SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

METHODS AND UNCERTAINTIES IN LIQUEFACTION HAZARD ASSESSMENT FOR NUCLEAR POWER PLANTS

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ABSTRACT

Experience shows that the nuclear power plant can be safely designed for vibratory effects of earthquakes. Contrary to this, the plants can be heavily damaged by effects of earthquake-induced phenomena like tsunami, soil liquefaction after surviving the ground shaking effects. In the paper, the problems in nuclear power plant's safety analysis methodology are outlined for the case of soil liquefaction. Depending on the applied method, the liquefaction hazard assessment may provide very scattering results and might lead to controversial conclusions. In the paper different approaches and methods for liquefaction hazard assessment are considered. Practical problems of the selection of appropriate methods are demonstrated on the example of Paks Nuclear Power Plant, Hungary. For comparison, records of one SPT, one CPT and one shear wave velocity measurement, that were located very close to each other, were chosen from the site and the liquefaction potential was assessed by altogether nine of the newest and most commonly used empirical correlations. The results show big variance even by the same test-based methods. Epistemic uncertainties increase further when post liquefaction settlements are computed. To handle the uncertainties we propose a probabilistic multiple-scenario approach that is appropriate for safety analysis of the power plant on a given probability level.

INTRODUCTION

Proper understanding and assessment of safety of nuclear power plants (NPPs) with respect to external hazards became very important after 11th of March 2011, the accident of Fukushima NPP. Analysis of accident sequences initiated by extreme rare external events is required for demonstration of low annual probability of reactor core damage ($\leq 10^{-5}$/a) or large early releases ($\leq 10^{-7}$/a) and for the development of severe accident management methods and procedures. The analyses have to account events with extreme low annual probability of exceedance, up-to 10^{-7}/a, while the probability of exceedance for the design base level is usually set for 10^{-4}/a. There are well-developed deterministic and probabilistic methods for safety analyses of nuclear power plants (see ASME 2008; IAEA 2009, 2010).

In case of external events the adequacy of safety analyses and conclusiveness of the results is mainly limited by the epistemic uncertainty of the hazard definition that is growing rapidly with decreasing probabilities considered. Safety analysis for external events becomes even more difficult if the secondary phenomena to the external events or combinations of external events have to be considered, e.g. earthquake and earthquake induced soil liquefaction or tsunami. The difficulties are

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related to the hazard assessment of the secondary phenomenon and to the assessment of superposed effects of the earthquake and the secondary phenomenon.

As it is shown in the paper, significant part of epistemic uncertainties in evaluation of liquefaction and post liquefaction settlement arise from the application of different methods. In the paper, liquefaction potential was assessed by altogether nine of the newest and most commonly used empirical SPT-, CPT- and shear wave velocity-based correlations (Youd et al. 2001, Cetin et al. 2004, Idriss and Boulanger 2008, Robertson and Wride 1998, Moss et al. 2006, Juang et al. 2006, Idriss and Boulanger 2008, Andrus and Stokoe 2000, Kayen et al. 2013). Based on the calculations the results show big variance even by the same test-based methods. Epistemic uncertainties increase further when post liquefaction settlements are computed. To handle the uncertainties we propose a probabilistic multiple-scenario approach that is appropriate for safety analysis of the power plant on a given probability level.

THEORETICAL AND PRACTICAL PROBLEMS IN NPPs SAFETY ASSESSMENT FOR LIQUEFACTION

In case of NPPs, the liquefaction should not be considered as a design base event. If the soil at the site is susceptible to the liquefaction, soil improvement and appropriate foundation design have to be applied for excluding the potential hazard. However, at some NPP sites, soil liquefaction has to be considered as a beyond design basis event. Depending on the site conditions liquefaction can cause flow failure, lateral spread, ground oscillation, loss of bearing strength and ground settlement, etc. These effects can result in building settlement or tilting, relative displacement between adjacent buildings that result in loss of integrity, or relative displacement between buildings and underground piping and cables that can result in damage of these communication lines. Latter affects mainly the power cables of the emergency power-supply and the piping to the ultimate heat sink. Tilting can cause mechanical failures to those structures that survived the strong motion vibrations. In case of such sites/plants analysis of the plant response to earthquake and subsequent liquefaction is required for the definition of safety margins and development of severe accident measures.

Analysis of liquefaction effects on the plant safety should be properly embedded into the analysis of seismic safety hence the liquefaction is caused by the earthquake, and the site response (the surface ground motion) is affected by the increasing non-linearity of liquefying layers, and the damaging effects of liquefaction follow the effects of vibratory motion with certain time-delay, i.e. liquefaction causes loss of safety functions after the plant survived the effects of the vibratory ground motion. The seismic safety analysis of nuclear power plants consists of the following steps:

1. Seismic hazard analysis, including hazard analysis of liquefaction.
2. Modelling of the plant response to the initiating event caused by the earthquake. The output of this step is a list of the structures, systems and components (SSCs) required for getting the plant into safe, controlled condition.
3. Definition, whether the SSCs identified above sustain the effects of the vibratory motion.
4. Deterministic or probabilistic analysis that demonstrates the acceptability of plant safety and identifies the needs for upgrading measures.
5. Development and implementation of emergency measures and procedures.

Taking into account the considerations above, the tasks of seismic safety analysis have to be properly extended for accounting the earthquake and liquefaction phenomena, their effects and consequences.

Probabilistic safety analysis of NPPs for the case of liquefaction requires definition of the liquefaction hazard curve and the fragility curves of SSCs due to the liquefaction. The fragility is the conditional probability of loss of safety function versus engineering demand parameters (EDP) that characterise the effect of the liquefaction on the structure considered. The EDP has to be selected in accordance with the failure modes typical for the structure. Final result of the analysis is the annual probability of core damage or early large release.

Empirical methods based on SPT, CPT and shear wave velocity measurements has been developed and widely used for the assessment of liquefaction susceptibility (see Youd et al, 2001, Seed et al, 2003). These methods provides a “yes or no” statement (factor of safety is less or larger than a predefined value) regarding susceptibility of some soil layers. This type of statement can be used in the probabilistic safety analysis, only, if a cliff-edge effect is associated to the liquefaction and a “yes or no” type conclusion can be made regarding loss of function of the SSCs. Unfortunately the results of the widely used empirical liquefaction models are rather uncertain and they predict the onset of liquefaction on different level of confidence (Juang et al, 2002). It means that there is an ill-defined interval between sure liquefaction and sure no liquefaction that can be described by interval representation of fragility (Katona 2012).

During the last ten years new probabilistic procedures were also developed for the evaluation of liquefaction potential that were based on the enlarged databases of SPT, CPT and shear wave velocity measurements (Cetin et al. 2004, Moss et al. 2006, Juang et al. 2006, Idriss and Boulanger 2012, Kayen et al. 2013). They give the probability of liquefaction conditional upon ground shaking with some specified return period. The applicability of this type of probabilistic procedures in probabilistic safety analysis of NPPs is similar as deterministic empirical methods and is also limited.

Additionally, procedures computing unconditional probabilities of liquefaction occurrence have been developed as well (Atkinson et al. 1984, Marrone et al. 2003, Goda et al. 2011). These methods combine the elements of probabilistic seismic hazard analysis with deterministic or probabilistic empirical methods of liquefaction potential evaluation. This combination leads to a formal estimate of the annual probability of liquefaction that explicitly includes both uncertainties in regional seismicity parameters and in the conditional probability of liquefaction. The method not only allows calculating the composite liquefaction hazard from all seismic sources and the range of possible events, but, through deaggregation of the results, allows assessing the relative contribution of various magnitudes, distances, or specific seismic sources.

A Performance-based Earthquake Engineering (PBEE) probabilistic framework for evaluation of the risk associated with earthquake at a particular site has been developed by Cornell and Krawinkler (2000), Deierlein et al. (2003) and Zareian and Krawinkler (2009). In the PBEE, the earthquake is characterised by an intensity measure (IM). The IM are linked to selected EDP that are correlated to the damage measures (DM) via corresponding conditional probability distributions. The risk associated with DM has to be expressed in some decision variables, DV applicable for measuring the losses. The mean annual rate of exceedance of a given DV level can be calculated if the annual rate of the IM and the conditional probabilities connecting the IM to EDP, the EDP to DM and the DM to DV are known. This concept fits to the probabilistic safety analysis of nuclear power plants if it is limited to the definition of conditional probability of EDP that can be considered as independent variable of the fragility of plant SSCs due to liquefaction.

For evaluation whether a component in a system will fail, the EDPs characterising the effects/actions caused by the liquefaction have to be known as a function of intensity measures, IM_i, i.e. $EDP_i = \varphi \; IM_1, IM_2 \cdots$. In the probabilistic seismic safety analysis, the fragility and the hazard are defined as functions a non-negative single load parameter, the PGA, though it is obvious that the damage of the SSCs depends also on the length of strong motion, frequency content of the vibratory motion, etc. (see Katona 2010). Unfortunately, in case of liquefaction, there aren’t simple correlations for the engineering demand parameters that would define the fragility as a function of a single intensity measure.

As per experience, the volumetric strain ε_p can be selected for EDP. A functional relationship between ε_p and PGA and moment magnitude can be established, $\varepsilon_p = \varphi \; PGA, M_w$ (see, e.g. Tokimatsu and Seed 1987). For exact calculation of conditional probability of exceedance for ε_p the bivariate distribution of PGA and moment magnitude have to be known for each exceedance level of earthquake hazard. Similar difficulty is in place even in case of evaluation of liquefaction susceptibility. The multivariate distribution of intensity measures can be obtained by processing the results from a site-specific hazard analysis with deaggregation. Hwang et al. (2000), Kramer and Mayfield (2007), Mayfield et al. (2010) have described a performance-based approach that evaluate the liquefaction potential with modification of the original PBBE framework to take into account the bimodal distribution of IM. Their paper showed how the entire range of potential ground shaking can be considered in a fully probabilistic liquefaction potential evaluation using a performance-based earthquake engineering PBEE framework. The SPT based probabilistic method of Cetin et al. (2004) is built in the procedure of Kramer and Mayfield and the final result is a direct estimate of the return period of liquefaction. Contrary to this, the calculation of the annual rate of exceedance of the EDP would be rather simple, if a single intensity measure could be selected for calculation of EDP. From this point of view the studies relating the EDP and Arias intensity or cumulative absolute velocity (CAV) are promising (see e.g. Kramer and Mitchell 2006). The advantage of using CAV, as intensity measure is manifold: The CAV (as well as the Arias intensity) expresses the cumulative feature of generation of excess pore pressure. The CAV can be used as independent variable for fragility in case of accumulating damage processes like low-cycle fatigue (see Katona 2011).

Deterministic safety analyses for NPPs assess the integrity and function of the plant structures, systems and components (SSCs) while calculating the loads, stresses and strains and comparing these to the code allowable values. The deterministic analyses can be rather sophisticated, using coupled soil-structure model, or simplified calculating the structural response to a given effect of liquefaction. In the latter case, the safety analysis is limited to the assessment of the response of plant structures to the given soil settlement. As per experience, the ground settlement/volumetric strain due to liquefaction has been recognised as the most decisive (Dashti et al, 2010). Obviously, the differential settlement can be the most dangerous one that may occur either below the foundation of a building or between adjacent structures. There are simple methods for calculation of the settlement (see e.g. Tokimatsu and Seed 1987, Zhang, Robertson and Brachman 2002). The empirical based liquefaction models are recommended by the nuclear regulations (see e.g. US NRC 2003). The soil response to the earthquake excitation can be calculated by more sophisticated methods, e.g. effective stress method. There are also finite element or finite difference methods for calculation of the nonlinear soil-structure response in case of liquefaction. A probabilistic element is also present in the deterministic calculations hence the input parameters used for the calculation of settlement and soil-structure interaction are defined on a certain non-exceedance probability level and derived from the probabilistic seismic hazard assessment (PSHA).

Basic problem of the deterministic analysis of liquefaction effects on the plant safety that the results provided by different methods are scattering due to the uncertainty of assessment of both liquefaction resistance and load part causing the liquefaction.

It is obvious from the above considerations that the proper form of the liquefaction hazard characterization depends on the framework of the safety analysis where the hazard characterization is used. The liquefaction hazard assessment has to be based on a comprehensive seismic hazard assessment. The liquefaction characterization has to take into account what parameters are needed for the evaluation of damage of identified structures. It means those liquefaction effects are of interest, which are best correlated to failure modes. As it also shown in the above consideration the empirical liquefaction models play essential role in both deterministic and probabilistic safety analysis of nuclear power plants. In the paper the uncertainty of the empirical based liquefaction models will be analysed. It will be shown that depending on the method applied, the liquefaction assessment provides very scattering results and leading to controversial conclusions.

In the paper different approaches and methods for liquefaction hazard assessment are considered from the point of view of utilisation in the safety analysis of NPPs. Practical problems of selection of appropriate methods are demonstrated on the example of Paks Nuclear Power Plant, Hungary.

PROBLEMS IN LIQUEFACTION AND POST LIQUEFACTION SETTLEMENTS IN CASE OF PAKS NPPS

Paks NPP site is situated near the Danube-river, in the central part of the Pannonian Basin that can be characterized by moderate seismicity. The basin is filled with several kilometers thick sediments of different ages. The power plant is sited on the floodplain of the River Danube. Below the power plant itself a thick Pannonian (upper Miocene) strata can be considered as the base formation beginning at 27-30 m under the ground level. This stratum mainly contains very dense fine-grained sand, clay and mudstone. The overlying Pleistocene stratum is 20-25 m thick, and its lower section is made up of sandy gravel, and gravelly sand, which is lying under fluvial well-graded fine sand. In the Holocene, this layer was covered with fluvial sand, silt and clay deposits. The most-upper layer of the soil profile contains fill with variable thickness (Ove Arup 1995). The site ground water level is in hydraulic connection with the Danube but the samples from control wells show a much more consistent ground water level. The average ground water level is in 8 m below the surface.

In 1994 and 1995 an extensive site investigation program was performed at the power plant. The research program consisted different types of field measurements, CPT and SPT soundings, geophysical investigations and permeability measurements, which allowed the unprecedentedly detailed description of the subsurface conditions. The detailed site survey has indicated that the saturated sandy layers between 10 and 20 m below the ground level are susceptible to liquefaction. Seismic and liquefaction hazard assessments performed in the 90's and in the last decade showed that liquefaction does not occur at the probability of design base level (10^{-4}/year, PGA=0.25g) and the post-earthquake settlement is about 12 mm. Factor of safety against liquefaction was estimated by simplified method of Seed and Idriss. Seismic settlement was computed by semi-empirical method of Tokimatsu and Seed (1987).

Between 2003 and 2007, while extending the hazard computations to very low annual probabilities (up to 10^{-7}/year) for the probabilistic seismic safety analysis, effects of the liquefaction on the plant safety had been assessed. In a very conservative way, a cliff-edge effect was associated with the onset of the liquefaction. This simplified method for accounting the effects of liquefaction results in a high contribution of the liquefaction to the core damage frequency. The outcome of the study motivated an in-depth revision of the liquefaction hazard and analysis of its consequences in 2007. These studies gain specific attention after severe accident at Fukushima Dai-ichi plant and became one of the most important post-Fukushima measures.

It has been recognized that the differential settlements and relative displacements between the different buildings and piping seems to be the major issue from the point of view of ensuring basic safety functions. This differential movement can be caused by slight variability of depth and thickness of these sediments. Therefore settlements have to be regarded as the dominant EDP and settlement hazard curves have to be determined.

To determine post liquefaction settlement, procedures of Tokimatsu and Seed (1987) moreover Ishihara and Yoshimine (1992) were used. Using Ishihara and Yoshimine's method, the settlement of ground surface for 10^{-4}/y case was estimated to 11 and 9.9 cm at the eastern and western side of the main reactor building, respectively. The computations resulted 23.8 cm for the post liquefaction settlement when Tokimatsu and Seed method was applied. The seismic settlement under dry conditions was assessed to be 11 cm using Tokimatsu and Seed (1987) method. Numerical computations using effective stress method, also strengthen that liquefaction occurs only at lower than 10^{-4} annual probabilities (Győri et al. 2002) and 9 mm surface settlement was obtained for the design base ground motion level (Győri et al. 2011). Numerical effective stress methods need a constitutive soil model and beside the variation of soil parameters, they are very sensitive to the applied input acceleration time histories too.

It is obvious, adequate assessment of the plant safety and decision on the upgrading measures is rather difficult on the basis of these scattering results. Differences between the results of computations arise from the use of different input parameters and from different approaches of the same type of computation procedures. Uncertainties come from the loading and resistance side of liquefaction and post-liquefaction assessment irrespective of the use of analytical or empirical methods.

Since in earthquake engineering practice, mostly the empirical based liquefaction models are recommended, therefore we have dealt with them in this paper. Below, the results given by some well-known and newer methods of liquefaction potential and settlement assessment are compared for the site conditions of Paks NPP.

COMPARISON OF STRESS BASED LIQUEFACTION EVALUATION METHODS

For comparison of liquefaction potential assessment methods, records of one SPT, one CPT and one shear wave velocity measurement, that were located very close (within 5 m) to each other, were chosen from the site. Penetration resistance and wave velocity records of the selected individual SPT, CPT and V_S measurements can be seen in Figure 1. In the calculations below, the groundwater level was assumed to be 8 m below the surface. The CSR was calculated for peak ground acceleration (a_{max})

of 0.25g, which corresponds to design basis earthquake. From the point of view of liquefaction hazard the moment magnitude of controlling earthquake is equal approximately to 6.0.

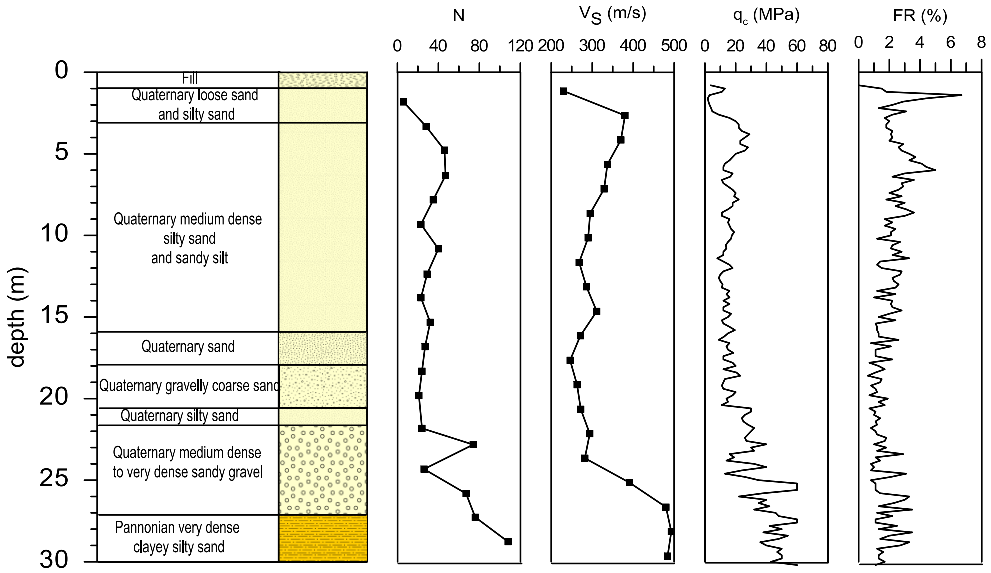


Figure 1. Soil profile, SPT blow counts (N), shear wave velocities (Vs) CPT penetration resistances (qc) and friction ratios (FR) measured at the studied point

Liquefaction potential was assessed by altogether nine of the newest and most commonly used empirical SPT-, CPT- and shear wave velocity-based correlations (Table I).

Table 1. Summary of empirical methods in comparison

Method		NCEER 1996 workshop			Berkeley University			Idriss and Boulanger (2008, 2012)	Juang et al. (2006)
		Youd et al. (2001)	Robertson and Wride (1998)	Andrus and Stokoe (2000)	Cetin et al. (2004)	Moss et al. (2006)	Kayen et al. (2013)		
CPT	deterministic		X			X		X	X
	probabilistic					X			X
SPT	deterministic	X			X			X	
	probabilistic				X			X	
Vs	deterministic			X			X		
	probabilistic						X		

The seismic demand is represented by the cyclic stress ratio (CSR):

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65\frac{a_{\max}}{g}\frac{\sigma_v}{\sigma'_v}r_d \ . \qquad (1)$$

Calculation of CSR (Eq. 1) requires the values of both the total (σ_v) and the effective overburden stress (σ'_v) with depth. In the calculations this site-specific r_d was used, but for comparison the results of the simplified equations were also presented (Fig. 2.).

It was found that the correlation of *Cetin et al.* is the most conservative from the SPT-based methods (Fig.3a.). The procedures of *Youd et al.* and *Idriss and Boulanger* show good agreement with each other, and they give 40-60% higher factors of safety in the critical depth than *Cetin et al.* The most conservative probabilistic correlation, the method of *Cetin et al.* predicted 8% of probability for liquefaction to occur; in contrarily *Idriss and Boulanger* estimated less than 0.01% of probability (Fig. 3b.). It is important to note that most of the methods set 15% of probability as criterion for boundary.

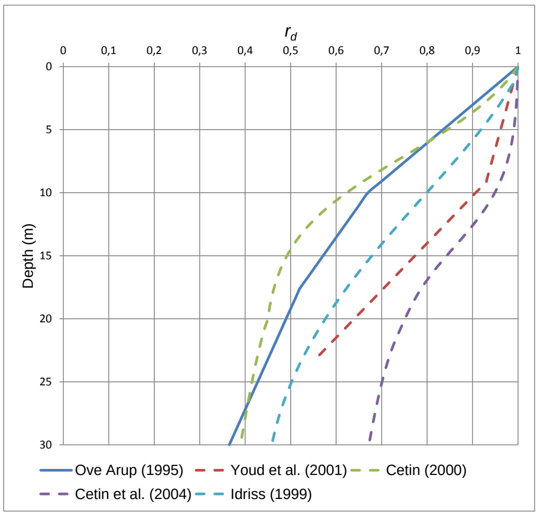
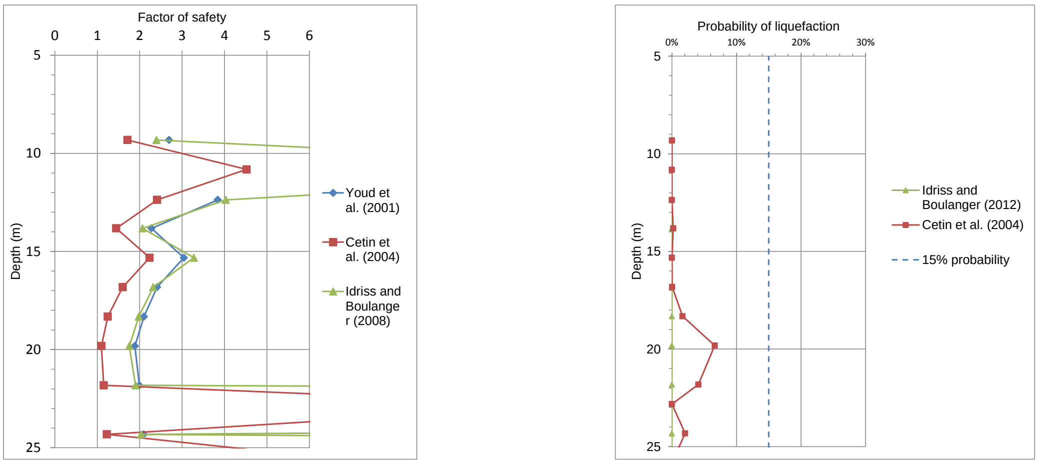


Figure 2. Comparison of the site-specific r_d (referred as Ove Arup 1995) with the results of the presented different simplified correlations



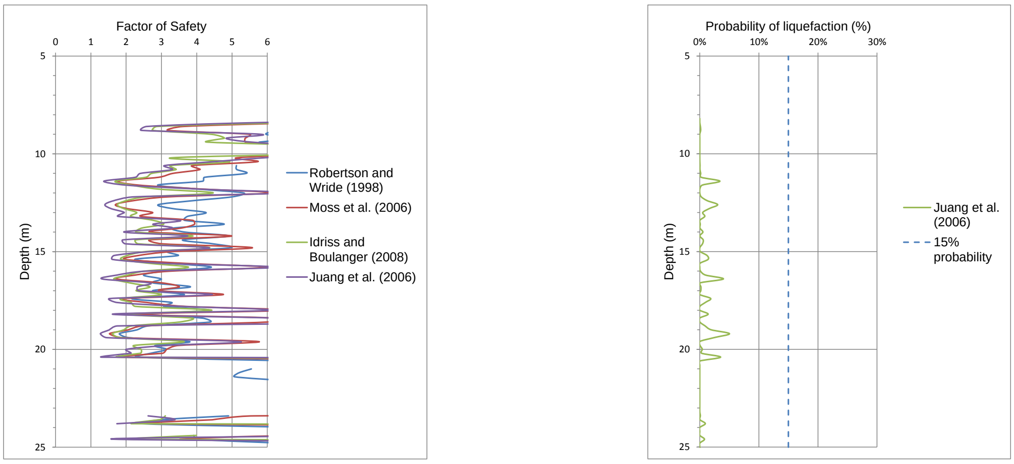
a) b)

Figure 3. Comparison of deterministic (a) and probabilistic (b) SPT based empirical methods

From the CPT-based procedures *Robertson and Wride* proved to be the least conservative (Fig. 4a, Fig. 5.) especially in the silty sand strata, which supports other researchers' findings that it overestimates safety in silty sands (Idriss and Boulanger 2008). As the lowest factors of safety are of interest, comparison of CPT-based methods was made by connecting local minimums and thus obtaining lower boundary curves of the methods (Fig. 6a). This shows that the correlation of *Juang et al*. is the most conservative; however, due to the rapidly increasing CRR curve of it, it also gives the highest FS values at the local maximums. The results of *Moss et al*. and *Idriss and Boulanger* (CPT) agree well with each other.

Two shear wave velocity-based methods were evaluated, the most commonly used method of *Andrus and Stokoe* proved to be far the least conservative from all of the methods. The recently published correlation of *Kayen et al*. gave much lower values (Fig.6b.).

Comparison of the NCEER methods (*Youd et al., Robertson and Wride and Andrus and Stokoe*) showed that the SPT-based method is the most conservative, the CPT-based is less conservative and the V_S-based method is far the least conservative (Fig. 7a). Comparison of the Berkeley University methods (*Cetin et al., Moss et al. and Kayen et al.*) also showed that SPT-based method gives the most conservative estimate of factor of safety against liquefaction (Fig. 7b).



a)	b)

Figure 4. Comparison of deterministic (a) and probabilistic (b) CPT based empirical methods

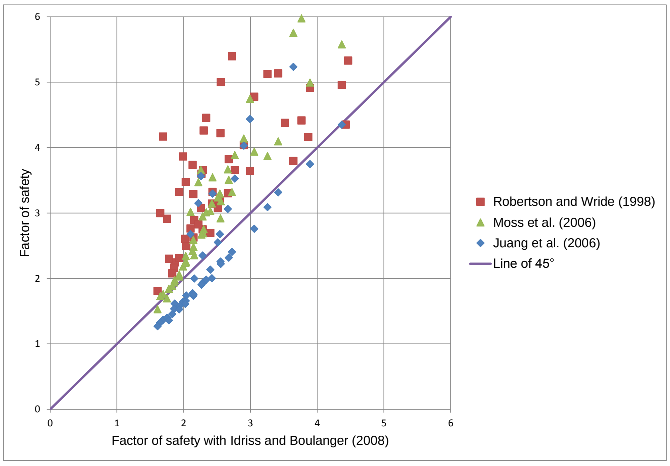
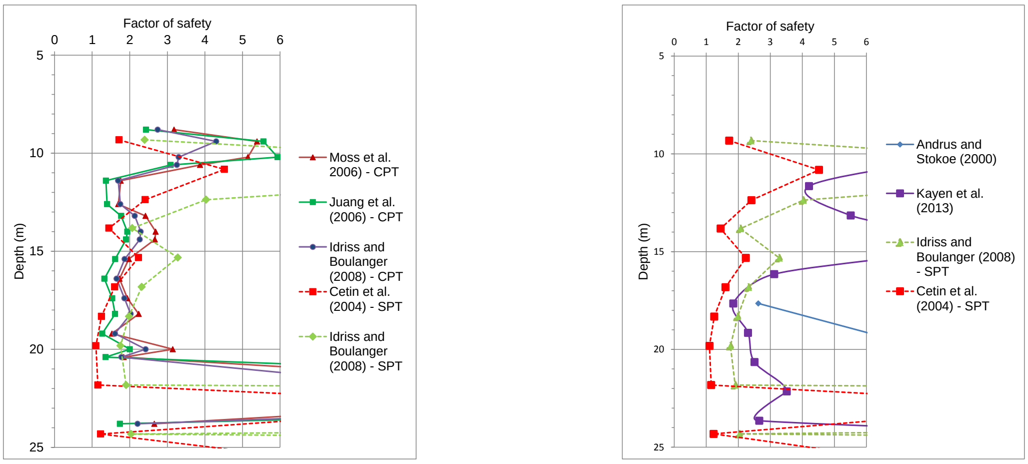
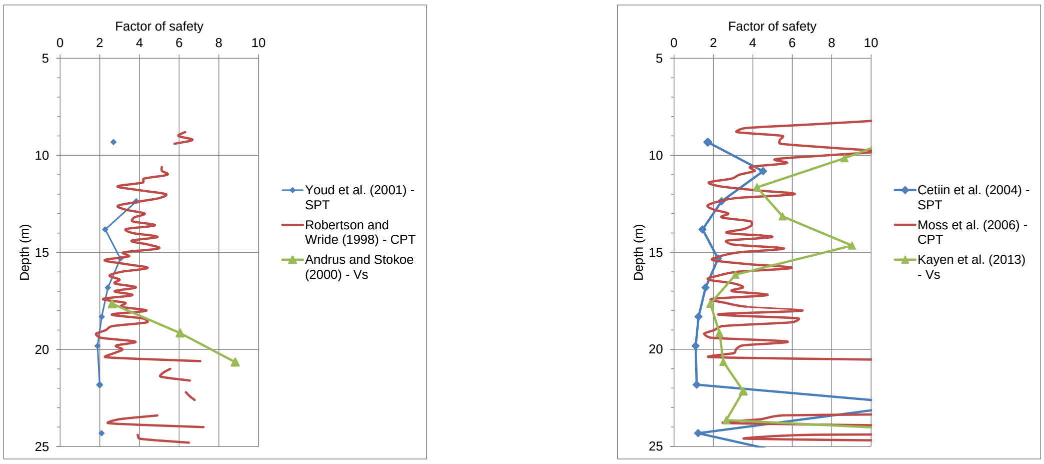


Figure 5. Factors of safety computed by different deterministic CPT based procedures versus factor of safety computed with method of Idriss and Boulanger (2008)



a)	b)

Figure 6. Lower boundary curves of CPT based deterministic methods (a) and shear wave velocity based methods (b) compared with the SPT based procedures of Cetin et al.(2004) and Idriss and Boulanger (2008)



a)

b)

Figure 7. Comparison of different methods proposed by the NCEER (a) and developed in the Berkeley University (b)

Although the results of the methods applied vary considerably, but all of them agree that factor of safety against liquefaction is higher than 1.0 at any depth for the given site conditions and for the design basis earthquake. The lowest values occur between 1.0 and 2.0 depending on the considered method.

However, although the NCEER methods represent the last consensus solution for liquefaction triggering assessment and they are widely used in practice, advancements in the last 15 years have surpassed them. New liquefaction case histories had been gathered since the NCEER workshop and the expanded databases allowed the CRR curves to be more controlled by field data. Recent studies also have shown inconsistency in the treatment of corresponding probability to deterministic CRR curves. The SPT-based CRR curve of *Youd et al.* corresponds to a probability of 31% and the V_S-based CRR curve of *Andrus and Stokoe* corresponds to a probability of 26% (Juang et al. 2002). In contrast, subsequent methods aimed probability of 15% as deterministic boundary (Seed 2010), as it was originally suggested by Seed and Idriss (1971). This inconsistency also makes more difficult the interpretation of the results.

Direct comparison of results from the same depths may be misleading if the layers are inclining. In the silty sand layer (<16 m) the local minimums of *Juang et al*. give similar result as *Cetin et al.* The procedures of *Moss et al*. and *Idriss and Bouanger* (CPT) is found to be intermediate between the SPT-based correlations. As gravel content increases with depth the lower boundary curves of the CPT-based methods converge toward the SPT-based result of *Idriss and Boulanger*.

Because large particles can distort the measurement results of penetration tests, shear wave velocity measurement is recommended in gravelly soils, which is more directly related to the relative density of the soil. Although up until now SPT and CPT methods were preferred because of the more extensive database and past experience, the recently published correlation of *Kayen et al*. was derived from even a larger database than any of the examined methods. As the critical layer was found to be partly the gravelly sand deposit, V_S-based result of *Kayen et al*. may be regarded with great emphasis. In general, the V_S-based methods give the least conservative estimates of factor of safety along the whole profile. From the SPT-based methods *Idriss and Boulanger* agrees the best with the values of *Kayen et al*. From the CPT-based methods *Juang et al*. gives more conservative values than *Kayen et al*., and the lowest factor of safety of *Kayen et al*. agrees well with the lowest values of *Moss et al*. and *Idriss and Boulanger*.

Analyzing the effect of stress reduction factor has shown that significant differences can be between the results if r_d is determined from site response analysis or simplified equations. Using site specific r_d, differences between the result given by Seed et al. (2004) and Idriss and Boulanger (2008) SPT based methods are larger as if their own simplified equations would be used (Fig. 8). Therefore at the selection of the method careful consideration is necessary.

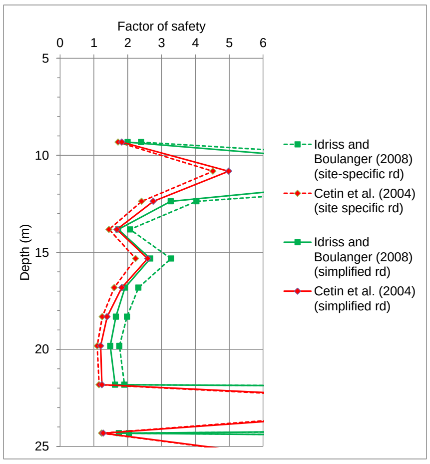


Figure 8. Factor of safety versus depth computed by Seed et al. (2004) and Idriss and Boulanger SPT based methods and using simplified and site specific stress reduction factor

The analysis conducted in this study shows that the most susceptible layer for liquefaction is located between 16 and 22 m depths, what agree well with the results of *Győri et al. (2004)* who used nonlinear effective stress method to evaluate liquefaction potential. This critical depth deserves attention, because based on the soil description of SPT samples and core from an adjacent borehole, gravelly sand can be found in this depth, and initially the critical layer was anticipated to be around 10 m depth, where grain size distribution falls into the interval of most liquefiable soils. However, the result should be treated with caution, because this depth is around the depth for which simplified procedures have been verified and uncertainty in the results can be significant. It should be mentioned that relatively large depth of the critical layers unfavorably influences pore pressure dissipation, but on the other hand the layers are underlain by gravelly deposit, which facilitate the dissipation of excess pore pressure.

Although liquefaction has low probability in case of design base earthquake, excess pore pressure may develop in the soil, what may cause settlement. Therefore we have studied some procedures of post-liquefaction settlement assessment too. Large majority of these methods are based also on the empirical liquefaction potential evaluations. Therefore their uncertainties partly also arise from the uncertainties of the liquefaction assessment methods. In this study we have compared surface settlements computed by Ishihara and Yoshimine (1992), Cetin et al. (2009) SPT based, moreover Zhang et al. (2002) CPT based methods.

Ishihara and Yoshimine method determines the volume strain using SPT blow-counts normalized to clean sand and factor of safeties. To compute these quantities, three methods (Youd et al. 2001, Cetin et al. 2004, Idriss and Boulanger 2006) were used. Because the FS has shown significant differences therefore large scattering can be seen among the computed settlements (2.2, 80.4 and 4.9 mm respectively).

Cetin et al. (2009) procedure is based on CSR and SPT blow-counts normalized to clean sand. Because the normalization proposed by Youd et al. (2001), Cetin et al. (2004), Idriss and Boulanger (2006) differs only slightly from each other and site specific r_d was applied so the obtained settlement values were very similar (5.9, 5.1 and 4.3 mm respectively). The method proposes the use of a weight factor against depth. It takes into account the observation that deeper layers play less important role and liquefaction below 18 m depth is insignificant in surface settlements.

Procedure of Zhang et al. (2002) computes the volume strain from the factor of safety against liquefaction and the CPT tip resistance normalized to clean sand. The authors propose the use of Robertson and Wride (1998) method to compute the FS. Because this is one of the least conservative liquefaction assessment methods therefore the smallest value was obtained for the surface settlement (0.7 mm).

CONCLUSIONS

In the paper the problems of safety analysis of Paks NPP have been discussed for the case of liquefaction. Different liquefaction analysis methods have been discussed from the point of view of applicability in the nuclear power plant safety assessment framework. Main focus of the paper was the analysis of empirical methods widely used in engineering practice and their results have been compared for the case of Paks site and design base earthquake.

It is shown that epistemic uncertainties are rather large and limit very much the decisiveness of the analyses. Therefore the applicability of the liquefaction hazard assessment methods that do not account on epistemic uncertainties is rather limited. In case of empirical methods, uncertainties of loading side depend on maximum surface acceleration and magnitude, which originate from the aleatory and epistemic uncertainties of PSHA. But significant part of epistemic uncertainties arises from the application of different methods. A very important contributor to uncertainties is the stress reduction factor. It can be obtained using simplified equations developed by different authors or during site response computations. Although the latter can be regarded as the most accurate because it takes into account the actual soil properties, it have also significant uncertainties that come from the variability of soil profile, from the measurement errors of different soil parameters and the earthquake loading. Conservatism of cyclic resistance ratios developed by different authors is different and the situation is even more complicated because the methods developed for different in situ geotechnical measurement have different resolution. Changes in fines content and unit weight have less effect on the factor of safety, while fluctuation of ground water level has hardly any influence on it. These findings agree well with the results of previous studies prepared for Paks NPP (Győri et al. 2011, Tóth et al. 2008).

Considering the significance of epistemic uncertainties, application of a logic tree methodology for liquefaction hazard assessment seems to be justified. A detailed description of logic tree methodology is described for example by Győri et al (2011) where the logic tree has two basic branches: one for empirical models and the other one for the effective stress analytical model. This method accounts both aleatory and epistemic uncertainties. The reviewed empirical methods can be accounted in braches of the logic tree. This method fits best to the probabilistic safety assessment of nuclear power plants because it gives a conditional probability distribution of liquefaction or settlement on a predefined ground shaking on different probability level.

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