Site-specific comparison and evaluation of empirical liquefaction potential assessment methods

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ABSTRACT: Earthquake-induced liquefaction potential of a site is most commonly evaluated using one the simplified empirical methods. The core of these methods is the comparison between the seismic loading exciting the soil and the resistance of soil; the latter is expressed in terms of an in-situ test, such as Standard Penetration Test (SPT), Cone Penetration Test (CPT) or shear wave velocity (Vs) measurement. The goal of this research was a site-specific analysis and comparison of these procedures to estimate their conservativism and select the most appropriate for the test site, where all three in-situ tests were available in close proximity to each other. As the test site was subjected to an extensive site exploration program, the seismic loading was determined with both the recommendations of simplified procedures and a detailed site response analysis. Comparison showed that factor of safety with depth can show big variance even with the same test-based methods, and significant difference can be also observed in the results of site-specific analysis and simplified equations characterizing the seismic loading.

1 INTRODUCTION

In the past decades, nuclear power plants safely survived earthquakes all over the world. But secondary effects can heavily damage them, as it was the case of the Fukushima Daiichi plant in 2011, where the earthquake-triggered tsunami caused fatal consequences. Another example is the Kashiwazaki-Kariwa Nuclear Power Station also in Japan where the area suffered differential settlement due to liquefaction after a magnitude of 6.6 earthquake in 2007 that caused fire in the plant.

The Paks Nuclear Power Plant is located in Southern Hungary. The seismicity in the vicinity of the Plant is relatively low. The site is located next to the Danube River on top of loose fluvial sediments. Originally, the plant was not designed for earthquakes. In the 90's a probabilistic seismic and liquefaction hazard assessment was performed and liquefaction was found to be a beyond design basis hazard, which means that its annual probability was less than 10^{-4}/a. Later a seismic probabilistic safety assessment was carried out that showed that liquefaction could be one of the essential contributors of core damage. The most critical consequence of liquefaction is the differential settlement, what can cause distress and cracks to structures and can also damage pipelines and their connections to buildings. This finding motivated the current investigation of liquefaction hazard.

2 SOIL PROFILE

The Paks Nuclear Power Plant (Paks NPP) site mainly comprises fluvial sediments of the Danube River. The average stratigraphy consists of 2 m thick fill, 5 m Holocene sand and silt, 10 m Pleistocene sand, and below that 11 m thick Pleistocene gravel. The Miocene layers below the gravel were considered as bedrock. The average groundwater table is 8 m below the surface. A comprehensive geotechnical exploration (both in-situ and laboratory tests) were carried out to better understand the site conditions and update the already existing site exploration database. Numerous CPTs and a few SPTs were penetrated around the reactor buildings, which later served as the basis of liquefaction potential evaluation.

3 METHODS

Liquefaction potential for a given ground motion level can be evaluated with two main approaches, with analytical and empirical approaches. The first attempts to model the soil behavior under seismic loading explicitly in a site response analysis with an appropriate constitutive model. The accuracy of the results depends on the suitability of the constitutive model and the accuracy of input parameters. The main benefit of this approach that it can trace pore pressure and strain development during shaking. On the other hand, the input parameters of the model require substantial field and laboratory testing and are often difficult to determine, thus this method is mainly used for research and large projects.

Among the empirical methods, the cyclic stress-based method is the most commonly used in practice. In this method factor of safety against liquefaction is obtained by comparing the soil resistance to the seismic demand. The seismic demand is expressed by the cyclic stress ratio (CSR) which is the function of unit weight, groundwater table, the soil column flexibility, peak ground acceleration and earthquake magnitude. Soil resistance is expressed by the cyclic resistance ratio (CRR), which can be determined with semi-empirical correlations using in-situ tests, such as SPT, CPT or shear wave velocity measurement. Newer methods can give the probability of liquefaction occurrence instead of factor of safety. Empirical assessment has much wider usage than explicit models, primarily because it's easier and less expensive to implement. Although, depending on the selected empirical equation sets, the liquefaction assessment may provide very scattering results and might lead to controversial conclusions.

4 COMPARISON OF RESULTS

For current study a location was selected where CPT, SPT and shear wave velocity measurement was performed in close proximity to each other. This allowed the comparison of different liquefaction potential evaluation methods. Altogether 2 SPT-based and 4 CPT-based methods were compared and evaluated.

All the empirical methods require the maximum peak ground acceleration and magnitude as input parameters for the seismic demand so a site effect calculation was carried out to determine these. The variability of the soil profile was taken into account by Monte Carlo analysis. The computations gave 0.29g as mean peak ground acceleration for 10^{-4}/a probability level. From liquefaction hazard point of view the magnitude of the controlling earthquake was set to 6.0.

The nonlinear flexibility of the soil column is generally taken into account by the shear stress reduction factor. Besides the more accurate and site-specific site response analysis, it can be also determined using simplified equations of the empirical methods. These equations were derived based on statistical analysis of many site response analyses of different soil profiles excited by various ground motions. Application of these methods on the study's soil conditions shows that there is high uncertainty involved in the simplified equations of different authors (Figure 1).

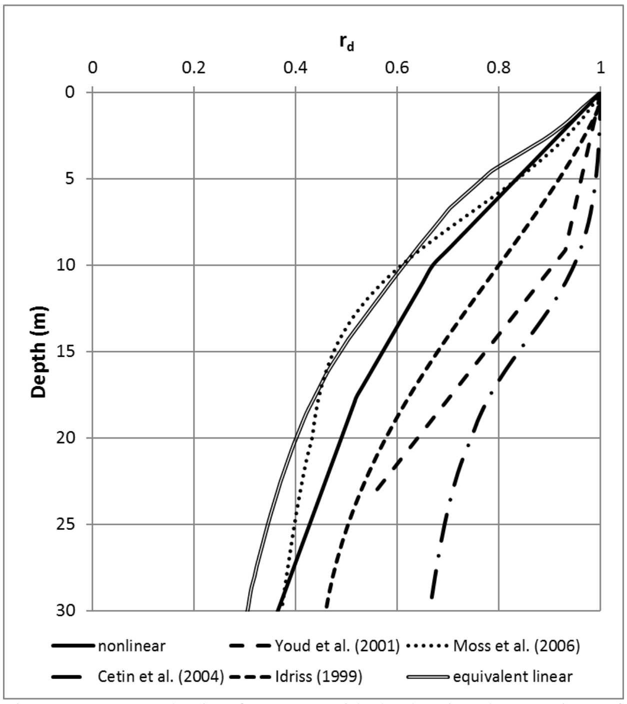

Figure 1. Stress reduction factor (r_d) with depth using the equations of different simplified methods and equivalent linear and nonlinear site response analysis

Figure 2 shows the result of six different deterministic liquefaction potential evaluation methods. As it is reflected by the figure, large uncertainty can be observed in the factor of safety values even among the same in-situ test-based methods. The remarkable difference between the SPT results triggered an on-going debate between the procedures' authors that still hasn't been concluded. At the selection of the most appropriate method not just the applicability of the method for the particular site is the only aspect, but it is also important to maintain compatibility with the method integrated into the probabilistic liquefaction hazard assessment.

5 CONCLUSION

Results of liquefaction assessment show large scattering even if the applied empirical methods are based on the same type of in-situ measurements. Applying procedures that are based on different type of measurements further increase the uncertainties. The choice of appropriate methods to compute differential settlements needs careful consideration if different types of in-situ measurements are available on the area. Significant part of epistemic uncertainties arises from the application of different methods. In case of Paks NPP, the most susceptible layers lie relatively deep. This depth is around the limit for which the simplified methods have been verified.

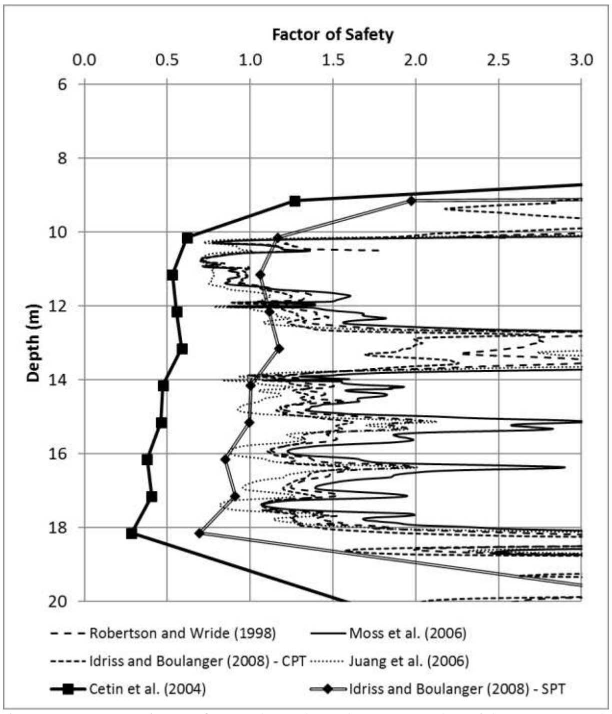

Figure 2. Comparison of CPT-based (Robertson and Wride, Moss et al., Idriss and Boulanger and Juang et al.) and SPT-based (Cetin et al. and Idriss and Boulanger) results of empirical liquefaction potential evaluation for the selected location

6 REFERENCES

Cetin, K. O., Seed, R. B., Der Kiureghian, A., Tokimatsu, K., Harder, L. F., Kayen, R. E., and Moss, R. E. S. (2004): *Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential*. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 130(12), 1314–340.

Idriss, I.M. 1999. An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential, *Proceedings, TRB Workshop on New Approaches to Liquefaction*, Publication No. FHWARD- 99-165, Federal Highway Administration.

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

Juang, C.H., Fang, S.Y., and Khor, E.H. (2006). "First Order Reliability Method for Probabilistic Liquefaction Triggering Analysis Using CPT." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 3, 337-350.

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.

Youd, T. L., Idriss, I. M., Andrus, R. D., Arango, I., Castro, G., Christian, J. T., Dobry, R., Finn, W. D. L., Harder, L. F., Hynes, M. E., Ishihara, K., Koester, J. P., Liao, S. S. C., Marcuson, W. F., Martin, G. R., Mitchell, J. K., Moriwaki, Y., Power, M. S., Robertson, P. K., Seed, R. B., and Stokoe, K. H., (2001): *Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils*. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 127(10), 817–33.