

Estimating soil fines contents from CPT data

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ABSTRACT: In order to verify soil property correlations between Standard Penetration Test (SPT) and Cone Penetration Test (CPT) results, a specially designed field investigation and laboratory testing program was implemented. The field exploratory investigation program included grouped SPT and CPT explorations at selected locations. Each test group included two hollow-stem auger borings utilizing a standard penetration sampler and a modified California sampler, respectively, and a seismic CPT sounding. These SPT borings and CPT sounding were placed at the vertices of a triangle around which a circle with a diameter approximately 3m (10 feet) could be circumscribed. This paper presents the results of the comparison between laboratory measured fines contents and the calculated fines contents based on CPT data interpretation. From this information, a new empirical relationship is proposed. A comparison with published data from various papers and reports indicates that this proposed new relationship appears to provide a more reasonable estimation of fines contents of soils.

1 INTRODUCTION

Due to its advantages such as the continuous data sampling, repeatability and the economic efficiency, the Cone Penetration Test (CPT) has been widely accepted and is more and more used for in situ soil investigations. With the increasing use of computer software, CPT results are directly utilized in liquefaction and seismic settlement estimations. Several publications are available for liquefaction analysis (e.g. Robertson & Wride, 1998; Idriss & Boulanger 2008) and seismic settlement estimation (e.g. Zhang, et al. 2002; Idriss & Boulanger 2008; Yi, 2010). On the other hand, since, in most cases, actual soil samples are not recovered during CPT investigations, no laboratory soil testing is performed. Interpretation of CPT data with regard to the estimated soil parameters becomes important in the application of CPT results, especially, fines content. Fines content has proven to be an important factor in the evaluation of soil resistance (strength) in liquefaction and seismic settlement analysis. Several correlations with regard to the estimation of fines contents from CPT data have been proposed in recent years (e.g. Robertson & Wride 1998; Idriss & Boulanger 2008; Cetin & Ozan 2009). However, the data collected by this author shows that current correlations appear to estimate fines contents which fall on the lower bound of the collected data. This may cause an underestimation of the corrected clean sand resistance and an overestimation of the liquefaction potential. The intention of the present work is to compare various interpretations with measured data and propose a new correlation. The validity of the proposed new correlation has been verified by comparing data obtained from published papers and reports.

2 FIELD INVESTIGATIONS

In order to compare the measured data with those estimated based on CPT interpretations, a specially designed field investigation program was set up and performed on a selected site (Site A). This site is located near the southern edge of the San Bernardino Valley, a portion of the Peninsular Ranges Geomorphic Province, and on a relatively youthful geomorphic surface associated with alluvial fans emanating from the Loma Linda Hills to the south and within the San Timoteo Wash. The native surficial materials at the site consist of very young sandy alluvial valley deposits of late Holocene age (Morton 1978; Morton and Miller, 2006).

The soil conditions underlying this site were explored by means of three groups of exploratory borings and CPT soundings. Each group included two exploratory borings (one boring using a standard SPT sampler and the other boring using a modified California (MC) sampler) and one CPT sounding. In order to compare the results, soil borings and CPT sounding were placed close enough together so that soils at approximately the same depth could reasonably be assumed to be identical. On the other hand, they were placed far enough apart so as not to affect the penetration resistance results. It was finally determined to place soil borings and CPT sounding on vertices of an approximately equilateral triangle forming a circumcircle approximately 3m (10 feet) in diameter. A total of three groups of such borings and soundings were placed in an approximately equilateral triangular layout so as to cover the entire site with an area approximately 330 meters square.

The MC sampler related results are not related to the topic of this paper and will be reported in other papers.

2.1 *Exploratory Borings and Sampling*

The soil borings were drilled with hollow-stem auger, per ASTM D6151, using a truck-mounted CME 75 drill rig equipped for soil sampling. The diameter of SPT borehole was of 20.3 cm (8 inches). The inside diameter of the auger was 15.2 cm (6 inches). The standard SPT sampler was 5 cm (2 inches) in outer diameter and 3.5 cm (1-3/8 inches) in inner diameter. Samplers were driven at intervals of 76.0 cm (2.5 feet) with an automatic hammer that drops a 63.5 kilograms (140-pound) weight 76.0 cm (30 inches) for each blow. Blowcounts were recorded. Bulk samples obtained from standard SPT sampler were utilized for fines contents and/or Atterberg limits testing.

2.2 *CPT Soundings*

All CPT soundings were performed per ASTM D-5778, utilizing a specially designed all-wheel-drive 222 kN (25 ton) truck mounted CPT rig. A seismic piezocone with surface areas of 10 cm² for tip and 150 cm² for friction sleeve and pore pressure transducer installed was utilized. The CPT sounding was pushed to practical refusal which was approximately at 20 ± 0.5 meters below existing ground surface. Shear wave velocity was measured every 76.0 centimeters (2.5 feet) throughout the soundings.

2.3 *Laboratory Testing*

Included in the laboratory testing program were field moisture content and field dry density tests on all relatively undisturbed samples returned to the laboratory from the MC sampler. Fines content testing was performed on all samples obtained from the standard SPT sampler by washing soils through an ASTM No. 200 (75- μ m) sieve. Atterberg limits tests were conducted on selected clayey type soils as an aid to classification.

2.4 *CPT Results and Fines Contents*

The distributions of tip resistance and sleeve friction of the CPT-1 profile are shown in (a) and (b) of Figure 1, respectively. Figure 1(c) thru (e) show the distributions of measured fines contents of all 3

CPT soundings and the fines contents estimated based on Robertson & Wride (1998) and Idriss & Boulanger (2008) correlations. Overall, it can be seen that measured fines contents are generally higher than estimated values. This difference exists both vertically and laterally throughout the site.

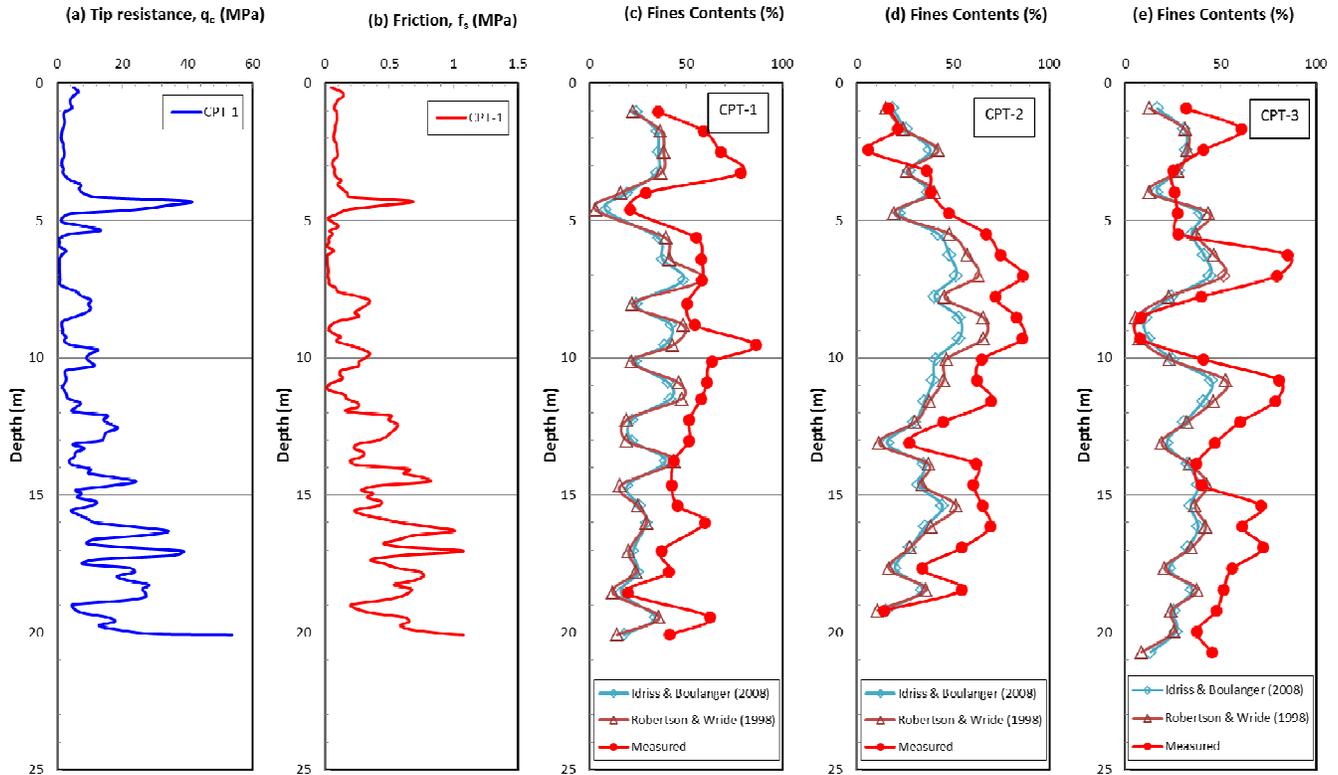


Figure 1. Distributions of representative CPT results and measured and calculated fines contents

2.5 Data Collected from Other Sites

In order to produce a more representative correlation, 133 samples of measured fines contents from a total of 11 sites including the site mentioned above were collected and utilized. All of these sites geologically consist of very young to young sandy, late Holocene age alluvial deposits with low plasticity. For all of these sites, soil samples were generally collected from soil borings no more than 3m (10 feet) distant from CPT soundings. With the removal of extreme data that was believed to obviously represent different soil types, 124 valid data points are plotted in Figure 2 of measured fines contents versus soil behavior type (referred to as *SBT* hereafter) index (I_c) as originally constructed by Robertson & Wride (1998). The green dots show the results with Plasticity Index (PI) of between 4% and 8%. These samples were generally classified as silty sand (ML) or sandy clay (CL).

3 FINES CONTENTS CORRELATIONS

3.1 Existing correlations

Several correlations have been proposed in recent years (e.g. Robertson & Wride 1998; Idriss & Boulanger 2008; Cetin & Ozan 2009). Robertson & Wride (1998) use the term, “*apparent fines content*” (referred to as *FC* hereafter), since the CPT is influenced by more than just fines content, and suggest the following average relationship correlated to the *SBT* index (I_c).

$$\text{If } I_c < 1.26, FC = 0\% \quad (1a)$$

If I_c is between 1.26 and 3.5, $FC(\%) = 1.75I_c^{3.25} - 3.7$ (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 follows:

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

Where Q_m is the normalized CPT penetration resistance and F_R is the normalized friction ratio.

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

$$F_R = f_s / (q_c - \sigma_{v0}) \times 100\%$$
 (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 the component n varies from 0.5 in sands to 1.0 in clays (Robertson & Wride 1998).

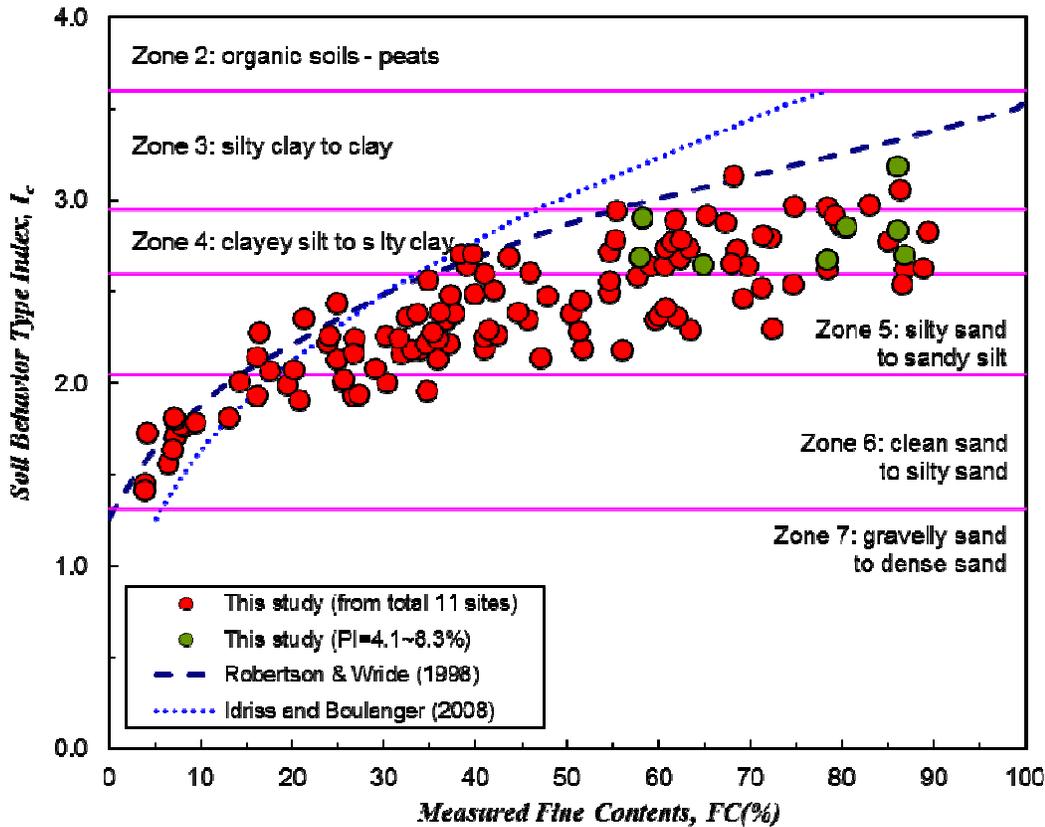


Figure 2. Measured Fines Contents versus Soil Behavior Type Index

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

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

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

$$FC = (R_{FC} - 238.50) / 1.75 \times 100 \pm 20.93 (\%)$$
 (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 $q_{t,1,net}$.

Data plotted on Figure 2 indicates that measured fines contents are generally lower than Robertson & Wride's (1998) curve, while Idriss & Boulanger (2008) may overestimate the fines contents for approximately $I_c < 2.00$ and underestimate the fines contents for $I_c > 2.50$. Because Cetin & Ozan (2009) use a different index, the correlation is not plotted in Figure 2.

3.2 Proposed Correlation

Figure 3 plots the data collected by this author from a total of 11 project sites as well as from various published papers and reports. Equations (1) and (3) as well as the *SBT* zones defined by Robertson & Wride (1998) are also shown in the Figure 3. It can be seen that both equations underestimate the fines content, especially when I_c is larger than approximately 2.5. 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.

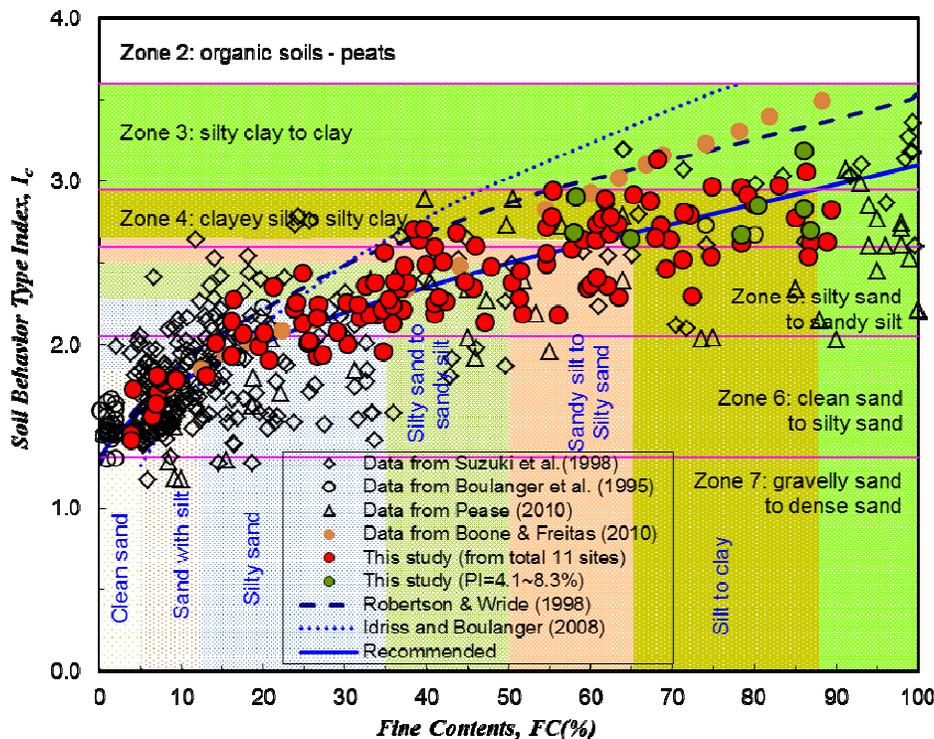


Figure 3. Relationships of Soil Behavior Type Index, Fines Contents and Soil Classification

Based on the measured fines contents data as shown in Figure 3, it is suggested that the following relationship could be utilized to better estimate the values of fines contents for given values of I_c .

$$I_c < 1.31, \quad FC(\%) = 0 \quad (5a)$$

$$1.31 \leq I_c < 2.5, \quad FC(\%) = 42.0I_c - 55.0 + 10\sin\left(\left(\frac{I_c - 2.5}{1.19}\right)\pi\right) \quad (5b)$$

$$2.5 \leq I_c < 3.1, \quad FC(\%) = 83.3I_c - 158.3 \quad (5c)$$

$$I_c \geq 3.2, \quad FC(\%) = 100 \quad (5d)$$

$$1.31 < I_c \leq 2.36 \text{ and } F_R < 0.6\%, \quad FC(\%) = 5.0F_R \quad (5e)$$

Equation (5e) was modified from Equation (1d) based on fines content data in the Moss Landing report (Boulanger et al., 1995). Equation (5) was plotted in Figure 3 as the solid blue line. It can be seen that this line approximates the average of the measured fines contents with respect to I_c . The correlation between Equation (5), fines contents and soil types based on USCS classification are also plotted in Figure 3. Based on these relationships, the boundaries of soil behavior type proposed by Robertson (1990) could be refined as shown in Table 1 to be more consist with respect to the USCS.

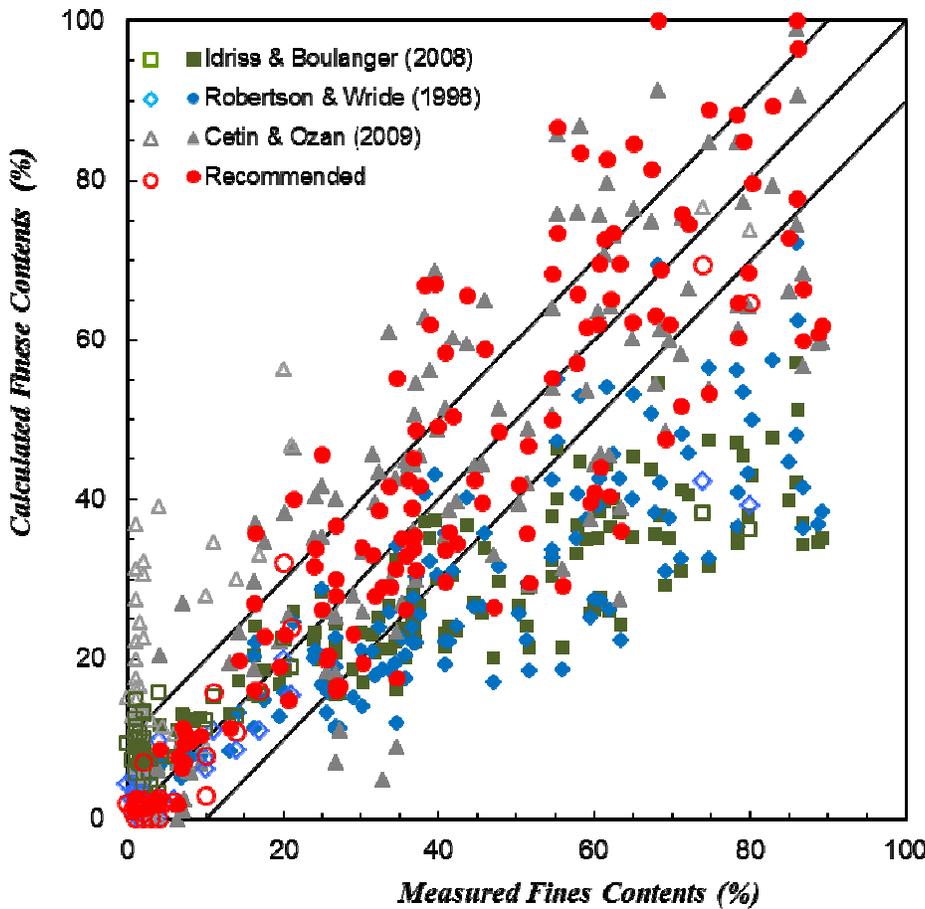


Figure 4. Comparison of Measured and Calculated Fines Content

The comparison of the measured and calculated fines contents is presented in Figure 4. For the same symbol in this figure, e.g. circular, the filled symbols represent data collected by this author and the empty symbols represent the data from Moss Landing report (Boulanger et al., 1995). Although data scatterings still exist, it still can be seen that both Robertson & Wride's and Idriss & Boulanger's meth-

ods seems to underestimate the fines content, especially for measured fines contents higher than approximately 25%, while Cetin & Ozan's method may overestimate the fines content when fines content is less than approximately 15%. Although the data scattering of Cetin & Ozan's and recommended methods seems similar for fines content higher than 15%, 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
$1.31 \leq I_c < 1.59$	6c	Clean sand	0 ~ 5.0
$1.59 \leq I_c < 1.83$	6b	Sand with silt	5.0 ~ 12.0
$1.83 \leq I_c < 2.276$	6a to 5c	Silty sand	12.0 ~ 35.0
$2.276 \leq I_c < 2.50$	5b	Silty sand to sandy silt	35.0 ~ 50.0
$2.50 \leq I_c < 2.68$	5a to 4b	Sandy silt to silty sand	50.0 ~ 65.0
$2.68 \leq I_c < 2.95$	4a	Silt mixture: clayey silt to silty clay	65.0 ~ 87.4
$2.95 \leq I_c < 3.10$	3b	Silty clay	87.4 ~ 100
$3.10 \leq I_c < 3.60$	3a	Clay	100
$I_c \geq 3.60$	2	Organic soils: peats	100

4 SUMMARY

With the increasing use of computer programs to aid in the interpretation of CPT results, it is sometimes necessary to estimate the fines contents, especially for liquefaction potential and seismic settlement calculations. In order to confirm the measured data with those estimated based on CPT interpretations, a specially designed field investigation and laboratory testing program was conducted. The measured fines contents were compared with those calculated using various existing correlations. A new correlation between fines contents and SBT Index, I_c , was proposed and proved to provide a better estimation of fines contents.

It should be noted that all soil samples collected for this study are derived from very young to young sandy, Holocene age alluvial deposits with low plasticity. Although limited Atterberg Limits data is available, the overall PI is expected to be less than 12% based the author's experience and test results on late Holocene age alluvial deposits. Soil with high plasticity may exhibit different correlations as pointed out by Robertson & Wride (1998). However, soils with low plasticity generally are potentially liquefiable (Seed et al., 2003; Idriss & Boulanger, 2008). As such, it is opinion of this author that the proposed new correlation is suitable for cyclic shear resistance corrections in liquefaction potential and seismic settlement analyses.

5 ACKNOWLEDGMENTS

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