Assessment of liquefaction potential based on combined CPT and shear wave velocity measurements using energy concept

Évaluation du potentiel de liquéfaction à partir des mesures combinées du CPT et de la vitesse d'onde de cisaillement à l'aide du concept d'énergie

Zoltán Bán, András Mahler
Department of Engineering Geology and Geotechnics, Budapest University of Technology and Economics, Hungary, ban.zoltan@epito.bme.hu
Tamás János Katona
MVM Nuclear Power Plant Paks Ltd, Paks, Hungary
Erzsébet Győri
Seismological Observatory, MTA CSFK GGI, Hungary

ABSTRACT: For liquefaction potential assessment, simplified empirical methods are the most commonly used in engineering practice. The triggering earthquake is considered by its magnitude and maximum horizontal acceleration on the ground surface. 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. The resistance of soil is usually determined based on an in-situ test, such as Standard Penetration Test (SPT), Cone Penetration Test (CPT) or shear wave velocity measurement (V_S). In more complex or high risk projects CPT and V_S measurements are often performed at the same location. However, as the most commonly used empirical methods are based on either of these tests, combined usage of both in-situ indices in one method is limited. For the above mentioned reasons the aim of this research was twofold: to develop an empirical method where the results of CPT and V_S measurements are used in parallel and can supplement each other, and to utilize the energy-related concept at the characterization of seismic demand.

RÉSUMÉ : Pour l'évaluation du potentiel de liquéfaction du site, les méthodes d'évaluation empiriques simplifiées sont de nos jours couramment utilisés dans la pratiques d'ingénierie. Le déclenchement d'un tremblement de terre est considéré par sa magnitude et par l'accélération maximale horizontale sur la surface du sol. L'incapacité de l'accélération maximale caractérisant tout mouvement du sol et l'incertitude complexe résultant de la nécessité d'information de mouvement de deux sols ont propulsé le développement de l'intensité de mesures liée à l'énergie. Habituellement, la résistance du sol est déterminée sur la base d'un test in-situ, tel que l'essai de pénétration au cône (CPT) ou la mesure de la vitesse des ondes de cisaillement (Vs). En plus des projets complexes ou à haute risque les deux mesures sont souvent effectuées au même endroit. Cependant, comme les méthodes empiriques les plus couramment utilisées sont basées sur chacune de ces essais, l'utilisation combinée in-situ des deux indices en un seul méthode est limitée. Pour des raisons mentionnées ci-dessus le but de cette recherche était double: élaborer une méthode empirique lorsque les résultats de CPT et les mesures Vs sont utilisés en parallèle et peuvent se compléter mutuellement, ainsi qu'utiliser le concept lié à l'énergie à caractériser la demande sismique.

KEYWORDS: liquefaction, CPT, shear wave velocity, energy concept

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 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. 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 such as nuclear power plants, CPT and V_S measurements 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 location, empirical liquefaction potential evaluation can be performed using either of them, but combined use of the data in one single method has been limited. For the above mentioned reasons the aim of this research was twofold: to develop an empirical method where the results of CPT and V_S measurements are used in parallel and can supplement each other, and to utilize the energy-related concept at the characterization of seismic demand. The effort was based on the assumption that the results of the two in-situ tests supplement each other since they characterize the behaviour of granular systems at different levels of strain.

2 USE OF CPT AND V_S IN LIQUEFACTION POTENTIAL EVALUATION

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 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 (2003), 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 susceptibility evaluation. For very long time the method of Andrus and Stokoe (2000) was used almost exclusively. Very 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.

Although, both V_S and CPT tip resistance (q_c) strongly depend on relative density and effective stress state, they can supply complementary information about the soil, as the former is a small strain property, while the latter is a large strain one. As discussed by Schneider et al. (2004), V_S in sands is controlled by the number and area of grain-to-grain contacts, on the other hand, penetration resistance in sands is controlled by the interaction of particles being sheared by and rotating around the penetrometer

3 FRAMEWORK OF ENERGY CONCEPT

3 .1 *Seismic loading*

Energy related methods are a relatively new concept. The approach originated from the observation that hysteretic dissipated energy can be related to volumetric strain and thus pore pressure generation. There have been several proposals for estimating dissipated energy from site intensity measures such as Arias intensity (I_h) and Cumulative Absolute Velocity (CAV). Arias intensity and CAV have the advantage that they reflect frequency content, amplitude and duration of the ground motion however their application is limited due to the lack of experience and verification. Both Arias intensity and CAV are integral parameters, and as pore pressure builds up progressively during the shaking they can better track the increase of excess pore pressure.

The Arias intensity-based method presented by Kayen and Mitchell (1997) is a promising alternative to replace stress-based methods. Originally developed by Arias (1970) to quantify the destructiveness of earthquake motions on buildings, Arias intensity (I_h) 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:

$$I_h = \frac{\pi}{2g}\left[\int_0^{t_0} a_x^2(t)dt + \int_0^{t_0} a_y^2(t)dt\right] \qquad (1)$$

where $a_x(t)$ and $a_y(t)$ are the horizontal acceleration time histories in the x and y directions, respectively; g is the acceleration due to gravity; and t_0 is the total duration of earthquake shaking.

Arias intensity at the surface of the soil profile can be converted to its corresponding value at any depth using a reduction parameter that was statistically derived by Kayen and Mitchell (1997):

$$r_b = \exp\left(\frac{35}{M_w^2} \cdot sin(-0.09 \cdot z)\right) \qquad (2)$$

where M_w is the moment magnitude of the earthquake; z is the depth below the ground surface in meters; and the term ($-0.09\times z$) is in radians.

3 .2 *Soil capacity*

Effective overburden stress can profoundly influence CPT measurements. This effect is typically accounted for by normalizing the tip resistance measured at a given depth and vertical effective stress to a reference effective stress of 100 kPa. In the present study, the iterative formula of Idriss and Boulanger (2008) was adopted.

The role of fines on liquefaction susceptibility is a somewhat contentious topic. The conclusions of recent studies of the subject are rather controversial. Nevertheless, it is agreed that if the fines content 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. Although many researchers reported an initial increase then a decrease in liquefaction potential as fines content (FC) increases, all the most widely used empirical methods apply monotonically increasing fines content correction. In the present study, equivalent clean sand values of the tip resistance have been determined using the updated equation of Boulanger and Idriss (2014).

A huge drawback of CPT compared to SPT that soil samples are not obtained during the test thus soil classification cannot be made directly. Although for many of the case histories the actual fines content was available in their source database, to keep consistency between the input data and the intended future use of the method, fines content was determined empirically using the soil behavior index (I_c) recommended by Robertson and Wride (1997) and the expression developed by Boulanger and Idriss (2014). However, it should be noted that general correlations between FC and I_c exhibit large scatter.

As well as CPT tip resistance, V_S is also routinely normalized to an equivalent value measured at 100 kPa effective overburden stress, for which the formula of Robertson et al. (1992) was used. Small strain shear modulus (G_{max}) is closely related to V_S. As the small strain stiffness of sands, silts and clays are of a similar range, V_S measurement do not allow detecting small differences in fines content, i.e. V_S is relatively insensitive to FC. Several studies showed (Andrus and Stokoe 2000, Kayen et a. 2013) that increase in fines content to 35% has a maximum adjustment of 5 m/s, which is even smaller than the accuracy of shear wave velocity measurement itself. Compared to uncertainties arising from other parts of the methodology this uncertainty is fairly negligible. Thus, fines content correction of shear wave velocity has been neglected.

3 .3 *Input variables 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 Arias intensity at the critical depth (I_{hb}), which was obtained by multiplying Arias intensity with Equation 2.

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. Baecher and Christian (2003) recommended that variables should be transformed so that their frequency distribution should be approximately normal. Following this guideline Arias intensity has been included in the regression by its natural logarithm, while q_{c1Ncs} and V_{S1} remained untransformed.

4 FIELD CASE HISTORY DATASET

The first and most time-consuming step of recent study was the collection of liquefaction/non-liquefaction field case history catalogue. Through careful review of existing CPT and V_S databases 98 cases were found where both measurements were 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 (2003) and V_S 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 Bay and Cox (2001), Ku et al. (2004), Moss et al. (2005), Moss et al. (2009), Cox et al. (2013), Boulanger and Idriss (2014), Batilas et al. (2014). 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). For each case the following information was available: the moment magnitude (M_w), depth of the critical layer, groundwater level, total (σ_v) and effective overburden pressure (σ'_v), CPT tip resistance and sleeve friction (f_s) and shear wave velocity in the critical layer.

Arias intensity of the cases expected at the surface was determined using Kayen's (1993) attenuation relationship for soft soil sites:

$$I_h = M_w - 3.8 - 2 \cdot log(r^*) \tag{3}$$

where r^* is the closest distance between the site and the fault rupture plane. 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.

A summary of the dataset is presented in Table 1.

Table 1. Summary of the compiled case history database

	Liquefied cases		*Non-liquefied cases*	
Parameter	*Mean*	*Std.dev*	*Mean*	*Std.dev*
M_w	7.33	0.64	7.16	0.90
$ln(I_{hb})$ (m/sec)	1.72	1.08	1.20	1.56
q_{c1} (MPa)	5.18	2.68	10.14	6.95
V_{S1} (m/s)	152.72	29.89	181.17	67.41

5 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. Moss (2009) and Kayen et al. (2013) adopted Bayesian updating technique (developed for probabilistic assessment of liquefaction initiation by Cetin et al. (2002)), while Boulanger and Idriss (2014) used maximum likelihood estimation to develop their resulting correlation.

The key components of these methods 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. Adopting the approach of Cetin et al. (2002) the following limit state function has been formed:

$$g = \theta_1 V_{S1} + \theta_2 q_{c1Ncs} + \theta_3 ln(I_{hb}) + \theta_4 + \varepsilon \tag{4}$$

where: $\theta_{1\ldots4}$ are the set of unknown parameters, and ε is the model error term. The latter is introduced to account for the influences of the missing variables and the possible incorrect model form. If ε is assumed to be normally distributed with zero mean, the probability of liquefaction can be expressed as:

$$P_L = \Phi\left[-\frac{g-\varepsilon}{\sigma_\epsilon}\right] \tag{5}$$

where Φ is the standard normal cumulative probability function, and σ_ε is the standard deviation of the model error term.

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 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, Baecher and Christian 2003) while the sum of the weights should remain 2.0. According to these guidelines the corresponding weight factors for liquefaction and non-liquefaction cases are 0.62 and 1.38, respectively. Then the likelihood function takes the following form:

$$L = \prod_{liq}\left[\Phi\left(-\frac{g-\varepsilon}{\sigma_\epsilon}\right)\right]^{0.62} \times \prod_{non}\left[\Phi\left(\frac{g-\varepsilon}{\sigma_\epsilon}\right)\right]^{1.38} \tag{6}$$

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.

6 PROBABILITY OF LIQUEFACTION

The logistic regression using the likelihood function in Equation 6 yields the following result:

$$P_L = \Phi\left[-\frac{0.078V_{S1}+0.221q_{c1Ncs}-4.48ln(I_{hb})-29.06}{4.91}\right] \tag{7}$$

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

In a previous publication of the authors (Bán et al. 2016) the same methodology described herein was followed to develop an equation within the empirical cyclic stress based framework that utilizes the simultaneous availability of CPT and V_S. Present study can be considered as its continuation, where the same dataset was used, but to make a step forward, the commonly used a_{max} and M_w intensity measures were replaced with Arias intensity.

The regressed error term of the standard deviation is somewhat higher than that of obtained for the cyclic stress method, however the result is still promising given that energy related empirical methods have seen little refinement so far. Theoretically energy related integral parameters 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 for) can be traced back to two main reasons: 1. attenuation relationships for a_{max} are much more advanced than for any other motion related parameters, and the comprehensive research of previous authors resulted in more reliable datasets than that of this study; 2. as the available source material for this research was limited, for many cases simplification of the used attenuation relationship was necessary (see Chapter 4) that also increased the inherited uncertainty of the method.

It shall be noted that the σ_ε value only incorporates model uncertainty. The measurement errors or parameter uncertainty have not been considered in the analysis.

The cyclic resistance ratio for a given probability of liquefaction can be expressed by rearranging Equation 7:

$$I_{hb} = exp\left[\frac{0.078V_{S1}+0.221q_{c1Ncs}-29.06+4.91\Phi^{-1}(P_L)}{4.48}\right] \quad (8)$$

This can be used in deterministic analysis by selecting a probability contour to separate liquefaction and non-liquefaction states.

7 CONCLUSION

For high-risk projects CPT and V_S measurement are often performed on the same location however the possibility to characterize the soil's resistance with both indices in one single empirical liquefaction method was limited.

Present study is the continuation of the authors' previous work, where a method was developed within the empirical cyclic stress liquefaction potential assessment framework where the result of CPT and V_S measurement are used in parallel and can supplement each other. The effort is based on the assumption that the results of the two in-situ tests supplement each other since they characterize the behaviour of granular systems at different levels of strain. This research has made a step forward by utilizing the promising energy concept for describing the earthquake induced seismic loading and replacing a_{max} and M_w with Arias intensity.

In the first step by careful reviewing of the already existing liquefaction case history datasets, sites were selected where the records of both measurements are available and for each case Arias intensity was calculated. After implementing the necessary corrections on the gathered 98 case histories with respect to fines content, overburden pressure, logistic regression was performed to obtain probability contours of liquefaction occurrence. The proposed formula is an initial attempt to exploit the advantages offered by the measurements of two soil parameters instead of one and the energy related intensity measure.

This research is far from being considered as completed, there is still considerable more work to be done. As the dataset is relatively small, in the first round more emphasis was put on the quantity rather than the quality of the data. However, it is believed that future improvement of attenuation relationships and if the magnitude of the database will allow proper quality assessment, omission of low quality data can improve the reliability of the methodology.

8 REFERENCES

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.

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, *Proceedings of ISC5*, Gold Coast, 5-9 September 2016. (in press).

Batilas, A., Pelekis, P., Vlachakis, V., & Athanasopoulos, G. 2014. Soil Liquefaction/Nonliquefaction in the Achaia-Ilia (Greece) 2008 Earthquake: Field Evidence, Site Characterization and Ground Motion Assessment. *International Journal of Geoengineering Case Histories* 2(4): 270-287.

Bay, J.A., & Cox, B.R. 2001. *Shear wave velocity profiling and liquefaction assessment of sites shaken by the 1999 Kocaeli, Turkey earthquake*. PEER Project Report SA3017-18336, Pacific Earthquake Engineering Research, Berkeley.

Baecher, G.B. & Christian, J.T. 2003. *Reliability and statistics in geotechnical engineering*. Chichester: John Wiley & Sons Inc.

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.

Cox, B.R., Boulanger, R.W., Tokimatsu, K., Wood, C.M., Abe, A., Ashford, S., Donahue, J., Ishihara, K., Kayen, R., Katsumata, K., Kishida, T., Kokusho, T., Mason, H.B., Moss, R.E.S., Stewart, J.P., Tohyama, K., & Zekkos, D. 2013. Liquefaction at strong motion stations and in Urayasu City during the 2011 Tohoku-Oki earthquake. *Earthquake Spectra* 29(S1): S55-S80.

Idriss, I.M. & 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. & 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.

Ku, C.-S., Lee, D.-H., & Wu, J.-H. 2004. Evaluation of Soil Liquefaction in the Chi-Chi, Taiwan Earthquake Using CPT. *Soil Dynamics and Earthquake Engineering* 24(9-10): 659-673.

Moss, R.E.S. 2003. *CPT-based probabilistic assessment of seismic soil liquefaction initiation*. Doctor of Philosophy dissertation, University of California, Berkeley.

Moss, R.E.S., Collins, B.D. & Whang, D.H. 2005. Retesting of Liquefaction/Nonliquefaction Case Histories in the Imperial Valley. *Earthquake Spectra* 21(1): 179-196.

Moss, R.E.S., Kayen, R.E., Tong, L., Liu, S., Cai, G. & Wu, J. 2009. *Reinvestigating liquefaction and nonliquefaction case histories from the 1976 Tangshan earthquake*. PEER Project Report 2009/102, Pacific Earthquake Engineering Center, Berkeley.

Robertson, P.K., Woeller, D.J., & 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. & Wride, C.E. 1997. Cyclic liquefaction and its evaluation based on SPT and CPT. In Youd, T.L. & Idriss, I.M. (eds.), *NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, Proceedings, Salt Lake City*, Technical Report NCEER-97-0022: National Center for Earthquake Engineering Research.

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

Schneider, J.A., McGillivray, A.V. & Mayne, P.W. 2004. Evaluation of SCPTU intra-correlations at sand sites in the Lower Mississippi River valley, USA. In Viana Da Fonseca, A. & Mayne, P.W. (eds), *Geotechnical & Geophysical Site Characterization; Proc. ISC-2, Porto, 19-22 September 2004*. Rotterdam: Millpress.