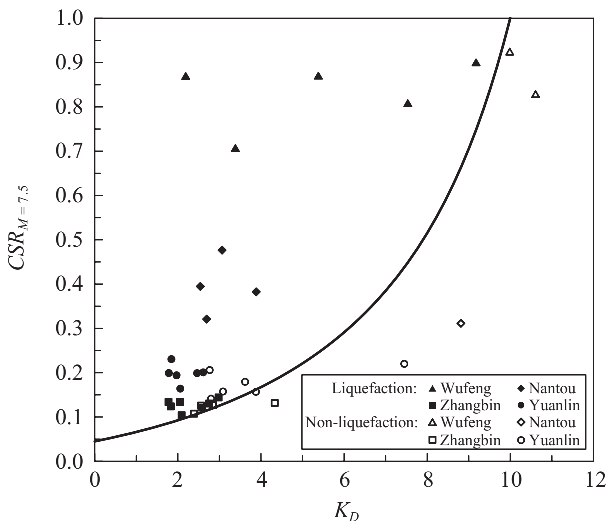


Fig. 9. Examination of the proposed $CRR_{7.5}$-K_D boundary curve for liquefaction evaluation using *CPT*- q_c data corrected by Robertson and Wride [14].

SPT data set and existing methods by Youd *et al.* [20] and Idriss and Boulanger [4]. However, it should be noted that the $N_{1,60cs}$-E_D correlation expressed in (15a) is employed in Figs. 7 and 8 to compute the E_D value based on the *SPT* data. The accuracy of the $CRR_{7.5}$-E_D curve in evaluating the liquefaction resistance of soils is essentially satisfactory as reflected by the result that 28 of 31 data points in Fig. 7 and 27 of 31 data points in Fig. 8 can be accurately estimated. Additional evaluation of accuracy of the $CRR_{7.5}$-E_D curve in both liquefaction and non-liquefaction zones can be referred to Table 3. Comparing the results in Figs. 7 and 8 with those in Figs. 5 and 6, the capability of the $CRR_{7.5}$-E_D curve in the accuracy of evaluating the liquefaction resistance of soils is slightly higher than that of the $CRR_{7.5}$-K_D curve, especially for the high $CSR_{7.5}$ scenarios.

3. Examination of the Proposed *DMT*-Based Method Using the *CPT* Data

In this section, the *DMT*-based $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D boundary curves (Eqs. (13a) and (13b)) are examined through the collected *CPT* data of liquefied and non-liquefied cases performed shortly after the Chi-Chi earthquake in Wufeng, Nantou, Zhangbin and Yuanlin. Figure 9 displays the results of examining the *DMT*-based $CRR_{7.5}$-K_D curve (Eq. (13a)). The method proposed by Robertson and Wride [14] for determining $CSR_{7.5}$ and $q_{c1N,cs}$ as well as the $q_{c1N,cs}$-K_D correlation

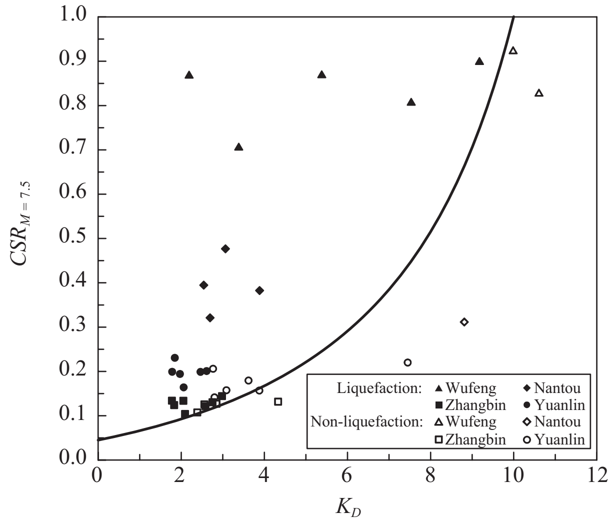


Fig. 10. Examination of the proposed $CRR_{7.5}$-K_D boundary curve for liquefaction evaluation using *CPT*- q_c data corrected by Youd *et al.* [20].

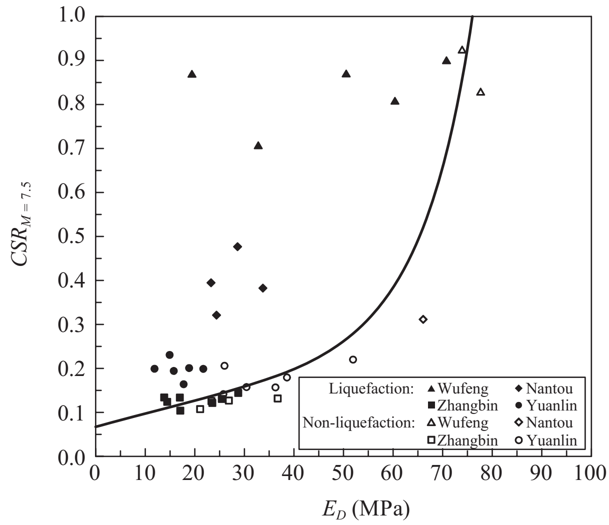


Fig. 12. Examination of the proposed $CRR_{7.5}$-E_D boundary curve for liquefaction evaluation using *CPT*- q_c data corrected by Youd *et al.* [20].

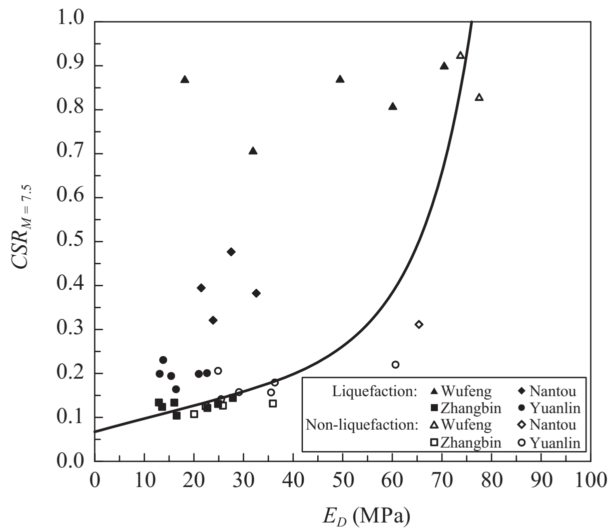


Fig. 11. Examination of the proposed $CRR_{7.5}$-E_D boundary curve for liquefaction evaluation using *CPT*- q_c data corrected by Robertson and Wride [14].

(Eq. (14b)) established by Tsai *et al.* [18] are employed together to examine the intended curves. Note that the procedure for estimating the $CSR_{7.5}$ proposed by Robertson and Wride [14] is identical to that by Youd *et al.* [20] as expressed in (2) to (5). Detailed scenarios and results of examining the $CRR_{7.5}$-K_D boundary curve can be referred to Table 3. As shown in Fig. 9, the accuracy of the $CRR_{7.5}$-K_D curve in assessing $CRR_{7.5}$ of soils is satisfactory in light of 28 of 35 data points can be accurately estimated (22 of 29 points in the liquefaction zone and 6 of 6 points in the non-liquefaction zone, respectively; see Table 3). Note that all the seven inaccurate points are non-liquefied and specifically, only one point is significantly far away from the $CRR_{7.5}$-K_D curve. Generally, the applicability of this boundary curve in evaluating $CRR_{7.5}$ of soils is considered acceptable. In addition, Fig. 10 shows the results of examining the $CRR_{7.5}$-K_D curve using the methods proposed by Youd *et al.* [20]. Essentially, the accuracy of the $CRR_{7.5}$-K_D curve is satisfactory in light of 28 of 35 data points can be accurately estimated (see Table 3).

Figures 11 and 12 examine the applicability of the $CRR_{7.5}$-E_D curve (Eq. (13b)) based on the same *CPT* data set and existing methods by Robertson and Wride [14] and Youd *et al.* [20]. It is noticeable that the $q_{c1N,cs}$-E_D correlation expressed in (15b) is applied in Figs. 11 and 12 to compute the E_D value through the *CPT* data. Overall, the accuracy of the $CRR_{7.5}$-E_D curve in evaluating $CRR_{7.5}$ of soils is satisfactory as reflected by the fact that 28 of 35 data points in Fig. 11 and 29 of 35 data points in Fig. 12 can be accurately estimated. Comparing the results in Figs. 11 and 12 with those in Figs. 9 and 10, the difference in the estimation of $CRR_{7.5}$ of soils using the $CRR_{7.5}$-E_D and $CRR_{7.5}$-K_D curves is insignificant.

V. DISCUSSIONS

The difference of accuracy of the $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves in liquefaction evaluation based on the *SPT*-$N_{1,60cs}$ estimated by Youd *et al.* [20] and Idriss and Boulanger [4] is fairly insignificant, while the similar results in liquefaction evaluation based on the *CPT*-$q_{c1N,cs}$ estimated by Robertson and Wride [14] and Youd *et al.* [20] can be also obtained. In fact, such results should be expected because the *SPT*-$N_{1,60cs}$ boundary curves proposed by Youd *et al.* [20] and Idriss and Boulanger [4] are close to each other. In this regard, it may be desirable to study the difference in evaluating the $CSR_{7.5}$ and $N_{1,60cs}$ (or $q_{c1N,cs}$) of soils between various existing methods

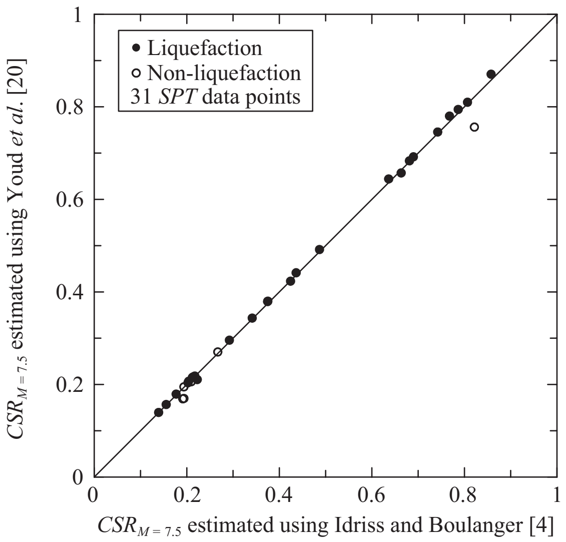


Fig. 13. Comparison of $CSR_{7.5}$ estimated using Youd *et al.* [20] and Idriss and Boulanger [4].

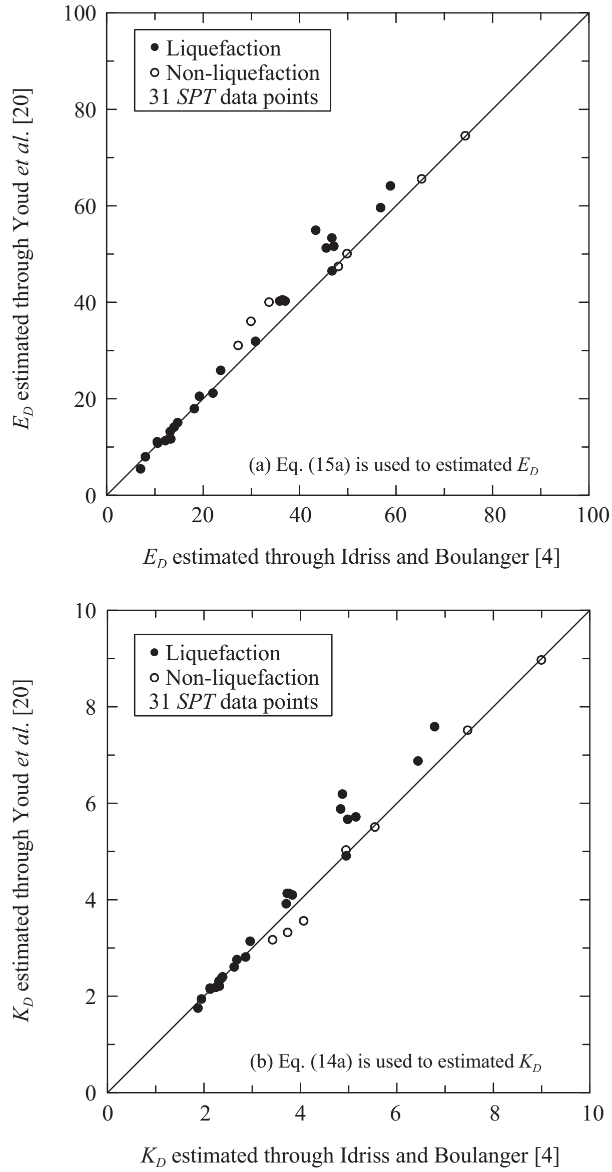


Fig. 14. Comparison of estimations of K_D and E_D based on correlations between K_D (or E_D) and $N_{1,60cs}$, and various existing methods for estimating $N_{1,60cs}$.

based on the collected case histories caused by the Chi-Chi earthquake.

Figure 13 shows the comparison of $CSR_{7.5}$ estimated for the critical soil layer of each case using Youd *et al.* [20] and Idriss and Boulanger [4]. The $CSR_{7.5}$ estimated using Youd *et al.* [20] is essentially identical to that estimated using Idriss and Boulanger [4]. This result is comparable with the conclusion by Juang [5], which indicated that the $CSR_{7.5}$ calculated based on the recommendation of Youd *et al.* [20] is very comparable with that recommended by Idriss and Boulanger [4] for case histories they analyzed. For the estimation of K_D and E_D through the *SPT*-$N_{1,60cs}$ (see Fig. 14), the difference of K_D or E_D estimated using the various methods at relative lower levels (e.g., $K_D < 3$; $E_D < 20$) is minute, whereas the values of K_D or E_D estimated beyond the range ($K_D \geq 3$; $E_D \geq 20$) using Youd *et al.* [20] are slightly greater than those estimated using Idriss and Boulanger [4]. However, for the estimate of K_D and E_D through C*PT*- $q_{c1N,cs}$ (see Fig. 15), all data points except one fall on the 1:1 perfect correlation line. Those results may be able to interpret the finding that the accuracy of $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves in liquefaction evaluation based on various test data (*SPT* or *CPT*) and various existing methods is similar.

VI. CONCLUSIONS

The liquefaction evaluation of soils for preventing and/or mitigating the earthquake-induced damage to facilities is often a challenge that requires proper attention of a geotechnical engineer. Although the existing *SPT*- and *CPT*-based methods of liquefaction evaluation are extensively used in the engineering design, to incorporate additional analytical methods into the process of liquefaction evaluation for obtaining the consistent liquefaction evaluation is desirable as indicated by Youd *et al.* [20]. The *DMT* may be a potential alternative to be used to estimate $CRR_{7.5}$ of soils. This study collected a number of liquefied and non-liquefied case histories, in which the in-situ *SPT* and/or *CPT* data are available, caused in the Chi-Chi earthquake (M_w = 7.6) to examine the *DMT*-based $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D boundary curves developed by Tsai *et al.* [18]. The performance of the $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves reveal that the accuracy of the two curves in evaluating the $CRR_{7.5}$ of soils is satisfactory and the difference in accuracy of the two curves, as reflected by the statistics in Table 3, is insignificant based on either of *SPT* and *CPT* data. Such results demonstrate that the correlations between $N_{1,60cs}$ (or $q_{c1N,cs}$) and K_D (or E_D) as well as the $CRR_{7.5}$-K_D and $CRR_{7.5}$-E_D curves established by Tsai *et al.* [18] may be capable of rea-

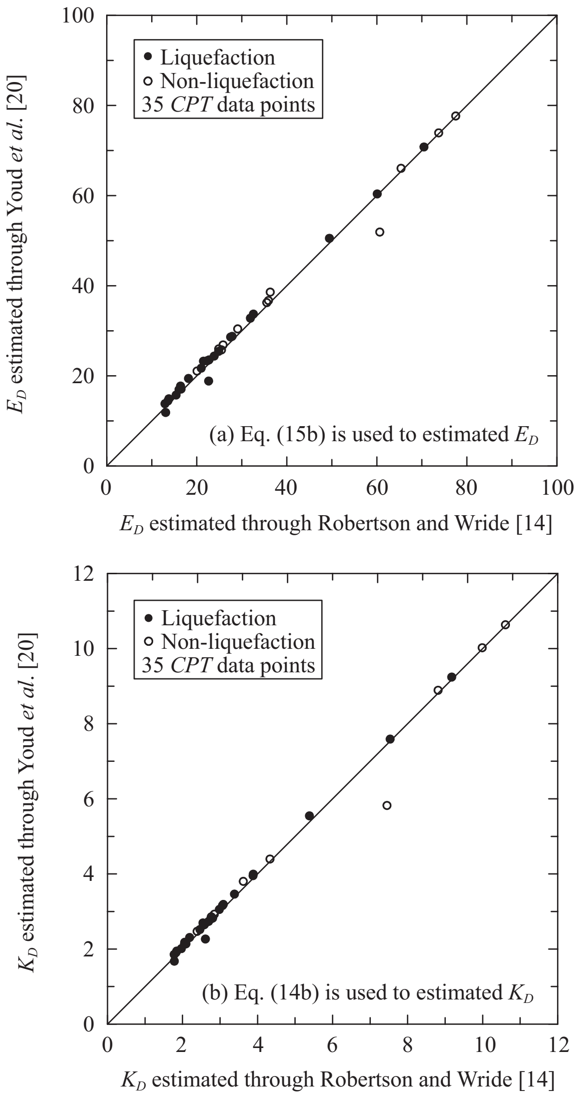


Fig. 15. Comparison of estimations of K_D and E_D based on correlations between K_D (or E_D) and $q_{c1N,cs}$, and various existing methods for estimating $q_{c1N,cs}$.

sonably estimating the triggering of liquefaction. Results show that the *DMT*-based method has a potential to be a practically useful tool for liquefaction evaluation in light of $CSR_{7.5}$ values of soils, ranging from 0.1 to 0.9, induced by the Chi-Chi earthquake is moderately representative. However, it is desirable to directly conduct *DMTs* in the liquefied and non-liquefied areas of the Chi-Chi earthquake to obtain more K_D and E_D data of soils for further validating the developed *DMT*-based liquefaction evaluation method although the results of this study are preliminarily satisfactory.

REFERENCES

1. Andrus, R. D. and Stokoe, K. H., "Liquefaction resistance of soils from shear-wave velocity," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 126, No. 11, pp. 1015-1025 (2000).
2. Chu, B. L., Hsu, S. C., and Chang, Y. M., "Ground *behavior* and liquefaction analyses in central Taiwan-Wufeng," *Engineering Geology*, Vol. 71, No. 1-2, pp. 119-139 (2004).
3. EERI, "Chi-Chi, Taiwan, earthquake of September 21, 1999, reconnaissance report," *Earthquake Spectra*, Supplement A to Vol. 17, in: Uzarski, J. and Arnold, C. (eds.), Earthquake Engineering Reserach Institute (EERI), Publication No. 2001-02, April, Oakland, CA (2001).
4. Idriss, I. M. and Boulanger, R. W., "Semi-empirical procedures for evaluating *liquefaction* potential during earthquakes," *Soil Dynamics and Earthquake engineering*, Vol. 26, pp. 115-130 (2006).
5. Juang, C. H., Fang, S. Y., and Khor, E. H., "First order reliability method for probabilistic liquefaction triggering analysis using *CPT*," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 132, No. 3, pp. 337-350 (2006).
6. Juang, C. H., Yuan, H., Lee, D. H., and Lin, P. S., "Simplified cone penetration test-based method for evaluating liquefaction resistance of soils," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 129, No. 1, pp. 66-79 (2003).
7. Ku, C. S., *A Study on Soil Classification and Liquefaction Evaluation Based on CPT*, PhD Dissertation, Department of Civil Engineering, National Cheng Kung University, Tainan, Taiwan (2001). (In Chinese)
8. Lee, D. H., Ku, C. S., and Yuan, H., "A study of the liquefaction risk potential at Yuanlin, Taiwan," *Engineering Geology*, Vol. 71, No. 1-2, pp. 97-117 (2004).
9. Lin, M. L., Liao, H. J., and Ueng, T. S., "The geotechnical hazard caused by Chi-Chi earthquake," *Proceeding of International Workshop on the September 21, 1999 Chi-Chi Earthquake*, Taichung, Taiwan, pp. 113-123 (1999).
10. MAA, "Site investigation of liquefied soil at Nantou and Wufeng areas," Moh and Associates (MAA), Taipei, Taiwan (2000). (In Chinese)
11. MAA, "Soil liquefaction Assessment and Remediation Study, Phase I (Yuanlin, Dachun, and Shetou)," Summary Report and Appendices, Moh and Associates (MAA), Taipei, Taiwan (2000). (In Chinese)
12. NCREE, "Reconnaissance Report of the *Geotechnical* Hazards Caused by Chi-Chi Earthquake," National Center for Research in Earthquake Engineering (NCREE), Taipei, Taiwan (2000). (In Chinese)
13. Robertson, P. K. and Campanella, R. G., "Liquefaction potential of sands using the *CPT*," *Journal of Geotechnical Engineering*, ASCE, Vol. 111, No. 3, pp. 384-403 (1985).
14. Robertson, P. K. and Wride, C. E., "Evaluating cyclic liquefaction potential using the cone penetration test," *Canadian Geotechnical Journal*, Vol. 35, pp. 442-459 (1998).
15. Seed, H. B., "Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes," *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 105, No. GT2, pp. 201-255 (1979).
16. Seed, H. B. and Idriss, I. M., "Simplified procedure for evaluating soil liquefaction potential," *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 97, No. SM9, pp. 1249-1273 (1971).
17. Seed, H. B., Tokimatsu, K., Harder, L. F., and Chung, R. M., "The influence of *SPT* procedures in soil liquefaction resistance evaluations," *Journal of Geotechnical Engineering, ASCE*, Vol. 111, No. 12, pp. 1425-1445 (1985).
18. Tsai, P. H., Lee, D. H., Kung, G. T. C., and Juang, C. H., "Simplified *DMT*-based methods for evaluating liquefaction resistance of soils," *Engineering Geology*, Vol. 103, No. 1-2, pp. 13-22 (2009).
19. Youd, T. L. and Idriss, I. M., *Proceedings of NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*, National center for earthquake engineering research, State University of New York at Buffalo (1997).
20. Youd, T. L., Idriss, I. M., Andrus, R. D., Arango, I., Castro, G., Christian, J. T., Dobry, R., Finn, W. D. L., Harder, L. F., Hynes, M. E., Ishihara, K., Koester, J. P., Liao, S. C., Marcuson, III W. F., Martin, G. R., Mitchell, J. K., Moriwaki, Y., Power, M. S., Robertson, P. K., Seed, R. B., and Stokoe, II K. H., "Liquefaction resistance of soils: summary report from 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils," *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, Vol. 127, No. 10, pp. 817-833 (2001).