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 $K_D$. An $Q_{cn}$-$K_D$-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. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, http://creativecommons.org/licenses/by/4.0/.

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 $Q_t$ resistance), has been observed by numerous researchers, either in the calibration chamber (e.g., Jamiołkowski 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 $Q_t$ 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, $q_t$ 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, Jamiołkowski 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 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,
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. (1a) 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 $K_0$, (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, uncedmented, 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
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. (1a) and (1b)

$$\text{CRR} = \exp\left(\frac{Q_{cn}}{540} + \frac{(Q_{cn}/67)^2}{2} - \frac{(Q_{cn}/80)^3}{2} + \frac{(Q_{cn}/114)^4}{2} - 3\right)$$

with $Q_{cn} = 25K_D$  \hspace{1cm} (1a)

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 CRR as the geometric average between a first CRR estimate obtained from $Q_{cn}$ [Eq. (1a)] and a second CRR estimate obtained from $K_D$ [Eqs. (1a) and (1b)], namely

$$\text{Average CRR} = \left(\text{CRR from } Q_{cn}\right) \times \left(\text{CRR from } K_D\right)^{0.5}$$

(2)

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

$K_D$-$Q_{cn}$ Correlation

Eq. (1b), 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 $I_d > 3$, 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.
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 uncremented sand in mind. If the sand contains fines or is cemented, estimating CRR is much more complex. For example, the cementation can be ductile (toothpaste-like) 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 not be sufficient to add the $K_D$ information to $Q_{cn}$. The knowledge of $G_s$ (small-strain shear modulus) could possibly help, because high $G_s/q_s$ and/or high $G_s/M_{DMD}$ (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 uncremented sand.

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