Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0769

Development of an energy-based liquefaction potential assessment method based on combined use of CPT and shear wave velocity measurement

Z. Bán
Budapest University of Technology and Economics, Budapest, Hungary

A. Mahler
Budapest University of Technology and Economics, Budapest, Hungary

E. Győri
Kövesligethy Radó Seismological Observatory, Budapest, Hungary

ABSTRACT: Cyclic stress-based empirical liquefaction potential assessment is generally based on the results of CPT, SPT or shear wave velocity (V_S) measurements. 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 CPT. However, combined use of both in-situ indices in one single empirical method has been limited. After the compilation of a case history database, the authors have developed a combined probabilistic method where the results of CPT and V_S measurement can be used in parallel. The fact that peak ground acceleration, used commonly for empirical liquefaction assessment, is not capable of characterizing the entire ground motion impelled the development of energy-related intensity measures to characterize seismic demand. To adopt this approach, the developed equation was also derived with Arias intensity as the intensity measure characterizing the ground motion. The main goal of this paper was to evaluate the prediction capability of the developed equations on an independent dataset of the 2010-2011 Canterbury Earthquake Sequence and compare it with commonly used empirical procedures. Although, our cyclic stress-based equation had worse overall performance than the most commonly used empirical methods, the result was still promising as it yielded the lowest number of mispredicted cases. On the other hand, the performance of the Arias intensity-based equation reflected a major drawback in the procedure.

Keywords: liquefaction, CPT, shear wave velocity, Arias intensity

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 consider this hazard, from which the in-situ test-based empirical methods are the most commonly used in practice.

The triggering earthquake is considered by its magnitude and maximum horizontal acceleration on the ground surface (a_{max}). 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 (V_S) measurement. 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. In order to surmount this issue, the authors have developed an empirical method, which exploits both the results of CPT and V_S measurement (Bán et al. 2016).

The inability of peak acceleration to characterize the entire ground motion and the complex uncertainty arising from the need of two ground motion information impelled the development of energy-related intensity measures to characterize seismic demand. This motivated the authors to recalculate the above-mentioned empirical method by using a well-known energy-related measure, the Arias intensity instead of a_{max} to characterize the seismic loading (Bán et al. 2017).

The first part of this paper summarizes the development of the procedures and the obtained equations, and in the second part, their performance is evaluated on an independent dataset.

2 USE OF CPT AND V_S IN LIQUEFACTION POTENTIAL EVALUATION

Since the introduction of cyclic shear stress approach (Seed and Idriss 1971) several empirical methods have been published by different authors that can give a relatively reliable quantification of factor of safety or probability of liquefaction. 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). As the use of CPT for ground profile characterization is very popular its application for liquefaction potential evaluation is also prevalent.

Compared with CPT- and SPT-based methods, the methods based on V_S tests are less widely used in practice for liquefaction potential evaluation. For very long time the method of Andrus and Stokoe (2000) was used almost exclusively. 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 EMPIRICAL LIQUEFACTION POTENTIAL EVALUATION FRAMEWORK

3.1 Field case history dataset

Development of an empirical procedure starts with the compilation of an extensive and quality database of liquefaction and non-liquefaction cases from previous earthquakes. Through careful review of existing CPT and V_S datasets, 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 V_S dataset of Kayen et al. (2013), which were supplemented with additional case histries gathered from several other publications. 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 Seismic loading

According to the framework of cyclic stress-based simplified empirical procedures, seismic demand induced by an earthquake can be represented by the Cyclic Stress Ratio (CSR) at a depth z below ground surface using the following expression (Seed and Idriss 1971):

$$\mathrm{CSR} = 0.65 \frac{a_{max}}{g} \frac{\sigma_v}{\sigma'_v} r_d \tag{1}$$

Where g (m/s^2) is the gravitational acceleration, r_d is the shear stress reduction factor, σ_v and σ'_v (kPa) is the total and effective vertical stress, respectively.

The CSR is generally normalized to 7.5 magnitude and 1 atm effective vertical stress to take into account duration – or number of equivalent cycles – of different earthquakes and the dependency of cyclic liquefaction on effective overburden stress. For these corrections, the recommendations of Idriss and Boulanger (2008) were followed.

Energy related methods are a relatively new concept. The approach originated from the observation that hysteric dissipated energy can be related to volumetric strain and thus pore pressure generation. There have been several proposals for estimating dissipated energy both directly from earthquake source parameters, and from site intensity measures such as Arias intensity (I_h). Originally developed by Arias (1970) to quantify the destructiveness of earthquake motions on buildings, Arias intensity is “the sum of the two component energy per unit weight stored in a population of undamped linear oscillators evenly distributed in frequency, at the end of earthquake shaking.” Arias intensity may be computed using the following equation:

$$\mathrm{I}_h = \frac{\pi}{2g}\left[\int_0^{t_0} a_x^2(t)dt + \int_0^{t_0} a_y^2(t)dt\right] \tag{2}$$

Where $a_x(t)$ (m/s^2) is the horizontal acceleration time history in the x-direction, $a_y(t)$ (m/s^2) is the horizontal acceleration time history in the y-direction, and t_0 (sec) is the total duration of earthquake shaking.

Arias intensity at the surface of the soil profile can be converted to its corresponding value at the liquefied critical depth (I_{hb}) using a reduction parameter that was statistically derived by Kayen and Mitchell (1998):

$$r_b = exp\left(\frac{35}{M_w^2} sin(0.09z)\right) \tag{3}$$

Where z (m) is the depth below the ground surface, M_w is the moment magnitude and the term (-0.09×z) is in radians.

Arias intensity of the compiled cases was determined using Kayen’s (1993) attenuation relationship for soft soil sites:

$$\log(I_h) = M_w - 3.4 - 2\log(r^*) \tag{4}$$

Where r* is the Pythagorean distance between the site and the closest distance to the fault rupture plane at the earthquake focal depth. As in most of the cases, the closest distance to the fault rupture plane was not available in the aforementioned datasets; as a simplification r* was replaced by the Pythagorean distance calculated from the epicentral distance and focal depth.

An Arias intensity-based liquefaction potential evaluation procedure was presented by Kayen and Mitchell (1997). Although, it is a promising alternative to replace stress-based methods and Arias intensity has the advantage that it reflects frequency content, amplitude and duration of the ground motion, its application is limited due to the lack of experience and verification.

3.3 Soil capacity

The effect of overburden stress on CPT meausrement is typically accounted for by normalizing the tip resistance measured at a given depth to a reference effective stress of 100 kPa. Similarly to CSR, the procedure recommended by Idriss and Boulanger (2008) was followed to take into account this effect. The role of fines on liquefaction susceptibility is a somewhat contentious topic. Nevertheless, it is agreed that if the fines content (FC) exceeds approximately 35-40%, 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. For the development of the equation, equivalent clean sand values of the tip resistance were determined using the updated equation of Boulanger and Idriss (2014). As well as CPT tip resistance, V_S is also routinely normalized to an equivalent value measured at 100 kPa effective overburden stress (Robertson et al. 1992). V_S measurement is not capable of detecting small differences in fines content, i.e. V_S is relatively insensitive to FC. Compared to uncertainties arising from other parts of the methodology this correction would be fairly negligible; thus, FC correction of shear wave velocity was neglected.

3.4 Input parameters for logistic regression

After performing all of the above discussed normalization 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 loading parameter that is the magnitude and effective stress corrected cyclic stress ratio (CSR*) in the cyclic stress-based approach, and the Arias intensity (I_{hb}) in the energy-related approach.

There is no general agreement how the variables should be incorporated in the logistic regression, should they be used in their logarithmic, polynomial or untransformed form. A general recommendation is that variables should be transformed so that their frequency distribution should be approximately normal. Following this guideline, the loading parameters (CSR and Arias intensity) were included in the regression by its natural logarithm, while q_{c1Ncs} and V_{S1} remained untransformed.

4 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 in Section 3.1, the dataset contains significantly more liquefaction cases than non-liquefaction cases; this bias is undesirable in logistic regression and can adversely affect the result. A way to address this issue is to weight each class of cases according to the proportion of the other’s class population in the total database (Cetin et al. 2002). 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.

5 PROBABILITY OF LIQUEFCATION

The logistic regression using the likelihood function yielded the following result for the cyclic stress-based method (i.e. when the loading is described by the CSR) (Figure 1):

$$\mathrm{P}_L = \Phi\left[\frac{0.08V_{S1}+0.177q_{c1Ncs}-8.40ln(CSR^*)-46.04}{3.46}\right] \tag{5}$$

The following equation was obtained when the loading parameter was replaced with the energy-related Arias intensity:

$$P_L = \Phi\left[\frac{0.078V_{s1}+0.221q_{c1Ncs}-4.48ln(I_{\text{hb}})-29.06}{4.91}\right] \tag{6}$$

The denominator, that is the standard deviation of the error term, is of particular interest since it describes the efficiency of the liquefaction relationship.

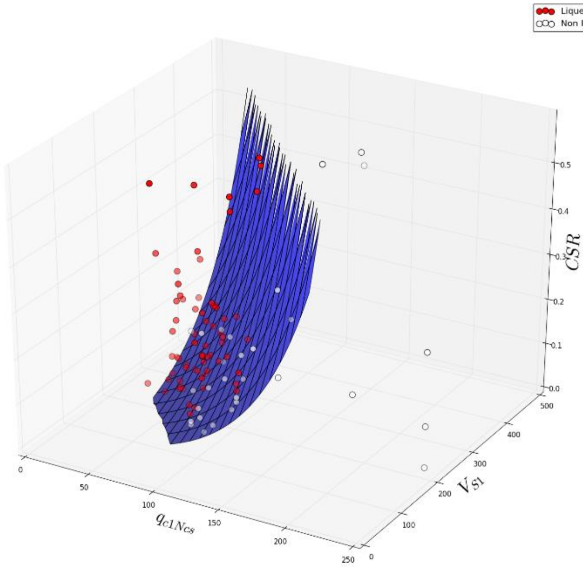

Figure 1 Cyclic resistance ratio surface corresponding to 50% of liquefaction probability (solid squares – liquefaction cases, hollow circles – non-liquefaction cases)

The regressed standard deviation of the error term for the cyclic stress-based method is somewhat higher than that of other commonly used methods however the result is still promising given that this formula has seen little refinement so far. The regressed Arias intensity-based method seems less efficient (i.e. higher denominator) even though energy related integral parameters theoretically better quantify earthquake-imposed demands, which means that the standard deviation of error term should be lower in this methodology. The resulted inverse tendency (namely the logistic regression resulted in higher standard deviation) can be traced back to two main reasons: 1. attenuation relationships for a_{max} are more advanced than for any other motion-related parameter, and the comprehensive research of previous authors resulted in a much more reliable quantification of a_{max} for the liquefaction dataset than that the authors could achieve for Arias intensity; 2. as the available source material for this research was limited, simplification of the used attenuation relationship was necessary for many cases that also increased the inherited uncertainty of the method.

The Cyclic Resistance Ratio (CRR) for a given probability of liquefaction can be expressed by rearranging Equation 5 and 6. This way, the equations can be used in deterministic analysis by selecting a probability contour (typically P_L= 15%) to separate liquefaction and non-liquefaction states

6 PERFORMANCE OF PROCEDURES

6.1 2010-2011 Canterbury Earthquake Sequence

The 2010–2011 Canterbury Earthquake Sequence consisted two major earthquakes that induced widespread liquefaction: the M_w 7.1, 4 September 2010 Darfield and the M_w 6.2, 22 February 2011 Christchurch earthquakes. These ground motions were recorded across Christchurch and its environs by a dense network of strong motion stations. Also, due to the severity and spatial extent of liquefaction resulting from the 2010 Darfield earthquake, an extensive subsurface characterization program took place with over 10,000 CPT soundings (Green et al. 2014).

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. The paper of Green et al. (2014) presented 50 high-quality CPT test liquefaction case histories which consisted of 25 sites analysed for both the Darfield and Christchurch earthquakes. Besides, the compilation of quality liquefaction data, their goal was to compare and evaluate commonly used, cylcic stress- and CPT-based liquefaction evaluation procedures. An error index was used to quantify the overall performance of the procedures in relation to liquefaction observations. It was concluded that among them, 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.

In a subsequent research of the same authors (Wood et al. 2017), they examined 46 of the 50 case histories using shear wave velocity profiles derived from surface wave methods. The V_S profiles have been used to evaluate the two most commonly used Vs-based simplified liquefaction evaluation procedures (Andrus and Stokoe and Kayen et al.). It was found that the Kayen et al. procedure outperforms the Andrus and Stokoe procedure 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 combined methods and comparison with the most commonly used and best performing CPT- and V_S-based methods (i.e. with the procedures of Idriss and Boulanger and Kayen et al.).

6.2 Evaluation of procedures

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" predictions for the analysed data. The two error indices used by the two papers are slightly different due to the nature of the CPT- and Vs-based procedures (i.e. the catalogue of the V_S-based method of Kayen et al. didn't have wide enough range to properly account for the Kσ effect). 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 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, mispredictions were quantified in terms of factor of safety (FS). On an individual case basis, the error index (EI) equals zero for a correct prediction of a Liquefaction or No Liquefaction case and equals the absolute value of 1 minus FS for mispredicted cases. Similarly to the referenced papers, 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:

$\mathrm{EI} = 0$ for correct prediction (7)

$\mathrm{EI} = FS - 1$ for mispredicted liquefaction case

$\mathrm{EI} = 0.5(1 - FS)$ for mispredicted nonliquefaction 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. Green et al. (2014) and Wood et al. (2017) categorized liquefaction cases based on their severity as "no liquefaction", "minor liquefaction", "moderate liquefaction" and "severe liquefaction" case. For this study, the latter 3 cases were considered as simply liquefaction cases and the first category was obviously the no liquefaction case.

Table 1. Error index and number of mispredicted sites for the evaluated liquefaction evaluation procedures

Earthquake	Parameter	Idriss and Boulanger (2008)	Kayen et al. (2014)	Bán et al. cyclic stress-based	Bán et al. Arias intensity-based
Darfield	error index	0.731	0.498	1.450	3.893
	number of mispredicted sites	5	3	5	10
Christchurch	error index	0.433	0.943	0.711	0.893
	number of mispredicted sites	6	6	2	2
Total	error index	1.164	1.440	2.162	4.786
	number of mispredicted sites	11	9	7	12

Among the cyclic stress-based procedures, the equation of the authors has the highest error index term, so it has the worst prediction capability. As it is concluded by Wood et al. (2017) and confirmed by present comparison, the total error values indicate slightly better performance of Idriss and Boulanger CPT-based procedure than Kayen et al. Vs-based method. However, if one considers not the error index but the number of mispredicted sites, the equation recommended by the authors outperforms the other two methods. 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 1.1), for which the developed combined formula predicted correct response.

The Arias intensity-based equation has by far the worst performance among the examined methods. Given that the development of the equation is based on exactly the same dataset as the authors' cyclic stress-based formula and followed the exact same procedure, the calculated and used Arias intensity values for the compiled dataset are the only reason behind this considerably worse performance. This implies that even though, Arias intensity is theoretically a better parameter to quantify earthquake demand, the simple attenuation relationship used for its determination is not advanced enough to reliably characterize earthquake loading with regard to liquefaction. This means that the accurate determination of Arias intensity (or any other loading parameter) should be a cornerstone for any energy-related liquefaction potential assessment procedure that might not be achieved by using simple attenuation relationships.

7 CONCLUSION

CPT and V_S measurement are often performed on the same location however the possibility to characterize liquefaction potential with both indices in one single empirical method was limited so far. The authors have developed a cyclic stress- and an Arias intensity-based empirical method to quantify liquefaction hazard based on the combined use of CPT tip resistance and V_S. The performance of the derived equations was then evaluated using an independent dataset of the 2010-2011 Canterbury Earthquake Sequence. It was found that the developed cyclic stress-based equation has worse performance than other commonly used methods however the results are still promising as it yielded the lowest number of mispredicted cases. The developed Arias intensity-based equation has the worst performance among the examined methods, implying that use of simple attenuation relationships might not be sophisticated enough to determine the loading demand for the development of such procedure.

8 REFERENCES

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

Arias, A. 1970. A Measure of Earthquake Intensity, *Seismic Design for Nuclear Power Plants* (ed. R.J Hansen), 438-483

Bán Z., Mahler A., Katona T.J. and 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

Bán Z., Mahler A., Katona T.J. and Győri E. 2017. Assessment of liquefaction potential based on combined CPT and shear wave velocity measurements using energy concept, In: Woojin, L., Jong-Sub, L., Hyun-Ki, K., Dong-Soo, K. (eds*), Proceedings of 19th International Conference on Soil Mechanics and Geotechnical Engineering,* Seoul, South Korea, pp. 1469-1472

Boulanger, R.W. and 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. and 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. and Boulanger, R.W. 2008. *Soil Liquefaction during Earthquakes*, Monograph MNO-12, Earthquake Engineering Research Institute, Oakland.

Kayen R. 1993. *Accelerogram Energy Approach for Prediction of Earthquake-Induced Ground Liquefaction*, Doctor of Philosophy dissertation, University of California, Berkeley.

Kayen, R and Mitchell, J.K. 1997. Assessment of Liquefaction Potential During Earthquakes by Arias Intensity, *Journal of Geotechnical and Geoenvironmental Engineering* **123(12)**, 1162-1174

Kayen, R., Moss, R.E.S., Thompson, E.M., Seed, R.B., Cetin, K.O., Der Kiureghian, A., Tanaka, Y. and 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. and 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., Woeller, D.J., and Finn, W.D.L. 1992. Seismic cone penetration test for evaluating liquefaction potential under cyclic loading, *Canadian Geotechnical Journal*, **29(4)**, 686–695

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

Seed, H.B. and 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 and Cubrinovski, M. 2017. Vs-Based Evaluation of Select Liqufaction Case Histories from the 2010-2011 Canterbury Earthquake Sequence, *Journal of Geotechnical and Geoenvironmental Engineering,* **143(9)**, 04017066.