Relative efficacy of CPT- versus Vs-based simplified liquefaction evaluation procedures

Efficacité relative du CPT - par rapport aux procédures d'évaluation de liquéfaction simplifiée basée sur Vs

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ABSTRACT: The focus of the study presented herein is an assessment of the relative efficacy of recent Cone Penetration Test (CPT) and small strain shear wave velocity (Vs) based variants of the simplified procedure. Towards this end Receiver Operating Characteristic (ROC) analyses were performed on the CPT- and Vs-based procedures using the field case history databases from which the respective procedures were developed. The ROC analyses show that Factors of Safety (FS) against liquefaction computed using the most recent Vs-based simplified procedure is better able to separate the "liquefaction" from the "no liquefaction" case histories in the Vs liquefaction database than the CPT-based procedure is able to separate the "liquefaction" from the "no liquefaction" case histories in the CPT liquefaction database. However, this finding somewhat contradicts the assessed predictive capabilities of the CPT- and Vs-based procedures as quantified using select, high quality liquefaction case histories from the 2010-2011 Canterbury, New Zealand, Earthquake Sequence (CES), wherein the CPT-based procedure was found to yield more accurate predictions. The dichotomy of these findings may result from the fact that different liquefaction field case history databases were used in the respective ROC analyses for Vs and CPT, while the same case histories were used to evaluate both the CPT- and Vs-based procedures.

RÉSUMÉ: Celles-ci incluent le Cone Penetration Test (CPT) et la vitesse de cisaillement en petite déformation (Vs) des ondes, parmi d'autres. L'objectif de l'étude présentée ici est une comparaison de l'efficacité relative des procédures récentes d'évaluation simplifiée de liquéfaction basée sur CPT et Vs. À cette fin, les analyses du Receiver Operating Characteristic (ROC) sont effectuées sur les deux procédures en utilisant les bases historiques de données de champ à partir desquelles les procédures ont été élaborées. Les résultats impliquent que la Vs est une meilleure mesure in-situ pour évaluer le potentiel de liquéfaction que les indices de CPT. Toutefois, cette conclusion est en contradiction avec les capacités prédictives des procédures basées sur CPT et Vs. Ces capacités ont été évaluées en utilisant des histoires de cas de liquéfaction de haute qualité de la séquence de tremblement de terre de 2010-2011 Canterbury, Nouvelle-Zélande, (CES). La dichotomie de ces découvertes est probablement le résultat de l'utilisation de différentes bases de données d'histoires de cas dans les analyses ROC alors que les mêmes histoires de cas de la SCE ont été utilisées pour évaluer les procédures basées sur CPT et Vs.

KEYWORDS: liquefaction, simplified procedure, earthquake.

1 INTRODUCTION

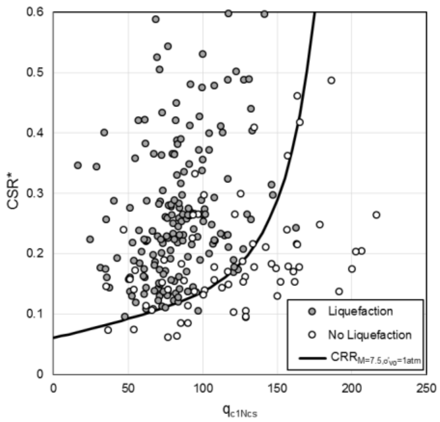
Simplified liquefaction evaluation procedures have become the standard of practice worldwide for evaluating liquefaction potential of sandy soil deposits. Since the initial inception of the Standard Penetration Test (SPT) based simplified procedure by Whitman (1971) and Seed and Idriss (1971), variants based on other in-situ indices have been developed. These include Cone Penetration Test (CPT) based and small strain shear wave velocity (Vs) based procedures. All of the procedures have undergone periodic updates as additional field case histories were documented and/or as the profession's understanding of the mechanics of liquefaction improved.

The focus of the study presented herein is an assessment of the relative efficacy of recent CPT-based versus Vs-based simplified procedures in predicting liquefaction triggering. Specifically, the relative efficacy of the deterministic CPT-based procedure by Boulanger and Idriss (2014) versus the deterministic Vs-based procedure by Kayen et al. (2013) is assessed. Towards this end, Receiver Operating Characteristic (ROC) analyses are performed on each of the procedures, using the case histories from the databases on which the respective procedures were developed. Additionally, the predictive capabilities of the procedures are assessed using select, high quality liquefaction case histories from the 2010-2011 Canterbury, New Zealand, Earthquake Sequence (CES).

The simplified procedures and the analyses performed to assess their relative efficacy are discussed below.

2 SIMPLIFIED PROCEDURES

Boulanger and Idriss (2014) (BI14) and Kayen et al. (2013) (Kea13) are the most recently developed procedures for the respective in-situ test indices, at least that the authors are aware of. Plots of the deterministic Cyclic Resistance Ratio curves normalized to a M7.5 event ($CRR_{M7.5}$) for the two procedures are shown in Figure 1, along with the case history data used to develop the respective curves.



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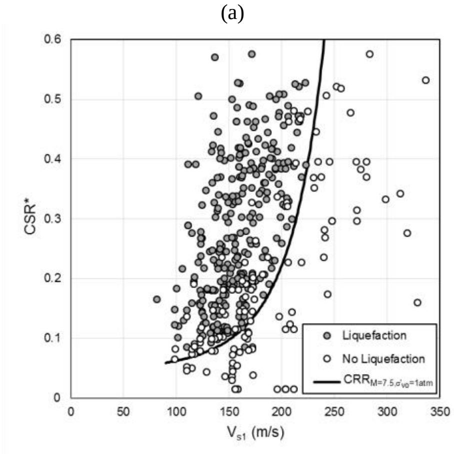

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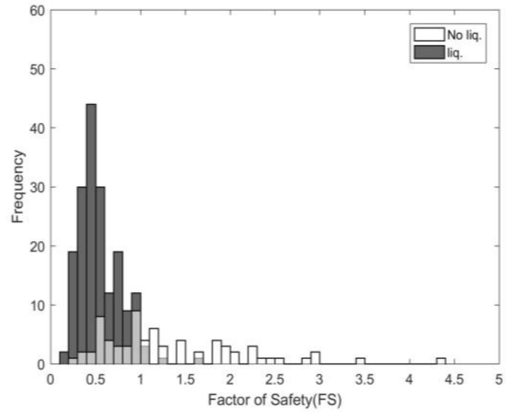
Figure 1. Deterministic $CRR_{M7.5}$ curves for (a) BI14 and (b) Kea13, both plotted along with case history data used to develop the respective curves.

The Factor of Safety (FS) against liquefaction triggering is defined as:

$$FS = \frac{CRR_{M7.5}}{CSR^*} \tag{1}$$

where: CSR* = Cyclic Stress Ratio normalized to a M7.5 event and corrected to effective overburden stress of 1 atm and level ground conditions (i.e., K_σ and K_α, respectively). Histograms of the FS of case histories used develop the IB14 and Kea13 $CRR_{M7.5}$ curves (and plotted in Figure 1) are shown in Figure 2.



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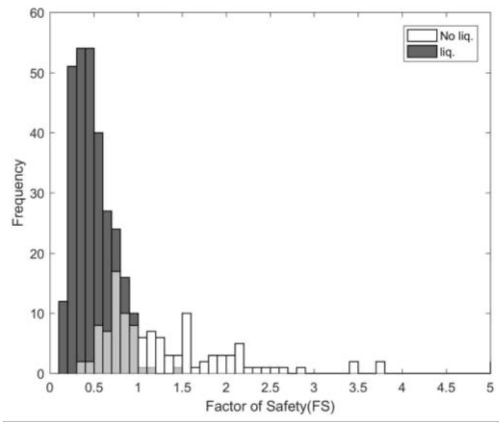

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Figure 2. Histograms of FS for the case history databases used to develop the (a) BI14 (182 Liq cases; 71 No Liq cases) and (b) Kea13 (291 Liq cases; 124 No Liq cases). Note that 8 of the 124 No Liq cases for the Kea13 database have FS > 5, up to 20, and are not plotted. (The light gray bars indicate the overlapping of the white and dark gray bars.)

3 ROC ANALYSES

To assess the relative efficacy of CPT vs. Vs tests for evaluating liquefaction triggering ROC analyses are used. ROC analyses have been widely adopted to analyze the performance of classifier systems, including extensive use in medical diagnostics (e.g., Fawcett, 2005), but by comparison, the use of ROC analyses in geotechnical engineering is relatively limited (e.g., Oommen et al., 2010; Maurer et al., 2015a,b). In any ROC analysis application, the distributions of "positives" (e.g., Liq cases) and "negatives" (e.g., No Liq cases) overlap when the frequency of the distributions are expressed as a function of diagnostic test results (e.g., FS computed using the CPT- or Vs-based simplified liquefaction evaluation procedures).

ROC analyses are particularly valuable for evaluating the relative efficacy of competing diagnostic indices (e.g., CPT- vs. Vs-based indices), independent of the subjective positioning of the deterministic $CRR_{M7.5}$ curves, which is reflected in the computed FS using the BI14 or Kea13 procedures. However, the shape of the $CRR_{M7.5}$ does influence the results of the ROC analyses, but this is viewed as being of secondary significance (e.g., BI14 used a fixed shape for their $CRR_{M7.5}$ and performed a regression analysis to determine the vertical position of the curve in terms of probability of liquefaction). A ROC curve is a plot of "True Positive Rate" (TPR) (e.g., liquefaction is predicted and was observed) versus "False Positive Rate" (FPR) (e.g., liquefaction is predicted, but did not occur). This is conceptually shown in Figure 3. For evaluating the relative efficacy of CPT- vs. Vs-based indices for predicting liquefaction triggering, TPR and FPR are computed from the Liq and No Liq case history distributions assuming a range of FS that designate the threshold below and above which liquefaction is predicted to occur and not to occur (i.e., we do not a priori assume this threshold value is FS = 1).

In ROC curve space, random guessing is indicated by a 1:1 line through the origin (i.e., equivalent correct and incorrect predictions). A perfect model plots along the left vertical and upper horizontal axes, connecting at point (0,1). This type of model indicates the existence of a threshold value that perfectly segregates the dataset (e.g., all Liq case histories have a FS below this threshold and all No Liq cases have a FS above this threshold). The area under a ROC curve (AUC) is equivalent to the probability that Liq cases have a lower computed FS than No Liq cases (e.g., Fawcett, 2005). As such, a larger AUC indicates better model performance, and hence a superior in-situ test index for evaluating liquefaction potential.

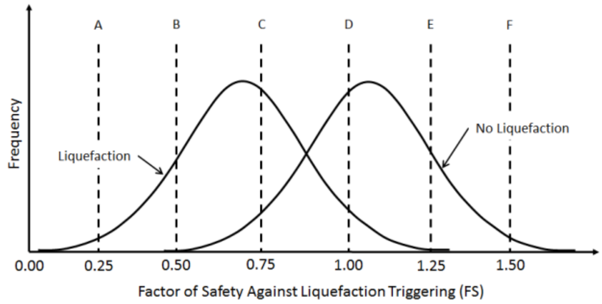
A ROC analysis was performed using the histograms of the FS for both the BI14 and Kea13 case history databases shown in Figure 2. The ROC curves for BI14 and Kea13 are shown in Figure 4. The AUC for BI14 and Kea13 are 0.872 and 0.922, respectively, implying that Vs-based indices are superior to CPT-based indices for evaluating liquefaction potential.

4 2010-2011 CES SELECT CASE HISTORIES

The 2010–2011 Canterbury, New Zealand, earthquake sequence (CES) began with the 4 September 2010, M_w7.1 Darfield earthquake and included up to ten events that induced liquefaction. Most notably, widespread liquefaction was induced by the Darfield and M_w6.2 Christchurch earthquakes. The authors performed post-earthquake field investigations at 24 sites that liquefied during the Darfield event but had no or only minor surficial liquefaction manifestations resulting from the Christchurch event, or vice versa. Additionally, in order to minimize the uncertainty in the seismic loading, these sites were selected because they are relatively close to strong motion stations. CPT soundings and seismic surface wave testing (i.e., spectral analysis of surface wave, SASW, multi-channel spectral analysis of surface waves, MASW, and passive array testing) were performed at all of these sites.

Green et al. (2014) and Wood et al. (2017) used an Error Index (E_I) approach to access the efficacy of various CPT- and Vs-based simplified liquefaction evaluation procedures, respectively, using the CES case histories. The CPT-based procedure by BI14 was not included in the CPT-centric study by Green et al. (2014) because BI14 postdates Green et al. (2014). Also, BI14 included the select 2010-2011 CES case histories in their database used to develop their $CRR_{M7.5}$ curve, which would inherently bias the E_I computed for the procedure using the CES case histories (i.e., yield lower error).

The Error Index (E_I) proposed by Green et al. (2014) and Wood et al. (2017) equals zero if all case histories are correctly predicted by a given simplified procedure. However, E_I will be greater than zero and will increase in value as the number, "magnitude," and "significance" of mispredictions increase. In this regard, the "magnitude" of a misprediction relates to how much the computed FS is less than one for a false positive prediction or how much the FS is greater than one for a false negative prediction. Also, the "significance" of a misprediction relates to the significance of the consequences of a misprediction. For example, in the authors' opinion mispredicting a Liq case potentially has more significant consequences than mispredicting a No Liq case; accordingly, the authors assign weights equal to 1.0 and 0.5 for these respective mispredictions. Mispredictions of "minor" liquefaction cases were assigned a weight of 0.75.



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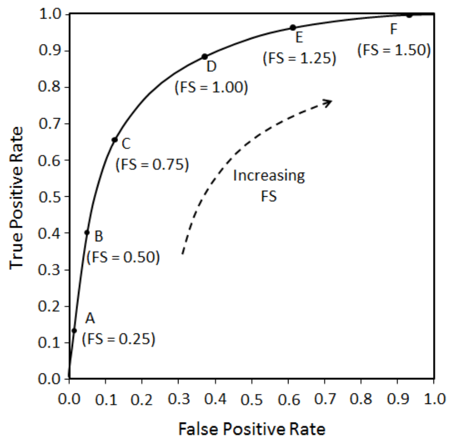
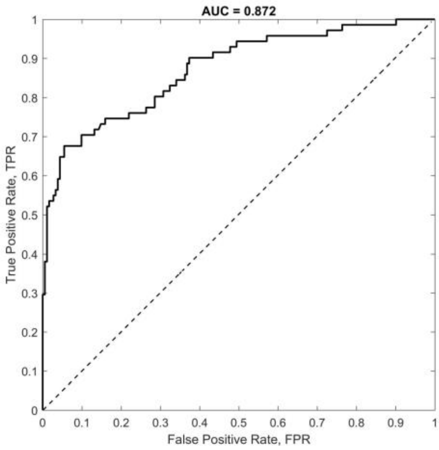


(b)

Figure 3. Conceptual illustration of ROC curve: (a) Distribution of Liquefaction (Liq) and No Liquefaction (No Liq) case histories as a function of FS; and (b) ROC curve developed from Liq and No Liq distributions.

The E_I was computed for the Idriss and Boulanger (2008) (IB08) CPT-based liquefaction procedure, an earlier variant of BI14, for 48 case histories from the 2010-2011 CES. IB08 mispredicted 3 of the Darfield earthquake case histories and 4 of the Christchurch earthquake cases, resulting in a combined E_I of 0.083. Again, because BI14 included the select 2010-2011 CES in their database used to develop their $CRR_{M7.5}$ curve, E_I computed for BI14 using the CES case histories is lower than that for IB08. In contrast, Kea13 mispredicted 5 of the Darfield earthquake case histories and 7 of the Christchurch earthquake cases, resulting in a combined E_I of 0.275, which is significantly higher than E_I value from BI08, but still significantly lower than the E_I values from the other two CPT-based methods documented in Green et al. (2014) and Wood et al. (2017). Also, it should be noted that the critical layers used to compute the E_I values were those selected from analysis of the CPT sounding data, as discussed in Green et al. (2014), which potentially negatively biases the E_I value computed for Kea13.



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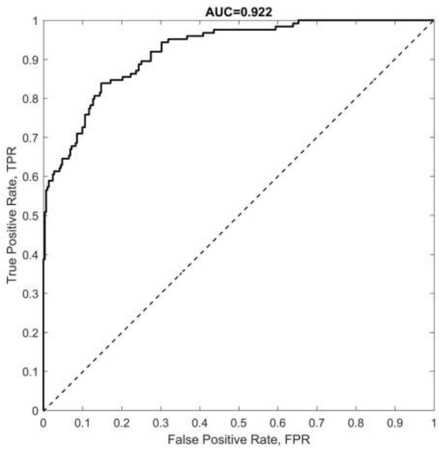

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Figure 4. ROC curves for: (a) BI14 and (b) Kea13.

5 DISCUSSION AND CONCLUSION

The relative efficacy of CPT- vs. Vs-based indices for evaluating liquefaction triggering determined from the ROC analyses differs from that based on the analyses of select, high quality case histories from the 2010-2011 CES. One reason for this dichotomy may be that E_I is a function of both the shape and position of the $CRR_{M7.5}$ curve for a given liquefaction evaluation procedure, in contrast to ROC analysis where AUC is primarily a function of the shape of the $CRR_{M7.5}$ curve. Additionally, and likely more significantly, E_I values for the CPT- and Vs-based procedures were computed using the same case histories, while the ROC analyses were performed using the respective databases used to develop BI14 and Kea13. As a result, the computed AUC values are not directly comparable, unless the case history databases used by BI14 and Kea13 truly reflect a random sampling of all ranges of possible field-earthquake scenarios, which is unlikely. Towards this end, additional effort is required to scrutinize the composition of the liquefaction case history databases used to develop the respective simplified procedures. Also, as noted above, the critical layers identified for the CES case histories were based solely on the CPT measurements, which could potentially bias the computed E_I values in favor of BI14.

Finally, the Vs liquefaction case histories in the Kea13 Vs database were derived primarily from surface wave testing and assumed to be normally dispersive (soft layers nearest to the surface and phase velocity increasing with wavelength) and not highly heterogeneous. For a number of sites in Christchurch, silty soils and/or non-liquefiable layers create heterogeneous deposits that deviate from the "typical liquefaction" case history sites detailed in Kea13. Inherently, this can limit the predictive capabilities of Vs-based procedures leading to more uncertainty in the obtained Vs values due to potential problems with non-uniqueness in the inversion process. Regardless, it seems that both the BI14 and Kea13 procedures are fairly accurate based on both ROC and E_I assessments. There are benefits to utilizing both CPT- and Vs-based procedures together, when feasible. Towards this end, it is important to remember that accurate Vs-based liquefaction evaluations are often dependent on supporting data obtained from either SPT or CPT tests (e.g., fines content, soil plasticity, etc.). Thus, Vs-based evaluations should ideally not be performed alone.

6 ACKNOWLEDGEMENTS

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