Incorporating the Stress History Parameter K_D of DMT into the Liquefaction Correlations in Clean Uncemented Sands

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Abstract: This paper analyzes the possibility of reducing the uncertainty of the cyclic resistance ratio (CRR) estimates by incorporating stress history into the liquefaction correlations. A way of obtaining this objective stems from the combination of two well-recognized notions: (1) sensitivity of the flat dilatometer test (DMT) parameter K_D to stress history, and (2) necessity of stress history information to obtain better estimates of the liquefaction resistance. The main aim of this paper is to develop a framework providing CRR estimates based not on the one-to-one correlations CRR-Q_{cn} or CRR-K_D, but on a correlation based at the same time on both Q_{cn} and K_D. A Q_{cn}-K_D-CRR correlation has been constructed by combining the current CRR-Q_{cn} and CRR-K_D correlations. It is expectable that an estimate based at the same time on two measured parameters is more accurate than estimates based on just one parameter. 'A chart is presented providing estimates of CRR based at the same time on both Q_{cn} and K_D. **DOI: 10.1061/(ASCE)GT.1943-5606.0001380.**

Introduction

It is widely recognized that the cyclic resistance ratio (CRR) estimates by cone penetration test (CPT) are not always of a satisfactory reliability. For example, Robertson and Wride (1998) wrote "CRR by CPT may be adequate for low-risk projects. For high-risk projects estimate CRR by more than one method," and Idriss and Boulanger (2006) wrote "The allure of relying on a single approach (e.g., CPT-only) should be avoided." This uncertainty has stimulated a large number of studies, which however do not consider the addition of fresh collateral independent easily measured information on stress history.

This paper analyzes the possibility of reducing said uncertainty using the flat dilatometer (DMT) horizontal stress index K_D (often alternatively called stress history index).This possibility stems from the combination of two notions that are well recognized today: (1) sensitivity of K_D to stress history, and (2) necessity of stress history information to obtain better estimates of the liquefaction resistance.

1. The higher sensitivity to stress history of K_D, compared with the sensitivity of Q_{cn} (normalized cone tip Q_c resistance), has been observed by numerous researchers, either in the calibration chamber (e.g., Jamiolkowski and Lo Presti 1998) or in the field (e.g., Schmertmann et al. 1986; Jendeby 1992; Marchetti 2010). An expressive example, clearly illustrating the different sensitivity, is shown in Fig. 1 (Lee et al. 2011). CPT and DMT were executed in the calibration chamber on 40 large specimens of Busan silica sand, partly normally consolidated (NC) and partly previously preconsolidated to overconsolidation ratio (OCR) in the range 1–8. Then the Q_{cn} and K_D obtained before and after the preconsolidation were compared. The two diagrams in Fig. 1 confirm that K_D is considerably more reactive to OCR than Q_{cn}. A consequence of Fig. 1 is that the same Q_{cn} can correspond to various values of K_D, as shown in the schematic example in Fig. 2. In the example Site 2 has the same q_c profile as Site 1, but has a higher K_D, suggesting higher stress history, and hence higher CRR. This benefit would not be detected by just the two identical profiles of Q_{cn}. Another interesting consequence of Fig. 1 is the necessity of both Q_{cn} and K_D to evaluate OCR in sand. If only K_D is known and is entered in Fig. 1(b), its value could be due to a low relative density D_r and a high OCR or to a high D_r and a low OCR. In order to evaluate OCR, q_c must also be available to provide an indication of D_r on the horizontal axis.
2. The necessity of stress history information for assessing liquefaction resistance CRR has long since been recognized (e.g., Youd and Idriss 2001; Salgado et al. 1997; Monaco and Schmertmann 2007; Harada et al. 2008). Even before, Jamiolkowski et al. (1985), based on extensive calibration chamber studies, had warned "Reliable predictions of liquefaction resistance of sand deposits having complex stress-strain history require the development of some new in situ device [other than CPT or SPT] much more sensitive to the effects of past stress-strain histories, because stress history produces a small increase in penetration resistance, but a significant increase in CRR and in stiffness of a cohesionless soil."

Construction of a Q_{cn}-K_D-CRR Correlation

The main aim of this paper is to develop a framework providing CRR estimates based not on the one-to-one correlations of CRR-Q_{cn} or CRR-K_D, but on a correlation based at the same time on both Q_{cn} and K_D. This Q_{cn}-K_D-CRR correlation, as shown in this section, has been constructed by combining the current CRR-Q_{cn} and CRR-K_D correlations.

CRR-Q_{cn} *Correlation*

Today's standard practice for evaluating the liquefaction resistance CRR is to use the well-known correlations CRR-Q_{cn} described in numerous papers (e.g., Youd and Idriss 2001; Robertson and Wride 1998; Idriss and Boulanger 2006). The CRR-Q_{cn} correlations,

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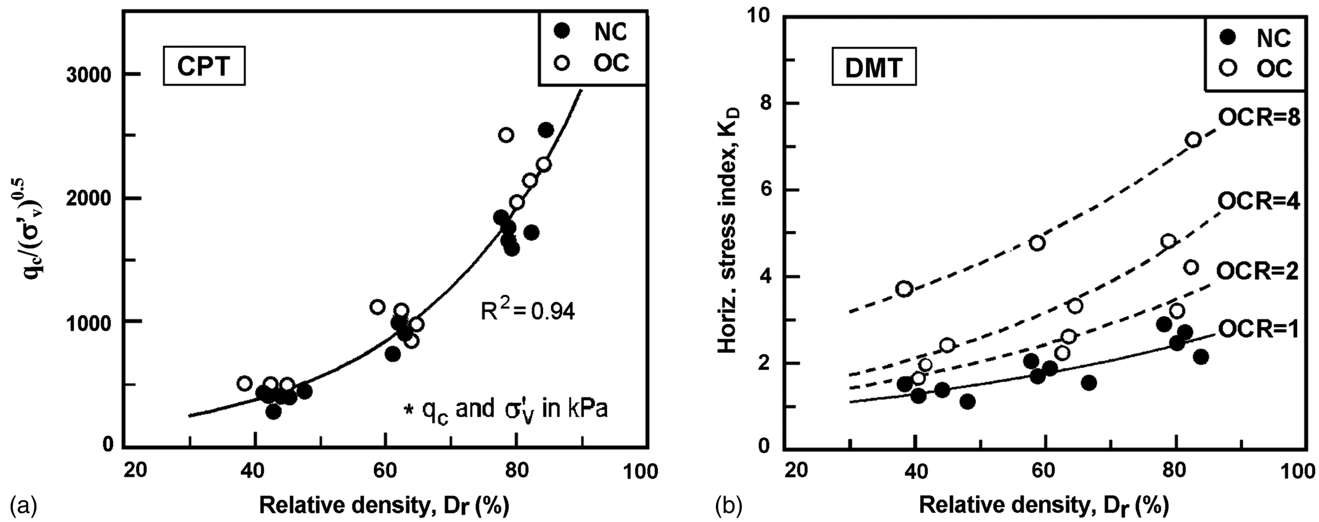


Fig. 1. Sensitivity of CPT and DMT to stress history: (a) CPT; (b) DMT (Reprinted from Engineering Geology, Vol. 117, No. 3-4, Moon-Joo Lee, Sung-Kun Choi, Min-Tae Kim, Woojin Lee, "Effect of stress history on CPT and DMT results in sand", pp. 259-265, Copyright (2011), with permission from Elsevier)

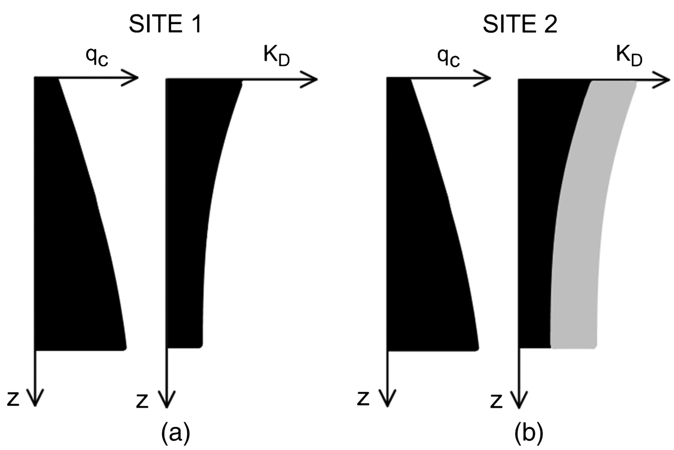
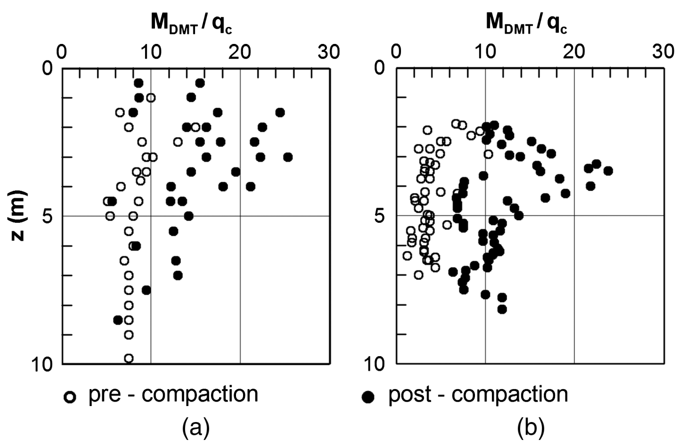


Fig. 2. Schematic profiles of two sites having the same q_c but different K_D



$$\mathrm{OCR} = 0.0344\,(M_{DMT}/q_c)^2 - 0.4174\,(M_{DMT}/q_c) + 2.2914$$

(c)

Fig. 3. (a) M_{DMT}/q_c before and after compaction (data from Jendeby 1992); (b) M_{DMT}/q_c ratio before and after compaction (data from Balachowski and Kurek 2015); (c) correlation OCR versus M_{DMT}/q_c (Monaco et al. 2014)

despite various uncertainties, are the result of a large number of documented real earthquake data. The CRR-Q_{cn} correlation adopted in this paper, Eq. (1*a*) ahead in the paper, is the Idriss and Boulanger (2006) correlation (somewhat more conservative than the previous Robertson and Wride correlation).

CRR-K_D Correlation

CRR estimates are also made using CRR-K_D correlations. This section provides some background on these correlations. The first CRR-K_D correlations go back to Marchetti (1982) and Robertson and Campanella (1986). Since then, numerous updated curves have been produced (e.g., Reyna and Chameau 1991; Monaco et al. 2005; Tsai et al. 2009; Robertson 2012). These research efforts have been stimulated by the fact that the factors increasing K_D of a sand also increase its liquefaction resistance. For example, Robertson and Campanella (1986) listed the following factors: (1) relative density, (2) in situ K_o, (3) stress history and prestressing, (4) aging, and (5) cementation. Robertson and Campanella (1986) also pointed out that it is not possible to identify the individual contribution of each factor to K_D. On the other hand, when K_D is low, none of these factors is high, that is the sand is loose, uncemented, in a low horizontal stress environment, and has little stress history. A sand under these conditions may be prone to liquefaction. In this paper, the term stress history is meant to globally include any factor making the sand more stable than a freshly deposited sand.

- Sensitivity of K_D to OCR: Schmertmann et al. (1986) observed that, upon compaction (which increases OCR), the percentage increase of M_{DMT} (the constrained modulus by DMT) was twice the percentage increase of q_c (the increase of M_{DMT} is primarily due to the increase of K_D). More recently numerous compaction jobs include before-after CPTs and DMTs. The presentation of the comparisons often includes the before-after M_{DMT}/q_c versus z profiles [Figs. 3(a and b)]. The fact that M_{DMT}/q_c increases with compaction indicates that M_{DMT} (and hence K_D) increases with OCR at a faster rate than q_c, confirming the

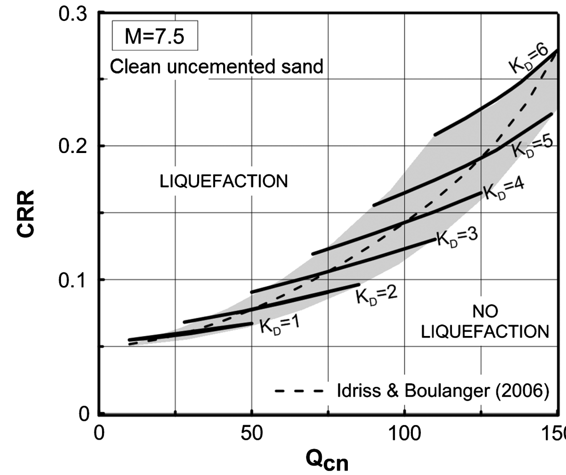


Fig. 4. Chart for estimating CRR in clean sand based on Q_{cn} and K_D

Schmertmann et al. (1986) observation, and is in agreement with Fig. 1. The M_{DMT}/q_c profiles also permit an evaluation of the achieved OCR increase, using, e.g., the Monaco et al. (2014) equation OCR - M_{DMT}/q_c in Fig. 3(c).

- Sensitivity of K_D to pure prestressing: K_D has been found to be substantially more sensitive than penetration resistance to pure prestressing, consisting in cycles of loading-unloading along the K_o line, followed by unloading to the initial vertical and horizontal stress, without locked-in horizontal stresses (Jamiolkowski and Lo Presti 1998; Marchetti 1982).
- Sensitivity of K_D to aging: Results shown by Monaco and Schmertmann (2007) and in the various references mentioned by them, by Marchetti (2010) and by Kurek and Balachowski (2015), indicate that K_D is substantially more sensitive to aging than penetration resistance.

The CRR-K_D correlation adopted in this paper is the Idriss and Boulanger (2006) correlation combined with $Q_{cn} \approx 25K_D$, following a procedure suggested by Robertson (2012). Thus the adopted CRR-K_D correlation is given by the combination of Eqs. (1*a*) and (1*b*)

$$\mathrm{CRR} = \exp[(Q_{cn}/540) + (Q_{cn}/67)^2 - (Q_{cn}/80)^3 + (Q_{cn}/114)^4 - 3] \tag{1a}$$

$$\text{with} \quad Q_{cn} = 25K_D \tag{1b}$$

Combining the CRR-Q_{cn} *Correlation and the* CRR-K_D *Correlation*

A combined correlation for estimating CRR based on Q_{cn} and K_D has been obtained by adopting as CRR the geometric average between a first CRR estimate obtained from Q_{cn} [Eq. (1*a*)] and a second CRR estimate obtained from K_D [Eqs. (1*a*) and (1*b*)], namely

$$\text{Average CRR} = [(\text{CRR from } Q_{cn}) \times (\text{CRR from } K_D)]^{0.5} \tag{2}$$

Eq. (2) has been plotted in Fig. 4 as a function of Q_{cn}.

K_D-$Q_{cn} \approx 25$ *Relation*

Eq. (1*b*), suggested by Robertson (2012), used in the previous sections, is highly approximate. It was obtained by Robertson by interpolating a straight line through the Tsai et al. (2009) data points [Fig. 5(a)]. Figs. 5(b–d) have been added in Fig. 5 as additional examples

of the Q_{cn}-K_D correlation in clean sand. All data are for a DMT material index Id > 3, i.e., for clean sand. The three added figures essentially confirm both the average value 25, and the considerable dispersion. The high observed dispersion in the K_D-Q_{cn} relation is, to a large extent, the consequence of the higher reactivity of K_D to stress history (Fig. 1). If the scatter were small, it would mean that Q_{cn} and K_D contain equivalent information, which is negated by Fig. 1. The high scatter indicates that K_D contributes fresh collateral independent information to the characterization of the sand.

Comments on the Q_{cn}-K_D-CRR *Chart in Fig. 4*

- A plot similar to Fig. 4 was proposed by Harada et al. (2008), who suggested using K_o as a parameter in the curves. It is observed that K_o in sand can be estimated, e.g., by the correlations developed by Baldi et al. (1986) expressing K_o as a function of K_D and Q_{cn}, but these estimates are often uncertain and subjective, while K_D is accurately, easily, and unequivocally determined. Moreover, K_D is a cumulative parameter reflecting, besides K_o, other stress history factors increasing CRR.
- The essence of Fig. 4 is to estimate CRR from Q_{cn} by the everyday CPT correlations. Then if K_D is higher than average ($K_D > Q_{cn}/25$), increase CRR; if K_D is lower than average, reduce CRR. Described in this way Fig. 4 appears to be common sense, supporting the expectation that the real earthquake data points will plot not far from the curves.

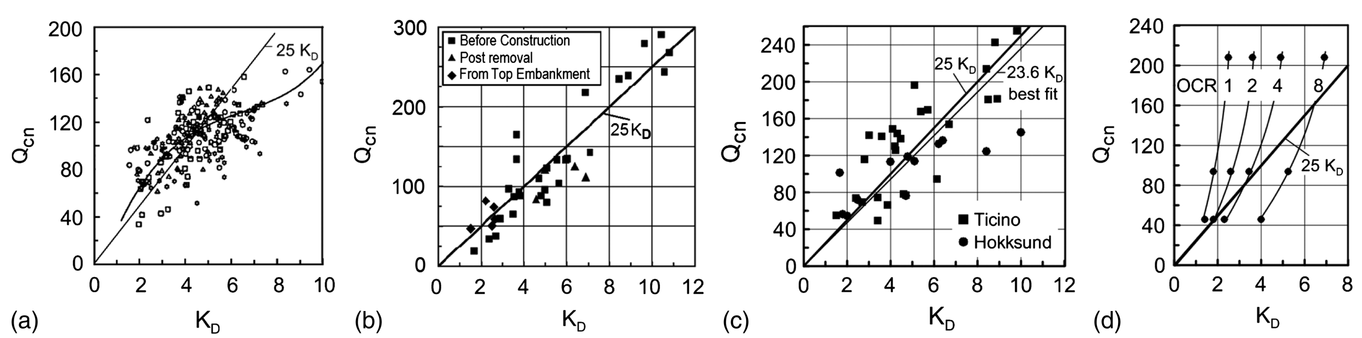


Fig. 5. K_D-Q_{cn} relations: (a) from five Taiwan sand sites [reprinted from Engineering Geology, Vol. 103, No. 1-2, Pai-Hsiang Tsai, Der-Her Lee, Gordon Tung-Chin Kung, C. Hsein Juang, "Simplified DMT-based methods for evaluating liquefaction resistance of soils", pp. 13-22, Copyright (2009), with permission from Elsevier]; (b) from Treporti research site; (c) from calibration chamber results (data from Baldi et al. 1986); (d) derived from Fig. 1

- The K_D = constant lines have a limited length because, for any given K_D, only a limited range of Q_{cn} exists, as can be seen in Fig. 5.
- The CRR provided graphically by Fig. 4 can alternatively be calculated using Eq. (2), where CRR from Q_{cn} is Eq. (1*a*) and CRR from K_D is the combination Eqs. (1*a*) and (1*b*).
- Fig. 4 requires considerable real earthquake verification. It is to be regarded as an initial framework for initiating the accumulation of colocated Q_{cn}-K_D-CRR data points.

Concluding Remarks

- Numerous studies have shown that K_D is an effective indicator of stress history and that information on stress history is necessary to obtain reasonable estimates of CRR. This paper analyzes the possibility of reducing the uncertainty in estimating CRR by incorporating the DMT stress history index K_D into the liquefaction correlations.
- By combining the commonly used CRR-Q_{cn} and CRR-K_D correlations to estimate CRR, a plot has been constructed (Fig. 4) providing estimates of CRR based at the same time on both Q_{cn} and K_D. It is expectable that an estimate based at the same time on two measured parameters is more accurate than estimates based on just one parameter.
- The essence of Fig. 4 is estimating CRR from Q_{cn} by the everyday CPT correlations. Then, if K_D is higher than average ($K_D > Q_{cn}/25$), increase CRR; if K_D is lower than average, reduce CRR. Described in this way Fig. 4 appears to be common sense, supporting the expectation that the real earthquake data points will plot not far from the curves.
- Fig. 4 was constructed with clean uncemented sand in mind. If the sand contains fines or is cemented, estimating CRR is much more complex. For example, the cementation can be ductile (toothpastelike) or fragile (glasslike), a quality that affects either Q_{cn} or K_D and the sand liquefaction behavior. Fine content may possibly have effects similar to a ductile cementation. Clearly the unknowns are too many and it may be not sufficient to add the K_D information to Q_{cn}. The knowledge of G_o (small-strain shear modulus) could possibly help, because high G_o/q_c and/or high G_o/M_{DMT} (Schnaid et al. 2004; Cruz et al. 2012) are also indicators of cementation. Even the dilatometer modulus E_D from DMT could possibly help. Considerable additional study is clearly necessary if the sand is not a clean uncemented sand.

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