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Research Article

Applicability of Pseudoprobabilistic Method of Liquefaction Hazard Assessment for Nuclear Power Plants at Diffuse Seismicity Sites

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For the new nuclear power plants, the hazard of liquefaction due to earthquakes should be excluded by appropriate site selection or eliminated by engineering measures. An important question is how to define a quantitative criterion for negligibility of the liquefaction hazard. In the case of operating plants, liquefaction can be revealed as a beyond-design-basis event. It is important to learn whether the liquefaction hazard has a safety relevance and whether there is a sufficient margin to the onset of liquefaction. The use of pseudoprobabilistic method would be practicable for the definition of probability of liquefaction, but it could result in overconservative results. In this paper, the applicability of the pseudoprobabilistic procedure is demonstrated for the sites in diffuse seismicity environment and for low hazard levels that are typical for nuclear safety considerations. Use of the procedure is demonstrated in a case study with realistic site-plant parameters.

1. Introduction

Seismic safety of nuclear power plants (NPPs) is ensured by adequate definition of the design basis earthquake and its effects and by the utilization of design methods justified by experimental evidences. Since the characterisation of earthquake hazard is inevitably burdened by epistemic and aleatoric uncertainties, the design shall provide for an adequate margin to protect the structures, systems, and components (SSCs) ultimately necessary to eliminate scenarios progressing to severe accident or an abrupt change to a severe plant condition ("cliff-edge effect"), even if a beyond-design-basis earthquake would happen. For the newly built plants, depending on the national regulations of the particular country, different values of plant seismic margin should be demonstrated. For example, in the European countries, a margin equal to 1.4 times the design-basis peak ground acceleration (PGA_{DBE}) is required, while in the U.S., a margin 1.67 times the PGA_{DBE} (see [1]). In the case of operating plants, effort should be taken to ensure a plant margin is close to these values, WENRA [2]. In the frame of post-Fukushima actions, margins above the design basis hazards have been investigated for the majority of operating plants. Generally, for assessment of margin, the plant high-confidence-of-low-probability-of-failure value is evaluated, see the methodology in EPRI [3].

The Fukushima accident triggered the investigation of hazards associated to the earthquakes as well. Liquefaction is one of those consequential phenomena that is causally correlated to the earthquake, but it does not necessarily occur with the earthquake. Therefore, the liquefaction hazard should be investigated and evaluated for siting of new NPPs; see, e.g., IAEA [4] and IAEA [5]. The safety relevance of the liquefaction hazard for operating plants at soil sites could also be necessary to assess, as it happened in the frame of the post-Fukushima stress test; see, e.g., HAEA [6].

An interpretation of sufficiency of margin to liquefaction and the concept for definition of criteria of adequacy of screening out the liquefaction hazard have been proposed by Katona [7] as it is outlined below.

For the new nuclear power plants, the liquefaction should be excluded by appropriate site selection or should be eliminated by engineering measures. For screening out the hazard, a conservatively calculated factor of safety to the liquefaction (FS_L) is applied for the case of design basis earthquake (DBE); see US NRC [8] and KTA [9]. Application of these methods use rather limited geotechnical and seismological information. For screening out, the above-referred regulations require $FS_L > 1$. However, the criteria value of FS_L is a matter of engineering experience and judgement. In deterministic sense, the statement on the susceptibility of the soil to liquefaction is a dichotomy. As a matter of fact, the phenomenon is not deterministic. Even if $FS_L > 1$, it does not mean that the liquefaction hazard is negligible absolutely. An important practical question is how to define a quantitative criterion for screening-out the liquefaction hazard. Moreover, this statement should also be interpreted within the probabilistic framework of the nuclear safety requirements. For example, the early large release of radioactive substances could be accepted if its annual frequency is $\leq 10^{-6}$. This is a cumulative value that should be obtained by summing-up all possible accident sequences. Consequently, the annual frequency of early large release due to particular sequences triggered by liquefaction should strictly be $\ll 10^{-6}$, let say $\sim 10^{-7}$. This assumption includes implicitly that the liquefaction once happened would trigger an accident sequence; i.e., the liquefaction causes a cliff edge effect. It is a reasonable assumption, since a more precise value could be defined by a probabilistic safety analysis of the plant for the liquefaction hazard that is not feasible at the stage of investigation for a new site. For a state-of-the-art probabilistic safety analysis, an appropriate engineering damage parameter (EDP) should be identified for the liquefaction, the fragility of the SSCs necessary to eliminate abrupt changes to severe plant condition should be evaluated versus EDP, and the plant response to the liquefaction should be modelled. Thus, the annual probability of core damage frequency or early large releases should be calculated and compared to the performance targets. According to these assumptions, the liquefaction hazard due to design basis earthquake can be screened-out, if $p_{\mathrm{DBE}} \cdot P(\mathrm{liq} \mid \mathrm{DBE}) < \sim 10^{-7}$, where p_{DBE} is the annual probability of design basis earthquake and $P(\mathrm{liq} \mid \mathrm{DBE})$ is the conditional probability of liquefaction due to design basis earthquake. It has to be mentioned that nuclear regulations in different countries set p_{DBE} between 10^{-4} to 10^{-5}, for example, in Finland for newbuilt $10^{-5}/a$ median, STUK [10]; in Hungary for newbuilt $10^{-5}/a$ mean, HAEA [11]; and for the operating plant $10^{-4}/a$ mean, HAEA [12].

Considerations should also be made whether liquefaction can occur due to an earthquake, for which the requested margin should be justified. In the case of new plants, the peak ground acceleration of this earthquake is assumed to be 1.4 (or 1.67) times larger than the peak ground acceleration of the design basis earthquake (PGA_{DBE}). It is important to know whether this margin earthquake with peak ground acceleration PGA_{ME} and $PGA_{ME} \leq 1.4\,(\text{or } 1.67) * PGA_{DBE}$ would cause liquefaction. For the margin earthquake, the criterion $P(\mathrm{liq} \mid \mathrm{ME}) \leq 10^{-1}$ was proposed by Katona [7]. Here, it is conservatively assumed that the liquefaction could result in cliff-edge effect. Therefore, a 10% margin above the onset of liquefaction due to margin earthquake is suggested. This is similar to the concept in ASCE/SEI 43-05 [13], where the probability of unacceptable performance should be $\lesssim$10% for an earthquake with $1.5 * PGA_{DBE}$, while the probability of unacceptable performance should be $\lesssim$1% for design basis earthquake.

In the case of operating plants, the liquefaction hazard and its consequences have been investigated to some extent for 41 operating NPPs at soil sites in the U.S. in the frame of individual plant examination for external events program; see NUREG-1742, U.S. NRC [14]. These analyses have shown that liquefaction could be an essential contributor to the core damage, if the hazard is not negligible. Similar conclusion was made on the basis of seismic probabilistic safety assessment for Paks NPP [15] in the frame of periodic safety review. In the case of operating plants, liquefaction can be recognized during a periodic or focused safety assessment; see examples in the European Union stress tests and particularly the Hungarian stress test report in HAEA [6]. In the case of operating NPPs, there are two important questions to be answered in the frame of safety reviews: (1) whether the liquefaction hazard should be neglected for the design basis earthquake; (2) whether the margin to liquefaction is sufficient, i.e., whether the margin earthquake with $PGA_{DBE} < PGA_{ME} < 1.4\,(\text{or } 1.67) * PGA_{DBE}$ would not cause liquefaction. If the hazard could not be neglected, the consequences of liquefaction should be thoroughly analysed, and the plant safety should be justified. Paks NPP in Hungary is an example of this case; see Katona et al. [16, 17].

From the aforementioned considerations, the specific nuclear aspects of the characterisation/evaluation of liquefaction hazard can be recognized. First of all, the investigation of the hazard should be extended to annual probabilities $\ll 10^{-4}/a$ that are practically an order of magnitude less than that in the case of nonnuclear building practice. For the nuclear power plant sites, performance of demanding geotechnical site survey is required; see, e.g., IAEA [18]. In spite of this, due to the very low probabilities considered and complexity of the phenomenon, the liquefaction hazard characterisation is burdened with uncertainty; see, e.g., Győri et al [19]. The probabilistic framework of nuclear safety assessment requires probabilistic approach of the hazard characterisation. The compliance with probabilistic acceptance criteria for core damage and early large releases is demonstrated by level 1 and 2 probabilistic safety assessments (PSA) of the plants with respect to earthquakes and liquefaction. These analyses require application of sophisticated methodologies for the liquefaction consequences, such as probabilistic liquefaction hazard assessment (PLHA) [20]. Nevertheless, there is a practical need for simple evaluation methods for liquefaction hazard applicable for screening and margin assessments.

A simplified method for assessment of the margin to liquefaction has been proposed by Katona [7], which is based

on the calculation of probability of liquefaction by the method proposed by Cetin et al. [21] using a single pair of mean values of free-field maximum horizontal acceleration, a_{max}, and moment magnitude, M_w, taken from deaggregation results of the probabilistic seismic hazard assessment (PSHA). The application of the method has been demonstrated for a low-to-moderate seismicity nuclear site.

A recently published study of Franke et al. [22] demonstrates that the pseudoprobabilistic methods based on the use of a single pair of a_{max} and M_w taken from the deaggregation results can significantly overestimate the liquefaction hazard for low seismicity sites compared to the results obtained by the performance-based assessment method.

The critique by Franke et al. [22] has indisputable relevance to the method proposed by Katona [7] for the assessment of adequate margin to liquefaction, since this method seems to have the same drawback of selecting a single pair of a_{max} and M_w for a certain hazard level, and it was used in the calculation of the probability of liquefaction.

It is obvious that there is a realistic need to have a possibly simple method for the evaluation of the liquefaction hazard with acceptable level of conservatism that can be used at the phase of site evaluation, when a decision on the relevance of possible hazards should be made. Furthermore, in the case of the operating NPPs at soil sites, a cost-effective method for assessment of the liquefaction hazard would be practical, when the liquefaction reveals as a possible safety issue recognised in the frame of periodic or ad hoc safety reviews.

The aim of this paper is to analyse the conservatism of the method proposed by Katona [7] and justify its applicability for the aforementioned purposes, while the findings of Franke et al. [22] will be accounted for. To achieve this goal, the results of Franke et al. [22] obtained for the return periods of maximum 2475 years will be confronted with the results of analyses performed for the return periods $T \geq 10000$ years typical for design and safety analyses for nuclear power plants. The PSHA is the starting point of the studies performed by Katona [7] and Franke et al. [22]. In both cases, the site is of low-to-moderate seismicity.

In the paper, it is demonstrated that, in the nuclear applications, it is reasonable to use a pair of properly identified a_{max} and M_w, both as mean values, for the evaluation of the liquefaction hazard. The results obtained in the presented way will be acceptable, conservative, and applicable for the screening and margin assessment purposes.

In the paper, the adequacy and acceptable conservatism of calculation of probability of liquefaction are demonstrated for a typical site in a low-to-moderate, diffuse seismicity region like the Paks site in the middle of the Pannonian Basin, Hungary.

2. The Site and Site-Related Issues

The analysis below is performed for the Paks site, that is, an alluvium site located in the central part of the Pannonian Basin, at coordinates 46°34′21″N 18°51′15″E. There are four VVER-440/213 units at the site, and construction of two new VVER units is foreseen. The site in this study is the same as that considered by Katona [7].

The seismotectonic features and seismic hazard assessments for the Pannonian Basin are presented in plenty of studies; see, e.g., Tóth et al. [23, 24] and Giardini et al. [25]. The site of seismic hazard has been analysed by the comprehensive probabilistic method and extensive geological, geophysical, seismological, and neo-tectonic investigations. The PSHA for the operating plant at the Paks site and the geological, geophysical, and seismological investigations supporting the PSHA have been reviewed by competent international organisations and also reviewed and updated every ten years in the frame of periodic safety reviews. Additional review of the PSHA has been made in the frame of post-Fukushima stress test. The most recent and very detailed documentation on the seismotectonic investigations for the new nuclear units at the Paks site have been made public at the website of the project company Paks II Ltd in Hungary. Based on these investigations, the seismic design basis for the operating plant as well as for the new project has been approved by the Hungarian Atomic Energy Authority. The four VVER-440/213 units at the site the DBE is defined by $PGA_{DBE} = 0.25$ g at $10^{-4}/a$ exceedance probability. The operating plant has been upgraded for this DBE. The seismic design basis for the new plant is set to 0.34 g at $10^{-5}/a$ exceedance probability.

In the floodplain of the Danube, the sandy and sandy-silt layers below the groundwater table are prone to liquefaction. The site of liquefaction hazard has been intensively investigated during the last thirty years; see, e.g., Győri et al. [26]. Hazard assessments also included performance-based probabilistic liquefaction hazard analysis (PLHA) by methods proposed by Kramer and Mayfield [20]. Since the liquefaction hazard cannot be eliminated even for DBE, the consequences of liquefaction for the operating plant structures have been thoroughly analysed by deterministic methods, and the functionality of SSCs needed for fundamental safety functions have been demonstrated; see Katona et al. [17]. It was found that the dominating liquefaction effects are the uneven building settlement and differential settlement between adjacent structures.

In the case of the operating plant at Paks, an important practical question is whether the safety functions will be available if the uneven building settlement exceeds the values defined for the DBE. This may happen either because of the uncertainty of the calculations or because of an earthquake exceeding the DBE. The direct answer is rather difficult. However, the question can be reformulated by asking whether the most probable M_w and a_{max} values at the exceedance level (for example, $10^{-5}/a$) that should be lower than the design base ($10^{-4}/a$) will result in significant increase of the probability of liquefaction P_L.

In the case of new plants, the Hungarian national regulation HAEA [11] requires justification of the core damage frequency $<10^{-5}/a$ and early large releases of $<10^{-6}/a$. These requirements are more precise than those for the operating plants [12]. In the case of new plants, the liquefaction hazard should be eliminated by soil stabilization and a proper

foundation design to meet these safety criteria. The adequacy of soil improvement and the margin to onset of the liquefaction should also be assessed.

3. The Method

As it has been described by Katona [7], the probability of liquefaction can be calculated, for example, by the formula of Cetin et al. [27]:

$$P_{\mathrm{L}} = \Phi\left[\frac{(N_1)_{60}(1+\theta_1\cdot \mathrm{FC}) - \theta_2 \ln \mathrm{CSR}_{\mathrm{eq}} - \theta_3 \ln M_{\mathrm{w}} - \theta_4 \ln(\sigma'_{\mathrm{vo}}/p_{\mathrm{a}}) + \theta_5\cdot \mathrm{FC} + \theta_6}{\sigma_\varepsilon}\right], \tag{1}$$

where Φ is the standard normal cumulative distribution function, $(N_1)_{60}$ is the corrected SPT resistance, FC is the fines content in percent, M_{w} is the moment magnitude, σ'_{vo} is the initial vertical effective stress, and p_{a} is atmospheric pressure in the same units as σ'_{vo}; σ_ε is the measure of the estimated model uncertainty; and $\theta_1 \div \theta_6$ are model coefficients obtained by regression. In equation (1), the cyclic stress ratio, $\mathrm{CSR}_{\mathrm{eq}}$, should be calculated via equation (2), but the magnitude scaling factor (MSF) should be neglected. This is indicated as $\mathrm{CSR}_{\mathrm{eq}}$. The CSR is as follows:

$$\mathrm{CSR} = 0.65\frac{a_{\max}}{g}\cdot\frac{\sigma_{\mathrm{vo}}}{\sigma'_{\mathrm{vo}}}\cdot\frac{r_{\mathrm{d}}}{\mathrm{MSF}}, \tag{2}$$

where $a_{\max}$ is the peak ground surface acceleration, g is the acceleration of gravity in the same units as $a_{\max}$, σ_{vo} is the initial vertical total stress, σ'_{vo} is the initial vertical effective stress, and r_{d} is the depth reduction factor.

In our calculations, for $\mathrm{FS_L}$ and $\mathrm{P_L}$ the relation

$$\mathrm{FS_L} = \frac{\mathrm{CRR}(\mathrm{P_L} = 50\%)}{\mathrm{CRR}(\mathrm{P_L})} = \exp\left[\frac{(-\sigma_\varepsilon\cdot\Phi^{-1}(P_{\mathrm{L}}))}{\theta_6}\right], \tag{3}$$

has been used by Cetin et al. [27]. The probability of liquefaction can be derived from equation (3) as follows:

$$P_{\mathrm{L}} = \Phi\left[\frac{-\theta_6\cdot\ln(\mathrm{FS_L})}{\sigma_\varepsilon}\right]. \tag{4}$$

Using the values for θ_6 and σ_ε from the paper of Cetin et al. [21],

$$P_{\mathrm{L}} = \Phi\left[\frac{-13.32\cdot\ln(\mathrm{FS_L})}{2.7}\right] = \Phi(-4.93\cdot\ln(\mathrm{FS_L})), \tag{5}$$

where $\Phi()$ is the standard cumulative normal distribution and $\Phi^{-1}()$ is its inverse.

In our case, the probability of liquefaction is calculated assuming that an earthquake happens with $\overline{a}_{\max}$ at a given annual frequency $\lambda_{\overline{a}_{\max}}$. The probabilistic way for the calculation of the probability of liquefaction could be based on the evaluation of the bivariate density $p(a_{\max}, M_{\mathrm{w}})$ for $a_{\max}$ and M_{w} and on the conditional probability $P[\mathrm{FS_L} < \mathrm{FS_L^*} \mid (a_{\max}, M_{\mathrm{w}})]$, Juang et al. [28].

Another option is to calculate the annual frequency $\Lambda_{\mathrm{FS_L^*}}$ of $\mathrm{FS_L} \le \mathrm{FS_L^*}$ due to all possible pairs of $a_{\max}$ and M_{w} and plot it versus $\mathrm{FS_L}$, as proposed by Kramer and Mayfield [20]:

$$\Lambda_{\mathrm{FS_L^*}} = \sum_{j=1}^{N_{M_{\mathrm{w},j}}}\sum_{i=1}^{N_{a_{\max,i}}} P\left[\mathrm{FS_L} < \mathrm{FS_L^*} \,\middle|\, (\overline{a}_{\max}, M_{\mathrm{w},i})\right]\Delta\lambda_{a_{\max,i}M_{\mathrm{w},j}}. \tag{6}$$

A probabilistic formulation of the answer to our question can be written as follows:

$$\Lambda_{\mathrm{FS_L^*},\overline{a}_{\max}} = \lambda_{\overline{a}_{\max}}\cdot\sum_{j=1}^{N_{M_{\mathrm{w},j}}} P\left[\mathrm{FS_L} < \mathrm{FS_L^*} \,\middle|\, (\overline{a}_{\max}, M_{\mathrm{w},i})\right]\Delta\lambda_{M_{\mathrm{w},j}}, \tag{7}$$

where the $\overline{a}_{\max}$ is fixed. It is assumed that the sum in (7) can be approximated by $P[\mathrm{FS_L} < \mathrm{FS_L^*} \mid (\overline{a}_{\max}, \overline{M}_{\mathrm{w}})]$, where $\overline{M}_{\mathrm{w}}$ is the mean value of magnitudes contributing to the hazard $\overline{a}_{\max}$ derived from the deaggregation matrix. The total annual probability of liquefaction is as follows:

$$P\left[\mathrm{FS_L} < \mathrm{FS_L^*} \,\middle|\, (\overline{a}_{\max}, \overline{M}_{\mathrm{w}})\right] * \lambda_{\overline{a}_{\max}}. \tag{8}$$

Analysis of the distribution of $\overline{M}_{\mathrm{w}}$ contributing to the hazard $\overline{a}_{\max}$ should be performed to learn whether the assumption made in equations (7) and (8) is valid.

4. Considerations on the Deaggregation of PSHA Results for Sites in Diffuse Seismicity Area

The deaggregation matrix $p_{\mathrm{PGA,T}}(M_{\mathrm{w},i}, d_j)$ expresses the contribution of the events with magnitude $M_{\mathrm{w},i}$ in magnitude bin $\Delta M_{\mathrm{w},i}$ at a distance d_j in a distance bin Δd_j to the PGA of the given hazard level (with fixed return period T or annual exceedance probability). Examples for deaggregation matrices are shown in Figures 1 and 2 for the return periods 4464 and 12642 years, respectively.

Analysing the deaggregation matrix for the studied site, two important observations can be made.

The earthquakes close to the site are dominating in the hazard, and the distribution of the distances to the site tends to be narrower with lower hazard levels, i.e., with higher return periods considered. At $10^{-5}/a$ level, 70% of events contributing to the hazard are in the bin $d_j = 10$ km, and more than 90% of the events are within the distance of 0 to 20 km. Practically, just-below-the-site distance bins dominate in the hazard. Although the distance has no importance in the future calculations, this is an important feature of the site in diffuse seismicity area.

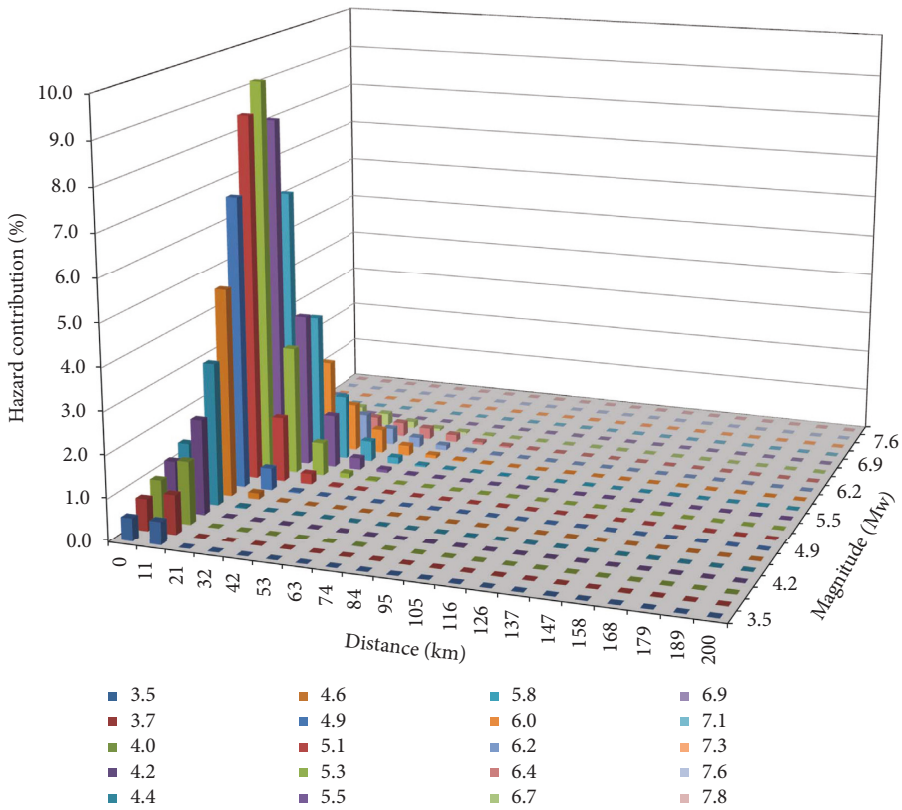

Figure 1: Deaggregation matrix for 4464 years return period.

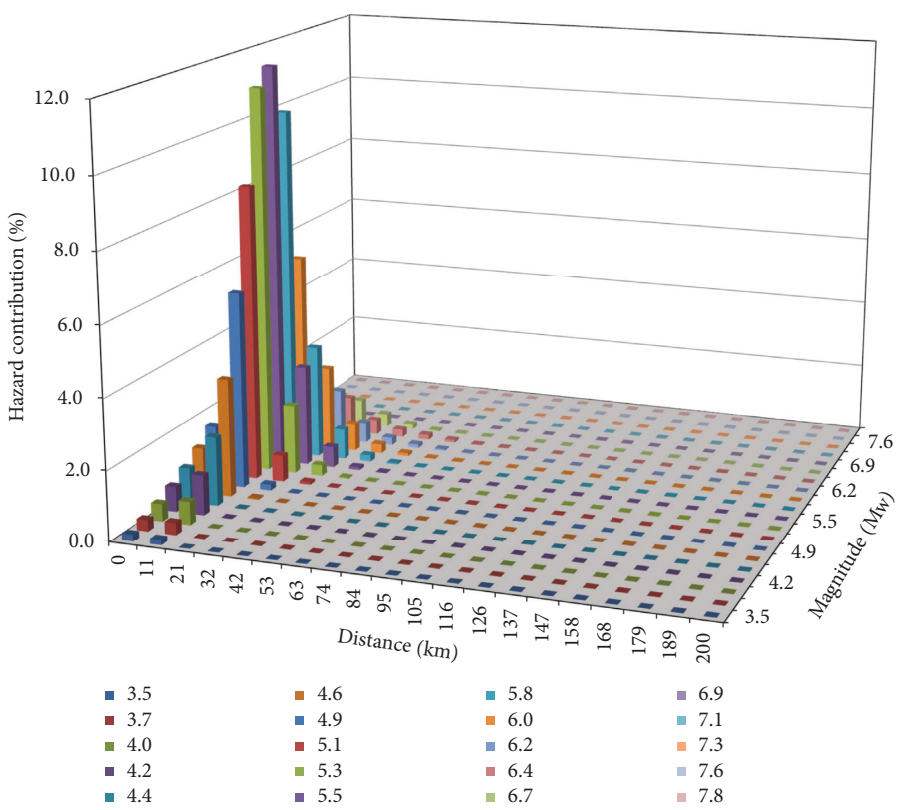

Figure 2: Deaggregation matrix for 12642 years return period.

The events with high magnitudes are dominating the hazard, and the distribution of the contribution of magnitudes dominating the hazard tends to be narrower with hazard levels, i.e., with higher return periods considered. This is shown in Figure 3.

At $10^{-5}/a$ level, approximately 70% of events contributing to the hazard are in the magnitude bins $5.3 \le M_{w,i} \le 6.0$. The distribution of the magnitude contribution is tending to the distribution of the cut-off magnitude modelled by truncated normal distribution as it is shown in Figure 4.

The aforementioned tendencies are in place for return periods greater than $T > 5 \cdot 10^{-3}$ years. In the case of $T < 5 \cdot 10^{-3}$ years, essentially the same wide range of magnitudes contributing to the hazard can be observed for the Paks site as it was the case in the study by Franke et al. [22].

The change of the pattern of magnitude distribution to the hazard with increasing return periods allows us to come to a different conclusion as it was made by Franke et al. [22]; i.e., the selection of the mean $\overline{M}_{w,i}$ from the deaggregation of a given $\overline{a}_{max}$ at a given hazard level would not necessarily result in overconservative assessment of the liquefaction hazard.

Acceptability of the results of liquefaction hazard evaluation for the selected site via the methodology proposed in Section 3 and for the purposes defined in the Section 1 can be demonstrated by comparison of these results with results of calculation performed by the methods proposed by Kramer and Mayfield [20]. It will be shown that in the case of periods of $T \ge 10000$ years, typical for considered nuclear applications and for the sites in low to moderate environment, the conservatism of the proposed methodology is acceptable contrary to the findings made by Franke et al. [22] for similar sites but for return periods of maximum 2475 years.

5. Conservatism of the Pseudoprobabilistic Screening and Margin Assessment Method

From the aforementioned consideration, it can be concluded that the pseudoprobabilistic procedure defined by equations (1)–(8) comprises of the following calculation steps:

(1) The peak ground acceleration for the outcrop/base rock should be defined using the mean hazard curve for the given level of hazard.

(2) $\overline{M}_w$ should be defined as mean value magnitudes contributing to the hazard from the deaggregation matrix.

(3) $\overline{a}_{max}$ at free field should be calculated by multiplying the peak ground acceleration for the outcrop/base rock by the amplification function. Here two options have been considered:

  (a) The amplification function has been calculated by the total stress method.

  (b) The approach of Bazzurro and Cornell [29] has been applied.

(4) Probability of liquefaction is calculated by equations (2) and (5).

The analysis has been performed for the liquefaction-prone layers between 10 and 20 meters depths, below the groundwater table at the Paks site. For the site, very detailed seismological, geotechnical, and hydrogeological investigations have been performed, high resolution geotechnical mapping is available, and comprehensive PSHA and detailed liquefaction hazard assessment have been performed by different methods. Figure 5 shows annual frequency $\Lambda_{FS_L^*}$ of $FS_L \le FS_L^*$ versus FS_L in the layers between 10 and 20 meters depth at the site calculated by the method of Kramer and Mayfield [20] with the SPT-based correlation of Cetin et al. [21].

The FS_L values for different layers at hazard levels $10^{-4}/a$ and $10^{-5}/a$ that are determined from liquefaction hazard curves of Figure 5 are shown in Figure 6. This is the reference information for the evaluation of conservatism of the proposed method.

For the justification of acceptability of the proposed method, two levels $10^{-4}/a$ and $10^{-5}/a$ are considered and fixed, and the distribution of the $FS_L = FS_L^*$ values versus depth will be calculated by the PLHA as per reference and by the proposed method. The adequacy of the proposed method will be demonstrated by comparison of distribution of $FS_L = FS_L^*$.

The FS_L distribution versus depth calculated by PLHA and obtained by equation (3) for the pair of $\overline{a}_{max}, \overline{M}_w$ for $10^{-4}/a$ and $10^{-5}/a$ levels are shown in Figure 7.

As it has been expected from the considerations in Section 4, the FS_L values calculated back from the P_L tend to those obtained by PLHA with decreasing hazard levels.

For the Paks site, as an option to the calculation step 3a) above, the free-field PGA and response spectrum were also computed by the approach of Bazzurro and Cornell [29]. In this case, soil amplification is expressed in terms of a site-specific and frequency-dependent amplification function, $AF(f)$, where f is the generic oscillator frequency. The hazard at the surface is computed by convolving the site-specific hazard curve at the bedrock level with the probability distribution of this amplification function. These 3b-type calculations are indicated as GMRS-case (ground motion response spectra). The calculation via equation (3) has also been made for the pairs of mean free-field maximum horizontal acceleration defined as per GMRS-case and mean moment-magnitude for $10^{-4}/a$ and $10^{-5}/a$ hazard levels.

Comparison of the results for $10^{-4}/a$ and $10^{-5}/a$ hazard levels and for all calculation options is shown in Figure 8.

The FS_L values calculated using a pair of $\overline{a}_{max}, \overline{M}_w$ values as per GMRS-case are the best fits to the PLHA FS_L values. The reason why the GMRS-case fits better to the PLHA as the case, when the $\overline{a}_{max}$ has been calculated by the total stress method needs further clarification, and it will be subject of future investigations.

6. Conclusions

The pseudoprobabilistic approach for evaluation of liquefaction hazard that is based on a pair of for a_{max} and M_w selected from the deaggregation of hazard for a given return period is in the case of low to moderate seismicity

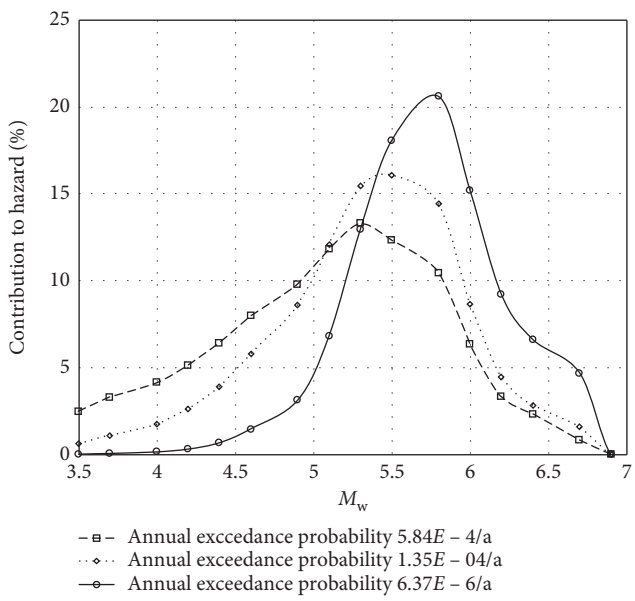

Figure 3: Contribution of magnitudes to the hazard at 5.84E − 04/a, 1.35E − 04/a, and 6.3E7 − 06/a levels.

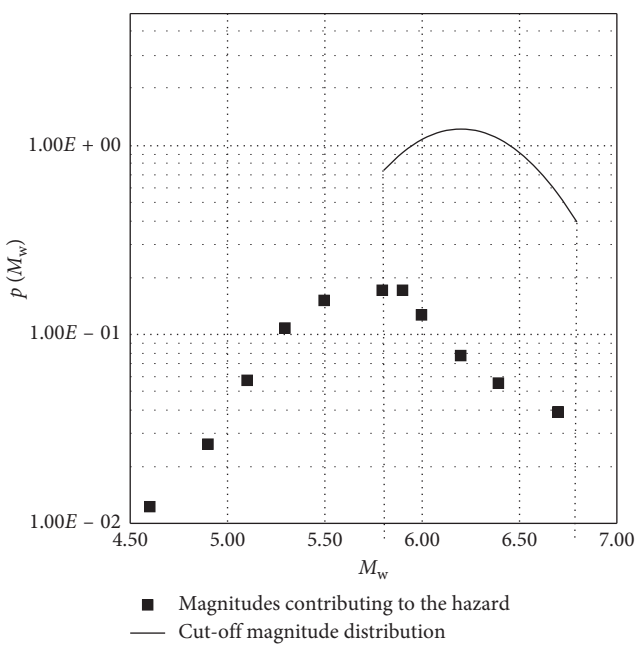

Figure 4: Distribution of the maximum magnitude in the PSHA model (truncated normal distribution with parameters: $\mu = 6.2$; $\sigma = 0{,}4$; M_w low = 5.8; M_w high = 6.4) and distribution of contribution of magnitudes to the 6.37E − 06/a level of hazard.

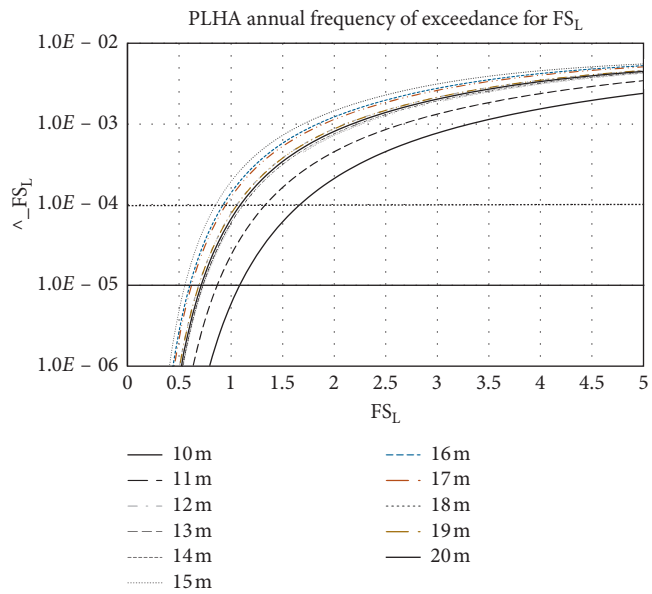

Figure 5: Annual frequency distribution for FS_L (hazard curve) for layers between 10 and 20 meters, calculated by the method of Kramer and Mayfield [20], with SPT-based correlation of Cetin et al. [21].

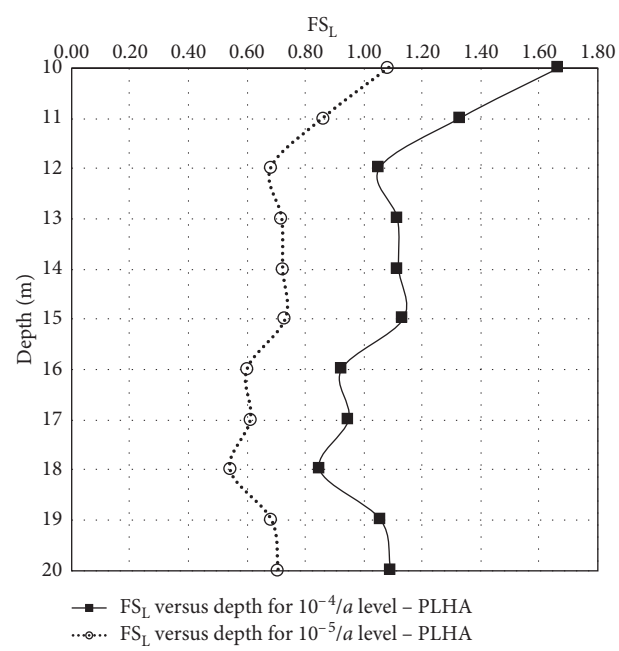

Figure 6: Distribution of FS_L in the layers between 10 and 20 meters depth at the site.

sites is overconservative, as is demonstrated by Franke et al. [22]. It has been shown above that the overconservatism is expressed if the return periods are equal or less than 2475 years, and it is related to the improper selection of the pair of a_{max} and M_w.

In the paper, a simple method is proposed for the evaluation of the liquefaction hazard for screening and margin assessment purposes. This method is based on the proper selection of M_w as the mean value from the distribution of magnitudes contributing to the mean a_{max} at the given hazard level. Although this method is conceptually the same as that which has been proposed by Franke et al. [22], the proposed selection of the pair a_{max} and M_w will not result in overconservative results for the return periods of $T \geq 10000$ years, where the near-to-the-site large earthquakes dominate the hazard.

The acceptability of the conservatism of the results calculated by the proposed method has been justified by

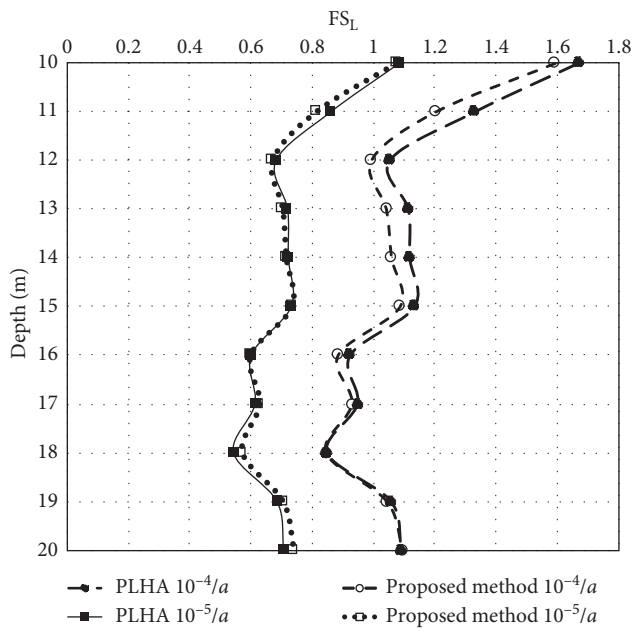

Figure 7: Comparison of FS_L distribution versus depth calculated by PLHA and the proposed pseudoprobabilistic method for $10^{-4}/a$ and $10^{-5}/a$ levels.

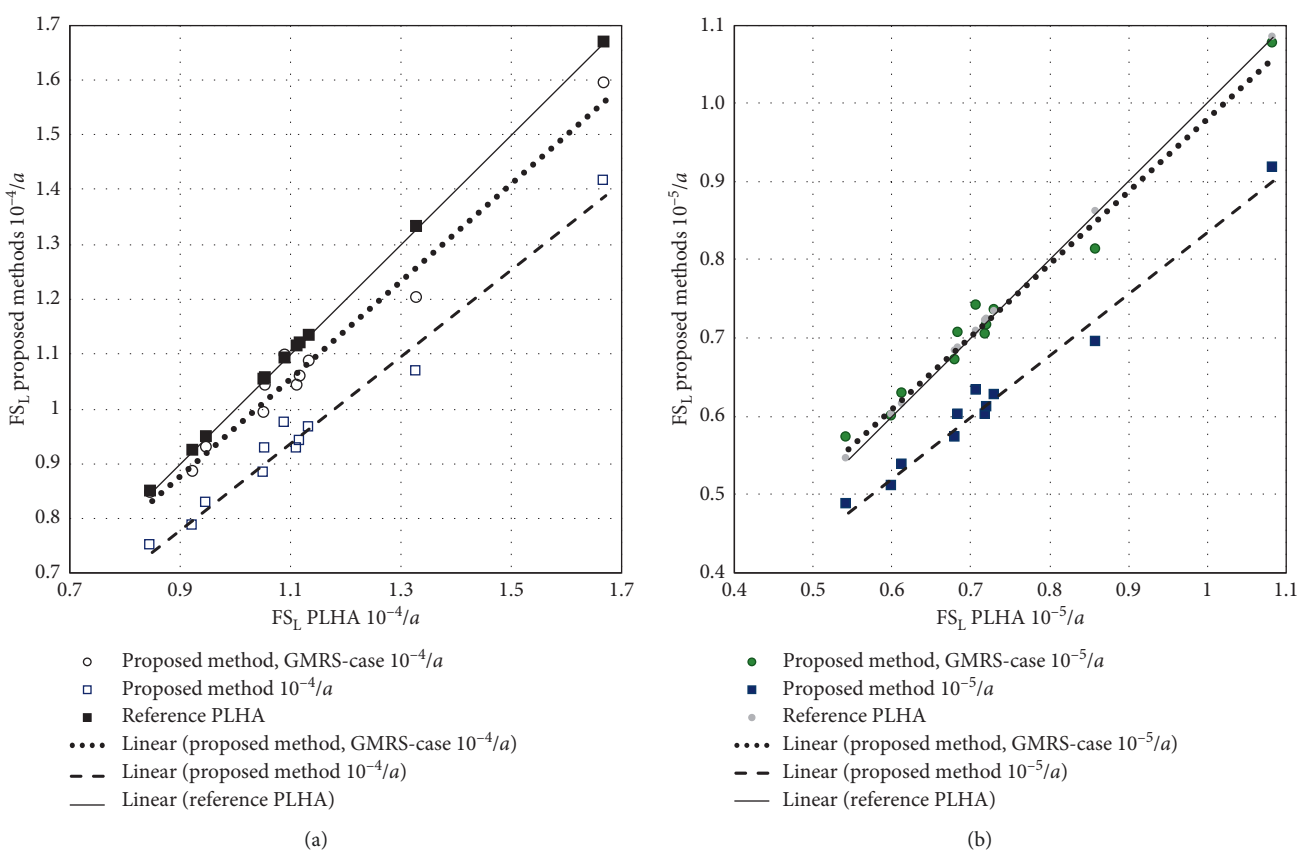

Figure 8: Comparison of FS_L results via PLHA to the FS_L values calculated by two options for the proposed method (hazard levels $10^{-4}/a$ and $10^{-5}/a$).

comparison of these results to those obtained by the performance-based method of Kramer and Mayfield [20]. The proposed method can be used for the screening of the liquefaction hazard and assessment of margin to liquefaction for the sites in the low-to-moderate diffuse seismicity area.

Data Availability

Additional data can also be made available by the corresponding author (katona.tamas.janos@mik.pte.hu) on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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