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Fines Content Correction Factors for SPT N Values – Liquefaction Resistance Correlation

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ABSTRACT: It is common practice to evaluate liquefaction potential from correlation between liquefaction resistance as determined from field performance of soil deposits during past earthquake events and in-situ pen-etration test results. Historically, Seed and co-workers started the correlation with SPT N values. In such cor-relations, the influence of non- or low-plastic fines is taken into account by correcting SPT N values with fines content correcting factors. The correction factors are based on empirical data. The correction factors increases with the increase in fines content (FC) up to FC of about 35% and remains constant with any further increase in FC. However, laboratory investigations show a significant reduction in the cyclic resistance of sands contain-ing FC greater than 35%. Furthermore, after re-visiting of the SPT N –liquefaction case histories, Green et al. (2006) observed a trend consistent with the significant drop in the cyclic resistance of soils containing FC> 35%. This paper provides a new set of correction factors that is consistent with field and laboratory observa-tions. The correction factors are applicable to wide ranges of FC greater than 35%.

1 INTRODUCTION

1.1 *General*

The most common practice to evaluate liquefaction potential (initiation or triggering) is to use correlation between liquefaction resistance as determined from field performance of soil deposits during past earthquake events and in-situ penetration test results. Historically, Seed and co-workers started the correlation with SPT N values. Such effort started with the "simplified" procedure by Seed and Idriss (1971). Using the correlation between liquefaction resistance and penetration test results relies on an extensive database of field performance for soil deposits which did or did not liquefy during past earthquake events. Databases of such performances were developed over the years (Tokimatsu and Yoshimi, 1983; Seed et al., 1984; Jamiolkowski et al., 1985; Ambraseys, 1988; Fear and McRoberts, 1995; Cetin et al., 2000; Idriss and Boulanger, 2006; and Shahien, 2007). The developed correlation was in the form of cyclic resistance ratio (CRR) versus SPT N values corrected for both procedure and effective overburden pressure $(N_1)_{60}$. The correlation was presented for clean sand base curve and for other values of fines content as shown in Figure (1). Similar correlations were developed for other in situ tests such CPT and Vs (e.g. Youd et al., 2001).

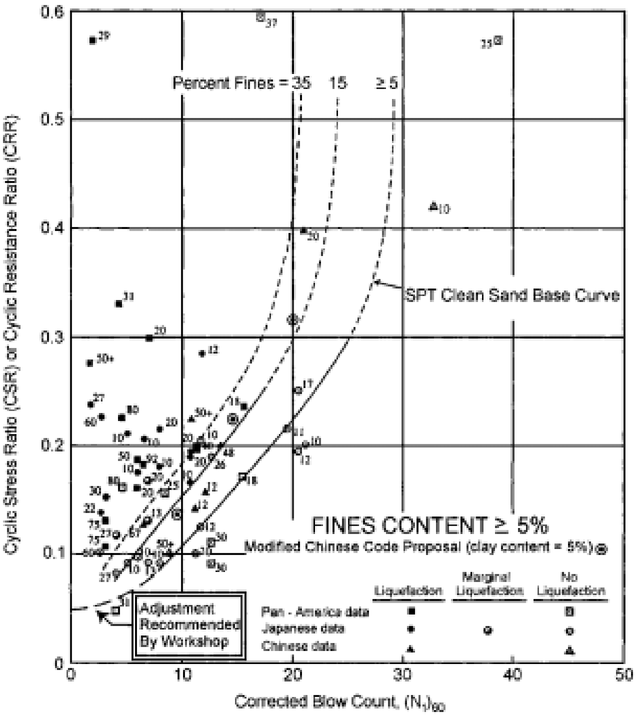

Figure 1. CRR versus $(N_1)_{60}$ curves based on case histories for various Fines Content (After Seed et al. (1984) modified by Youd et a. (2001)).

1.2 *Existing fines content correction factors*

It has been common practice to correct $(N_1)_{60}$ to equivalent clean sand $(N_1)_{60\text{-}CS}$ using the following expression:

$$(N_1)_{60-CS} = (N_1)_{60} + \Delta(N_1)_{60} \tag{1}$$

The fines content correction factors $\Delta(N_1)_{60}$ have been derived from Figure (1) by pairing the SPT $(N_1)_{60}$ value that corresponds to a certain value of CRR on the base clean sand curve with (FC≤5%) to the SPT $(N'_1)_{60}$ values corresponding to the same CRR on the other curves for sand with FC (Figure 2) (Shahien and Mesri, 1999).

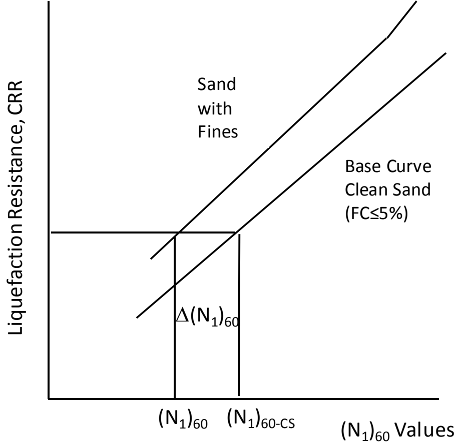

Figure 2. Schematic diagram showing the derivation of FC correction factors using base clean sand curve (Figure 1)

Table (1) lists the forms of existing correction factors available in the literature. Figure (3) shows the correction values of $\Delta(N_1)_{60}$ calculated from most of the references in Table (1). Some of the corrections were put in the form of $\Delta(N_1)_{60}$ such as Cetin et al. (2004) for sake of comparison with other corrections.

Table 1. Summary of FC correction factors in literature

Form	Reference
$(N_1)_{60\text{-}CS} = (N_1)_{60} + \Delta(N_1)_{60}$	
$\Delta(N_1)_{60}$ = constant	Seed et al. (1983)
$\Delta(N_1)_{60} = f(FC)$	Tokimatsu and Yoshimi (1983) Seed et al.(1984) – Terzaghi et al (1996) Kayen and Mitchell (1997) Shahien and Mesri (1999) Youd et al. (2001) Idriss and Boulanger (2006)
$\Delta(N_1)_{60}=g[FC,(N_1)_{60}]$	Idriss and Seed (1996) Robertson and Wride (1996)
$(N_1)_{60\text{-}CS} = C_{fines}(N_1)_{60}$	
$C_{fines}= k[FC,(N_1)_{60}]$	Cetin et al. (2004)

It should be noted that the correction by Shahien and Mesri (1999) was based on the conventional correction by Terzaghi and Peck (1948) for SPT N values of fine and silty sands. The original correction was N_{cs}=a+0.5(N-a) with a = 15. A modification was applied using a=20 instead of 15. Such modification was based on Peck (1997). It is interesting that such correction lies within the range of the other corrections. With the exception of the Shahien and Mesri correction, all the other corrections have limiting correction value for FC ≥ 35%. Further noted is the wide range of corrections.

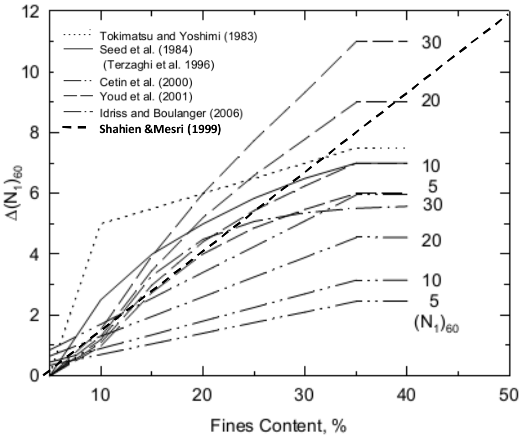

Figure 3. $\Delta(N_1)_{60}$ versus FC relationships in the literature

1.3 *Motivation and aim of this paper*

Most of the above mentioned correction factors suggest an increase in penetration resistance with the increase of FC until FC of about 35% after which no further increase in penetration resistance with increase in FC above 35%.

Green et al. (2006) used 98 case records of SPT N with liquefaction/no liquefaction from 14 earthquakes from existing databases to examine FC correction factors. The $(N_1)_{60}$ values obtained from the base curve “clean sand” with FC≤5% were corrected for FC using the correction factors of Youd et al. (2001) to produce family of curves for FC of 10%, 20%, 30% and >35%. The data records were plotted on these curves. Green et al. (2006) concluded that the Youd et al. (2001) corrected curves rationally divided the liquefaction/no liquefaction data for FC≤35%. Nevertheless, for FC>35% considerable chunk of “liquefied” number of data points fell well below the CRR curve in the "no liquefaction" zone (Figure 4). Such observation proved that the existing FC correction factors could lead to un-conservative liquefaction resistances. Green et al. (2006) suggested that no FC correction (i.e. no increase in $(N_1)_{60}$) should be applied in case of FC>35% until further investigations could better explain the concluded trend.

Idriss and Boulanger (2010) developed updated database of field liquefaction records and carried out similar exercise utilizing the Idriss and Boulanger (2006) correction factors. The conclusion of Idriss and Boulanger (2010) contradicts the conclusion of Green et al.(2006).

It should be noted that both investigation teams used filtering process to include good quality records. Green et al. (2006) used 98 cases, while Idriss and Boulanger (2010) used 230 cases. The contradiction between the two conclusions motivated the author to investigate the matter. Thus the aim of this paper is to provide a set of correction factors obtained using different approach.

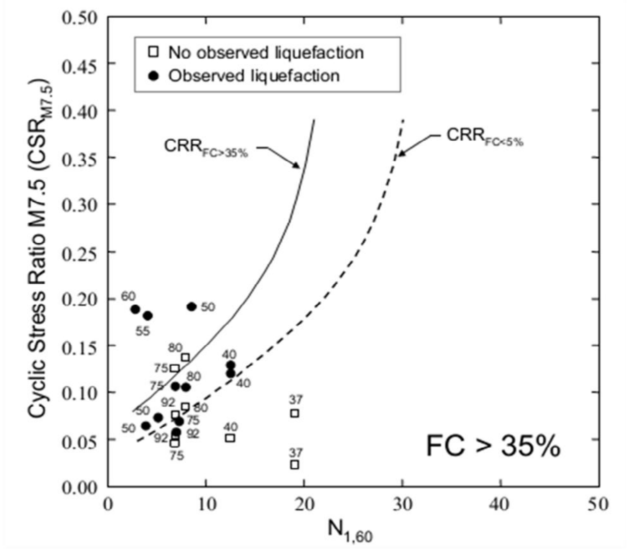

Figure 4. Results of re-analysis of SPT liquefaction case histories for FC > 35%. Numbers next to data points are the corresponding FC. (After Green et al., 2006)

1.4 *Proposed correction factors: Methodology*

As discussed earlier, most of the FC correction factors existing in the literature are derived from field performance correlation such as that in Figure 1. A different approach is followed in this paper. The proposed correction factors developed in this paper utilizes two correction factors; (1) Correction factors to correct influence of FC on penetration resistance, and (2) Correction factors to correct influence of FC on CRR. Combining both correction factors results in correction factors to correct influence of FC on CRR versus penetration resistance correlation.

2 CORRECTION FOR INFLUENCE OF FINES CONTENT ON PENETRATION RESISTANCE

2.1 *Influence of FC on penetration resistance*

Standard Penetration Test (SPT) is a dynamic test. Depending on the compressibility or contractiveness of the tested soil, a penetration induced excess porewater pressure tends to develop during penetration. The excess water pressure tends to dissipate with a rate that depends on the permeability of the soil. As non/low plastic fines content increases in the soil, the contractiveness increases thus the excess porewater pressure increases and the permeability decreases thus the dissipation of the water pressure tends to be slower. Both actions tend to decrease the measured SPT N values. Thus, as FC increases, the measured N value decreases and the deviation from representing the original state of denseness of the soil increases. Such deviation necessitates the correction of the measured N. Figure (5) shows relationship between measured N values and FC using the data from the database of Cetin et al. (2000).

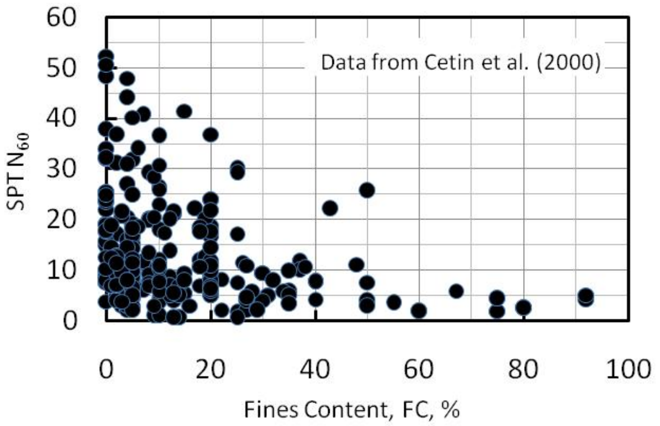

Figure 5. Relationship between SPT N_{60} versus FC.

2.2 *Penetration resistance versus Dr correlation*

Meyerhof (1957) proposed a correlation between the SPT N value and relative density, Dr, for clean sands based on chamber data in the following form:

$$\frac{N_1}{Dr^2} = a + b = 41 \tag{2}$$

Skempton (1986) collected more data of the kind for granular soils with different particle size characteristics. Skempton (1986) followed the same form and proposed that the relationship between $(N_1)_{60}$ and Dr to be in the following form:

$$\left(\frac{N_1}{Dr^2}\right) = a + b \tag{3}$$

where, a+b is constant that decreases with the increase in mean particle size of the granular soil.

Cubrinovski & Ishihara (1999), (2000) & (2001) used SPT measurements of field deposits along with data of high-quality undisturbed samples to prove that a+b defined as C_D is dependent on grain characteristics such as particle size, gradation and fines content. It was further suggested that grain characteristics can be well represented by void ratio range (e_{max}-e_{min}) or the difference in the void ratio between the loosest, e_{max}, and densest, e_{min}, packing states. The following correlation was proposed by Cubrinovski & Ishihara for gravelly, clean sand and sands with fines:

$$\frac{(N_1)_{60}}{Dr^2} = C_D = \frac{9}{\left(e_{max} - e_{max}\right)^{1.7}} \tag{4}$$

2.3 *Relationship between void ratio range and FC*

Cubrinovski & Ishihara (2002) proposed a relationship between void ratio range and FC for natural sandy and silty soils based on comprehensive data. The range of data used, as well as the average correlation by Cubrinovski & Ishihara, is shown in Figure (6). Shown also on Figure (6) back calculated values of the void ratio range based on the Youd et al (2001) correction. Figure (6) also shows the correlation peoposed ans used in this paper. The proposed relationship was influenced by the back calculated values.

Cubrinovski & Ishihara identified that the rate of increase in the void ratio range with the increase in FC changed around the FC of 30%. This is related to the difference in particle structure of sand in the two ranges separated by FC=30%. In the lower range, the particle structure is governed by coarse-grained fraction of the soil. On the other hand, in the upper range of FC, the soil structure is governed by the fine-grained fraction of the soil.

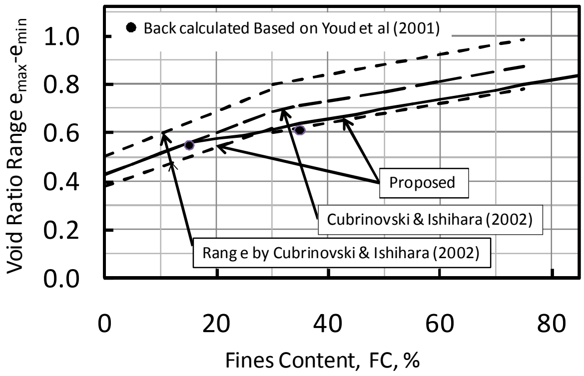

Figure 6. Relationship between e_{max}-e_{min} versus FC.

2.4 *Proposed correction for influence of FC on N*

Substituting values of the proposed correlation from Figure (6) in Equation (4), the relationship in Figure (7) is obtained between N values and FC for various relative densities.

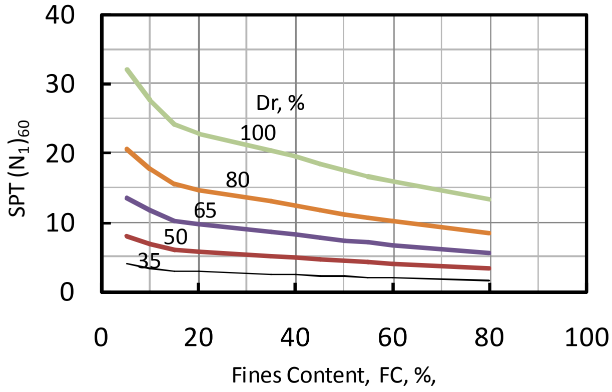

Figure 7. Correlation between $(N_1)_{60}$ versus FC for various Dr.

The range of data in Figure (7) resembles the range of data in Figure (5) taking into consideration the fact that in Figure (7) N values are corrected for the influence of effective overburden pressure, while in Figure (5) N values are not corrected for overburden pressure. The data in Figure (7) or Equation (4) is used to introduce correction factor for influence of FC on N values, RN_{FC}, that is shown in Figure (8).

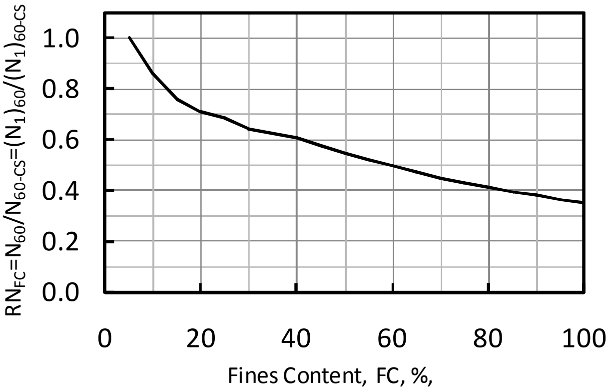

Figure 8. Correction for influence of FC on N.

3 CORRECTION FOR INFLUENCE OF FC ON CRR

Polito and Martin (2003) examined many of the laboratory parametric studies examining the influence of FC on CRR of sandy soils. Such an examination clarified the conflicting conclusions of these studies such as CRR increases, decrease and unaffected with the increase in FC. Furthermore, Polito and Martin (2001) introduced the concept of limiting fines content (LFC) showing that if the relative density of a non/low-plastic silt-sand mix is kept constant, the CRR of the mix is insensitive to FC up to the LFC, at which the CRR significantly reduces to a value that is almost unaltered by further increase in FC. Thus the LFC differentiate between two ranges of FC. The first one is the range in which the mix behaves as coarse grained soil with no significant influence of fines presence. In the second range, the mix behaves as fine grained soil with no significant influence of sand presence. Polito (1999) reported, confirmed by Cubrinovski and Ishihara (2002), that the LFC occurs in the range of 30% to 40%. Utilizing the data reported by Polito (1999) for Yatesville silt/sand mixture having Dr of 30%, The correction factor, $RCRR_{FC}$, to correct CRR for FC is introduced in Figure (9) based on Polito (1999) data. The correction factor has two values with a transition zone separating the above mentioned two ranges.

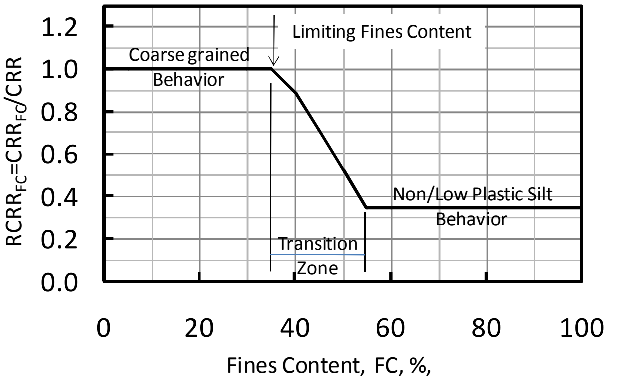

Figure 9. Correction for influence of FC on CRR (Modified after Polito, 1999)

4 COMBINED CORRECTION FOR INFLUENCE OF FC ON CRR-$(N_1)_{60}$ RELATIONSHIP

The correction factors in Figures (8) and (9) can be applied on the clean sand base curve shown in Figure (1). Figure (10) shows a clarifying sketch to explain how the CRR versus penetration resistance for silty sand with FC can be obtained. For FC ≤LFC, RN_{FC} <1 (Figure 8) and $RCRR_{FC}$=1 (Figure 9). Thus the resulting curve shall be a shift to the left reducing the penetration resistance values. On the other hand, for FC>LFC, RN_{FC}<1 (Figure 8) and $RCRR_{FC}$<1 (Figure 9). Thus the resulting curve shall reflect reduction in penetration resistance and reduction in CRR (Figure 10). Figure (11) shows the SPT clean sand base curve and CRR versus penetration resistance for various values of FC obtained using the corrections presented in this paper.

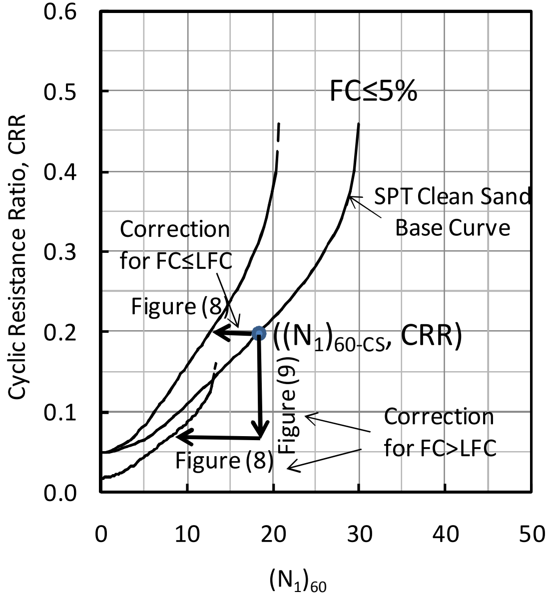

Figure 10. Combined correction for influence of FC on CRR versus $(N_1)_{60}$ relationship

It should be noted that the CRR versus $(N_1)_{60}$ curves for FC of 15% and 35% are almost identical to and confirming the curves of Youd and Idriss (2001) or youd et al (2001) showing higher cyclic re-sistance with the increase in FC. The curves for FC of 50%, 60% and 80% are different from what is currently known to be grouped with the curve of FC≥35%. The curves tend to reflect lower cyclic re-sistance close to or even lower than the curve for FC≤5%. The curves for FC of 50%, 60% and 80% tend to be close to each other to the extent that a single relationship can be proposed as shown in Fig-ure (12) in the next section.

5 FIELD CASE RECORDS CONSIDERATION AND PROPOSED RELATIONSHIP

As mentioned earlier, Green et al. (2006) used 98 case records of SPT N with liquefaction/no liquefac-tion from 14 earthquakes from existing databases to examine FC correction factors. The case records with FC>35% used by Green et al. (2006) (Figure 4) are used in this section to evaluate the curves obtained using the approach presented in this paper and shown in Figure (11). Those data are plotted in Figure (12) together with the relationships for FC of 35%, 50%, 60% and 80% from Figure (11).

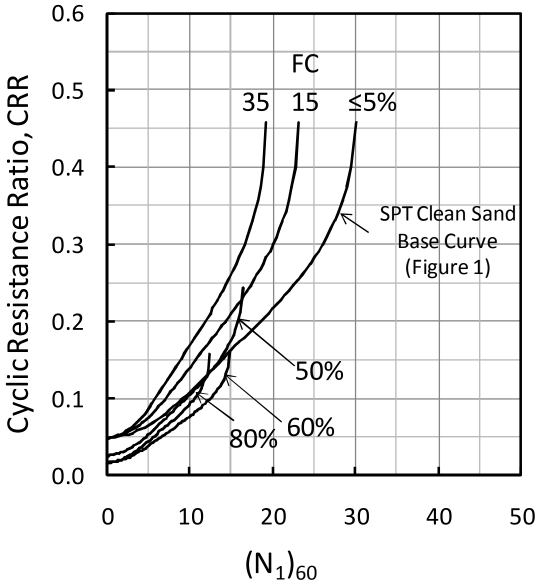

Figure 11. CRR versus $(N_1)_{60}$ for various FC

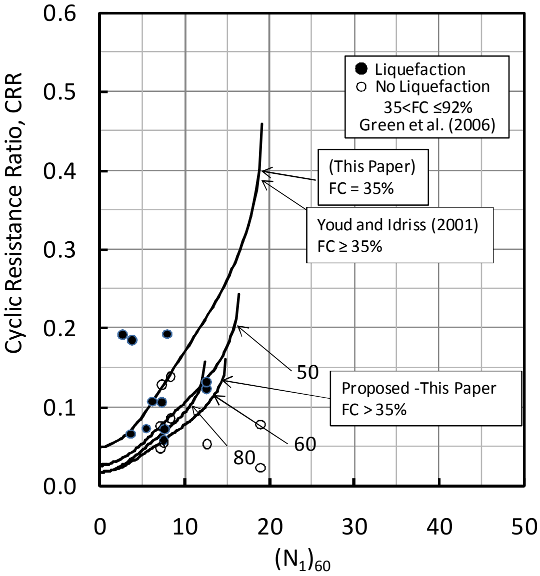

Figure 12. CRR versus $(N_1)_{60}$ for various FC and liquefaction/ no liquefaction case records for 35<FC≤92%

It is interesting to note that the liquefied case records could be well bounded by the bundle of curves for FC of 50%, 60% and 80% obtained by the approach presented in this paper. This is encouraging to the extent that a single curve can be proposed for FC>35% replacing the very close bundle of curves for FC of 50%, 60% and 80%. It should be noted that for FC in the range of 35 to 50%, there is a transition zone that can be conservatively ignored for practical purposes. Thus, based on the approach presented in this paper, the proposed CRR versus $(N_1)_{60}$ relationships for various non/low plastic FC are shown in Figure (13). The proposed curves are identical to those of Youd and Idriss (2001) for

FC≤35%. For FC≥35%, a single curve is proposed in this paper.

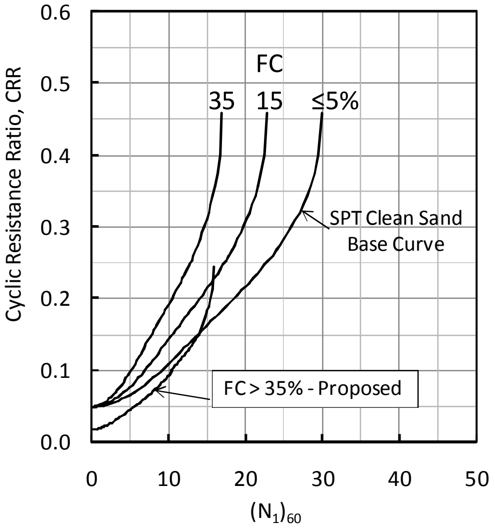

Figure 13. CRR versus $(N_1)_{60}$ for various FC and liquefaction/ no liquefaction case records for 35<FC≤92%

6 CONCLUSION

This paper presents an alternative approach to obtain fines contents correction to the liquefaction resistance versus penetration resistance relationship. The obtained correction confirmed the already existing one for fines content ≤ 35% (Youd et al., 2011). However, it provided new correction for fines content > 35% that is consistent with field case records.

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