INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

SIMSG ISSMGE

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Liquefaction Evaluation Based on Hybridized CPT- and V_S-based method

Z. Bán, A. Mahler

Budapest University of Technology and Economics, Department of Engineering Geology and Geotechnics

1 Introduction

Soil liquefaction is one of the most devastating secondary effects of earthquakes and can cause significant damage in the built infrastructure. For this reason, liquefaction hazard shall be considered in all regions where moderate-to-high seismic activity encounters with saturated, loose, granular soil deposits. Several approaches exist to quantify this hazard, from which the in-situ test based empirical methods are the most commonly used in practice. The resistance of soil is usually determined based on an in-situ test, such as Cone Penetration Test (CPT), Standard Penetration Test (SPT) or shear wave velocity measurement (V_S).

In more complex or high-risk projects, CPT and V_S measurement are often performed at the same location, commonly in the form of Seismic Cone Penetration Test (sCPT). However, even if the results of the two tests are available for the same spot, empirical liquefaction potential evaluation can be performed using either of them, but combined use of the data in one single method has been limited. The goal of this research was to develop an empirical method where the results of CPT and V_S measurement are used in parallel and can supplement each other.

2 Empirical Liquefaction Assessment Methods

The commonly used cyclic stress-based (empirical) methods calculate the seismic demand in form of equivalent uniform cyclic stress ratio (CSR) as it was first proposed by Seed and Idriss (1971):

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} = 0.65 \cdot \frac{\sigma_{v0}}{\sigma'_{v0}} \cdot \frac{a_{max}}{g} \cdot r_d \tag{1}$$

where τ_{cyc} is the cyclic shear stress, a_{max} is the maximum horizontal acceleration at the ground surface, g is the gravitational acceleration, r_d is a stress reduction

coefficient that accounts for the flexibility of the soil column, σ'_{v0} is the effective vertical stress and σ_{v0} is the total vertical stress at depth z. The r_d factor can be estimated most accurately with a detailed site response analysis, or as it the case in the practice, via simplified equations. *CSR* is then compared to the cyclic resistance ratio (CRR), which separates liquefaction and non-liquefaction case histories and can be determined from the relevant in situ index, to obtain factor of safety (FS).

Since the introduction of cyclic shear stress approach, several empirical methods have been published by different authors that can give a relatively reliable quantification of liquefaction hazard by determining factor of safety or probability of liquefaction occurrence. In current engineering practice, the most commonly used CPT-based methods are the procedures proposed by Robertson and Wride (1998), Moss et al. (2006), Idriss and Boulanger (2008) and Boulanger and Idriss (2014). Compared to CPT-based methods, procedures based on V_S tests are less widely used. For very long time, the method of Andrus and Stokoe (2000) was used almost exclusively. Recently, the work of Kayen et al. (2013) made a huge step in the advancement of V_S-based methods. Besides the advanced statistical framework adopted by the authors, the most remarkable accomplishment was the compilation of a global catalogue of 422 case histories.

3 Development of a Combined CPT- and V_S-based Method

3.1 Field Case History Dataset

The first and most time-consuming step of the development was the collection of a liquefaction/non-liquefaction field case history catalogue. Through careful review of existing CPT and V_S databases, 98 cases were found where both measurements are available. As locations where liquefaction occurred are more enticing for post-earthquake field investigators than sites where no apparent liquefaction occurred, the assembled dataset over represents liquefied sites (68 sites), relative to non-liquefied sites (30 sites). The core of the database was assembled from the CPT case history catalogue of Moss et al. (2006) and VS dataset of Kayen et al. (2013), from which 73 and 53 locations could be used, respectively. Additional case histories were gathered from the publications of various authors. For complete list of the used literature, see Bán et al. (2016). The final database consists case histories from 12 earthquakes (1975 Haicheng, 1976 Tangshan, 1979 Imperial Valley, 1981 Westmoreland, 1983 Borah Peak, 1987 Elmore Ranch, 1987 Superstition Hills, 1989 Loma Prieta, 1999 Chi-Chi, 1999 Kocaeli, 2008 Achaia-Elia, 2011 Great Tohoku).

3.2 Input parameters

According to the framework of simplified empirical procedures, the cyclic stress ratio is generally corrected to 7.5 magnitude and 1 atm effective vertical stress to take into account duration of different earthquakes and the dependency of cyclic liquefaction on effective overburden stress. For these corrections, the recommendations of Idriss and Boulanger (2008) was followed.

Effective overburden stress can also profoundly influence in-situ measurements. This effect is typically accounted for by normalizing the measured value to a reference effective stress of 100 kPa. It is generally agreed that the increase of fines content (FC) reduces the potential of soil to liquefy, and approximately at 35-40% FC, the coarser grains will "float" in the matrix of fine-size particles and the cyclic behaviour of the soil will be governed by the fines. Thus, it is common to normalize the resistance to an equivalent "clean sand" value. However, V_S measurement is not capable of detecting small differences in fines content, i.e. V_S is relatively insensitive to fines content. Compared to uncertainties arising from other parts of the methodology this correction would be fairly negligible; thus, fines content correction of the shear wave velocity was neglected.

After all the normalizations and corrections, three explanatory variables remained to participate in the logistic regression: the equivalent clean sand value of normalized overburden corrected cone tip resistance (q_{c1Ncs}), the overburden corrected shear wave velocity (V_{S1}), and the magnitude and the effective stress corrected cyclic stress ratio ($CSR_{M=7.5,\sigma'v=1atm}$).

3.3 Logistic regression

Logistic regression is often used to explore the relationship between a binary response and a set of explanatory variables. The occurrence or absence of liquefaction can be considered as binary outcome and the previously summarized three parameters are the explanatory variables. The key components of the regression are the formulation of a limit state model that has a value of zero at the limit state and is negative and positive for liquefaction and non-liquefaction cases, respectively, and a likelihood function that is proportional to the conditional probability of observing a particular event assuming a given a set of parameters. The approach of Cetin et al. (2002) was adopted to form the limit state function. Assuming the statistical independence of the observations compiled from different sites, the likelihood function can be written as the product of the probabilities of the observations. As it was noted, the dataset contains significantly more liquefaction cases than non-liquefaction cases; a weighting scheme (Cetin et al. 2002) was applied to address this issue. After taking the natural logarithm of the likelihood function that is more convenient to work with, the unknown parameters were determined using maximum likelihood estimation.

3.4 Probability of liquefaction

The logistic regression using the likelihood function yielded the following result:

$$P_L = \theta\left[\frac{0.080 \cdot V_{s1} + 0.177 \cdot q_{c1Ncs} - 8.40 \cdot ln\left(CSR_{M=7.5,\sigma'_v=1atm}\right) - 46.04}{3.46}\right] \quad (2)$$

where Θ is the standard normal cumulative probability function. The denominator, that is the standard deviation of the error term, is of particular interest since it describes the efficiency of the liquefaction relationship. The regressed value is somewhat higher than that of other commonly used methods, but it is still promising, since this method has seen little refinement so far. The CRR for a given probability of liquefaction can be expressed by rearranging Equation 2:

$$CSR_{M=7.5,\sigma'_v=1atm} = exp\left[\frac{0.080 \cdot V_{s1} + 0.177 \cdot q_{c1Ncs} - 46.04 + 3.46 \cdot \theta^{-1}(P_L)}{8.40}\right] \quad (3)$$

This can be used in deterministic analysis by selecting a probability contour (typically P_L= 15%) to separate liquefaction and non-liquefaction states. Figure 1 shows the probability surface corresponding to P_L = 50%.

More detailed description of the complied dataset and the development the above equations can be found in Bán et al. (2016).

4 Evaluation of Performance

The prediction capability of the developed equation was evaluated on an independent dataset of the 2010-2011 Canterbury Earthquake Sequence and the result was compared with commonly used empirical procedures. The 2010–2011 Canterbury earthquake sequence comprised two major earthquakes (Darfield M_w=7.1 and Christchurch M_w=6.2) that induced widespread liquefaction. The ground motions from these events were recorded across Christchurch and its environs by a dense network of strong motion stations.

The combination of well-documented liquefaction response during multiple events, densely recorded ground motions for the events, and detailed subsurface characterization provided an unprecedented opportunity to add numerous quality case histories to the liquefaction database. Green et al. (2014), besides the compilation of quality liquefaction data, compared and evaluated the performance of commonly used, deterministic, CPT-based liquefaction evaluation procedures. Based on an error index defined by the authors, it was concluded that the procedure proposed by Idriss and Boulanger (2008) results in the lowest error index for the case histories analysed, thus indicating better predictions of the observed liquefaction response.

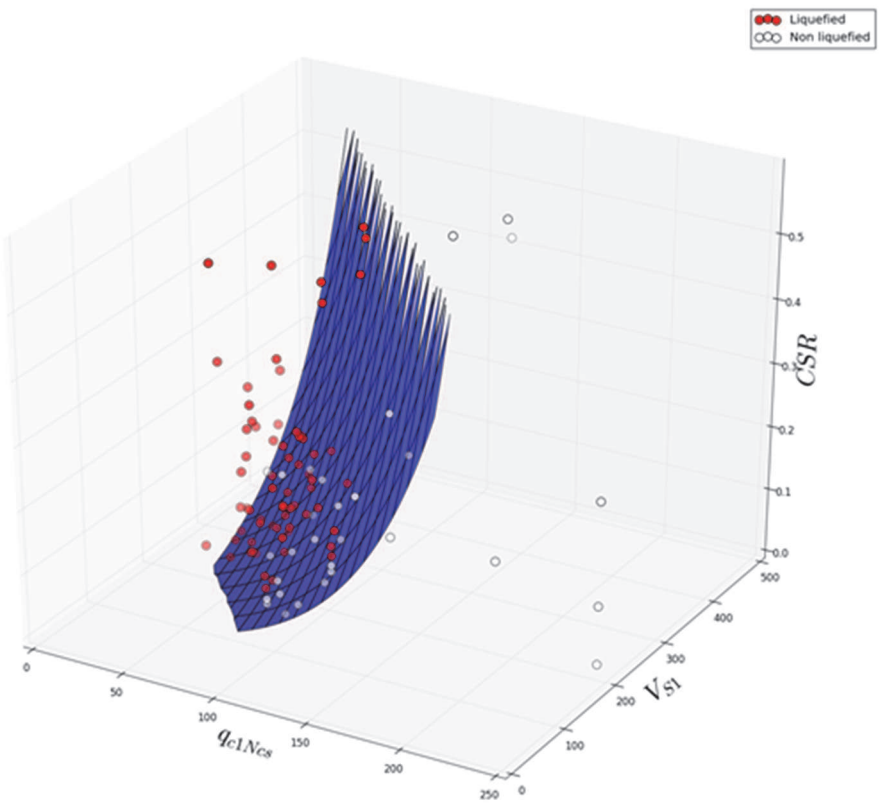

Fig. 1: Cyclic resistance ratio surface corresponding to 50% of liquefaction probability (solid squares – liquefaction cases, hollow circles – non-liquefaction cases).

In a subsequent research (Wood et al. 2017), the same authors performed an analogous assessment for the V_S-based liquefaction evaluation procedures as well. It was found that the Kayen et al. procedure outperforms the Andrus and Stokoe method but has slightly worse performance than that of the CPT-based Idriss and Boulanger method.

The compiled case histories of the Canterbury Earthquake Sequence and the fact that they were explored by both CPT and Vs measurement provide an excellent opportunity for the verification of the developed hybridized method and comparison with other commonly used methods.

The papers of Green et al. (2014) and Wood et al. (2017) define an error index to quantitatively assess which liquefaction evaluation procedure yields the "most accurate" prediction for the analysed data. The proposed error indices equal zero if all the predictions correctly match the field observations but increase in value as the number and "magnitude" of the mispredictions increases. For the present study, a similar concept was adopted to compare the different methods' prediction capability. To allow direct comparison of the methods and to adopt a slightly more straightforward approach, not the vertical distance from the CRR curve were used for quantification, but mispredictions were quantified in terms of factor of safety as Equation 4 shows. Similarly to the paper of Wood et al. (2017), to acknowledge

the varying significance of the consequences of mispredicting cases, weighting factors are included in the error index: 1.0 for mispredicted liquefaction cases, and 0.5 for mispredicted no Liquefaction cases.

$$EI = 0 \text{ for correct prediction} \tag{4}$$
$$EI = FS - 1 \text{ for mispredicted liquefaction case}$$
$$EI = 0.5 \cdot (1 - FS) \text{ for mispredicted no liquefaction case}$$

The computed error index values for the 46 case histories are summarized in Table 1. Please note that the values of error indices are different from those presented in Green et al. (2014) and Wood et al. (2017) due to the different error index definition.

Tab. 1: Error index and number of mispredicted sites for the three evaluated liquefaction evaluation procedures

Earthquake	Parameter	Idriss and Boulanger (2008)	Kayen et al. (2014)	Bán et al. (2016)
Darfield	Error index	0.731	0.498	1.450
	Mispredicted sites	5	3	5
Christchurch	Error index	0.433	0.943	0.711
	Mispredicted sites	6	6	2
Total for all sites	Error index	1.164	1.440	2.162
	Mispredicted sites	11	9	7

As the table shows, the equation of the authors has the highest error index term, so it has the worst prediction capability among the three examined methods. As it is concluded by Wood et al. (2017) and also confirmed by present comparison, the total error values obtained using Kayen et al. (2013) Vs-based procedure is higher than that of the Idriss and Boulanger (2008) CPT-based procedure indicating slightly better performance of the latter method. However, if one considers not the error index but the number of mispredicted sites, in that case the equation recommended by the authors outperforms the other two procedures. The higher error index of the authors' equation is mostly resulted by mispredicted no liquefaction sites for which both the CPT- and V_S-based method predicted liquefaction with factors of safety around 0.6-0.8. As both measurements predicted false response, the recommended formula based on both CPT and V_S also predicted false response but due to the combination of them, its factor of safety is much lower, around 0.3-0.4. On the other hand, during the Christchurch earthquake the

CPT- and V_S-based procedures predicted no liquefaction for some liquefied site (FS around 1.0-1.1), for which the recommended combined formula predicted correct response. Due to these factors the recommended combined equation predicted less false responses but where false prediction occurred, the magnitude of error was considerably higher than that of Idriss and Boulanger CPT- or Kayen et al. V_S-based method.

5 Conclusion

The authors have developed a hybridized empirical liquefaction potential assessment method, which is based on the parallel use of CPT tip resistance and shear wave velocity. As these parameters characterize the soil at different strain intervals, the two measurements can supplement each other and can provide non-redundant information about the soil conditions.

The prediction capability of the developed equation was evaluated on an independent dataset of the 2010-2011 Canterbury Earthquake Sequence. This was performed by means of an error index similar to those defined by Green et al. (2014) and Wood et al. (2017). It was shown that compared to the state-of-practice CPT-based empirical method of Idriss and Bulanger and V_S-based method of Kayen et al., the recommended combined equation of the authors has much higher error index, so it has the worst prediction capability among the three examined methods, but if the number of mispredicted sites is considered, it outperforms the other two procedures. The obtained results are promising, since the author's method has seen very little refinement so far, especially compared to the other two methods

6 Literature

Andrus, R.D. & Stokoe, K.H., II. (2000)
Liquefaction resistance of soils from shear-wave velocity. Journal of Geotechnical and Geoenvironmental Engineering 126(11): 1015–1025.

Bán Z., Mahler A., Katona T.J. & Győri E. (2016)
Liquefaction assessment based on combined use of CPT and shear wave velocity measurement, In: Lehane B.M., Acosta-Martínes A.E. and Kelly. R. (eds), Proceedings of 5th International Conference on Geotechnical and Geophysical Site Characterization, Gold Coast, 5-9 September 2016. pp. 597-602

Boulanger, R.W. & Idriss, I.M. (2014)
CPT and SPT based Liquefaction Triggering Procedures. Report No. UCD/CGM-14/01, University of California, Davis.

Cetin, K.O., Der Kiureghian, A. & Seed, R.B. (2002)
Probabilistic models for the initiation of seismic soil liquefaction. Structural Safety 24(1): 67–82.

Green, R. A., et al. (2014)
Select liquefaction case histories from the 2010–2011 Canterbury earthquake sequence. Earthquake Spectra, 30(1), 131–153.

Idriss, I.M. & Boulanger, R.W. (2008)
Soil Liquefaction during Earthquakes. Monograph MNO-12, Earthquake Engineering Research Institute, Oakland.

Kayen, R., Moss, R.E.S., Thompson, E.M., Seed, R.B., Cetin, K.O., Der Kiureghian, A., Tanaka, Y. & Tokimatsu, K. (2013)
Shear-Wave Velocity–Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential. Journal of Geotechnical and Geoenvironmental Engineering 139(3): 407-419.

Moss, R.E.S., Seed, R.B., Kayen, R.E., Stewart, J.P., Der Kiureghian A. & Cetin, K.O. (2006)
CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. Journal of Geotechnical and Geoenvironmental Engineering 132(8): 1032–1051.

Robertson, P.K. & Wride, C.E. (1998)
Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal 35(3): 442-459.

Seed, H.B. & Idriss, I.M. (1971)
Simplified procedure for evaluating soil liquefaction potential. Journal of the Soil Mechanics and Foundations Division 97(SM9): 1249-1273

Wood, C.M., Brady, R.C., Green, R.A, Wotherspoon R.M., Bradley, B.A & Cubrinovski, M. (2017)
Vs-Based Evaluation of Select Liquefaction Case Histories from the 2010-2011 Canterbury Earthquake Sequence. Journal of Geotechnical and Geoenvironmental Engineering 143(9): 04017066.