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COMPARISON OF THREE PROCEDURES FOR EVALUATING EARTHQUAKE-INDUCED SOIL LIQUEFACTION

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ABSTRACT

Over the past decade, major advances have occurred in both the understanding and the practice with regard to the evaluation of soil liquefaction potential during earthquakes. Among these advances, there are two analytical frameworks (i.e., Seed et al. (2003) and Idriss and Boulanger (2008) procedures), which are widely accepted by the industry. The most significant achievement of the new procedures is their new criteria for assessment of liquefaction potential of low-plasticity silts and clays. These two new procedures are changing the way the design and regulatory communities consider soil liquefaction evaluation and may likely become standard-of-practice in the near future.

This paper relates these two new procedures with the Youd et al. (2001) procedures by comparing the cyclic resistance ratio (CRR), the factor of safety (FS) against liquefaction, and the post-earthquake reconsolidation settlement (Δ) at different depths using both Standard Penetration Test (SPT)-based and Cone Penetration Test (CPT)-based methods. In addition, paired SPTs and CPTs are used to evaluate the relative performance between the SPT-based and the CPT-based correlations for each of these three procedures. Assessments of conservatism are made not only for the three analytical frameworks but also for correlations between SPT and CPT data. Discussions and recommendations oriented for practitioners are made on some components of each analytical framework.

INTRODUCTION

Over the past decade, major advances have occurred in both the understanding and the practice with regard to the evaluation of soil liquefaction potential during earthquakes. Among these advances, there are two analytical frameworks widely accepted by the industry: Seed et al. (2003) and Idriss and Boulanger (2008) procedures. These two procedures are changing the way the design and regulatory communities consider soil liquefaction evaluation, and may likely become new standard-of-practice in the near future. Even though liquefaction potential evaluation procedures within probabilistic frameworks have been proposed (Seed et al., 2003; Kramer and Mayfield, 2007; Cetin et al., 2009), we consider that it will take some time until these procedures are used in practice.

This paper first presents comparisons of these two new procedures with the Youd et al. (2001) procedures by comparing the CRR, the FS against liquefaction, and post-earthquake reconsolidation settlement (Δ) at different depths. Next, paired SPTs and CPTs field data were used to evaluate the relative performance between SPT-based and CPT-based correlations for each of these three procedures. Assessments of conservatism were made for the three analytical frameworks and between using SPT-based and CPT-based correlations. Discussions and recommendations are provided on some components of each analytical framework.

The purpose of this paper is two fold: (1) provide practitioners with technical insights into each of these three procedures; and, (2) present our findings from this comparison to assess suitability of each analytical framework for liquefaction potential evaluation.

RECENT MAJOR ADVANCES IN SOIL LIQUEFACTION EVALUATION

The “current standard-of-practice” for evaluating the potential of soil liquefaction during earthquakes is summarized in the paper titled “Liquefaction Resistance of Soils: Summary of Report from the 1996 National Center for Earthquake Engineering Research (NCEER) and 1998 NCEER/National Science Foundation (NSF) Workshops on Evaluation of

Liquefaction Resistance of Soils" (Youd et al 2001). The SPT-based and CPT-based liquefaction analysis procedures summarized in their paper will hereafter be referred to as the Youd et al. (2001) procedures. In recent years, there has been questioning on the conservatism of the Youd et al (2001) approach, especially for the liquefaction susceptibility assessment of silts and clays and for the CPT-based correlation primarily due to (1) augmented databases of field case histories, (2) improved evaluation of peak ground accelerations at case history sites, and (3) better understanding of the liquefaction behavior of silts and clays. Within the scope of this paper, it is not possible to discuss all major advances in greater detail. However, one of these advances regarding the liquefaction susceptibility criteria for silts and clays will be addressed more in detail.

The so-called "Modified Chinese Criteria" has been most widely used for assessing liquefaction susceptibility of clayey soils for two decades since it was proposed by Wang (1979). In the NCEER Working Group summary paper (1997) and the summary article by Youd et al. (2001) there was an agreement that the "Modified Chinese Criteria" should be re-examined for redefining the types of potentially liquefiable "cohesive" soils with silts and clays. But no consensus was reached at that time to establish improved criteria for defining the types of potentially liquefiable "cohesive" soils, and further study was suggested.

Post-earthquake reconnaissance efforts after the 1999 Chi-Chi (Taiwan) and the 1999 Kocaeli (Turkey) earthquakes (Bray and Stewart, 2000, Sancio et al., 2002) indicated that liquefaction and ground softening were observed in soil layers containing more than 15% particles finer than 5 mm. These soils should have behaved as non-liquefiable soils based on the "Modified Chinese Criteria".

Based on the above observations, Bray et al. (2001), Sancio et al. (2002), Sancio et al. (2003), and Seed et al. (2003) concluded that the percent "clay-size" criterion of the "Modified Chinese Criteria" is misleading and the activity of "clay-size" particles is more important for characterizing the behavior of silts and clays during earthquakes. The use of the "Modified Chinese Criteria" can be nonconservative for such soils. Based on the results of these studies, Seed et al. (2003) presented their recommendations regarding soil liquefaction susceptibility criteria for silts and clays as shown in Fig. 1. Their criteria are primarily based on Plasticity Index (PI), Liquid Limit (LL) and natural water content (w_c). Soils within Zone A are considered potentially susceptible to "classic" cyclically induced liquefaction that could be evaluated using the procedures discussed in their paper. Soils within Zone B may be liquefiable and need to be tested if the w_c is equal to or greater than 85% of the LL. Soils outside Zones A or B are not generally susceptible to "classic" cyclic liquefaction, but should be evaluated for potential cyclic softening.

Boulanger and Idriss (2006), in general, agreed with the conclusions of Seed et al. (2003) that new criteria are needed for characterizing liquefaction behavior of silts and clays. However, based on the results of field case histories and some additional laboratory tests, they concluded that only PI is needed to assess the liquefaction susceptibility of silts and clays. Based on their studies, fine-grained soils appear to transition from a behavior that is more fundamentally like sands to a behavior that is more fundamentally like clays over a fairly narrow range of PI between 3 and 8 (Fig. 2). They recommended, for engineering practice, using a PI of 7 as the boundary between clay-like and sand-like behavior.

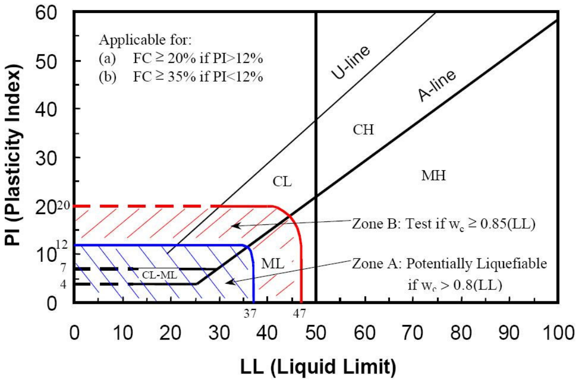


Fig. 1. Recommendations regarding assessment of liquefiable soil types (Seed et al., 2003)

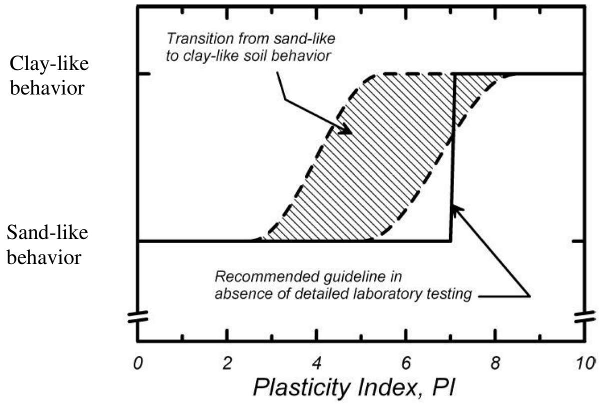


Fig. 2. Schematic of the transition from sand-like to clay-like behavior for fine-grained soils with increasing PI, and the recommended guideline for practice (Modified after Idriss and Boulanger, 2006)

The new liquefaction susceptibility criteria for silts and clays is a milestone achievement that would predict the occurrence of liquefaction for such soils that would be expected to be non-liquefiable based on the "Modified Chinese Criteria".

For the CPT-based correlations, Seed et al. (2003) have steered away from using the soil behavior type (I_c) approach proposed by Robertson and Wride, (1998), and instead have focused on an updated normalized tip resistance ($q_{c,1}$), friction ratio (R_f) and normalization exponent (c). However, this led to a problem on soil susceptibility criteria to be used with the CPT-based correlations. Lacking of such criteria makes the Seed et al. (2003) CPT-based correlations incomplete at this moment.

Similarly, Idriss and Boulanger (2008) CPT-based correlations do not include similar soil susceptibility criteria to be used in the calculation of the CRR values.

For this study, an I_c value of 2.6 as per the Youd et al. (2001) procedures was used along with the CRR calculations for both the Seed et al. (2003) and Idriss and Boulanger (2008) CPT-based correlations.

COMPARISON OF THREE LIQUEFACTION ANALYSIS APPROACHES

Although Seed et al. (2003) and Idriss and Boulanger (2008) presented their liquefaction analysis procedures based on the same analytical framework as summarized by Youd et al. (2001), various components of their respective procedures are significantly different from the Youd et al (2001) procedures (i.e., evaluation of C_N, K_σ, r_d, etc.). Comparison of each component does not capture the differences among the analytical frameworks. A meaningful comparison of these analytical frameworks can be made by comparing the values of $CRR_{M=7.5,\sigma_v^{'}=1}$ (i.e., the cyclic resistance ratio scaled to a magnitude of 7.5 and normalized to 1 atmospheric pressure), FS_{liq} (i.e., the factor of safety against liquefaction), and Δ_{liq} (i.e., post-liquefaction consolidation settlement) that could be estimated based on the measured penetration resistance at different depths. Accordingly, the conservatism of each analytical framework can be evaluated.

In what follows, both SPT-based and CPT-based correlations will be compared in terms of $CRR_{M=7.5,\sigma_v^{'}=1}$, FS_{liq} and Δ_{liq} values for various SPT N_{60} (i.e., the standard penetration blowcount standardized to 60% energy ratio) at different depths. The comparisons are made for depths of up to 60 feet, using the correlations from Youd et al. (2001), Idriss and Boulanger (2008), and Seed et al. (2003). The comparisons are for clean sands (fines content < 5%), a ground water table at the depth of 1 foot below the ground surface, an earthquake magnitude (M) of 7.5, and peak ground acceleration (PGA) of 0.45g. It should be noted that Seed et al. (2003) developed their correlations probabilistically and recommended that deterministic analyses use a curve of Probability of Liquefaction (P_L) equal to 15% at $(N_1)_{60cs}$ values less than or equal to 32. For this study, a P_L of 15% was used for comparisons.

SPT-Based Liquefaction Analysis Procedures

Figure 3a shows contours of the ratio CRR_{Seed}/CRR_{Youd}, where CRR_{Seed} is the $CRR_{M=7.5,\sigma_v^{'}=1}$ value from the Seed et al. (2003) procedures, and CRR_{Youd} is the $CRR_{M=7.5,\sigma_v^{'}=1}$ from the Youd et al. (2001) procedures. Figure 3b shows contours of the ratio CRR_{IB}/CRR_{Youd}, where CRR_{IB} is the $CRR_{M=7.5,\sigma_v^{'}=1}$ value from the Idriss and Boulanger (2008) procedures.

The comparisons in Fig. 3a show that the CRR_{Seed} values are typically within ±20% of the CRR_{Youd} for SPT N_{60} values of 2 to 22 at depths of 4 to 20 feet. The CRR_{Seed} values are generally 30 to 50% smaller than the CRR_{Youd} values at depths deeper than 20 feet. The calculated CRR_{Seed} values could be up to 50% less than the calculated CRR_{Youd} values for SPT N_{60} values of 7 to 21 at depth of 45 to 60 feet.

The comparisons in Fig. 3b show that the CRR_{IB} values are typically within ±20% of the CRR_{Youd} values for SPT N_{60} values of 2 to 22 at depths of 2 to 60 feet.

It should be noted that the areas in turquoise with a contour value of 1.7 (Figs 3a and 3b) represent the soils of sufficiently large SPT N_{60} values that are not liquefiable per the Youd et al. (2001) procedures. These SPT N_{60} values increase with increasing depths. This is also true for all other contour figures in this paper with the exception that this area could be represented by a different color depending on the maximum contour value.

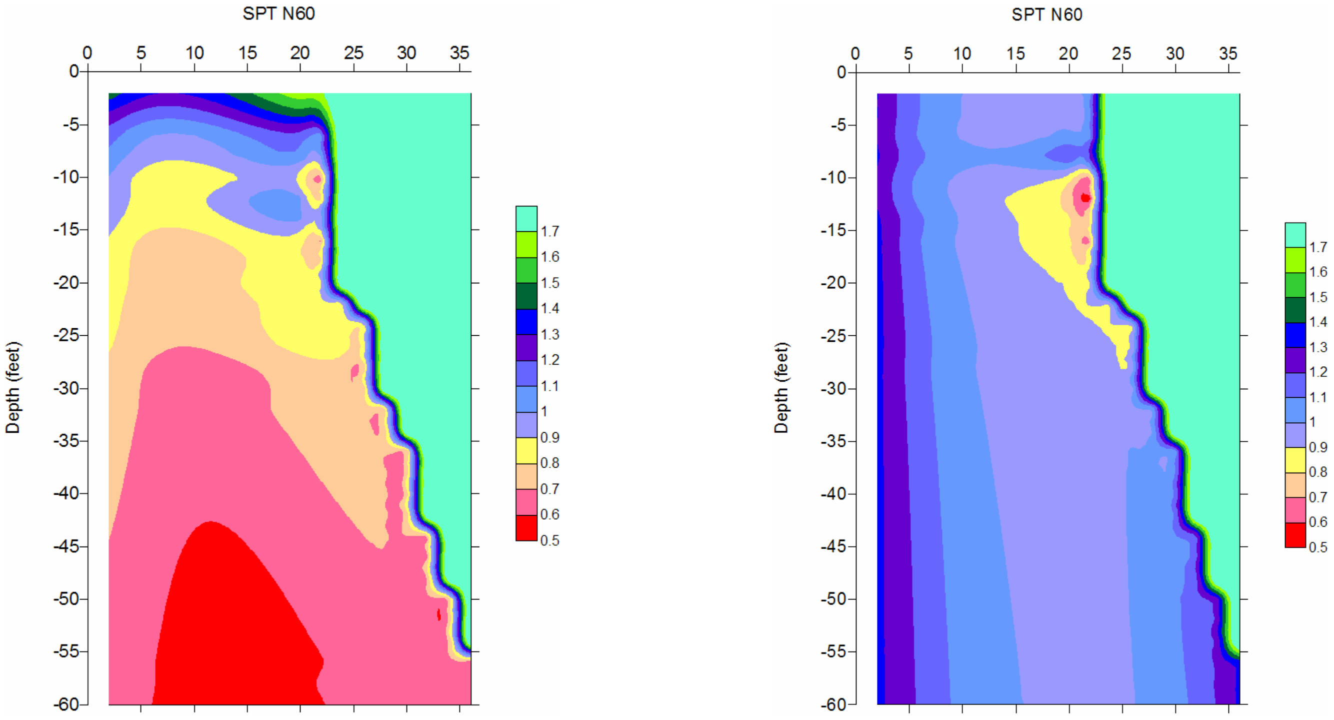
Figure 4a shows contours of the ratio FS_{Seed}/FS_{Youd}, where FS_{Seed} is the FS values against liquefaction from the Seed et al. (2003) procedures, and FS_{Youd} is the FS values from the Youd et al. (2001) procedures. Figure 4b shows contours of the ratio FS_{IB}/FS_{Youd}, where FS_{IB} is the FS values from the Idriss and Boulanger (2008) procedures.

The comparisons in Figure 4a show that FS_{Seed} values are smaller (in some cases by as much as 50%) than FS_{Youd} values for SPT N_{60} values of 6 - 22 at depths greater than 25 feet. For depths less than 15 feet and for N_{60} values of 2 to 22, FS_{Seed} values are 10 to 100% higher than FS_{Youd} values.

As can be seen in Figure 4b, the FS_{IB} values are typically within ±20% of the FS_{Youd} values. For SPT N_{60} values of 2 to 4 at depths of less than 35 feet, the FS_{IB} values are 30 to 40% greater than FS_{Youd} values.

It is of interest to point out that for shallow depths of less than 15 feet in Fig. 4a, the ratio FS_{Seed}/FS_{Youd} is significantly larger than the ratio FS_{IB}/FS_{Youd} in Fig. 4b. This difference could be primarily explained by the difference in the upper bound limits on the overburden correction factor, K_σ, by different procedures (i.e., 1.0 by Youd et al. (2001), 1.7 by Seed et al. (2003), and 1.1 by Idriss and Boulanger (2008)).

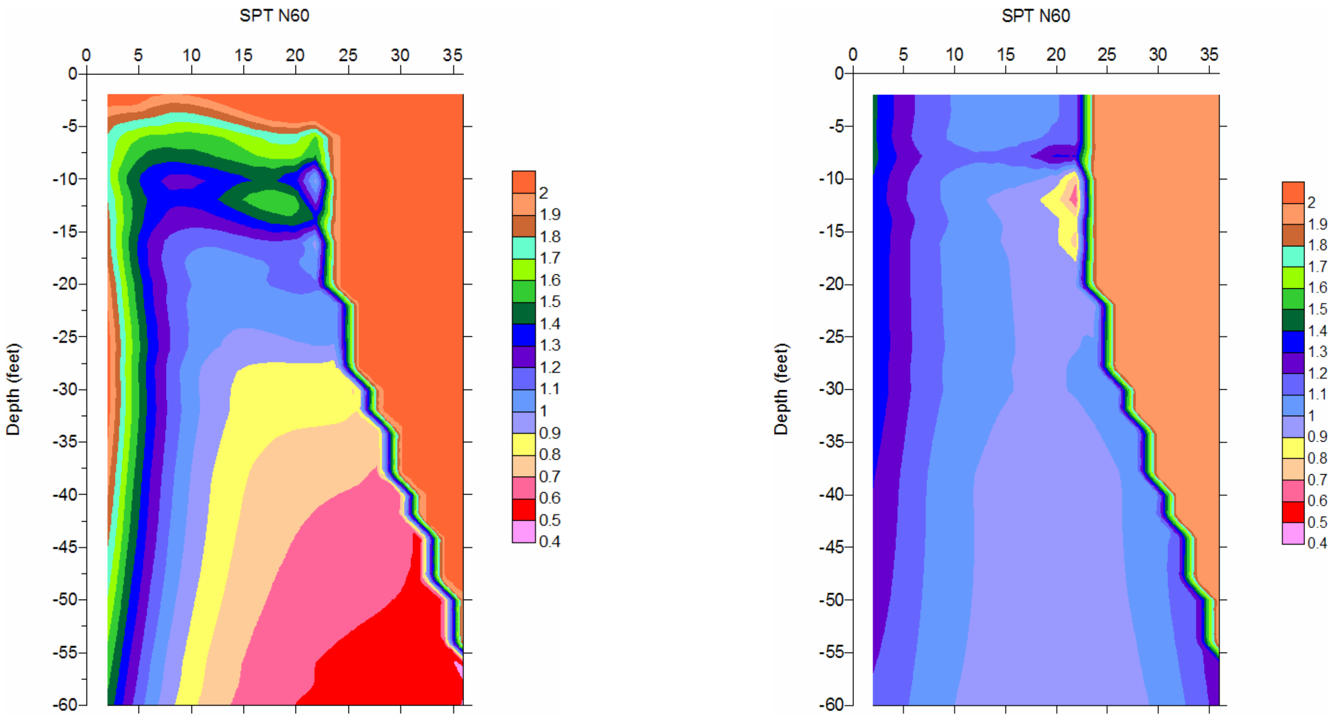
The comparisons in Figs 4a and 4b also show that for the soils with the same SPT N_{60}, the Idriss and Boulanger (2008) procedures is likely to predict the smallest FS value among the three procedures for SPT N_{60} values of 6 to 22 at depths of 2 to 25 feet. However, for the same SPT N_{60} values at depths of 25 to 60 feet, the Seed et al. (2003) method is likely to predict the smallest FS value.



(a) CRR_{Seed}/CRR_{Youd}

(b) CRR_{IB}/CRR_{Youd}

Fig. 3 Comparison of $CRR_{M=7.5,\sigma'_v=1}$ *from the Youd et al. (2001), Seed et al. (2003), and Idriss and Boulanger (2008): (a)* CRR_{Seed}/CRR_{Youd}*; and (b)* CRR_{IB}/CRR_{Youd}



(a) FS_{Seed}/FS_{Youd}.

(b) FS_{IB}/FS_{Youd}

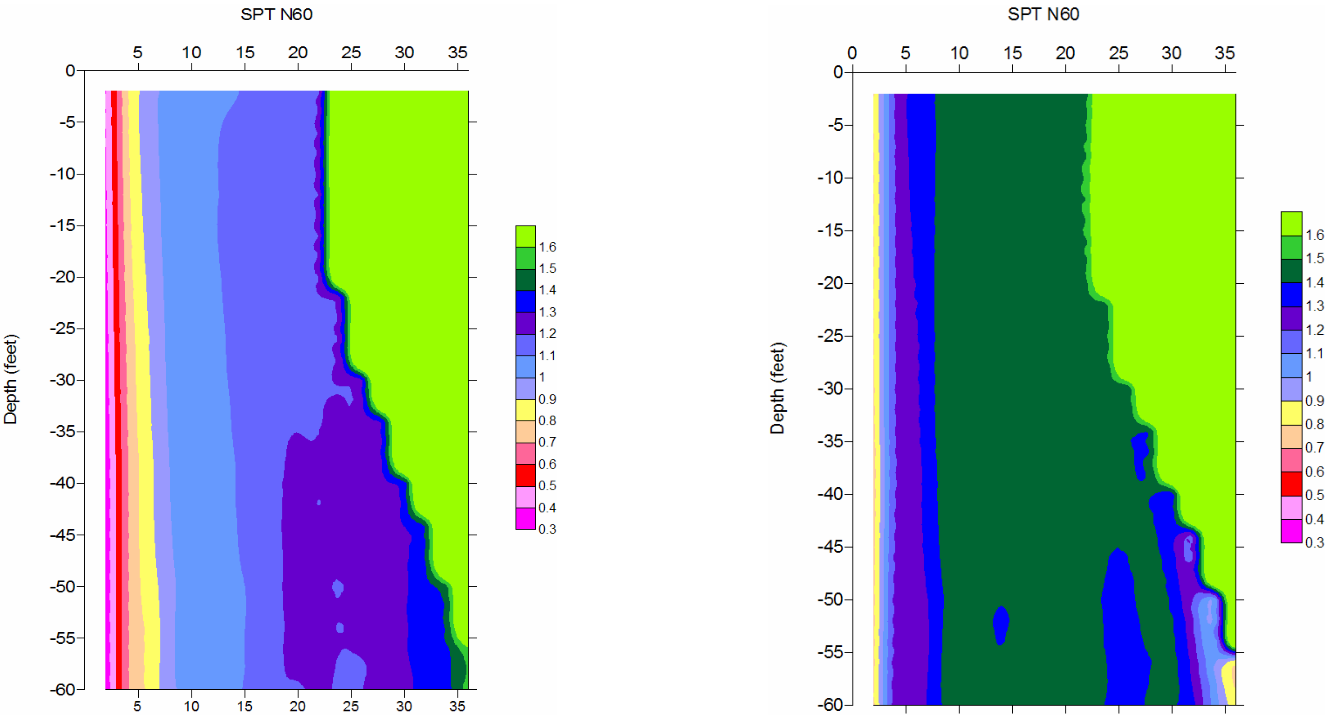
Fig. 4 Comparison of FS_{liq} *from the Youd et al. (2001), Seed et al. (2003), and Idriss and Boulanger (2008): (a)* FS_{Seed}/FS_{Youd}*; and (b)* FS_{IB}/FS_{Youd}

Figure 5a shows contours of the ratio $\Delta_{Seed}/\Delta_{Youd}$, where Δ_{Seed} is the post liquefaction reconsolidation settlement estimated using the Cetin et al. (2009) procedures, and Δ_{Youd} is the post liquefaction reconsolidation settlement estimated using the Tokimatsu and Seed (1987) procedures. Figure 5b shows contours of the ratio $\Delta_{IB}/\Delta_{Youd}$, where Δ_{IB} is the post-liquefaction reconsolidation settlement estimated using the Idriss and Boulanger (2008) procedures.

The comparisons in Fig. 5a show that the estimated settlements using Cetin et al. (2009) method are typically within ±10% of values estimated using Idriss and Boulanger (2008) method for SPT N_{60} values of 5 to 22. For SPT N_{60} values of less than 5, the Δ_{Seed} values are generally 30 to 80% smaller than Δ_{Youd}.

The comparisons in Fig. 5b show that the Δ_{IB} values are generally 40% larger than the Δ_{Youd} values for SPT N_{60} values of 8 to 22. When SPT N_{60} values change from 2 to 8, the ratio changes continuously from 0.8 to 1.3 at the same depth.

The comparisons in Figs 5a and 5b show that, for the same soil condition with the same SPT N_{60}, the Idriss and Boulanger (2008) procedures are most likely to estimate the largest settlement and thus are the most conservative.



(a)) $\Delta_{Seed}/\Delta_{Youd}$

(b) $\Delta_{IB}/\Delta_{Youd}$

Fig. 5 Comparison of Δ_{liq} *from the Tokimatsu and Seed (1987), Cetin et al. (2009), and Idriss and Boulanger (2008): (a)* $\Delta_{Seed}/\Delta_{Youd}$ *; and (b)* $\Delta_{IB}/\Delta_{Youd}$

CPT-Based Liquefaction Analysis Procedures

Similar comparisons were also made for CPT-based liquefaction analysis procedures using the Youd et al (2001), Seed et al. (2003), and Idriss and Boulanger (2008) approaches for various q_{cN} values at different depths.

Figures 6a and 6b show contours of the ratio CRR_{Seed}/CRR_{Youd} and the ratio CRR_{IB}/CRR_{Youd}, respectively.

The comparisons in Fig. 6a show that the CRR_{Seed} values are generally within ±10% of the CRR_{Youd} values for q_{cN} values of 35 to 105. The CRR_{Seed} values are 20 to 50% smaller than CRR_{Youd} for q_{cN} values less than 35 at depths of 2 to 60 feet. For the same q_{cN} value, the greater the depth, the smaller the ratio. The comparisons in Fig. 6b show that the CRR_{IB} values are generally 70 to 90% of the CRR_{Youd} values regardless of depths.

Figures 7a and 7b show contours of the ratio FS_{Seed}/FS_{Youd} and the ratio FS_{IB}/FS_{Youd}, respectively.

The comparisons in Fig. 7a show that the FS_{Seed} values are generally 10 to 70% larger than the FS_{Youd} values for q_{cN} values of 25 to 100. The FS_{Seed} values are generally 10 to 20%

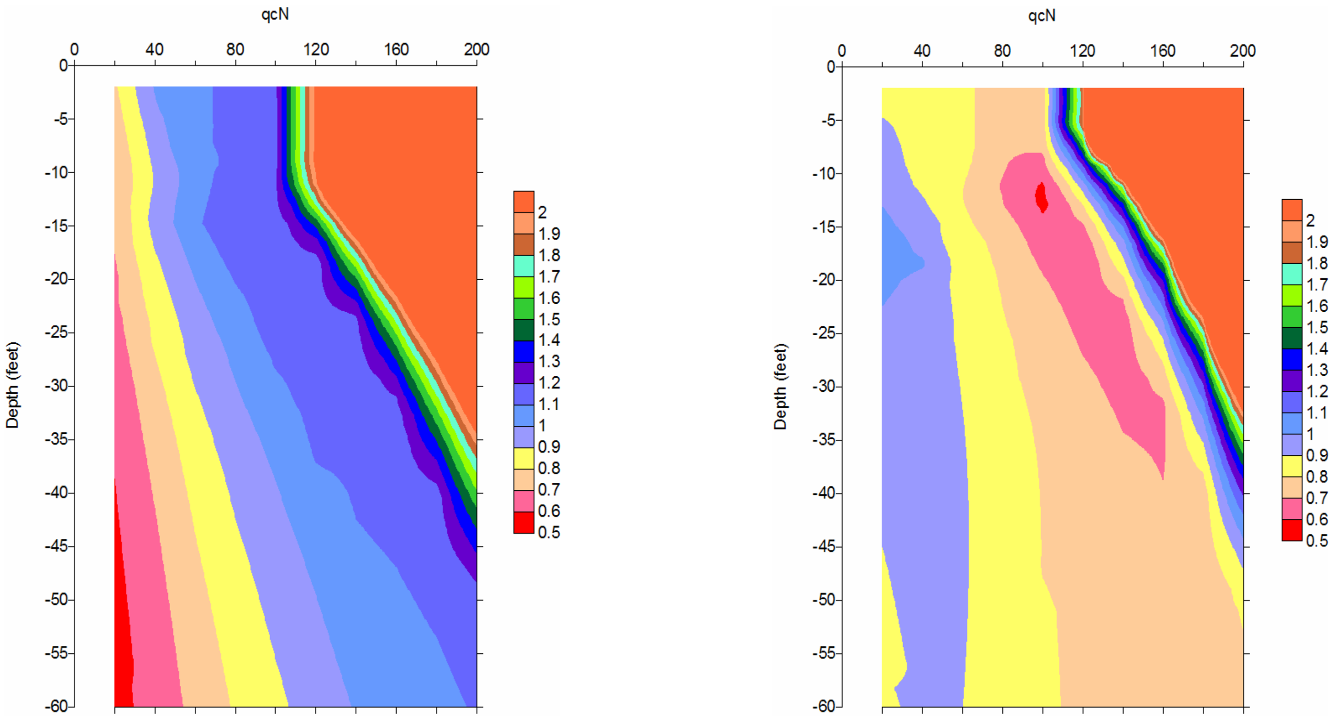
smaller than the FS_{Youd} values for q_{cN} values less than 25 at shallow depths and for q_{cN} values less than 40 at greater depths. Compared to Fig. 7b, the larger area in orange with a contour value of 2.0 is believed to be caused by a larger limit on the overburden correction factor, K_σ, by Seed et al. (2003) procedures (i.e., 1.7 by Seed et al. (2003), and 1.1 by Idriss and Boulanger (2008)).

The comparisons in Fig. 7b show that the FS_{IB} values are generally 60 to 90% of the FS_{Youd} values. The FS_{IB} values are about the same as the FS_{Youd} values only within a small area where the q_{cN} values are between 20 and 40 at depths of about 15 to 30 feet. In terms of the FS_{liq} values, the Idriss and Boulanger procedures are the most conservative based on the comparisons presented in Figs7a and 7b.

Figures 8a and 8b show contours of the ratio $\Delta_{Seed}/\Delta_{Youd}$ and the ratio $\Delta_{IB}/\Delta_{Youd}$, respectively.

The comparisons in Fig. 8a show that the Δ_{Seed} values are generally 10 to 70% larger than the Δ_{Youd} values. For q_{cN} values larger than about 170, the soil is not likely to liquefy. The contours show that the Δ_{Seed} values are smaller than the Δ_{Youd} values within approximately the upper 45 feet.

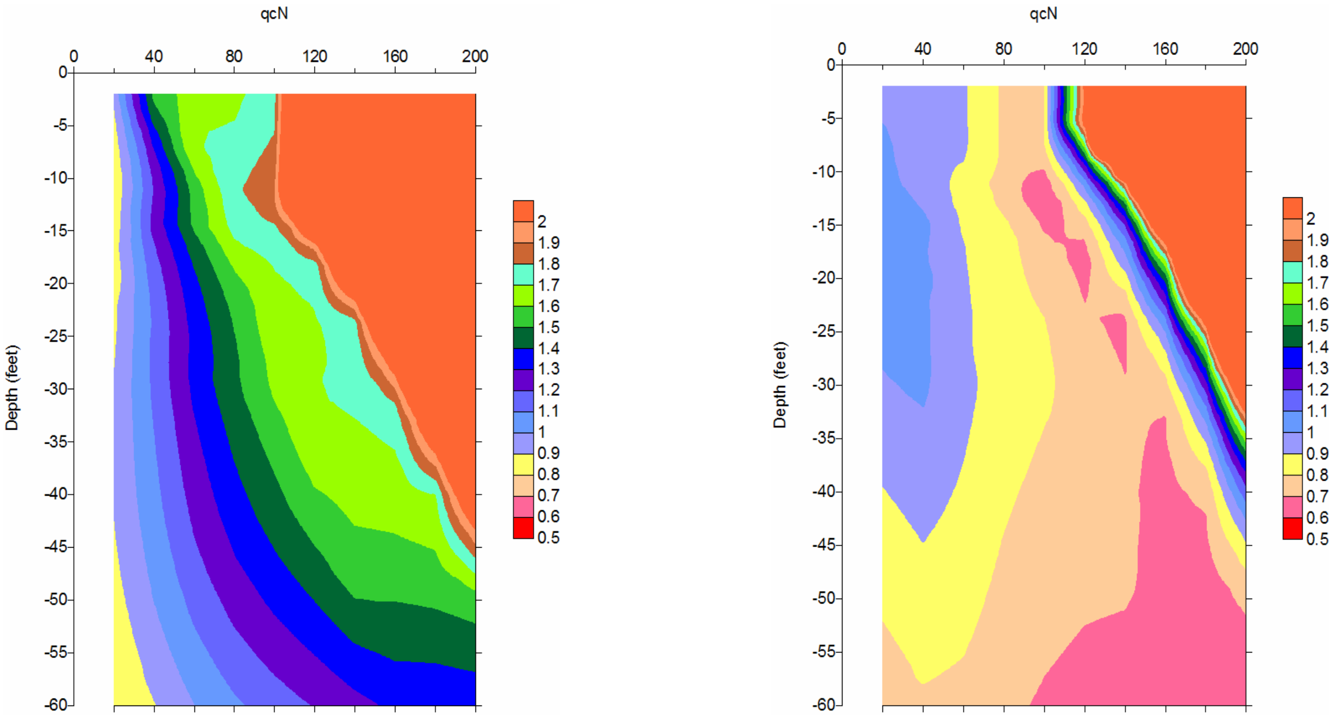
The comparisons in Fig. 8b show that the Δ_{IB} values are at least 30% larger than the Δ_{Youd} values. The Δ_{IB} values could be 100% larger than the Δ_{Youl} values for q_{cN} values of 60 to100 at depths of 2 to 60 feet, and for q_{cN} values of 100 to 160 at depths of 2 to 20 feet. It should be noted that the contour value is capped at 2 if the ratio $\Delta_{IB}/\Delta_{Youd}$ is greater than 2.



(a) CRR_{Seed}/CRR_{Youd}

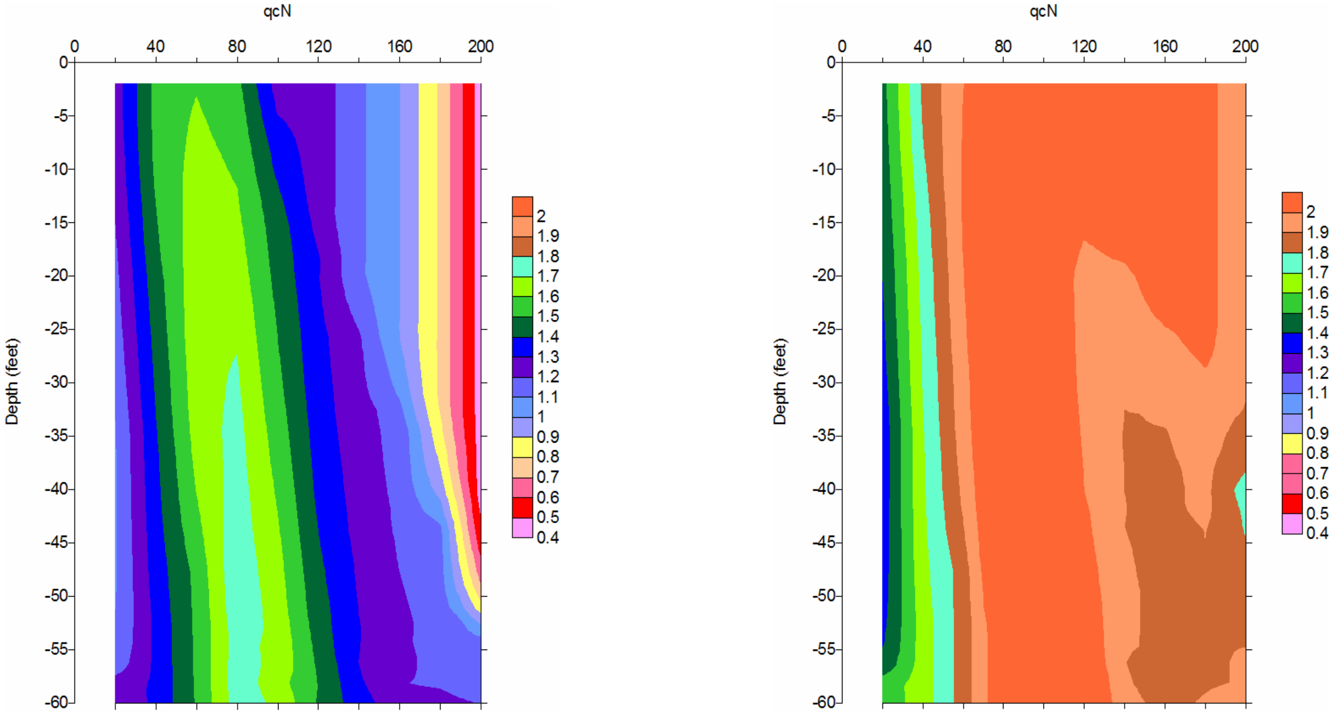
(b) CRR_{IB}/CRR_{Youd}

Fig. 6 Comparison of $CRR_{M=7.5,\sigma_v'=1}$ *from the Youd et al. (2001), Seed et al. (2003), and Idriss and Boulanger (2008): (a)* CRR_{Seed}/CRR_{Youd}*; and (b)* CRR_{IB}/CRR_{Youd}



(a) FS_{Seed}/FS_{Youd} (b) FS_{IB}/FS_{Youd}

Fig. 7 Comparison of FS_{liq} from the Youd et al. (2001), Seed etal. (2003), and Idriss and Boulanger (2008): (a) FS_{Seed}/FS_{Youd} ; and (b) FS_{IB}/FS_{Youd}



(a) $\Delta_{Seed}/\Delta_{Youd}$ (b) $\Delta_{IB}/\Delta_{Youd}$

Fig. 8 Comparison of Δ_{liq} from the Tokimatsu and Seed. (1987), Cetin et al. (2009), and Idriss and Boulanger (2008) :: (a) $\Delta_{Seed}/\Delta_{Youd}$; and (b) $\Delta_{IB}/\Delta_{Youd}$

COMPARISON OF SPT-BASED AND CPT-BASED CORRELATIONS

Over the years, the Youd et al (2001) SPT-based correlations have been better defined and have provided lower uncertainty than the Youd et al. (2001) CPT-based correlations due in large part to enhanced databases of field case histories and better data processing and correlation development (Seed et al., 2003). Compared to the SPT, however, the CPT offers advantages with regard to (1) cost and efficiency, (2) consistency in equipment and operators, and (3) continuity of data over depth. It has proved to be a valuable tool for characterizing subsurface conditions and assessing various soil properties, including estimating the potential for liquefaction (Idriss and Boulanger, 2008).

Baez et al. (2000) examined the SPT-based Youd et al. (2001) correlations and the CPT-based Youd et al. (2001) correlations using data from field case histories. Their studies showed that both SPT-based and CPT-based Youd et al. (2001) correlations appear to match well in terms of predicting the occurrence of liquefaction. However, their results suggest that CRR and FS against liquefaction may differ, in some cases by as much as ±30%. Their closer examination of the difference suggests that it is possible that in some cases either the CPT or SPT CRR correlations may not be conservative enough.

By the time the CPT-based correlations were summarized by Youd et al. (2001), the CPT-based correlations were based on a much smaller number of and lesser defined earthquake field case histories than SPT-based correlations. However, newly developed CPT-based correlations used enhanced data bases that contain more field case histories and better understanding and treatment of the PGA. These new correlations now represent almost the same level of accuracy and reliability relative to SPT-based correlations, including the Seed et al. (2003) and Idriss and Boulanger (2008) procedures.

Comparisons of the SPT-based and CPT-based correlations were made to assess the relative conservatism of the Youd et al. (2001), the Seed et al. (2003), and the Idriss and Boulanger (2008) procedures by comparing the calculated CRR values and FS values. Side-by-side SPTs and CPTs were selected for comparing the values of $CRR_{M=7.5,\sigma'_v=1}$ and FS_{liq} estimated based on the measured penetration resistance at different depths. These SPTs and CPTs were performed for a levee evaluation project in the San Francisco Bay Area, California. All borings were drilled using Failing 1500 drill rigs equipped with an automatic trip hammer using mud rotary method. All CPTs were accomplished using a Geoprobe Model 6625CPT rig. Selected paired SPTs/CPTs were performed no more than 10 feet apart in the horizontal direction and with a ground surface elevation difference of no more than 1.5 feet. The elevation difference for the paired SPTs/CPTs were taken into consideration to make sure the comparison was made at the same elevation. A total of 19 pairs of SPTs/CPTs were selected from a total of 46 pairs. The ground motion parameters used for all analyses include a moment magnitude of 7.5 and a PGA of 0.35g. A P_L value of 15% is assumed for the Seed et al. (2003) procedures. The ground water was assumed at 1 foot below the ground surface.

Youd et al. (2001) Procedures

Figure 9a shows values of CRR_{SPT} and CRR_{CPT}, where the CRR_{SPT} is the $CRR_{M=7.5,\sigma'_v=1}$ value from the SPT-based Youd et al. (2001) procedures, and the CRR_{CPT} is the $CRR_{M=7.5,\sigma'_v=1}$ from the CPT-based Youd et al. (2001) procedures. Figure 9b shows values of FS_{SPT} and FS_{CPT}, where the FS_{SPT} is the FS against liquefaction from the SPT-based Youd et al. (2001) procedures, and the FS_{CPT} is the FS from the CPT-based Youd et al. (2001) procedures.

The comparisons in Fig. 9a show significant scatter around the 1:1 correlation line. Regression analyses show that the best fit line is appreciably skewed with respect to the 1:1 correlation line. The skewed best fit line would suggest that the CPT procedures could predict a CRR value which is greater than the SPT procedures when the CRR value is less than 0.15, and smaller when the CRR value is greater than 0.15.

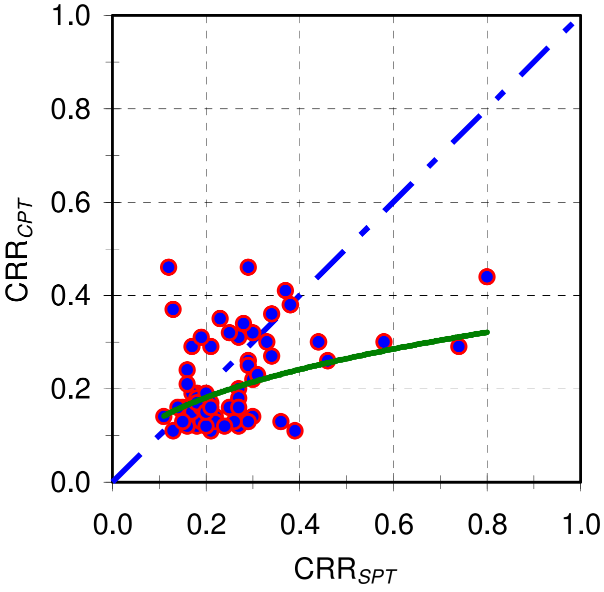


Fig. 9a Comparison of $CRR_{M=7.5,\sigma'_v=1}$ calculated from SPT- and CPT-based Youd et al. (2001) Procedures

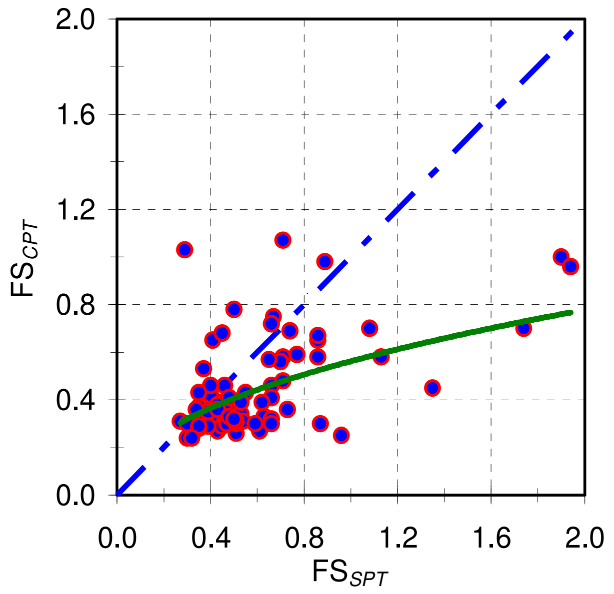


Fig. 9b Comparison of FS calculated from SPT- and CPT-based Youd et al. (2001) Procedures

Similarly, the comparisons in Fig. 9b show significant scatter around the 1:1 correlation line. Regression analyses show that the best fit line is appreciably skewed with respect to the 1:1 correlation line. The skewed best fit line would suggest that the CPT procedures could predict a FS value which is greater than the SPT procedures when the FS value is less than 0.3, and smaller when the FS value is greater than 0.3

It is of interest herein to compare Fig. 9b with Fig. 10 by Baez et al. (2000). Similar results of regression analyses are obtained with best fit lines in this study more skewed with respect to the 1:1 correlation line. The difference could be in large part explained by the nature of data used in each study. Baez et al. (2000) used data obtained from field case histories, meaning the liquefaction analysis procedures were applied to the limits of these data. Another possible source of difference could be the number of paired SPT/CPT-based FS values used in our study. Compared to 159 pairs of SPT based and CPT based FS values used by Baez et al. (2000), only 73 pairs of FS values are used in our study. In particular, more FS-values between 1.0 and 2.0 are needed to improve the correlation.

Seed et al. (2003) Procedures

Figure 11a shows values of CRR$_{SPT}$ and CRR$_{CPT}$, where CRR$_{SPT}$ is the $CRR_{M=7.5,\sigma_v'=1}$ value from the SPT-based Seed et al. (2003) procedures, and CRR$_{CPT}$ is the $CRR_{M=7.5,\sigma_v'=1}$ from the CPT-based Seed et al. (2003) procedures. Figure 11b shows values of FS$_{SPT}$ and FS$_{CPT}$, where FS$_{SPT}$ is the FS against liquefaction from the SPT correlations, and FS$_{CPT}$ is the FS from the CPT correlations.

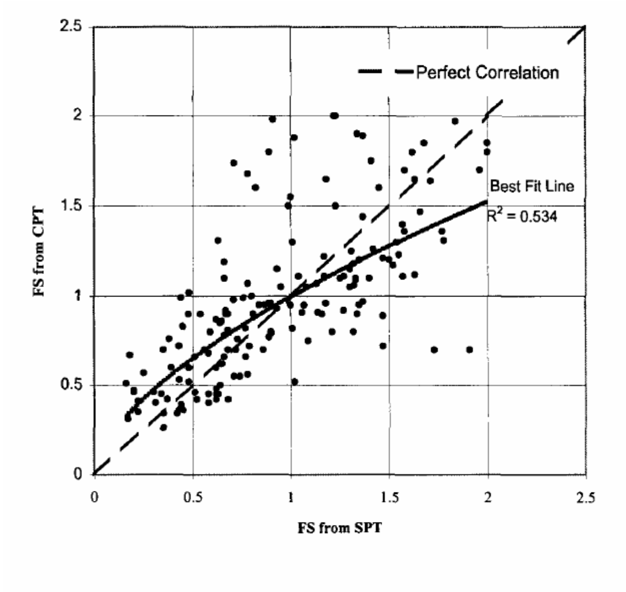


Fig. 10. Comparison between FS calculated from CPT and SPT data measured at the case history sites (Modified after Ggstrap and Youd, 1998)(Baez et al., 2000)

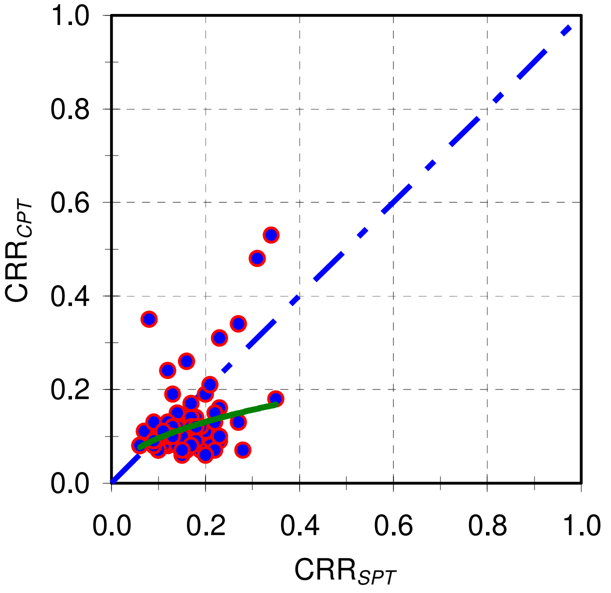


Fig. 11a Comparison of $CRR_{M=7.5,\sigma_v'=1}$ *calculated from SPT- and CPT-based Seed et al. (2003) Procedures*

As seen in Figs 11a and 11b, significantly scattered data around the 1:1 correlation line is observed. Both best fit lines are significantly skewed with respect to the 1:1 correlation line. The skewed best fit line in Fig. 11a would suggest that the CPT procedures could predict a CRR value which is greater than the SPT procedures when the CRR value is less than 0.1, and smaller when the FS value is greater than 0.1.

The skewed best fit line in Fig. 11b would suggest that the CPT procedures could predict a FS value which is greater than the SPT procedures when the FS value is less than 0.3, and smaller when the FS value is greater than 0.3.

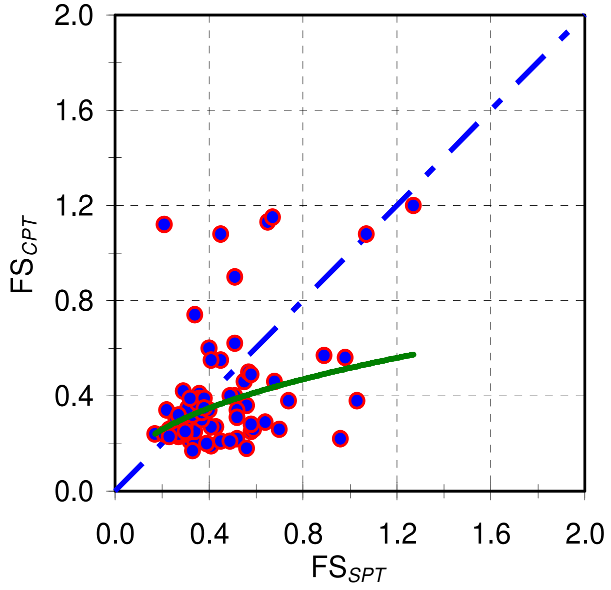


Fig. 11b Comparison of FS calculated from SPT- and CPT-based Seed et al. (2003) procedures

Idriss and Boulanger (2008) Procedures

Figure 12a shows values of CRR$_{SPT}$ and CRR$_{CPT}$, where CRR$_{SPT}$ is the $CRR_{M=7.5,\sigma_v^{'}=1}$ value from the SPT-based Idriss and Boulanger (2008) procedures, and CRR$_{CPT}$ is the $CRR_{M=7.5,\sigma_v^{'}=1}$ value from the CPT-based Idriss and Boulanger (2008) procedures. Figure 12b shows values of FS$_{SPT}$ and FS$_{CPT}$, where FS$_{SPT}$ is the FS against liquefaction from the SPT correlations, and FS$_{CPT}$ is the FS from the CPT correlations.

The data in Figs 12a and 12b shows significant scatter around the 1:1 correlation line. Similarly, both best fit lines are significantly skewed with respect to the 1:1 correlation line. The skewed best fit line in Fig. 12a would suggest that the CPT procedures could predict a CRR value which is greater than the SPT procedures when the CRR value is less than 0.1, and smaller when the CRR value is greater than 0.1. The skewed best fit line in Fig. 12b would suggest that the CPT procedures could predict a FS value which is greater than the SPT procedures when the FS value is less than 0.25, and smaller when the FS value is greater than 0.25.

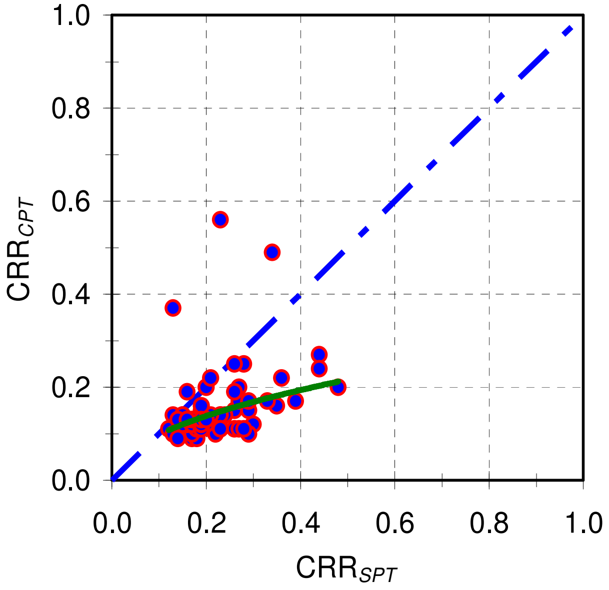


Fig. 12a Comparison of $CRR_{M=7.5,\sigma_v^{'}=1}$ *calculated from SPT- and CPT-based Idriss and Boulanger (2008) procedures*

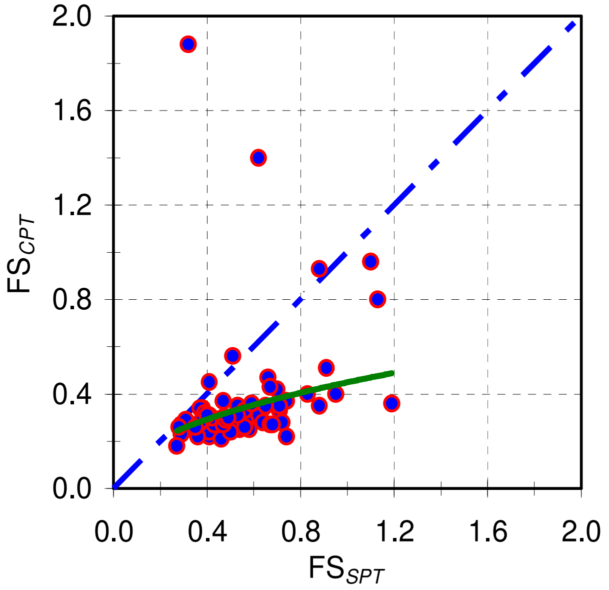


Fig. 12b Comparison of FS calculated from SPT- and CPT-based Idriss and Boulanger (2004) procedures

SUMMARY AND CONCLUSIONS

This paper presented the results of comparative studies of three liquefaction evaluation procedures, namely, Youd et al. (2001), Seed et al. (2003), and Idriss and Boulanger (2008). For this purpose, the three liquefaction susceptibility criteria were reviewed and compared with each other for sands as well as for silts and clays. Also, the three liquefaction evaluation procedures were compared in terms of the cyclic resistance ratio, factor of safety, and post-earthquake reconsolidation settlement. Our findings from these comparative studies are summarized as follows:

For the SPT-based correlations:

- The FS_{Seed} values are typically 10 to 50% smaller than the FS_{Youd} values for SPT N_{60} values of 6 to 22 at depths of 20 to 60 feet. Outside those ranges of depths and SPT N_{60} values, the FS_{Seed} values are usually 10 to 70% greater than the FS_{Youd} values. The FS_{IB} values are typically within ±20% of the $FS_{Youd.}$ values for SPT N_{60} values of 4 to 22 at depths of 2 to 60 feet. Therefore, Idriss and Boulanger (2008) procedures appear to be the most conservative among the three procedures.
- The Δ_{Seed} values are generally within ±20% of the Δ_{Youd} values for SPT N_{60} values of 4 to 22 at depths of 2 to 60 feet. The Δ_{IB} values are typically 30 to 40% larger than the Δ_{Youd} values for SPT N_{60} values of 5 to 22 at depths of 2 to 60 feet. Therefore, Idriss and Boulanger (2008) procedures appear as the most conservative among the three procedures, in terms of the estimated settlement.

For the CPT-based correlations:

- The FS_{Seed} values are generally larger than FS_{Youd} values, and the FS_{IB} values are typically 10 to 40% smaller than the FS_{Youd} values. Therefore, Idriss and Boulanger (2008) procedures are the most conservative.
- The Δ_{Seed} values are generally 10 to 80% larger than the Δ_{Youd} values for various q_{cN} values at various depths. The Δ_{IB} values are at least 30% larger than the Δ_{Youd} values. The Δ_{IB} values could be 100% larger than the Δ_{Youd} values for q_{cN} values of 60 to 100 at depths of 2 to 60 feet and for q_{cN} values of 100 to 160 at depths of 2 to 20 feet. Idriss and Boulanger (2008) procedures appear to be the most conservative.

For all three analytical frameworks including both SPT-based and CPT-based procedures, it appears that the Idriss and Boulanger (2008) procedures are likely the most conservative, and the Youd et al. (2001) are likely the least conservative. The Seed et al. (2003) procedures are in between regarding the conservatism.

It should be noted that all comparative studies among three liquefaction analytical frameworks were carried out assuming clean granular soils. The effect of fine contents correction by each framework was not examined in this paper due to the limited space. However, the authors believe that two new approaches would estimate more conservative results (i.e., smaller CRR and FS, and larger Δ) than the Youd et al. (2001) approach for granular soils with significant silts and clays and sand-like fine-grained soils.

For the relative performance between the SPT and CPT correlations, for all three approaches, the SPT correlations are most likely less conservative than the CPT correlations when the FS is greater than 0.3, and more conservative when the FS is smaller than 0.3. As indicated by correlation coefficients, however, the correlations are poor and not conclusive.

Comparisons between the SPT and CPT correlations also clearly indicate that significant difference can be obtained when comparing the FS between the SPT and CPT correlations. This difference could be partially attributed to the variability of the natural deposits. Nevertheless, it is the authors' opinion that the difference could be largely explained on the basis of the chosen liquefaction base curves for CRR which may inherently provide different results as could be observed in Figs 9a, 10b, and 11b where significant variance could be obtained when comparing the CRR between the SPT and CPT correlations.

It is worth noting that comparisons between the SPT and CPT correlations show that data (i.e., CRR and FS) are more scattering for soils with greater CRR values. This trend is more pronounced in Fig. 10 due to larger spanning of FS values.

It is the authors' opinion that the use of an analytical framework that is more or less conservative should be justified within the context of the nature of the project, depending on which, factor of safety or post-liquefaction reconsolidation settlement, becomes the more critical factor. For example, the occurrence of liquefaction that would lead to strength loss of soils is more critical than the magnitude of the liquefaction-induced settlement in the seismic fragility evaluation of levees, because the deviatoric-stress induced slope deformation is more critical than the volumetric induced deformation. In contrast, the liquefaction-induced volumetric settlement more likely controls the design of a building structure.

For the evaluation of the relative performance among these analytical frameworks, conclusions from this study are based on a total of only 19 paired high-quality SPTs/CPTs. It is the authors' suggestion that more data and analyses (e.g. field case histories) is needed to make a more conclusive judgment.

For high-profile projects (e.g., major dams), the cyclic stress ratio for liquefaction triggering analyses is usually calculated from site-specific response analyses. The selection of an analytical framework to calculate the cyclic resistance ratio could become a decisive factor for seismic fragility evaluations.

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