Overburden normalization of CPT data in sands to clays

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ABSTRACT: Frameworks for estimating soil properties from CPT penetration resistances must account for the effects of overburden stress on both the penetration resistance and the soil property of interest, including how such effects vary with soil type. For example, common procedures for estimating the liquefaction resistance of sands include functional terms that account for the effect of overburden stress on the penetration resistance (i.e., the C_N factor) and cyclic resistance ratio (i.e., the K_σ factor). Common procedures for estimating monotonic and cyclic undrained shear strengths of clays use different notations and functional terms. A single framework for all soil types is a necessary step toward more rational interpretation of properties for intermediate soils. This paper examines the use of a common framework for overburden normalizations of penetration resistance and cyclic resistance ratios in clean sand and ordinary sedimentary clay, with the normalizations cast in terms of either a constant state parameter (ξ) or a constant void ratio (e). The examination of these terms for clean sand and ordinary sedimentary clay provides useful bounds for generalization of these frameworks across intermediate soil types.

1 INTRODUCTION

CPT and SPT penetration resistances vary with overburden stress in all soil types, such that frameworks for estimating soil properties from penetration resistances have to account for the overburden stress in some way. The effects of overburden stress on penetration resistance and specific soil properties is different in clays than in sands, such that different approaches have been adopted for different soil types and problem applications (e.g., Robertson & Campanella 1983, Wroth 1984, Olsen & Malone 1988, Boulanger & Idriss 2004, Moss et al. 2006).

This paper examines the use of a common framework for overburden normalizations of penetration resistance and cyclic resistance ratios (*CRR*) in clean sand and ordinary sedimentary clay. The overburden normalization of penetration resistances conditional on either a constant state parameter (ξ) or a constant void ratio (e) are reviewed first, followed by the development of overburden correction factors for sand and ordinary clays. The overburden normalization of *CRR*, similarly conditional on either a constant ξ or constant e, is then examined for both soil types. The results provide useful bounds for the generalization of these frameworks across a range of intermediate soil types.

2 OVERBURDEN NORMALIZATION OF PENETRATION RESISTANCES

The effect of overburden stress on cone penetration resistance has been extensively studied, both experimentally and theoretically, with a number of important features having become well accepted. First, the measured tip resistance (q_c) must be corrected for unequal end area effects (Campanella et al. 1982), which in CPT literature is commonly expressed as,

$$q_t = q_c + (1 - a_r)u_2 \quad (1)$$

where q_t = the cone tip resistance corrected for unequal end area effects, a_r = area ratio for the cone tip, and u_2 = pore pressure measured behind the cone tip. The magnitude of this correction is typically quite small for sands (as $u_2 \approx u_0$), but can be significant for soft clays (as $u_2 > u_0$), especially offshore due to high hydrostatic water pressures (u_0). In literature related to liquefaction of sands, it is not uncommon to see the terms q_c and q_t used interchangeably even if the correction for unequal area effects has been performed. Explicit distinction between these terms is, however, advantageous in developing methods intended for a range of soil types.

Soil properties are best related to the net tip resistance ($q_{t,net}$) which is the tip resistance in excess of the in-situ total vertical stress (σ_v), rather than to the tip resistance directly (e.g., Robertson 1990). The net tip resistance can then be divided by the in-situ effective vertical stress (σ'_v) to obtain the parameter,

$$Q = \frac{q_t - \sigma_v}{\sigma'_v} = \frac{q_{t,net}}{\sigma'_v} \quad (2)$$

The term Q has been used extensively in soil behavior type classification schemes and soil property correlations (e.g., Robertson 2009), with a number of different subscripts indicating various assumptions important to a specific application. Herein subscripts are omitted from Q for clarity.

The net tip resistance varies nonlinearly with σ'_v by an amount that depends on soil type. It has therefore been desirable to further normalize the parameter Q to an equivalent reference stress condition, to produce a normalized parameter that is largely independent of σ'_v and which can be more uniquely correlated to various soil properties (e.g., *CRR*). The form of previous normalization schemes, as reviewed by Robertson (2009), generally assumes that Q varies in proportion to σ'_v raised to an exponent m, with m ranging from about 0.5 for sands to 1.0 for clays. The fundamental basis for determining the exponent m has not always been explicitly stated and appears to have been different for sands and clays in many cases.

One approach to stress-normalization is to target a normalized tip resistance that correlates to the properties of the same soil at the same void ratio at the specified reference stress (commonly taken as $\sigma'_v = P_a$ = 1 atm = 101.3 kPa = 2117 psf), with all other variables also remaining constant (e.g., same lateral earth pressure coefficient, same over-consolidation ratio, same cementation, same age, same stress and strain history). The normalized tip resistance for this approach may be expressed as,

$$Q_{1e} = \frac{q_t - \sigma_v}{P_a}\left(\frac{P_a}{\sigma'_v}\right)^{m_e} \quad (3)$$

or, in parts as,

$$Q_{1e} = \frac{q_t - \sigma_v}{P_a} C_{Ne} \quad (4)$$

$$C_{Ne} = \left(\frac{P_a}{\sigma'_v}\right)^{m_e} \quad (5)$$

where Q_{1e} = normalized net penetration resistance for the soil at the same void ratio and a σ'_v of 1 atm, C_{Ne} = overburden correction factor for normalizing at the same void ratio, and m_e = the stress exponent for normalizing at the same void ratio.

Overburden correction factors for sand have, for example, historically been developed for correlating to the properties of a sand at the same relative density (D_R), which is equivalent to targeting the same void ratio (e.g., Marcuson & Bieganousky 1977, Skempton 1986, Liao & Whitman 1986, Boulanger 2003). For this reason, the C_N factors presented in these earlier studies for sands would be better referred to as C_{Ne} factors. In addition, the overburden corrected penetration resistance (q_{c1}) referred to in many liquefaction analysis procedures for sands (e.g., Robertson & Wride 1998, Idriss & Boulanger 2008) would be better represented by the parameter Q_{1e}, recognizing that the two are approximately equal in sands.

A second approach to stress-normalization is to target a normalized tip resistance that correlates to the properties of the same soil at the same state parameter (ξ). The state parameter (Wroth & Bassett 1965, Been & Jefferies 1985) is the difference between the void ratio at critical state and the current void ratio at the same mean effective stress. In this case, the normalized tip resistance represents the tip resistance that would be obtained in the same soil at the same ξ at the specified reference stress (again taken as $\sigma'_v = P_a = 1$ atm), with all other variables also remaining constant (e.g., same lateral earth pressure coefficient, same over-consolidation ratio, same cementation, same age, same stress and strain history). The normalized tip resistance for this approach may be expressed as (Maki et al. 2013),

$$Q_{1\xi} = \frac{q_t-\sigma_v}{P_a}\left(\frac{P_a}{\sigma'_v}\right)^{m_\xi} \tag{6}$$

or, in parts as,

$$Q_{1\xi} = \frac{q_t-\sigma_v}{P_a} C_{N\xi} \tag{7}$$

$$C_{N\xi} = \left(\frac{P_a}{\sigma'_v}\right)^{m_\xi} \tag{8}$$

where $Q_{1\xi}$ = normalized net penetration resistance for the soil at the same ξ and a σ'_v of 1 atm, $C_{N\xi}$ = overburden correction factor for normalizing at the same ξ, and m_ξ = the stress exponent for normalizing at the same ξ.

Expected variations of C_{Ne}, $C_{N\xi}$, m_e and m_ξ for sands and clays are examined in the following sections to provide bounds on what might be reasonably expected for intermediate soils.

3 OVERBURDEN CORRECTION FACTORS C_{Ne} AND $C_{N\xi}$ FOR SAND

An example of the expected variation of net cone tip resistance with σ'_v in a typical sand is illustrated in Figure 1 based on the relationships proposed by Boulanger & Idriss (2004). These relationships were derived using the numerical model of Salgado et al. (1997) which was calibrated to a database of over 400 cone calibration chamber tests on several sands with σ'_v up to about 7 atm.

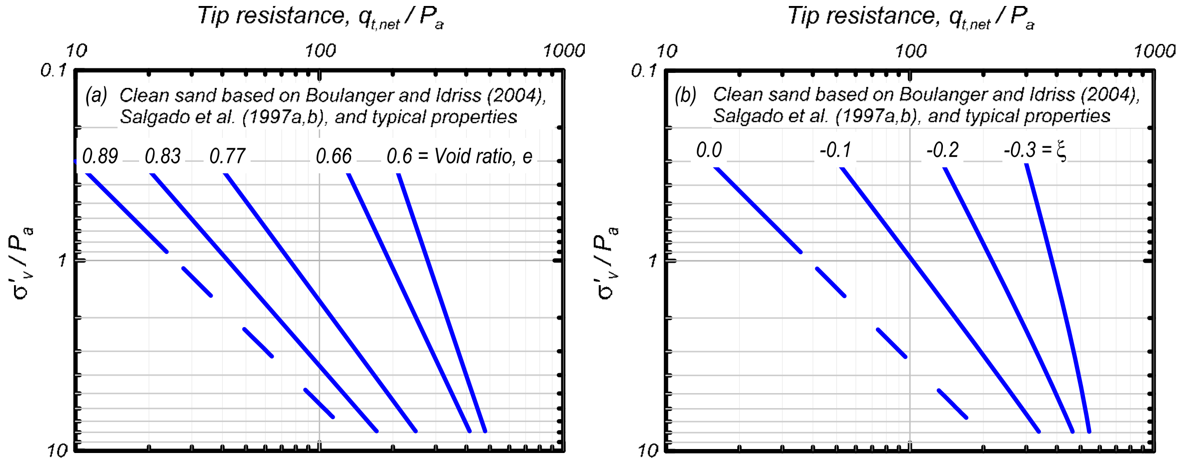

Figure 1. Net cone tip resistance versus overburden stress for a clean sand at: (a) a range of initial void ratios, and (b) a range of initial state parameters.

Boulanger & Idriss (2004) related D_R to the overburden normalized penetration resistance, which using the notation adopted herein and neglecting the small difference between $q_{t,net}$ and q_t in sands would be expressed as,

$$D_R = 0.465\left(\frac{Q_{1e}}{C_{dq}}\right)^{0.264} - 1.063 \qquad (9)$$

The parameter C_{dq} is a constant that varies with the characteristics of sand; Boulanger & Idriss (2004) indicated that C_{dq} values of 0.64 to 1.55 would encompass the relationships derived by Salgado et al. (1997a) for upper and lower ranges of sand properties. The ξ was determined from an empirical critical state line derived from Bolton's (1986) dilatancy relationship as,

$$\xi = \left(\frac{R}{Q - \ln\left(\frac{100p'}{P_a}\right)} - D_R\right)(e_{max} - e_{min}) \qquad (10)$$

where Q and R are empirical constants dependent on soil mineralogy (Bolton suggested values of 10 and 1.0, respectively, for quartz sands) and e_{max} and e_{min} are the maximum and minimum void ratios by reference tests, respectively. Boulanger & Idriss' (2004) expressions for C_{Ne} corresponds to Equation 5 with

$$m_e = 0.784 - 0.521D_R \qquad (11)$$

and their expression for $C_{N\xi}$ corresponds to

$$C_{N\xi} = \left(\frac{P_a}{\sigma'_v}\right)^{m_e}\left(\frac{D_R - \Delta D_{R,CS} + 1.063}{D_R + 1.063}\right)^{3.788} \qquad (12)$$

$$\Delta D_{R,CS} = \frac{1}{Q - ln\left(100\frac{1+2K_o}{3}\frac{\sigma'_v}{P_a}\right)} - \frac{1}{Q - ln\left(100\frac{1+2K_o}{3}\right)} \qquad (13)$$

where K_o is the coefficient of lateral earth pressure at rest.

The relationships in Figure 1a show $q_{t,net}$ versus σ'_v for a sand at five different void ratios (0.6, 0.66, 0.77, 0.83, and 0.89) corresponding to D_R of 0%, 20%, 40%, 80%, and 100% based on Q = 10, R = 1, K_o = 0.45, e_{max} = 0.89, and e_{min} = 0.6. The slopes of these q_t versus σ'_v graphs, in this log-log scale, correspond to the stress exponent m_e. These results illustrate how the stress exponent m_e increases with increasing D_R for sands (i.e., steeper lines in Figure 1a). The corresponding dependence of C_{Ne} on D_R is shown in Figure 2.

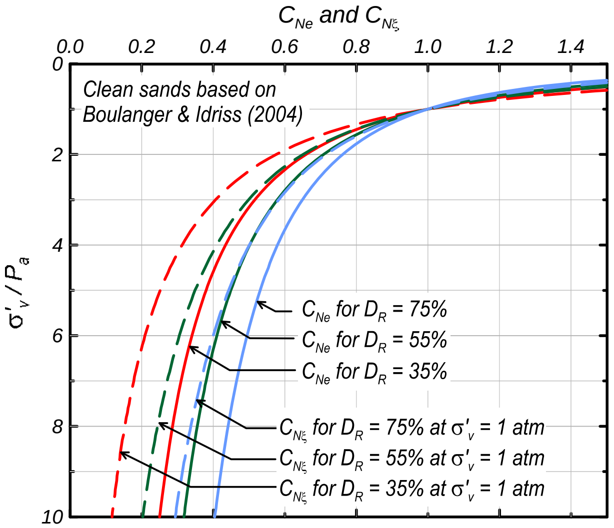

Figure 2. C_{Ne} and $C_{N\xi}$ relationships for sand as recommended by Boulanger and Idriss (2004).

The relationships in Figure 1b show $q_{t,net}$ versus σ'_v for the same sand at four different initial values of ξ (-0.3, -0.2, -0.1, and 0.0). These $q_{t,net}$ versus σ'_v graphs are slightly curved in this log-log scale. These results also illustrate how the stress exponent m_ξ will increase with increasing denseness for sands (i.e., more negative ξ). The corresponding dependence of $C_{N\xi}$ on denseness is shown in Figure 2 for ξ values corresponding to the same D_R, at $\sigma'_v = 1$ atm as examined for C_{Ne}. Comparing the curves in Figures 1 and 2 show that the m_ξ values are greater than m_e values for similar degrees of denseness.

4 OVERBURDEN CORRECTION FACTORS C_{Ne} AND $C_{N\xi}$ FOR CLAY

The expected variation of $q_{t,net}$ with σ'_v in a saturated deposit of an ordinary sedimentary clay is illustrated in Figure 3 based on established relationships between undrained shear strength (S_u), cone penetration resistance, and a set of typical soil properties. The relationships in Figure 3 are based on assuming that the clay's consolidation and shear strength behaviors are described by a Modified Cam Clay model with M=1.2, $\lambda = 0.2$, $\Gamma = 2.76$ and $\kappa = 0.025$. The S_u in isotropically consolidated undrained triaxial compression for the Modified Cam Clay model can be expressed as an undrained shear strength ratio,

$$\frac{S_u}{\sigma'_{vc}} = \frac{M}{2}\left(\frac{OCR}{2}\right)^{1-\frac{\kappa}{\lambda}} \qquad (14)$$

The undrained strength ratio obtained using this expression is,

$$\frac{S_u}{\sigma'_{vc}} = 0.327(OCR)^{0.875} \qquad (15)$$

which is the same form incorporated in the SHANSEP procedure by Ladd & Foott (1974). The void ratio can be computed from the consolidation stress and stress history, giving ξ as,

$$\xi = -ln\left[\left(\frac{2}{OCR}\right)^{\kappa-\lambda}\right] \qquad (16)$$

The cone penetration resistance is then computed using the expression,

$$q_t = N_{kt}S_u + \sigma_{vo} \qquad (17)$$

where N_{kt} is the cone bearing factor, which is assumed to be 14 for this example.

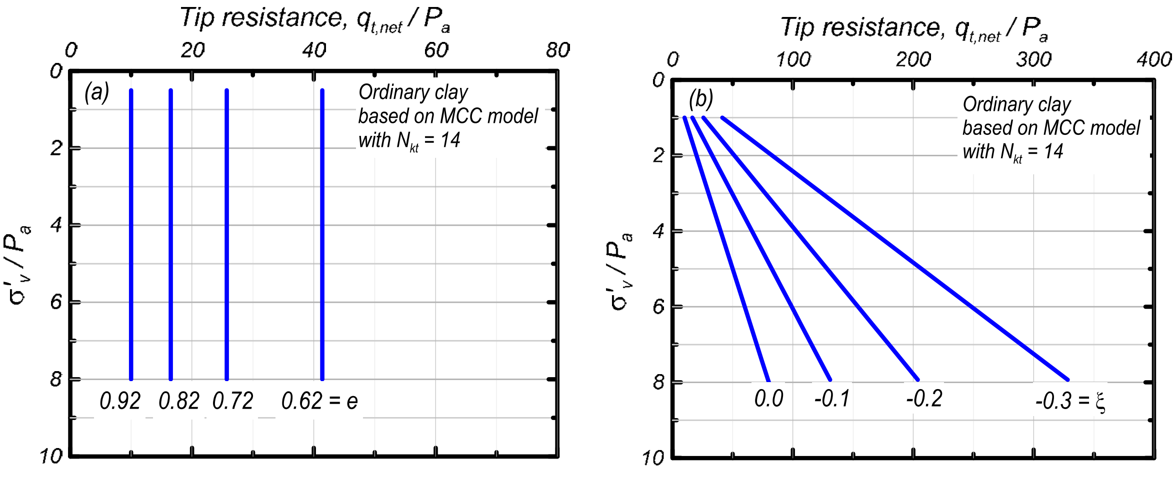

Figure 3. Cone tip resistance versus overburden stress for clay represented by the Modified Cam Clay (MCC) model at: (a) a range of initial void ratios, and (b) a range of initial state parameters.

The relationships in Figure 3a show $q_{t,net}$ versus σ'_v for the clay at four different initial void ratios (0.4, 0.5, 0.6, and 0.7). The values of $q_{t,net}$ are constant versus depth because a constant void ratio means that S_u is also constant versus depth; note that this also requires OCR to progressively decrease with increasing depth. The corresponding stress exponent m_e is thus equal to 0.0 for ordinary clay, which means that C_{Ne} = 1.0 for all stresses as shown in Figure 4.

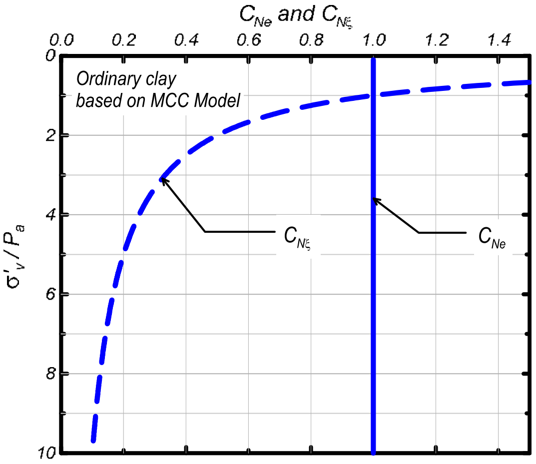

Figure 4. C_{Ne} and $C_{N\xi}$ relationships derived for ordinary sedimentary clay.

The relationships in Figure 3b show $q_{t,net}$ versus σ'_v for the clay at four different initial values of ξ (-0.3, -0.2, -0.1, and 0.0). The values of $q_{t,net}$ increase linearly with depth because a constant ξ means that *OCR* and S_u/σ'_{vc} are also constant with depth. The corresponding stress exponent m_ξ is thus equal to 1.0 for ordinary clays. The resulting $C_{N\xi}$ relationship, shown in Figure 4, varies more strongly with σ'_v than the corresponding $C_{N\xi}$ relationships for sand (Figure 2).

5 COMPARING OVERBURDEN CORRECTION FACTORS FOR SAND AND CLAY

The values for Q_{1e} and m_e derived for sand and clay in the previous sections are compared in Figures 5a and 5b, respectively. For the same void ratio, the Q_{1e} values are much greater in sand than in clay. The m_e values for sand range from about 0.75 at large void ratios (low D_R) to about 0.20 for small void ratios (high D_R), while the m_e values for clay are 0 for all void ratios.

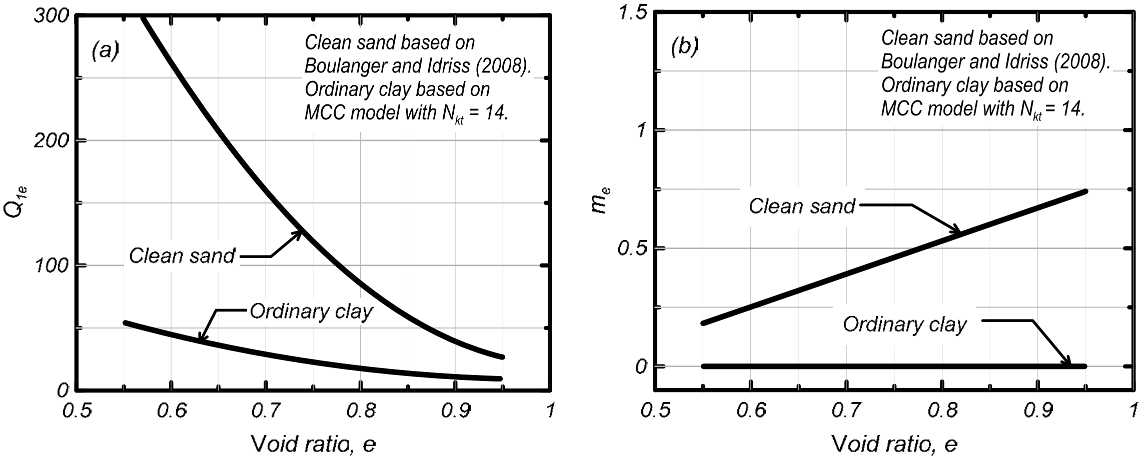

Figure 5. Normalized tip resistances (Q_{1e}) and normalization exponents (m_e) for a typical sand and clay at constant void ratio.

The values for $Q_{1\xi}$ and m_ξ derived for sand and clay in the previous sections are compared in Figures 6a and 6b, respectively. For the same ξ, the $Q_{1\xi}$ values are again much greater in sand than in clay. The m_ξ values for sand range from about 0.75 at loose-of-critical states (positive ξ) to about 0.35 for very dense-of-critical states (very negative ξ). The m_ξ values for clay are 1.0 for all ξ.

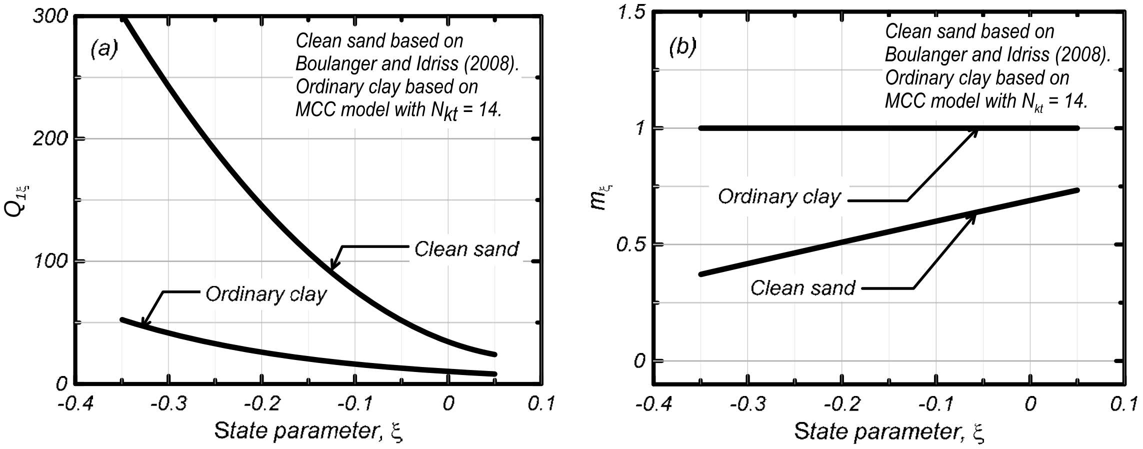

Figure 6. Normalized tip resistances ($Q_{1\xi}$) and normalization exponents (m_ξ) for a typical sand and clay at constant state parameter (ξ).

The trends and patterns depicted in Figures 5 and 6 provide a valuable reference framework for examining overburden correction factors for intermediate soils. These results illustrate the importance of clearly defining the purpose of the overburden correction factor (i.e., constant void ratio or constant state) and provide bounds on what might reasonably be expected for soils with characteristics intermediate to those of sands and clays.

6 *CRR* OVERBURDEN CORRECTION FACTORS, $K_{\sigma e}$ AND $K_{\sigma\xi}$

The effect of σ'_v on *CRR* is similarly represented by an overburden correction factor (K_σ) which was introduced by Seed (1983). The original definition of K_σ was based on *CRR* values being determined for the same soil at the same void ratio with all else also being equal (e.g., same *OCR*, same age, same cementation, same K_o), and thus might be more appropriately referred to as a $K_{\sigma e}$ factor. The $K_{\sigma e}$ factor is defined as,

$$K_{\sigma e} = \left(\frac{CRR_{\sigma'_{vc}}}{CRR_{\sigma'_{vc}=1atm}}\right)_{e=constant} \qquad (18)$$

where $CRR_{\sigma'vc}$ is the *CRR* of a soil under a specific value of σ'_{vc}, and $CRR_{\sigma'vc=1\ atm}$ is the *CRR* of the same soil when σ'_{vc} = 1 atm. If the two *CRR* values in the above equation are instead determined for the same soil at the same ξ (with all else also still being equal), then the term would instead be a $K_{\sigma\xi}$ factor.

The *CRR* values of sand have been shown to be approximately constant for a constant ξ (Pillai & Muhunthan 2001), and this observation was used by Idriss & Boulanger (2008) to derive $K_{\sigma e}$ factors like those shown in Figure 7a. The $K_{\sigma e}$ curves become steeper as the sand D_R increases; this trend reflects the fact that changing the σ'_v has a greater effect on the dilatancy of dense sands than of loose sands. The $K_{\sigma\xi}$ factor, on the other hand, is equal to 1.0 regardless of D_R (Figure 7b).

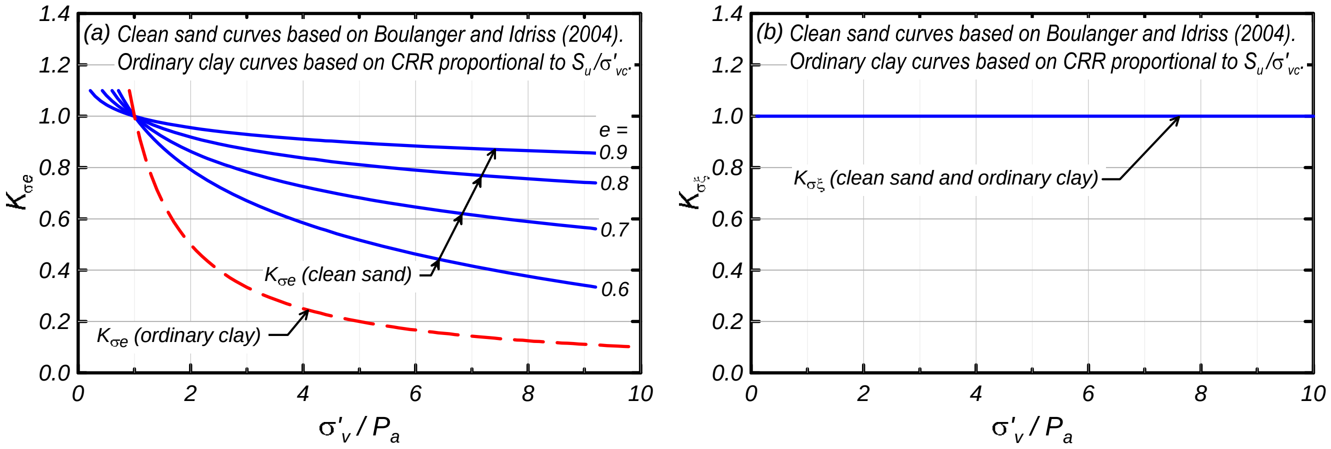

Figure 7. Comparison of K_σ relationships for a typical sand and clay depending on whether penetration resistance was normalized for (a) constant void ratio ($K_{\sigma e}$) or (b) constant state parameter ($K_{\sigma\xi}$).

The *CRR* of ordinary sedimentary clay is also approximately constant for a constant value of ξ, because (1) a constant value of ξ corresponds to a constant undrained strength ratio and (2) *CRR*s are approximately proportional to monotonic undrained strength ratios. Thus, the $K_{\sigma\xi}$ factor is approximately 1.0 for clays, just like for sands (Figure 7b).

The *CRR* of ordinary sedimentary clay at a constant void ratio, however, will be almost inversely proportional to σ'_{vc} because (1) a constant void ratio implies a constant undrained strength, S_u, (2) cyclic strength is approximately proportional to S_u, and (3) the *CRR* is the cyclic strength divided by σ'_{vc}. Thus, $K_{\sigma e}$ factor for clay is steeper than the corresponding curves for sand, as shown in Figure 7a.

7 CONCLUDING REMARKS

Common frameworks for overburden normalizations of penetration resistance and cyclic resistance ratios across a range of intermediate soil types were explored by their application to the bounding cases of clean sand and ordinary sedimentary clay. Relationships for overburden normalization of penetration resistances conditional on either a constant state parameter ($Q_{1\xi}$, m_ξ, and $C_{N\xi}$) or constant void ratio (Q_{1e}, m_e, and C_{Ne}) were presented for clean sand and ordinary sedimentary clay. Relationships for overburden normalization of cyclic resistance ratios conditional on either a constant ξ ($K_{\sigma\xi}$) or constant *e* ($K_{\sigma e}$) were similarly developed for both soil types, with the results illustrating how these two overburden stress terms are fundamentally interrelated.

The results presented herein provide useful bounds for further development and generalization of these frameworks across a range of intermediate soil types. For example, numerical simulations of cone penetration resistances using the constitutive model MIT-S1 have produced reasonable agreement with the C_{Ne} and $C_{N\xi}$ factors presented herein for clean sand and ordinary clay (Jaeger 2012). Ongoing work examining intermediate soil mixtures has similarly been promising.

8 ACKNOWLEDGEMENTS

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