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Case Study of CPT Application to Evaluate Seismic Settlement in Dry Sand

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ABSTRACT: Interpretations of geotechnical parameters based on Cone Penetration Test (CPT) data were performed and compared with Standard Penetration Test (SPT) data and laboratory testing results collected from various sites in California. Specific attention was paid to the estimation of fines content and conversion of CPT data to SPT $(N_1)_{60}$ blowcounts since they are often needed in seismic settlement evaluation of dry sand for the use of Pradel's (1998) method. A new relationship between volumetric strain, cyclic shear strain, and normalized tip resistance was derived based on the laboratory test data of Silver and Seed (1971) for dry clean sands. An example of the proposed CPT-based method is presented with a comparison to the results calculated using Pradel's original method as well as with the results based on SPT data from adjacent borings.

1 INTRODUCTION

Since its development in the 1950's, the CPT has become one of the most used and accepted in-situ testing methods for geotechnical investigation due to advantages such as continuum of sampling, repeatability, and economical efficiency. Since actual soil samples are not recovered during CPT, no laboratory soil testing is performed. Interpretation of CPT data with regard to soil parameters becomes important in the application of CPT results to various designs. Robertson & Campanella (1983a, 1983b) published two major papers in 1983 on the interpretation of CPT data. Since then, various papers have been published by researchers in this field (Mayne et al 2001; Mayne 2007; Robertson 2009).

CPT interpretations are widely applied in geotechnical engineering. Various methods have been established for the application of CPT results, such as evaluating shallow and deep foundation bearing capacities, liquefaction potential, as well as liquefaction-induced settlement and lateral spreading deformation (Lunne et al. 1997; Robertson & Wride 1998; Idriss & Boulanger 2008). However, there seems to be no work on the prediction of seismic settlement of dry sand directly based on CPT data. The intention of the present work is to compare various interpretations with measured data and propose a new method to estimate seismic settlement of dry sand directly based on CPT data. The validity of the proposed method has been verified by comparing the settlement analysis results from adjacent SPT borings and the analyses performed using traditional methods for dry sand settlement using SPT data.

2 CPT DATA INTERPRETATION

2.1 *Estimation of Fines Content*

Fines content is an important parameter used in the evaluation of liquefaction potential as it relates to the correction to clean sand resistance. Several correlations have been proposed in recent years (Robertson & Wride 1998; Suzuki et al. 1998; Idriss & Boulanger 2008; Cetin & Ozan 2009). Robertson & Wride (1998) use the term, *"apparent fines content"* (referred to as *FC* hereafter), and suggest the following relationship correlated to soil behavior type (referred to as *SBT* hereafter) index (I_c).

If $I_c < 1.26$, $FC = 0\%$ (1a)
If I_c is between 1.26 and 3.5, $FC(\%) = 1.75 I_c^{3.25} - 3.7$ (1b)
If $I_c > 3.5$, $FC = 100\%$ (1c)
If I_c is between 1.64 and 2.36, and $F_R < 0.5\%$, $FC = 5\%$ (1d)

The expression for I_c was derived by Robertson & Wride (1998) as

$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_R + 1.22)^2]^{0.5} \quad (2a)$$

where Q_{tn} is the normalized CPT penetration resistance and F_R is the normalized friction ratio.

$$Q_{tn} = [(q_c - \sigma_{v0}) / p_a][(p_a / \sigma_{v0}')^n] \quad (2b)$$

$$F_R = f_s / (q_c - \sigma_{v0}) \times 100\% \quad (2c)$$

where σ_{v0} is the total overburden pressure, σ_{v0}' is the effective overburden pressure, q_c is the measured tip resistance, f_s is the measure sleeve friction, p_a is atmospheric pressure, and component *n* varies from 0.5 in sands to 1.0 in clays (Robertson & Wride 1998).

Based on the data from Suzuki et al. (1998), Idriss & Boulanger (2008) derived a correlation between *FC* and I_c as

$$FC = 2.8 I_c^{2.6} (\%) \quad (3)$$

Cetin & Ozan (2009) proposed another approach based on a probabilistic method.

$$FC = (R_{FC} - 238.50)/1.75 \times 100 \pm 20.93 \ (\%) \quad (4a)$$

where. R_{FC} is a parameter similar to I_c.

$$R_{FC} = \sqrt{[\log(F_R) + 55.42]^2 + [\log(q_{t,1,net}) - 233.52]^2} \quad (4b)$$

where F_R is as defined in Equation 2c and $q_{t,1,net}$ is the normalized net cone tip resistance and is defined as

$$q_{t,1,net} = (q_t - \sigma_{v0}) / (\sigma_{v0}' / p_a)^c \quad (4c)$$

where *c* is a power law stress normalization exponent with a value between 0.25 and 1.0. Iterations are needed to calculate *c* and $q_{t,1,net}$.

The author collected 144 measured fines content results from 10 project sites. This data and another 244 data points from Suzuki et al. (1998) were plotted on an I_c versus *FC* chart in Figure 1 as originally constructed by Robertson & Wride (1998). The "solid circles" in Figure 1 show the data collected from southern California sites. The "empty circles" represent the data from 4 sites in Moss Landing obtained by Boulanger et al. (1995) in the investigation after the 1989 Loma Pieta earthquake. The diamonds illustrate data from Suzuki et al. (1998). Equations 1 and 3 as well as the *SBT* zones defined by Robertson & Wride (1998) are also shown in the figure. It can be seen that both equations underestimate the fines content, especially when I_c is larger than approximately 2.3. Moreover, by examining the relationship between *FC* and the *SBT* zone, it is clear that the relationship is inconsistent with that based on the Unified Soil Classification System (USCS) in which the fines content is defined as less than 5% for clean sand, between 5 and 12% for sand with silt, between 12 and 50% for silty sand, and higher than 50% for silt or clay. Although, Robertson & Wride (1998) did not directly utilize the *"Apparent Fine Content"* to correct the equivalent clean sand resistance, it is anticipated that this kind of correction may be performed by readers erroneously.

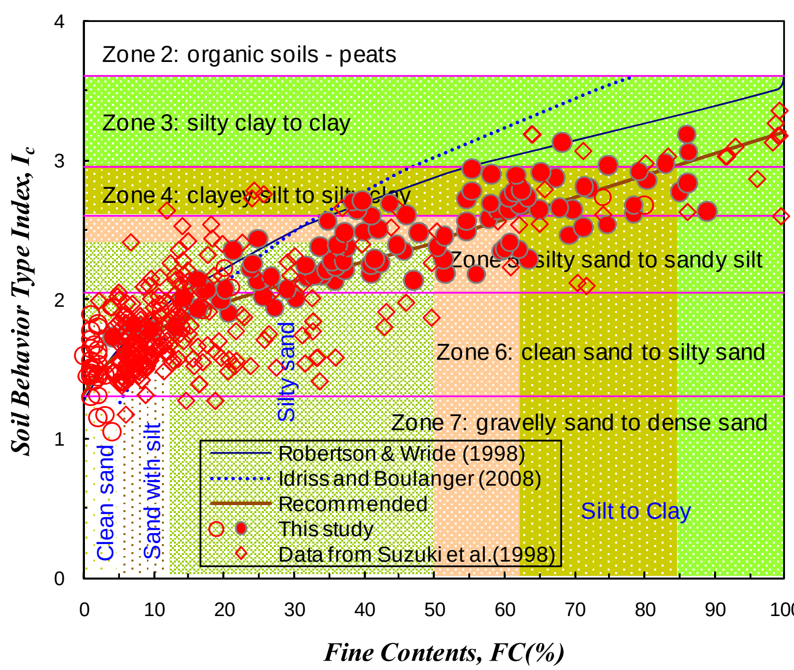

Figure 1. Relationships of Soil Behavior Type Index, Fines Content and Soil Classification

Based on the measured *FC* data as shown in Figure 1, it is suggested that the following relationship could be utilized to predict the values of *FC* for a given value of I_c.

$$I_c < 1.31, \qquad FC(\%) = 0 \tag{5a}$$

$$1.31 \le I_c < 2.325, \qquad FC(\%) = 43.67 I_c - 57.2 + 10\sin\left(\left(\frac{I_c - 2.325}{1.015}\right)\pi\right) \tag{5b}$$

$$2.325 \le I_c < 3.2, \qquad FC(\%) = 63.62 I_c - 103.59 \tag{5c}$$

$$I_c \ge 3.2, \qquad FC(\%) = 100 \tag{5d}$$

$$1.31 < I_c \le 2.36 \ \ and\ \ F_R < 0.6\%, \qquad FC(\%) = 5.0 F_R \tag{5e}$$

The correlation between Equation 5 and the measured *FC* data as well as the soil types based on USCS classification are also illustrated in Figure 1. Based on this relationship, the boundaries of soil behavior type proposed by Robertson (1990) could be refined as shown in Table 1 to obtain consistency with respect to the USCS.

The comparison of the measured and calculated fines content is presented in Figure 2. Fines content predicted by Equation 3 is less than that predicted by Equation 1 when $I_c > 2.47$ and was not included in the comparison. It can be seen that Robertson & Wride's method seems to underestimate the fines content while Cetin & Ozan's method may overestimate the fines content when fines content is less than approximately 20 percent, although the data scatter of Cetin & Ozan's and recommended methods seems similar for fines content higher than 20 percent. Overall, it can be seen that the proposed relationship (Eq. 5) generally provides better correlations with measured data.

Table 1. Boundaries of soil behavior type (refined from Robertson 1990)

Soil behavior type index, I_c	Zone	USCS Classification	Fines content (%)
$I_c < 1.31$	7	Gravelly sand to dense sand	0
$1.31 \le I_c < 1.61$	6a	Clean sand	0 ~ 5.0
$1.61 \le I_c < 1.81$	6b	Sand with silt	5.0 ~ 12.0
$1.81 \le I_c < 2.05$	6c	Silty sand	12.0 ~ 24.8
$2.05 \le I_c < 2.40$	5a	Silty sand	24.8 ~ 50.0
$2.40 \le I_c < 2.60$	5b	Sandy silt	50.0 ~ 61.8
$2.60 \le I_c < 2.95$	4	Silt mixture: clayey silt to silty clay	61.8 ~ 84.0
$2.95 \le I_c < 3.20$	3a	Silty clay	84.0 ~ 100
$3.20 \le I_c < 3.60$	3b	Clay	100
$I_c > 3.60$	2	Organic soils: peats	100

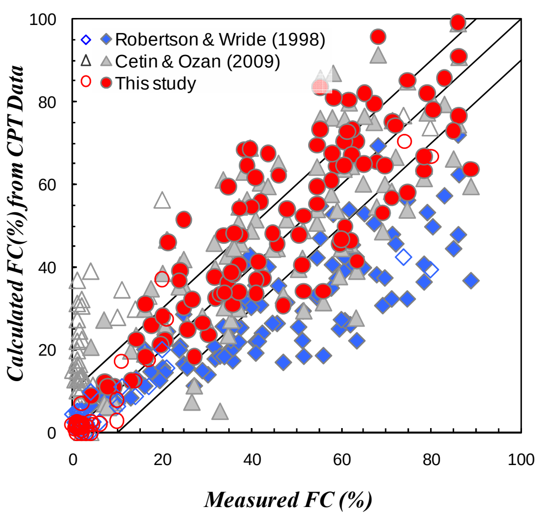

Figure 2. Comparison of measured and calculated fines content

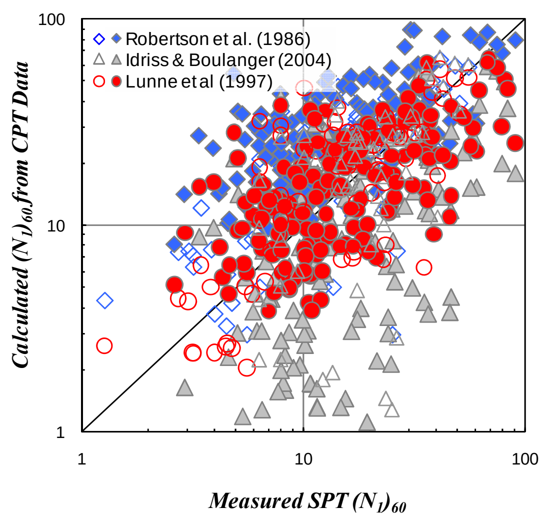

Figure 3. Comparison of measured and calculated $(N_1)_{60}$

2.2 *Conversion to SPT Blowcounts*

The conversion of CPT resistance to equivalent SPT $(N_1)_{60}$ blowcounts may not be as important as the prediction of fines content. However, if seismic-induced dry sand settlement is an important issue for a site, the conversion between CPT data and $(N_1)_{60}$ becomes necessary due to the absence of a method to directly calculate of seismic settlement of dry sand based on CPT data. Several methods have been proposed by individuals in past decades. Robertson et al. (1986) suggested $(q_c / p_a)/N_{60}$ ratios for each non-normalized soil behavior type classification zone.

Jefferies and Davies (1993) proposed a relation of q_c / N_{60} and I_c to provide a continuous variation with soil type. Lunne et al. (1997) revised Jefferies and Davies' relationships by utilizing the dimensionless variable (q_c / p_a) and a modified I_c to give the following equation.

$$(q_c / p_a)/N_{60} = 8.5(1 - I_c / 4.6) \qquad (6)$$

To evaluate liquefaction based on both SPT and CPT data, Idriss & Boulanger (2004) reevaluated the correlation between $(N_1)_{60}$, normalized tip resistance (q_{c1N}), and relative density (D_R) and recommended the following expressions.

$$q_{c1N} /(N_1)_{60} = (2.092 D_R + 2.224)^{3.788} / 46(D_R)^2 \qquad (7a)$$

For clean sand, Idriss & Boulanger (2004) suggested

$$D_R = 0.478(q_{c1N})^{0.264} - 1.063, \ (q_{c1N} > 21) \qquad (7b)$$

The equivalent $(N_1)_{60}$ calculated based on the above methods is compared in Figure 3 with the measured $(N_1)_{60}$. The data were collected from 10 sites including 6 sites from southern California (solid symbols) and 4 sites from Moss Landing, California (other symbols), for a total number of 241. Figure 3 indicates that, although a large scatter exists, the relationship by Robertson et al. (1986) tends to overestimate and Idriss & Boulanger's method (Eq. 7a) tends to underestimate $(N_1)_{60}$. The relationship shown in Equation 6 gives a more balanced distribution and is suggested by this author to be used when converting to $(N_1)_{60}$.

3 EVALUATION OF SEISMIC SETTLEMENT OF DRY SANDS

3.1 *Relative Density*

Silver & Seed (1971) indicated that one of the important parameter affecting the settlement of dry sand under cyclic loading is the relative density of the soil. Several relations between relative density and tip resistance have been proposed in the past. Tatsuoka et al. (1990) suggested a correlation as shown in the following equation.

$$D_R = -85 + 76 \log(q_{c1N}) \quad (\%) \qquad (8)$$

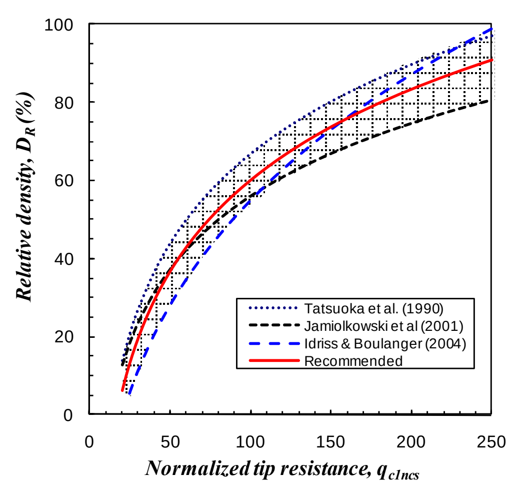

Figure 4. Relations between relative density and equivalent normalized clean sand resistance

Based on chamber testing results for clean sands, Jamiolkowski et al (2001) found a mean relationship as expressed in Equation 9. The original equation was slightly modified by using a consistent symbol for q_{c1N}.

$$D_R = 26.8 \ln(q_{c1N}) - 67.5 \quad (\%) \qquad (9)$$

The most recent work performed by Idriss & Boulanger (2004) is shown in Equation 7b. These relationships are plotted in Figure 4. Because the proposed relationships are based on test results for clean sand, an equivalent normalized clean sand tip resistance q_{c1Ncs}, instead of q_{c1N}, was adopted for the abscissa in Figure 4. It can be seen that above relationships generally give a range of the estimated D_R where the difference varies from approximately 10 to 20%. As such, an average value as expressed in Equation 10 is recommended.

$$D_R = 77.29\log(q_{c1N}) - 94.36 \quad (\%),\ (q_{c1N} \le 250) \qquad (10)$$

3.2 *Relationship between volumetric strain and shear strain of dry clean sand*

Silver & Seed (1971) conducted a series of one-directional cyclic shear tests on dry sand with relative densities of 45, 60, and 80%, and obtained relationships between volumetric and shear strains as shown in Figure 5. The relationship is obtained under 15 equivalent uniform strain cycles, equivalent to a magnitude of 7.5 earthquake.

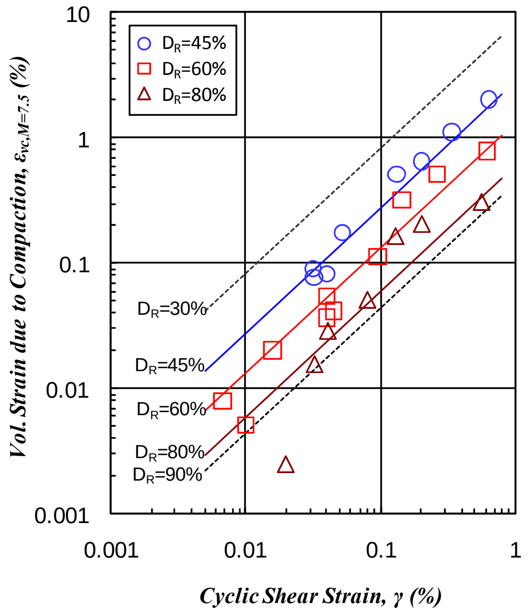

Figure 5. Relationship between volumetric strain and shear strain for dry clean sands (after Silver & Seed 1971)

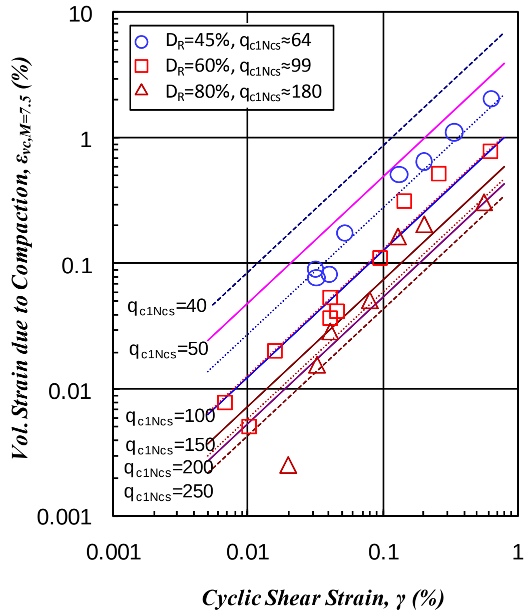

Figure 6. Relationship between volumetric strain, shear strain and normalized CPT tip resistance for dry clean sands

By adding Equation 10 into the relationships shown in Figure 5, the equivalent volumetric strain due to compaction could be expressed as a function of q_{c1Ncs} and cyclic shear strain as in Equation 11 and as shown in Figure 6.

$$\varepsilon_{vc,M=7.5} = 10^n \gamma,\ n = 18.4/(q_{c1Ncs})^{0.61} - 1 \qquad (11)$$

where γ is the cyclic shear strain and is calculated using Pradel's method.

3.3 *Corrections for earthquake magnitude and multidirectional shaking*

The relationships shown in Figures 5 and 6 are for 15 equivalent uniform strain cycles, equivalent to a magnitude 7.5 earthquake. By reviewing previous studies, Tokimatsu & Seed (1987) summarized a scale factor for earthquake magnitudes between 5.25 and 8.5. The original numerical data is expressed by Equation 12.

$$K_{vc,M} = \varepsilon_{vc,M} / \varepsilon_{vc,M=7.5} = 0.26M - 0.96 \qquad (12)$$

where M is the magnitude of an earthquake. Pyke et al. (1975) suggested that the volumetric strain should be doubled to account for the multidirectional effects. As such, the volumetric strain for any magnitude could be calculated using following equation.

$$\varepsilon_{vc,M} = 2 \cdot K_{vc,M} \cdot \varepsilon_{vc,M=7.5} \qquad (13)$$

3.4 *Case study of proposed method*

An example of the proposed modified CPT-based method is shown in Figure 8 for Site A located in southern California. The procedures adopted by Tokimatsu & Seed (1987) were followed in the calculation. The shear strain was calculated based on the Pradel's (1998) equation and the maximum shear modulus was estimated using the equation recently proposed by Robertson (2009). Figure 7 presents the measured tip resistance and the calculated shear strain, volumetric strain, and settlement. The volumetric strain and settlement calculated based on Pradel's method utilizing the converted $(N_1)_{60}$ (Equation 6) are also shown in the figure. It can be seen that the calculated settlements generally agree with each other.

For comparison, the results from data obtained from a SPT boring approximately 5 feet away from the CPT sounding are also illustrated in Figure 7. These results indicate that the new method provides good agreement with SPT results.

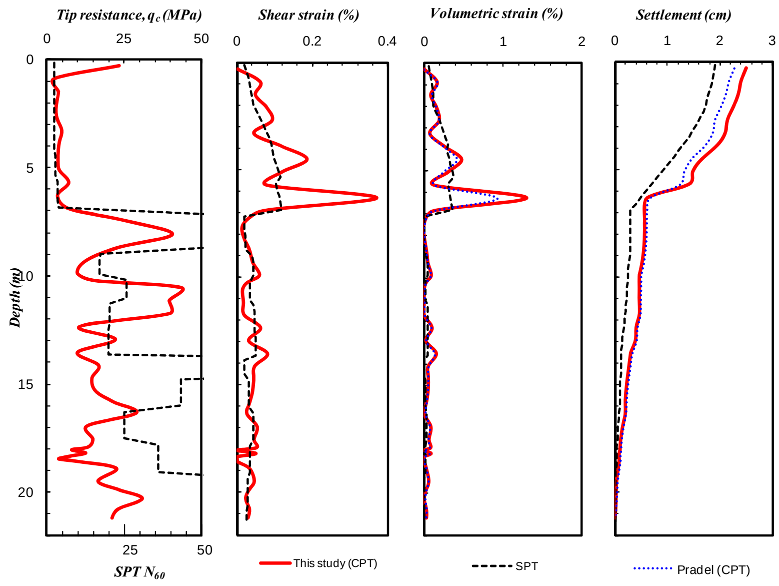

Figure 7. Calculated shear strain, volumetric strain, and settlement of dry sand for Site A

4 CONCLUSION

Interpretations of geotechnical parameters were performed based on CPT data obtained from 10 sites. A set of equations have been proposed based on data collected in this study and previous studies for calculating fines content, relative density, and the volumetric strain under cyclic loading of dry sand. By incorporating these equations into the procedures adopted by Tokimatsu & Seed (1987) and Pradel (1998), seismic settlement of dry sand was computed and compared with the results calculated using Pradel's method as well the results from adjacent SPT data. The results indicate good agreements between these results and suggest that the proposed method could be used in the prediction of seismic-induced settlement in dry sand based directly on CPT data. However, due to the absence of measured data, further verification of the proposed method will be necessary.

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