FEASIBILITY OF PROBABILISTIC LIQUEFACTION ASSESSMENT IN INDUSTRIAL PRACTICE: IS IT WORTH THE EFFORT?

E. Schiappapietra[1], F. Panico[2], F. Ioele[3], & P. Poggi[3]

[1] RINA Consulting S.p.A., Milan, Italy, erika.schiappapietra@rina.org

[2] RINA Consulting S.p.A., Genoa, Italy

[3] RINA Consulting S.p.A., Milan, Italy

Abstract: *Earthquake-induced liquefaction has been studied for decades since it poses major challenges for the geotechnical design of building foundations and buried pipes, to name but a few. While in the energy market liquefaction has been mainly investigated for the risk posed to oil and gas facilities, nowadays, it is still a key issue for the growing renewable energy industry. Indeed, it may cause excessive tilting and compromise the holding capacity of wind turbines. The most widely used methodologies in industrial applications are based on deterministic approaches, which evaluate the liquefaction potential along a soil profile for a specific design performance level. Despite the wide acceptance of such method, there are several shortcomings. For instance, they (1) do not provide the annual probability of liquefaction and (2) are based on a single earthquake scenario defined by a PGA for a given probability of exceedance and a characteristic magnitude, usually determined by deaggregation analyses. However, the design PGA is not controlled by a single scenario, but by multiple events and thus cannot be associated to a unique magnitude value. Nowadays, several methods have been developed within a probabilistic framework to overcome these issues. Nevertheless, the Probabilistic Liquefaction Hazard Assessment (PLHA) is still not common in industrial projects due to high computational effort. Should PLHA become standard practice in the near future? Is there a trade-off between complexity and feasibility? To answer such questions, this paper outlines a PLHA approach for industrial applications, which takes advantage of the OpenQuake-engine. The proposed methodology is applied to different real case-studies, which encompass both high and low-to-moderate seismicity areas. Results of the probabilistic approach are compared with conventional deterministic liquefaction procedures to investigate whether the former could provide significant advantages from an engineering point of view.*

1. Introduction

Earthquake induced ground shaking can trigger secondary effects, such as soil liquefaction, ground failure and tsunami. Liquefaction is a phenomenon for which the soil exhibits a fluid-like behaviour as a consequence of a reduction of soil shear strength due to a pore water pressure build up (e.g., Kokusho, 2017). Under rapid cycling loading induced by earthquakes, saturated loose cohesionless soils tend to decrease in volume, leading to an increase in pore water pressure. Ultimately, the excess pore water pressure equals the overburden pressure, and the soil experiences a complete loss of strength.

Liquefaction has been a major challenge for the geotechnical design of engineering structures (e.g., buried pipelines, offshore platforms, building foundations) founded on loose sand and silt in earthquake-prone regions. While in the energy market liquefaction has been mainly investigated for the risk posed to oil and gas facilities, yet it remains a key issue for the growing renewable energy industry. For instance, liquefaction constitutes a major threat for offshore wind turbines since it may cause excessive tilting for monopile-supported structures as well as compromise the holding capacity of floating systems (Kaynia, 2019; Bhattacharya et al., 2021).

The most widely used methodologies to assess the liquefaction potential in industrial applications are based on empirical procedures (e.g., stress-based approach by Seed and Idriss, 1971), which return either a factor of safety or a liquefaction probability conditioned to the occurrence of a specific earthquake scenario. Essential input parameters for these methods are the Peak Ground Acceleration (PGA) for a given probability of exceedance and the magnitude (M_W) of the design earthquake. The PGA, which represents the triggering factor, is usually determined through Probabilistic Seismic Hazard Assessment (PSHA), whereas M_W is obtained from hazard deaggregation of the PGA itself to account for their joint probability distribution. Despite the wide acceptance of such deterministic approaches, there are several shortcomings with regard to seismic hazard, soil resistance and soil characterization. Cetin et al. (2004, 2018) and Boulanger and Idriss (2016), among others, proposed advanced probabilistic correlations to assess liquefaction initiation, taking into account uncertainties associated to both the input parameters and triggering models. From a seismic input standpoint, conventional approaches neither provide the annual frequency of liquefaction, namely how often liquefaction can occur, nor give a complete picture of the liquefaction hazard. Indeed, the liquefaction potential is assessed only for a specific design performance level coupled with a magnitude value, appropriately chosen from deaggregation results. However, one should bear in mind that (1) the selection of a suitable M_W value is not straightforward and non-objective, (2) the design PGA is not controlled by a single scenario, but rather by multiple events so that it cannot be exclusively associated to a unique magnitude value, and (3) many earthquakes with different magnitude, distance and style of faulting can induce liquefaction with non-negligible probabilities, besides the design earthquake.

Nowadays, several methods have been developed within a probabilistic framework to overcome these issues (e.g., Goda et al., 2011; Ordaz et al., 2023). The primary goal of a fully Probabilistic Liquefaction Hazard Assessment (PLHA) is indeed estimating the unconditional annual probability of liquefaction occurrence, encompassing all possible scenarios and their corresponding probabilities. Despite its undeniable advantages, the PLHA approach is still not common in industrial applications and engineering practice due to the higher complexity and computational effort. Should PLHA become standard practice in the near future? Is there a trade-off between its complexity and its applicability?

To answer such questions, this paper outlines a PLHA approach for industrial projects, which combines a traditional liquefaction potential evaluation method based on CPT measurements (Robertson and Cabal, 2022) with a Monte Carlo simulation-based PSHA, performed with the OpenQuake-engine (Pagani et al., 2014). The goal of this paper is not to develop a new PLHA methodology, rather to investigate whether a PLHA approach could provide significant advantages from an engineering viewpoint compared to its deterministic counterpart. In this framework, the PLHA is applied to different real case-studies, which encompass both high and low-to-moderate seismicity areas. The same representative offshore site profiles are placed at three locations characterized by a different seismic hazard level to facilitate the comparison and better understand the effects of the seismic environment on the liquefaction potential.

2. Liquefaction potential evaluation

2.1. Deterministic liquefaction hazard analysis

Many different deterministic methods exist in literature to assess the cyclic liquefaction potential of a soil profile. Rios et al. (2019) distinguish three main categories of methods: stress-based methods, strain-based methods and energy-based methods. Stress-based methods were the first to be developed and the only applied in professional practice at present, whereas strain- and energy-based methods are typically used for research purposes.

In stress-based methods, factor of safety against liquefaction (*FS*) is computed as the ratio of cyclic resistance ratio (*CRR*) to cyclic stress ratio (*CSR*):

$$FS=\frac{CRR}{CSR} \tag{1}$$

CSR corresponds to the earthquake-induced cyclic stress ratio at a given depth *z* within the soil profile. According to the so-called "simplified procedure", originally proposed by Seed and Idriss (1971) (and recommended by Eurocode 8 - CEN, 2005), the irregular time history of shear stress related to an accelerogram can be transformed into an equivalent number of regular cycles having an amplitude equal to 65% of the maximum earthquake induced shear stress τ_{max}, therefore:

$$CSR = 0.65\ \frac{\tau_{max}}{\sigma'_{v0}} \tag{2}$$

where σ'_{v0} is the in situ effective vertical stress at depth *z*. Maximum shear stress τ_{max} can be estimated from dynamic response analyses or, following the simplified procedure, using an expression depending on the maximum horizontal acceleration as a fraction of gravity $\frac{a_{max}}{g}$ (i.e., the peak ground acceleration PGA), vertical total stress σ_{v0} at depth *z*, and a reduction factor r_d that accounts for the dynamic response of the soil profile:

$$CSR = 0.65\,\frac{a_{max}}{g}\frac{\sigma_{v0}}{\sigma'_{v0}}r_d \tag{3}$$

Factor r_d can be approximated up to 23 m depth by using the average curve reported by Seed and Idriss (1971), but alternative formulations proposed by other authors exist (e.g., Idriss, 1999).

CRR refers to the resisting capacity of the soil to liquefy and can be evaluated by different methods based on laboratory tests or *in situ* tests. Laboratory tests (e.g., cyclic triaxial tests or direct simple shear tests) are difficult to be applied in practice since *in situ* stress generally cannot be reestablished in the laboratory, and undisturbed specimens of granular soils cannot be retrieved unless special and expensive sampling techniques are used. Therefore, *in situ* tests have become the state-of-practice for routine liquefaction investigations (Youd and Idriss, 2001).

The *CRR* of the soil is estimated based on past case history performance linked to penetration resistance. Alternate methods to estimate *CRR* based on a mechanics approach have been suggested, but the case history-based methods remain the most popular approach (Robertson and Cabal, 2022). *In situ* test-based *CRR* assessment methods found in literature are based on standard penetration tests (SPT) (e.g. Seed et al., 1985), cone penetration tests (CPT) (e.g. Robertson and Wride, 1998; Boulanger and Idriss, 2014), shear-wave velocity measurements (V_s) (e.g. Andrus and Stokoe, 1997, 2000; Kayen et al., 2013), Becker penetration test (BPT) (Harder and Seed, 1986), and flat dilatometer test (DMT) (Monaco et al., 2005).

SPTs and CPTs are generally preferred because of the more extensive databases and past experience (Youd and Idriss, 2001). In recent years, CPT-based methods acquired increasing popularity due to the greater repeatability of such test and the continuous nature of its profile (Robertson and Wride, 1998) and now a larger cyclic liquefaction case history database (Robertson and Cabal, 2022).

In this work, the CPT-based methodology originally proposed by Robertson and Wride (1998) and successively updated (Robertson, 2009; Robertson and Cabal, 2015) to the more recent version (Robertson and Cabal, 2022) is adopted. According to Seed and Idriss (1982), *CRR* can be defined as:

$$CRR = CRR_{7.5}\ MSF \tag{4}$$

where $CRR_{7.5}$ is the cyclic resistance ratio standardized to earthquakes of magnitude 7.5, whereas *MSF* is a correction factor applicable to other magnitudes, called magnitude scaling factor. Following the work of Robertson and coworkers, the value of $CRR_{7.5}$ for sand-like (i.e., non-cohesive) soils can be estimated using the following simplified equations:

$$\begin{aligned} CRR_{7.5} &= 93\left[\frac{Q_{tn,cs}}{1000}\right]^3 + 0.08, \quad \text{If } 50 \le Q_{tn,cs} \le 160 \\ CRR_{7.5} &= 0.833\left[\frac{Q_{tn,cs}}{1000}\right] + 0.05, \quad \text{If } Q_{tn,cs} < 50 \end{aligned} \tag{5}$$

where $Q_{tn,cs}$ is the equivalent normalized clean sand cone resistance, which is a measure of the CPT penetration resistance at a given depth *z*, normalized by the *in situ* stress and soil type (i.e., fines contents and plasticity).

Magnitude scaling factor is calculated following Seed and Idriss (1982) proposal in the revised formulation reported by Youd and Idriss (2001):

$$MSF = \frac{10^{2.24}}{M_W^{2.56}} \tag{6}$$

where M_W is the magnitude of the design earthquake.

As for the determination of *CSR*, Robertson and Cabal (2022) methodology adopts Seed and Idriss (1971) simplified procedure (as reported in expression (3)) and extends the definition of factor r_d to depths higher than 23 m as follows:

$$\begin{aligned} r_d &= 1.0 - 0.00765 \cdot z, \quad \text{if } z < 9.15\ m \\ r_d &= 1.174 - 0.0267 \cdot z, \quad \text{if } 9.15\ m \le r_d \le 23\ m \\ r_d &= 0.744 - 0.008 \cdot z, \quad \text{if } 23\ m \le r_d \le 30\ m \\ r_d &= 0.5, \quad \text{if } r_d > 30\ m \end{aligned} \tag{7}$$

Therefore, following this method, factor of safety *FS* against liquefaction is computed by substituting expressions (5) and (6) in (4) to compute *CRR*, expression (7) in (3) to compute *CSR*, and finally using expression (1). The inputs required for the methods are the values of PGA and M_W for the design earthquake and the results of at least one CPT profile for the soil profile.

2.2. Probabilistic liquefaction hazard analysis

The PLHA approach proposed in this study is based on a three-step procedure: (1) performing a PSHA, which provides the probability of exceedance of an intensity measure (e.g., PGA) within a given time period; (2) estimating the liquefaction potential through stress-based methods (e.g., Robertson and Cabal, 2022) for each seismic event generated in (1); and (3) computing the annual frequency of occurrence of liquefaction. In particular, we employ the event-based calculator of the OpenQuake-engine to carry out the PSHA for the sites of interest through a Monte Carlo simulation-based technique (Pagani et al., 2014). In contrast to the classical PSHA, the event-based approach represents a breakthrough since it simplifies the integration of conventional deterministic liquefaction analysis into a probabilistic framework.

The annual frequency of liquefaction can be computed as follows:

$$v_L = \sum_{i=1}^{NE} P[L|E_i] \cdot v_{E,i} \tag{8}$$

where $P[L|E_i]$ is the probability of having liquefaction conditioned to the occurrence of the event E_i, $v_{E,i}$ is the annual frequency of occurrence of the event E_i, and *NE* is the number of earthquakes included in a synthetic catalogue from the PSHA. The event-based PSHA, indeed, generates synthetic earthquake catalogues by randomly sampling all possible ruptures that can occur according to the input source model. Each event is characterized by several parameters, such as the magnitude, hypocentre coordinates, strike, dip, rake and tectonic region, which are then used to calculate the ground shaking intensities (e.g., PGA) at the site of interest in combination with one or more suitable Ground Motion Models (GMMs). These outputs (e.g., M_W of each event and resulting PGA) are the input for the subsequent assessment of the liquefaction potential in terms of $P[L|E_i]$. In particular, in this study, we use the approach proposed by Robertson and Cabal (2022), as described in section 2.1, to compute the safety factor (*FS*) for each M_W-PGA pair, and Ku et al. (2012) to estimate the liquefaction probability based on *FS*:

$$P[L|E_i] = 1 - \Phi\left(\frac{0.102 + \ln FS}{0.276}\right) \tag{9}$$

where Φ is the standard normal cumulative distribution function. Note that any other methodology for liquefaction potential assessment can be used as alternative (e.g., Goda et al., 2011; Atkinson and Goda, 2013; Ordaz et al., 2023).

In a nutshell, the annual frequency of occurrence of liquefaction is obtained by repeating step (2) for all the events (M_W-PGA pairs) included in the synthetic catalogue. The annual frequency of liquefaction occurrence then is simply the weighted average of the liquefaction probabilities considering all possible events that can occur. Note that, in this study, we developed a specifically parallel computing Python algorithm to run the deterministic liquefaction analyses for each seismic event generated through the OpenQuake-engine and the considered soil profiles.

3. Case-studies

3.1. Seismotectonic context and seismic hazard

The proposed methodology is applied to different real case-studies, which include both high and low-to-moderate seismicity areas. We select three sites that are located offshore Ivory Coast, in the Gulf of Mexico and in the Western Black Sea (offshore Türkiye), respectively, to encompass different seismotectonic environments. To provide an overview of the seismic hazard at the sites, Figure 1 shows the hazard curves for PGA, whereas Figure 2 presents the PGA hazard deaggregation at the sites for specific design scenarios. In particular, we adopt the Extreme Level (ELE) and Abnormal Level Earthquake (ALE) design, as described in ISO 19901–2, to be compliant with seismic design procedures for offshore structures. The deaggregation results are shown in terms of magnitude, distance (R) and epsilon by means of 3D bar plots, which provide the percentage contribution to the hazard of each (M_W, R, ε) bin. Note that ε reflects the dispersion of ground motion with respect to the median predictions of the GMMs.

The comparison of the hazard curves suggests that the seismicity in Ivory Coast is significantly lower than the other two case-studies. The largest hazard values are found in the Gulf of Mexico, where high-magnitude subduction events contribute to the total hazard at the site. Seismic deaggregation results feature a bimodal distribution for the Gulf of Mexico and Western Black Sea case-studies, suggesting that the hazard is mainly controlled by near-source events with small-to-moderate magnitudes and more distant large magnitude ($M_W \geq 7.0$) earthquakes. Such bimodal distribution, in which the dominating events are spread on different magnitude-distance ranges, makes the selection of a suitable magnitude value crucial for liquefaction assessment through conventional deterministic approaches.

Note that an average shear-wave velocity in the uppermost 30 m ($V_{S,30}$) of 150 m/s is adopted in the seismic hazard assessment at the three locations to be compliant with the typical offshore soil profiles considered in this study (Section 3.2).

Offshore Ivory Coast

The study-area is located within 50 km from the coast of Ivory Coast and can be classified as a tectonically stable province, affected by a low seismic activity rate. Most of the seismicity affecting the site originated in southern Ghana, along the Akwapim fault zone, where several small-to-moderate magnitudes earthquakes occurred. Moreover, during the last centuries, the Gulf of Guinea was hit by several large seismic events, which were related to the activity of the major E-W to NE-SW oriented transform faults. The presence of such long transform faults and the thick seismogenic crust can induce an expected maximum magnitude of potential earthquake between M_W 6.5 to 7.5.

Campeche Bay, Gulf of Mexico

The site is located in the Campeche Bay comprising the southern part of the Gulf of Mexico, where it is partially enclosed by the Yucatan Peninsula. It is within a relatively passive tectonic area, but it is affected by the intense seismic activity occurring in about 50 – 200 km distance to the south, which is related to the overriding of the North American and Caribbean plates over the Cocos plate and smaller Rivera plate along the Middle American Trench. While near-source earthquakes of moderate-strong magnitudes dominate the hazard, the contribution of strong earthquakes generated by the subduction sources is actually far from being negligible, as also observed in Figure 2.

Black Sea, Offshore Türkiye

The field lies in the Western Black Sea, offshore Zonguldak, Türkiye. The Turkish coast of the Black Sea is a transition zone between the Pontides Belt and the North Anatolian Fault. While the Pontides Belt shows a very low seismicity, prevalently characterized by thrust faulting events occurring at shallow-to-intermediate depths, the North Anatolia Fault (NAF) zone is a highly seismic fault system which traverses northern Anatolia in an E-W direction, separating the Eurasian and Anatolian plates. The fault system runs for 1,400 km from the Marmara Sea to the east and is characterized by several faults with roughly E-W direction and high slip rates, capable of generating events of magnitude up to 8.0. Although being at about 100 km distance from the site, the NAF clearly influences the seismic hazard, as shown in Figure 2.

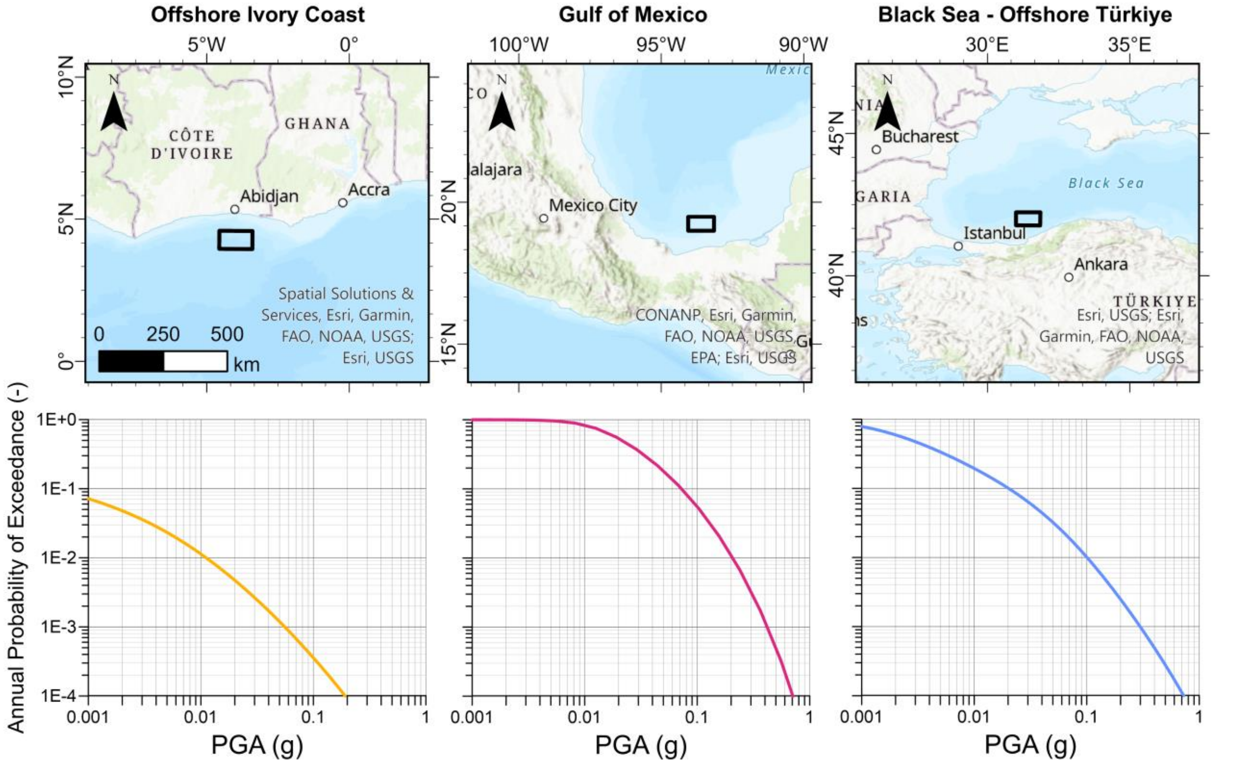

Figure 1. Top: study-regions with black box indicating the locations considered in each case-study; bottom: PGA mean hazard curves for each case-study obtained by considering a $V_{S,30}$ of 150 m/s.

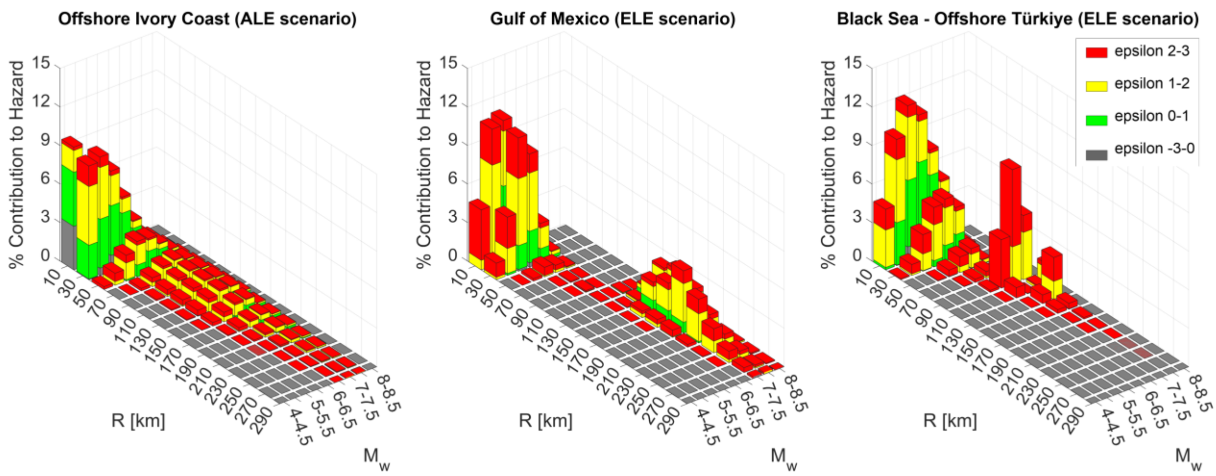

Figure 2. Magnitude, distance and epsilon deaggregation results at the different sites for PGA.

3.2. Representative soil profiles

For the current study, two CPTs representative of typical offshore sites, that can be subjected to liquefaction phenomena, were considered. The seafloor at these locations is covered by loose to medium dense sand to silty sand. The stratigraphy mainly consists of loose to medium dense silty sand/sand layers interbedded by stiff to hard clay and some layers of silt. In particular, the first CPT (hereinafter CPT-1) is characterized by loose to medium dense silty sand interbedded with soft to firm clay and sandy silt from seabed up to 30 m depth. The second CPT (hereinafter CPT-2) shows instead very loose to medium dense sand/silty sand layers alternated with some layers of soft to very stiff sandy clay. Figure 3 and Figure 4 illustrate the CPT-derived geotechnical properties in terms of cone resistance (q_C) and soil behaviour type index (I_C) (Robertson and Wride, 1998) at the two locations.

4. Results

4.1. PLHA

In this section, we present the outcomes of the probabilistic liquefaction hazard analyses for both the CPTs and for the three case-studies. The results are provided in terms of return period (RP) of liquefaction, which is computed as the inverse of the annual frequency of occurrence, as a function of the depth of the soil profile (Figure 3 and Figure 4).

The return period of observing liquefaction along the soil column is by far the highest for the Ivory Coast case-study owing to its lower seismic hazard. Both the soil profiles experience liquefaction on average once every about 2,000 years up to 10,000 years, depending on the considered layer. More interesting is the comparison between the Gulf of Mexico and Black Sea (offshore Türkiye) case-studies. While the latter shows a return period that increases from about 50 years to 350 years for CPT-1 and from 50 years to 250 years for CPT-2, the former features even lower return periods. These findings may reflect the differences in the seismotectonic context that characterises the two sites. Not only does the seismic hazard level (see Figure 1) have a primary effect on the liquefaction potential, but also the magnitude range of the events dominating the hazard significantly impacts the results. Indeed, larger-magnitude events are characterised by a greater number of stress cycles than smaller-magnitude earthquakes owing to the longer ground shaking duration. In the Gulf of Mexico case, the contribution of strong earthquakes (M_W up to 8.5) generated by the subduction sources is far from being negligible for any PGA level, thus leading to a higher liquefaction potential.

4.2. Comparison between probabilistic and deterministic approaches

We perform a deterministic liquefaction analysis for the three case-studies and for both the CPT profiles by following the methodology described in section 2.1. For the sake of brevity, we show here only the results for CPT-1. Besides, we focus our discussion on the Gulf of Mexico and Black Sea (offshore Türkiye) case-studies, which provide an idea about the advantages of a PLHA approach compared to its deterministic counterpart.

We adopt the ELE and ALE earthquake design to carry out a liquefaction analysis following the deterministic approach. For instance, ISO 19902 recommends that platforms should be founded in soils that are not susceptible to liquefaction during the ELE and ALE scenarios. Specifically, we assume a PGA for the ELE scenario of 0.23 g and 0.28 g for the Black Sea and Gulf of Mexico sites, respectively, based on the PSHA outcomes (Figure 1). Conversely, the selection of a suitable magnitude is non-trivial in both cases since the ELE deaggregation analysis (Figure 2) shows a bimodal distribution. We therefore select two M_W values: (1) $M_W = 6.0$, representing the events contributing the most with small-to-moderate magnitudes and short source-to-site distances; and (2) $M_W = 7.5$ to account for stronger events at longer distances, generated along the NAF fault systems for the Black Sea (Offshore Türkiye) location and from subduction sources for the Gulf of Mexico site. The results are shown in Figure 5. Both the case-studies share the same CRR being dependent only on the geotechnical characteristics of the soil profile (CPT-1) and on the M_W. On the other hand, the different PGAs affect the CSR values obtained at the two sites, with differences of about 20%. Despite the diverse CSR, the safety factor shows a very similar trend along the soil profile, with most of the layers susceptible to liquefaction. It follows that, independently of the seismotectonic context, the deterministic analysis provides analogous results in terms of liquefaction potential. Furthermore, if we consider one site at a time, the engineering judgement in selecting a characteristic magnitude may lead to biased outcomes, which can be excessively conservative or on the other hand underestimated. In our study, this is evident for layers deeper than 22 m (Figure 5), although such examples may not be very explicative, being the soil profile strongly subjected to liquefaction even for lower magnitude values.

5. Discussion

Section 4 presents the outcomes of the liquefaction analyses following both a probabilistic and a more conventional deterministic approach. Despite its relative simplicity, a deterministic procedure for liquefaction assessment has several drawbacks. First, as shown in section 4.2, the selection of a suitable M_W is not straightforward, especially in case of complex seismotectonic environments. Besides, the design PGA is not controlled by a single scenario, but rather by multiple M_W-R pairs and thus cannot be associated to a unique magnitude value. Second, this approach does not provide the annual occurrence frequency of liquefaction. It just returns a safety factor against liquefaction conditioned to the occurrence of a design earthquake scenario defined in terms of PGA, for a given probability of exceedance, and a characteristic magnitude. Although the return period is associated to the level of PGA, it is usually wrongly assumed that liquefaction happens every time the design earthquake scenario occurs. Third, the source-to-site distance is not considered in the analysis, which requires only PGA and M_W as seismic input parameters.

On the other hand, results presented in section 4.1 shed light on the importance of adopting a probabilistic approach in liquefaction assessment for the geotechnical design of engineering structures. Besides returning the annual occurrence frequency of liquefaction (i.e., how often liquefaction may occur), the PLHA also provides more robust and objective results compared to the more conventional deterministic procedure. The comparison of these approaches for the Gulf of Mexico and the Black Sea (offshore Türkiye) case-studies is rather explicative. Indeed, the deterministic analysis provides analogous results in terms of liquefaction potential. By contrast, the PLHA suggests that, under the same soil conditions, liquefaction occurs more often in the Gulf of Mexico instead of offshore Türkiye (once every 10-200 years vs once every 50-350 years, respectively), highlighting the importance of considering not only one characteristic M_W, but all events that contribute to the hazard at the site.

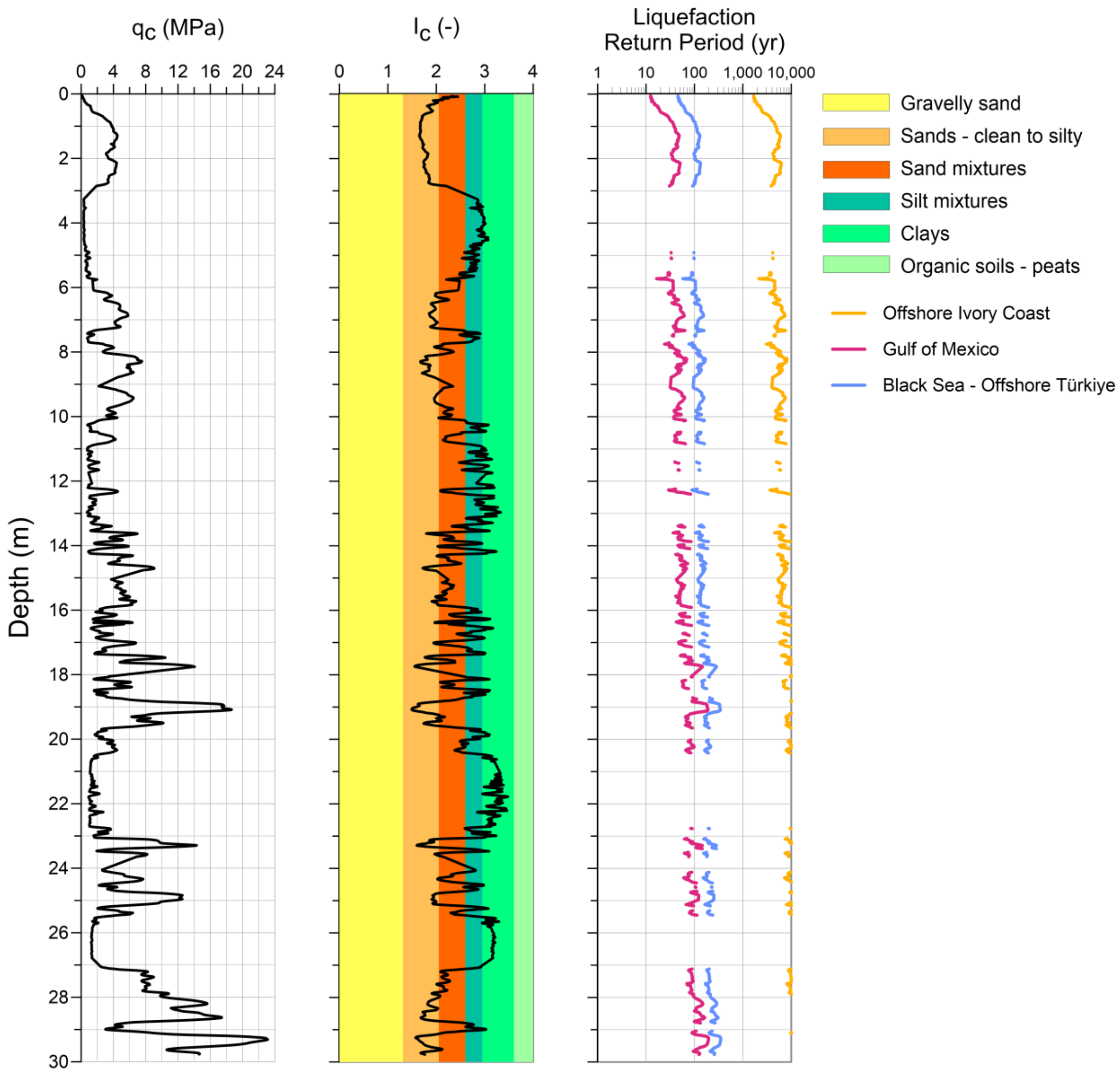

Figure 3. CPT-1: geotechnical characteristics in terms of cone resistance(q_C) and soil behaviour type index (I_C) and liquefaction return period for the three case-studies.

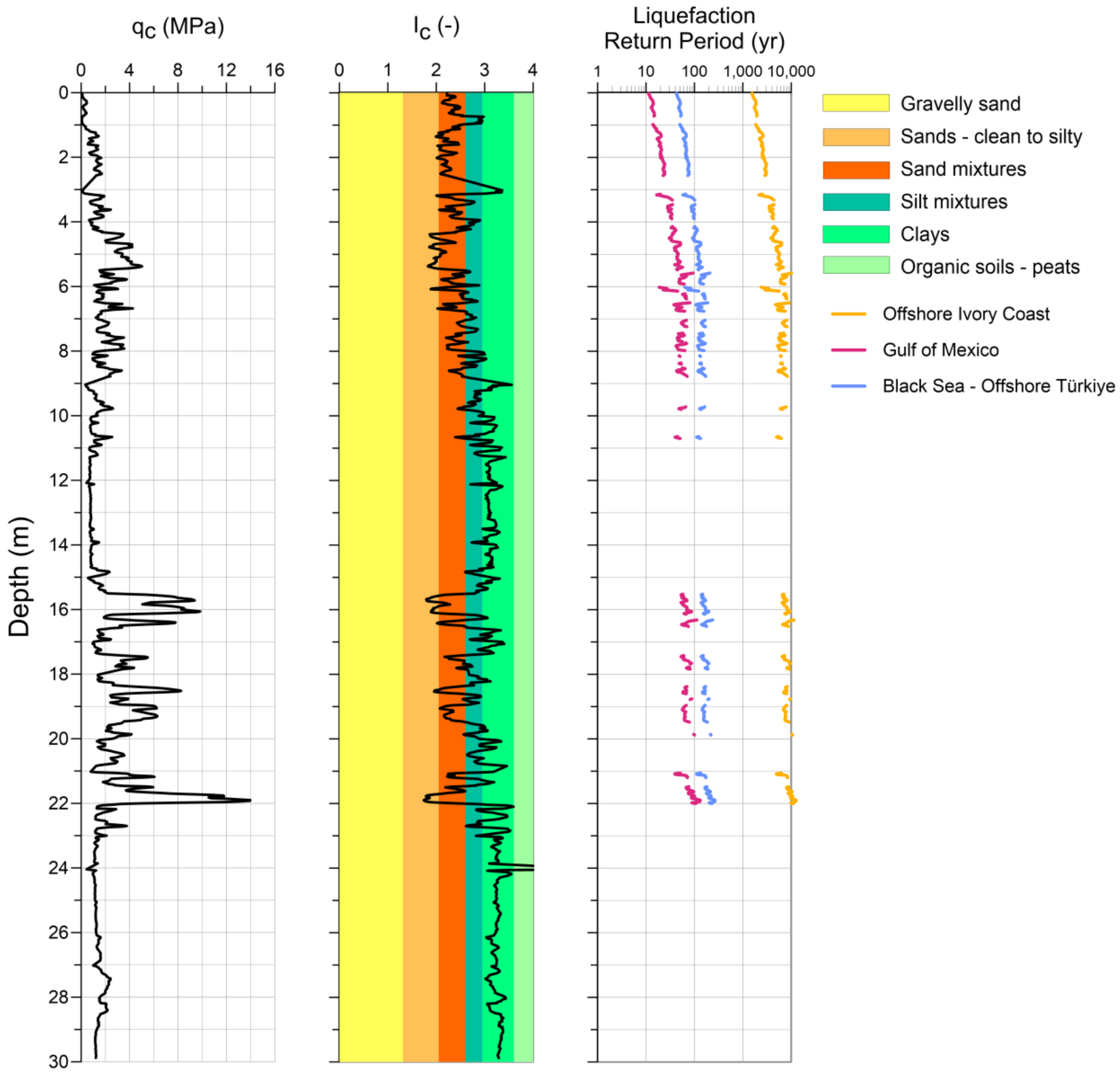

Figure 4. CPT-2: geotechnical characteristics in terms of cone resistance(q_C) and soil behaviour type index (I_C) and liquefaction return period for the three case-studies.

Although our outcomes demonstrate that a PLHA approach can provide a valuable step forward towards full-scale and more impartial liquefaction assessments, this study presents some caveats. Firstly, we only include uncertainties from a seismic hazard viewpoint. However, uncertainties in soil resistance and soil characterization should also be accounted for. For instance, the engineering practice to assess the likelihood of liquefaction is based on a set of case-studies of observation of liquefaction/non-liquefaction during earthquakes, which undoubtedly lead to a certain degree of uncertainty in the prediction of soil resistance. Besides, such relationships are correlated to *in situ* onshore data, which may not be applicable to offshore sites. Boulanger and Idriss (2016), among others, proposed a probabilistic liquefaction triggering correlation to account for model uncertainties in computing the CRR. Guan and Wang (2022 a, b) set up a probabilistic methodology to consider not only the model uncertainties, but also the soil spatial variability, which may have great implications in liquefaction potential assessment.

Secondly, in this study the seismic response of the soil is directly included in the PSHA analysis by means of linear and non-linear site amplification coefficients included in the GMMs. However, the accuracy of this prediction may be biased especially for offshore sites characterized by soft soils, given that (1) GMMs are calibrated on onshore data and (2) GMMs may not be applied for low values of $V_{S,30}$ (< 150 m/s). The introduction of a probabilistic Seismic Site Response Analysis (SSRA) would undoubtedly improve the assessment of the dynamic response of the soil, and therefore the estimation of the earthquake-induced cyclic stress ratio. Note that performing time-domain probabilistic SSRA is computationally expensive, which thus makes its application a cumbersome task.

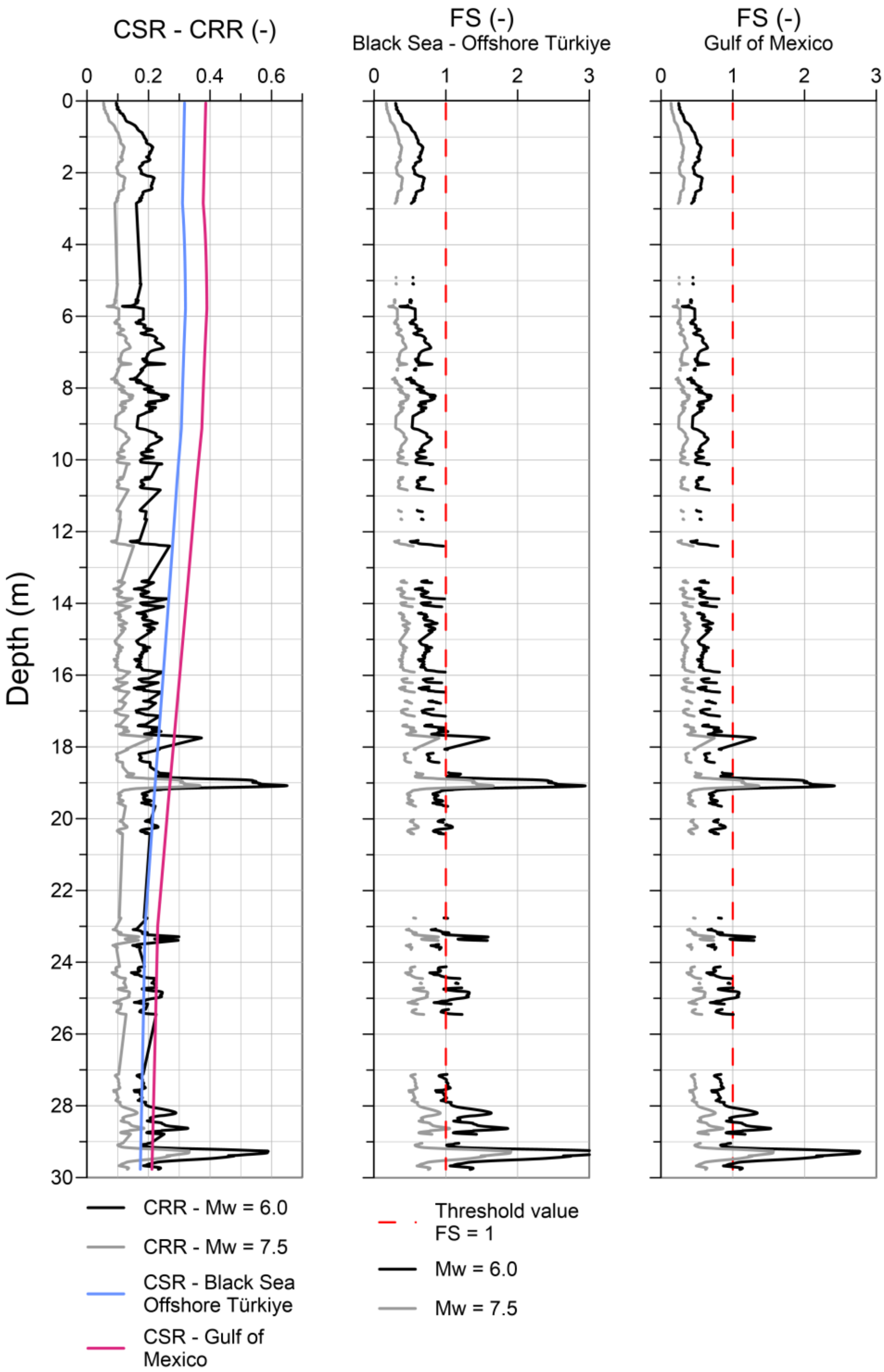

Figure 5. Deterministic liquefaction analysis for the Gulf of Mexico and Black Sea (Offshore Türkiye) case-studies considering CPT-1.

6. Conclusions

This paper aims at investigating whether a probabilistic approach to assess the liquefaction potential could provide significant advantages from an engineering viewpoint compared to its deterministic counterpart. We apply the PLHA methodology to different real case-studies, which encompass both high and low-to-moderate seismicity areas as well as complex seismotectonic environments. We mainly focus on uncertainties in the seismic hazard input, whereas further research needs to be carried out to account for the soil spatial variability and uncertainties in both liquefaction modelling and soil characterization. The inclusion of SSRA to evaluate the site-specific response of the soil column and thus to improve the estimation of CSR would also be object of future studies.

Concerning the definition of the seismic input, one of the main limitations of deterministic procedures to assess the liquefaction potential is to represent the seismic demand as a function of a characteristic earthquake magnitude and a PGA value for a given return period. This can lead to biased results due to: (1) the subjective role of expert judgement in the selection of characteristic M_W, and (2) the consideration of a single earthquake scenario, rather than all events that contribute to the hazard at the site. Besides, it does not provide any information on the return period of the liquefaction occurrence. These shortcomings can be overcome by implementing a PLHA approach, which, while providing indications about how often liquefaction occurs, also avoids the choice of the return period for which performing the assessment. Indeed, standard practice suggests evaluating the liquefaction potential for design scenarios, which are commonly defined following a limit-state-based approach. However, this may be misleading because structures in an offshore development may be designed according to different scenarios.

Is it therefore worth the effort to apply a PLHA approach in industrial practice? Despite the higher computational effort, we believe that PLHA would be of great value, especially when sites located in complex seismotectonic environments are of interest. The inclusion of uncertainties in liquefaction triggering model and soil characterization will further strengthen the advantages of this methodology. Finally, while providing a more rational way to quantify and optimize the design of structures, a thorough liquefaction probabilistic procedure would undoubtedly pave the way toward a risk-target design and a multi-hazard (i.e., fault-displacement, tsunami, etc.) probabilistic risk assessment.

7. References

Andrus, R.D., Stokoe K.H. (1997). Liquefaction resistance based on shear wave velocity. *In Procedures NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*. National Center for Earthquake Engineering Research (NCEER), State Univ. of New York at Buffalo, 89–128.

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

Atkinson G. M., Goda K. (2013). Probabilistic seismic hazard analysis of civil infrastructure. *In Handbook of seismic risk analysis and management of civil infrastructure systems (pp. 3-28). Woodhead Publishing.*

Bhattacharya S., Biswal S., Aleem M., Amani S., Prabhakaran A., Prakhya G.,- Lombardi D., Mistry H. K. (2021). Seismic design of offshore wind turbines: good, bad and unknowns. *Energies*, 14(12), 3496.

Boulanger R.W., Idriss I.M. (2014). CPT and SPT based liquefaction triggering procedures. *Report No. UCD/CGM-14/01*. Center for Geotechnical Modeling, University of California, Davis.

Boulanger R. W., Idriss I. M. (2016). CPT-based liquefaction triggering procedure. *Journal of Geotechnical and Geoenvironmental Engineering*, 142(2), 04015065.

CEN (2005). *Eurocode 8: Design of structures for earthquake resistance - Part 5: Foundations, retaining structures and geotechnical aspects*, Comité Européen de Normalisation, Brussels.

Cetin K. O., Seed R. B., Der Kiureghian A., Tokimatsu K., Harder Jr L. F., Kayen R. E., Moss R. E. (2004). Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. *Journal of geotechnical and geoenvironmental engineering*, 130(12), 1314-1340.

Cetin K. O., Seed R. B., Kayen R. E., Moss R. E., Bilge H. T., Ilgac M., Chowdhury K. (2018). SPT-based probabilistic and deterministic assessment of seismic soil liquefaction triggering hazard. *Soil Dynamics and Earthquake Engineering*, 115, 698-709.

Goda K., Atkinson G. M., Hunter J. A., Crow H., Motazedian D. (2011). Probabilistic liquefaction hazard analysis for four Canadian cities. *Bulletin of the Seismological Society of America*, 101(1), 190-201.

Guan Z., Wang Y. (2022a). CPT-based probabilistic liquefaction assessment considering soil spatial variability, interpolation uncertainty and model uncertainty. *Computers and Geotechnics*, 141, 104504.

Guan Z., Wang Y. (2022b). SPT-based probabilistic evaluation of soil liquefaction potential considering design life of civil infrastructures. *Computers and Geotechnics*, 148, 104807.

Harder L.F., Seed, H.B. (1986). Determination of penetration resistance for coarse-grained soils using the Becker hammer drill. *Rep. UCB/EERC-86/06*. Earthquake Engineering Research Center, University of California at Berkeley.

Idriss I.M. (1999). An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. *In Proceedings of the TRB workshop on new approaches to liquefaction*. Federal Highway Administration.

ISO (2020*). ISO 19902: Petroleum and natural gas industries – Fixed steel offshore structures*.

ISO (2022). *ISO 19901-2: Petroleum and natural gas industries – Specific requirements for offshore structures – Part 2: Seismic design procedures and criteria*.

Kayen R., Moss R.E.S., Thompson E.M., Seed R.B., Cetin K.O., 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.

Kaynia A. M. (2019). Seismic considerations in design of offshore wind turbines. *Soil Dynamics and Earthquake Engineering*, 124, 399-407.

Kokusho, T. (2017). *Innovative earthquake soil dynamics,* 1st Ed., CRC Press.

Ku C. S., Juang C. H., Chang C. W., Ching J. (2012). Probabilistic version of the Robertson and Wride method for liquefaction evaluation: development and application. *Canadian Geotechnical Journal*, 49(1), 27-44.

Monaco P., Marchetti S., Totani G., Calabrese M. (2005). Sand liquefiability assessment by flat dilatometer test (DMT). *In Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*. Millpress Science Publishers/IOS Press, pp 2693–2697.

Ordaz M., Salgado-Gálvez M. A., Mánica M. A., Ovando-Shelley E., Faccioli E., Osorio L., Madrigal M. C. (2023). Event-based probabilistic liquefaction hazard analysis for defining soil acceptance criteria. *Soil Dynamics and Earthquake Engineering*, 166, 107781.

Pagani M., Monelli D., Weatheril G., Danciu, L., Crowley H., Silva V., Henshaw P., Butler L., Nastasi M., Panzeri L., Simionato M., Vigano D. (2014). OpenQuake engine: An open hazard (and risk) software for the global earthquake model. *Seismological Research Letters*, 85(3), 692-702.

Rios S., Millen M., Seculin D., Viana da Fonseca A. (2019). Comparison between energy and stress based pore pressure methods in liquefiable deposits. *In 17th European Conference on soil Mechanics and Geotechnical Engineering (ECSMGE 2019)*. International Society for Soil Mechanics and Geotechnical Engineering.

Robertson P.K. (2009). Interpretation of cone penetration tests — A unified approach. *Canadian Geotechnical Journal*, 46(11), 1337-55.

Robertson P.K., Cabal K. (2015). *Guide to Cone Penetration Testing*. Sixth Edition. Gregg Drilling LLC, Signal Hill, California.

Robertson P.K., Cabal K. (2022). *Guide to Cone Penetration Testing*. Seventh Edition. Gregg Drilling LLC, Signal Hill, California.

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

Seed H. B., Idriss I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. *Journal of the Soil Mechanics and Foundations division*, 97(9), 1249-1273.

Seed H.B., Idriss I.M. (1982). Ground motions and soil liquefaction during earthquakes. *Earthquake Engineering Research Institute Monograph*, Oakland, California.

Seed H.B., Tokimatsu K., Harder L.F., Chung R. (1985). Influence of SPT procedures in soil liquefaction resistance evaluations. *Journal of Geotechnical Engineering*, 111(12), 1425-1445.

Youd T.L., Idriss I.M. (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*, 127(4), 297-313.