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Site liquefaction analysis via the contour diagram method: implications for offshore monopile design

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ABSTRACT: The renewable energy sector is rapidly expanding, with offshore wind energy gaining global significance. Designing bottom-fixed offshore wind turbines (OWTs) with monopile foundations in seismically active regions, particularly in coarse-grained soils, presents challenges due to the risk of soil liquefaction during earthquakes. Conventional design practices address seismic effects by reducing soil shear stiffness to account for excess pore water pressure (Δu) build-up. This study proposes a procedure for predicting Excess Pore Pressure build-up in coarse-grained soils using the cyclic contour diagram framework (CDF) under seismic loading. In this study, the PM4Sand soil model is employed to generate cyclic contour diagrams for a representative coarse-grained material. Site response analyses (SRA) are conducted in DEEPSOIL, and the resulting shear stress time histories are transformed into equivalent loading parcels to predict excess pore pressure using the CDF. Predictions are validated against PLAXIS 2D simulations employing the PM4Sand model. Finally, the proposed method is applied to assess the impact of seismic pore pressure build-up on monopile embedment depth. Results indicate that the proposed procedure offers a reliable alternative to conventional methods for evaluating liquefaction potential, providing improved insights for engineering practice in seismic design.

Keywords: liquefaction; contour diagram framework; site response analysis; numerical modelling; offshore wind

1 INTRODUCTION

Offshore Wind Turbines (OWTs) are playing a pivotal role in the global shift towards renewable energy, offering several advantages over onshore solutions. These include higher energy potential, larger turbine deployment, ample space for installations, and favourable regulatory support with minimal land-use conflicts or public opposition.

In recent years, offshore wind development has expanded into the Asia-Pacific (APAC) region, which is characterised by significant seismic activity. These conditions demand a re-evaluation of design strategies for monopile-supported OWTs (Pisanò et al., 2024). A key concern is the build-up of excess pore water pressure in coarse-grained soils during seismic loading, which can compromise the stability and performance of OWT foundations if not properly accounted for in design.

Seismic load assessment at sites of interest is typically performed through one-dimensional (1D) site response analyses (SRA). These analyses assume that the soil surface and bedrock extend infinitely in the horizontal direction and that seismic waves propagate vertically as horizontally polarized shear waves. Under these conditions, and assuming viscoelastic soil behaviour modelled as a Kelvin-Voigt material, the equation of motion reads:

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial z}\left(G \frac{\partial u}{\partial z} + \eta \frac{\partial^2 u}{\partial z \partial t}\right) \tag{1}$$

where ρ is the density of the soil, or of the water-soil mixture, G the shear modulus, η the viscous damping coefficient, and u the soil horizontal motion of the soil column as a function of time (t) and the depth coordinate (z). In Equation 1, soil nonlinearity is typically introduced by defining the shear modulus (G) as a function of shear strain $\gamma = \theta u/\theta z$. In the presence of water-saturated soil, the calculation of excess pore water pressure can be incorporated into the solution of Equation 1 using empirical formulations (e.g., Matasovic and Vucetic, 1993 and 1995). Similar procedures are employed by software such as DEEPSOIL for estimating pore pressure generation during dynamic loading. However, to rigorously capture the effects of excess pore pressure on the soil's shear and bulk stiffness, it is necessary to consider the dynamic equilibrium of the saturated soil column in the vertical direction, account for fluid flow within the soil–water mixture, and adopt a suitable soil constitutive model. This level of detail can be achieved through advanced numerical modelling, such as the PLAXIS 2D simulations presented in Section 3.2 of this study**.**

To offer a more practical alternative, this study proposes a simplified method based on the Contour Diagram Framework (CDF) by Andersen, (2015), enabling the prediction of excess pore pressure accumulation in coarse-grained soils under seismic loading. Its key advantage lies in bypassing the complexity of advanced cyclic soil modelling, relying instead on the numerical solution of Equation 1 using open-source tools. The method's predictive capability is validated through comparison with 1D site response analyses conducted in PLAXIS 2D using the PM4Sand model (Boulanger & Ziotopoulou, 2017), which incorporates detailed hydromechanical behaviour.

The proposed method, while broadly applicable to various geotechnical problems, is applied in this study to support monopile design for offshore wind foundations. Engineering-based relationships linking excess pore pressure build-up to reductions in soil shear strength and stiffness are used to assess the resulting impact on required embedment length. Related efforts to estimate liquefaction potential using the cyclic contour diagram framework (CDF) have been reported by Zhang et al. (2023), though their approach differs from the methodology presented in this study.

This paper is organised as follows: Section 2 reviews current liquefaction assessment practices and presents the proposed methodology. Section 3 outlines its validation, and Section 4 presents a case study examining the effect of seismic pore pressure build-up on monopile design.

2 CURRENT PRACTICE AND PROPOSED METHODOLOGY

Current liquefaction assessment practices rely on the comparison between the Cyclic Stress Ratio (CSR) and the Cyclic Resistance Ratio (CRR), typically expressed through a factor of safety defined as, $FOS = \frac{CRR}{CSR}$. The CSR is defined as $\left(CSR = \frac{\tau_{cyc}}{\sigma'_{vo}}\right)$ where τ_{cyc} is a representative cyclic shear stress at a given depth in the soil column for a specified seismic input, and σ'_{vo} is the effective vertical stress at that same depth. CRR quantifies the soil's capacity to resist liquefaction under cyclic loading and can be estimated using various well-established methodologies. Notable examples include the procedures developed by Boulanger and Idriss (2014) and the NCEER guidelines (Youd et al., 2001), which are commonly applied in practice based on SPT, CPT, or shear wave velocity correlations. Together, CSR and CRR provide the basis for evaluating liquefaction triggering potential, where a factor of safety (FOS) <1 indicates a potential for liquefaction, and FOS>1 suggests sufficient resistance under the imposed loading.

While such approaches have proven valuable in engineering practice, they have certain limitations. Specifically, their applicability is limited to shallow depths (lower than typical monopile embedment), they do not fully capture the complexity of the seismic response time history of the soil column and are primarily focused on assessing liquefaction triggering, without providing estimates of accumulated excess pore water pressure (Δu). This study aims to address these limitations through the proposed methodology.

Finally, when liquefaction potential is identified, foundation designers often use approaches that incorporate a representative degradation of soil strength or stiffness. For example, the Japanese Road Association (2002) recommends applying a degradation factor to adjust the ultimate strength of liquefied soil layers. This factor varies according to several criteria: the depth of the examined soil layer, the soil's CRR, and the significance of the infrastructure under consideration.

2.1 Proposed method for seismic Δu assessment

The proposed method employs simple SRA calculations based on solving the 1D wave equation (Equation 1) and combines it with soil data for the layer susceptible to liquefaction. Specifically, it employs the cyclic contour diagrams for pore pressure development, to predict pore pressure accumulation during seismic shaking. The proposed method involves the following steps:

- SRA is performed on the considered soil deposit under the examined seismic excitation by numerically evaluating Equation 1 – no consideration for excess pore water pressures.

- Shear stress time histories are extracted at key elevations, which are afterwards processed using the Range Pair Counting method. This procedure will return pairs of shear stress amplitudes and cycle counts (N).
- The derived shear stress segments are then used to obtain CSR–N pairs. The CSR segments are sorted into parcels of ascending amplitude.
- Contour diagrams for pore pressure development are employed, which are based on cyclic direct simple shear (CDSS) tests under undrained conditions for the soil layers susceptible to liquefaction.
- Finally, excess pore water pressure build-up (Δu) in the examined layer is estimated using the pore pressure accumulation procedure proposed by Andersen (2015). Assuming undrained soil conditions, the stress history—represented by the identified load parcels (CSR–N pairs)—is applied through the use of cyclic contour diagrams.

The Contour Diagram Framework (CDF), as developed by Andersen (2015), is also capable of accounting for partial soil drainage—where excess pore water pressure is generated by cyclic loading and simultaneously dissipated through consolidation. Two drainage mechanisms may be considered: (i) radial consolidation in a disk geometry, which is not applicable under one-dimensional (seismic) loading; and (ii) vertical (1D) consolidation, where drainage occurs toward more permeable layers. While the latter mode of consolidation can be incorporated into the proposed methodology, it was not examined in this study. It should be noted that the impact of partial drainage is generally limited during seismic events due to their short duration—unless the soil permeability is sufficiently high to permit significant dissipation of pore pressure within that short timeframe.

The proposed engineering procedure, although appealing due to its simplicity, comes with several important assumptions and limitations:

- The approach has been evaluated only under undrained soil conditions.
- Transforming irregular cyclic shear stress ratio time histories into CSR–N parcels introduces simplifications that may not fully capture the complexity of cyclic loading.
- The method decouples excess pore pressure generation from the nonlinear dynamic response of the soil column. Pore pressure is estimated post-analysis using the pore pressure accumulation procedure by Andersen (2015).

3 VALIDATION OF THE PROPOSED METHODOLOGY

This section evaluates the performance of the proposed method in predicting the excess pore water pressure ratio, $\Delta u/\sigma'_{v0}$ at selected depths within a soil column subjected to seismic loading. For this purpose, predictions from the proposed method are compared with results from PLAXIS 2D simulations of a soil column incorporating a medium-dense sand layer with a relative density (D_r) of 55% (see Section 3.2). The input seismic motion is a baseline-corrected, spectral-matched acceleration time series ($\ddot{u}_{base}$) from the Loma Prieta earthquake (WDS090), matched to a representative design spectrum for the APAC region (Figure 1).

The input motion is further scaled by factors of 0.25 and 0.5 to investigate the influence of varying acceleration amplitude on excess pore pressure development. The validation strategy comprises the following steps, which are detailed in the subsequent sections:

- Contour plots of the excess pore pressure ratio $\Delta u/\sigma'_{v0}$ are numerically generated using the PM4Sand model through stress-controlled undrained cyclic direct simple shear (CDSS) tests (Figure 2).
- Site response analyses (SRA) on the selected soil column are performed in DEEPSOIL V7.0 (DEEPSOIL, 2024), without incorporating empirical models for pore water pressure generation. CSR time histories are extracted for the (examined) liquefiable soil layer and converted into CSR–N parcels. These parcels are then input into the CDF to calculate a representative excess pore pressure ratio $\Delta u/\sigma'_{v0}$ for the seismic event.
- In parallel, SRA under undrained conditions are performed in PLAXIS 2D on the examined soil column under equivalent loading conditions, serving as a benchmark for the proposed methodology.
- Finally, the performance of the proposed method is assessed by comparing its results to those obtained from the PLAXIS 2D analyses (Table 4).

3.1 Cyclic contour diagrams

Cyclic contour diagrams for a medium-dense sand layer are numerically generated (see Figure 2) by simulating undrained, stress-controlled cyclic direct simple shear (CDSS) tests, with K_0 consolidation and initial overburden stress equal to 100 kPa. Soil constitutive behaviour follows the PM4Sand model which was calibrated following Vilhar et al. (2018) - calibration parameters listed in Table 1. The primary parameters are: D_{R0} - the initial relative density; G_0 - control parameter of the small strain shear modulus; hp_0 – control parameter of the contraction behaviour of the soil. Default values are used for the secondary parameters (Boulanger and Ziotopoulou, 2017), which are: $e_{\max}$ and $e_{\min}$ - the maximum and minimum void ratio; nb and nd – control parameters of the bounding and dilation surfaces; φ_{cv} – the critical state friction angle; ν – the Poisson's ratio; p_A – the atmospheric pressure; Q and R – parameters that define the critical state line as a function of relative density and confining stress.

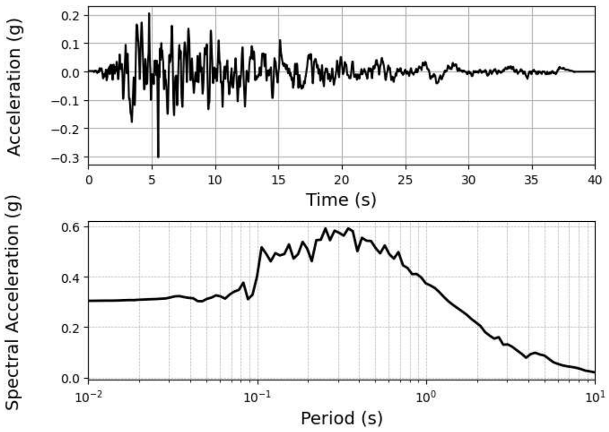


Figure 1. Acceleration time signal and spectral acceleration (5% critical damping) of the Loma Prieta WDS090 seismic motion.

Table 1. PM4Sand parameters.

Parameter	Value	Parameter	Value
D_{R0} (-)	0.55	nb (-)	0.5
G_0 (-)	677	nd (-)	0.1
h_{p0} (-)	0.4	φ_{cv} (-)	33°
p_A (kPa)	101.3	ν (-)	0.3
e_{max} (-)	0.8	Q (-)	10
e_{min} (-)	0.5	R (-)	1.5

3.2 SRA with PLAXIS 2D

Site response analyses of the soil column presented in Table 2 were numerically simulated with PLAXIS 2D. The liquefiable sand layer was simulated with the PM4Sand model (Table 1) under undrained conditions. For simplicity, the clay layers were modelled as linear elastic with uniform stiffness (with depth), while isochoric deformations were imposed by selecting Poisson's ratio equal to 0.495. Rayleigh damping is also incorporated with coefficients calculated to yield approximately 1% damping, in a relevant frequency range.

Dynamic analysis is performed in PLAXIS 2D, using automatic sub-stepping, employing a dense mesh of 15-noded elements. Dynamic boundary conditions are set to tied (uniform displacement and pore water pressure at every elevation) at the sides while the bottom is modelled as compliant base (Bentley Systems, 2024).

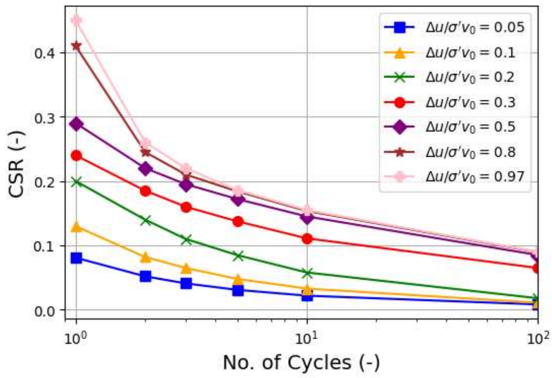


Figure 2. Cyclic contour diagram of a medium dense sand calculated employing the PM4Sand cyclic soil model.

Table 2. Soil column's layering and main properties.

Layer	Depth (m)	Unit weight (kN/ m^3)	G_0 (MPa)	V_s (m/s)
Clay 1	0-7	21	60.4	168
Sand	7-9	18	See Tables 1, 3	
Clay 2	9-40	21	60.4	168
Bedrock	40-42	22	63.3	168

3.3 SRA with DEEPSOIL

The simplified site response analysis of the soil column is carried out in DEEPSOIL, excluding any modelling of pore pressure generation. Similarly to the PLAXIS 2D analyses, the top and bottom clay layers and the bedrock are modelled as linear elastic (see Table 2). The sand layer is modelled using the General Quadratic/Hyperbolic (GQ/H) soil model, with detailed properties provided in Table 3. The shear strength (τ_{max}) was computed to match the soil capacity based on the critical state friction angle at the corresponding depth assuming drained behaviour. The shear wave velocity was computed to match the small strain shear modulus of the PM4sand model at the desired depth. Shear modulus degradation and damping curves are chosen from literature (Darendeli, 2001) selecting a lateral earth pressure coefficient (K_0) equal to 0.5, and 10 loading cycles at loading frequency of 1 Hz.

Table 3. Properties of the sand layer used in the GQ/H (General Quadratic/Hyperbolic) model in DEEPSOIL.

Parameter	Unit	Value
γ	kN/m^3	18
V_s	m/s	173
τ_{max} (at -7m)	kPa	95
τ_{max} (at -9m)	kPa	106

3.4 Results

The CSR time histories computed by PLAXIS 2D and DEEPSOIL at a depth of 8 m, for base input accelerations scaled by 0.5 and 1.0, are presented in

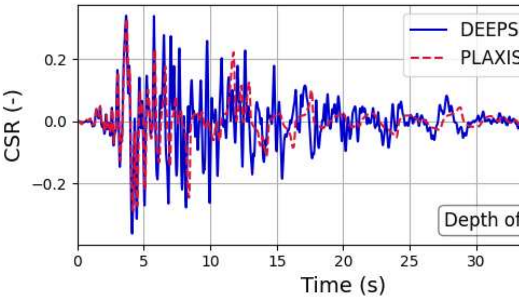


Figure 3 and Figure 4. For the motion scaled by 0.5, both DEEPSOIL and PLAXIS produce very similar CSR predictions. When the input motion is scaled to 1.0, the response computed by DEEPSOIL shows similar qualitative response to that observed for the 0.5x scaling of base excitation, while there is an expected increase in CSR amplitude due to the higher input acceleration. In contrast, the PLAXIS results exhibit notable qualitative deviations from the lower input acceleration case, attributed to excess pore water pressure build-up. This effect is further evidenced in Figure 4 which illustrates the calculated $\Delta u/\sigma'_{v0}$ time history calculated with PLAXIS 2D at soil layer under consideration. Figure 5 presents the $\Delta u/\sigma'_{v0}$ predicted by the proposed methodology i.e., by employing the CDF on the CSR time history extracted from DEEPSOIL results for each corresponding input motion. The results indicate that the proposed method predicts well the calculated pore water pressure build-up by PLAXIS 2D (Table 4, Figure 4. $\Delta u/\sigma'_{v0}$ time histories, simulated in PLAXIS 2D.Figure 4 and Figure 5).

Table 4. Comparison of $\Delta u/\sigma'_{v0}$ predictions (at 8 m depth) from the proposed method with PLAXIS 2D simulations.

$\ddot{u}_{base}$ scale factor (-)	$\Delta u/\sigma'_{v0}$ (-)	
	PLAXIS 2D	**Proposed method**
0.25	0.22	0.22
0.5	0.30	0.42
1	0.97	0.97

The maximum $\Delta u/\sigma'_{v0}$ predicted by the proposed method closely matches FEM results for scaling factors of 0.25 and 1.0. A larger deviation, approximately 40%, is observed for the case of $0.5\ddot{u}_{base}$. Overall, the method performs satisfactorily, producing reasonable predictions except in the intermediate loading case. The observed mismatch may be attributed to several factors: limitations discussed in Section 2.2; (minor) differences in CSR time histories computed by PLAXIS 2D and DEEPSOIL (Sections 3.1 and 3.3); and the use of contour diagrams developed for an initial overburden stress of 100 kPa -the actual in-situ vertical stress for the examined layer ranges from 77 to 93 kPa. While generating contour diagrams based on field-representative consolidation stresses would likely improve accuracy, it is worth noting that laboratory data available to engineers are often produced under consolidation conditions that do not precisely reflect in-situ stresses. Additionally, the cyclic contour diagrams were developed using two-way cyclic loading procedures, which do not fully account for the complexity of soil seismic shaking (see

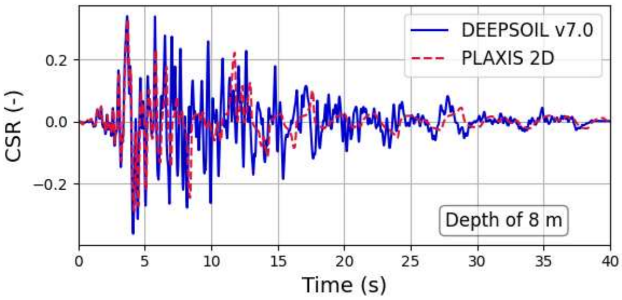


Figure 3).

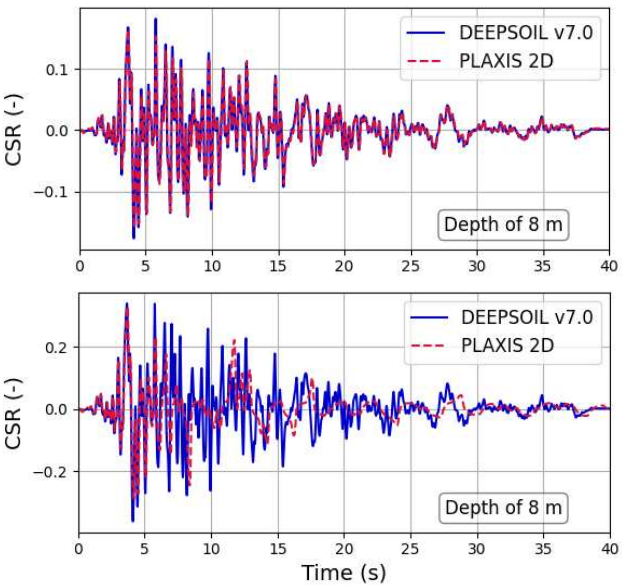


Figure 3 CSR time histories at 8 m depth, computed using PLAXIS 2D and DEEPSOIL v7.0. The top and bottom

figures correspond to base acceleration scaled by 0.5 and 1.0, respectively.

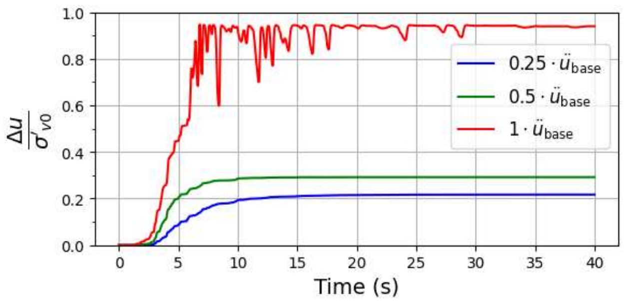


Figure 4. $\Delta u/\sigma'_{v0}$ time histories, simulated in PLAXIS 2D.

4 MONOPILE CASE STUDY

A case study was developed to apply the presented method to the concept design of a monopile foundation. Soil stratigraphy and general wind turbine characteristics were heuristically selected based on those from a wind turbine at an offshore wind farm in the Netherlands, where seismic activity is rare. However, hypothetical seismic loading is introduced in this study to evaluate the potential impact of soil liquefaction on the monopile foundation. The indicative design location features a soil profile with approximately 40 m of dense sand (Dr ~80%), and fines content increasing from 5% to 30%. Site-specific cyclic contour diagrams were utilized in the analysis; however, they are not included here due to data confidentiality. The monopile diameter is 9.5 m. The support structure is modelled employing one-dimensional (1D) Timoshenko beam elements while soil-structure interaction is incorporated via lateral soil reaction elements following the Beam-on-Winkler-Foundation (BWF) framework. Monotonic soil reaction curves are derived based on in-house SGRE procedures (Panagoulias et al., 2023). The seismic input motion presented in Section 3.2 is employed.

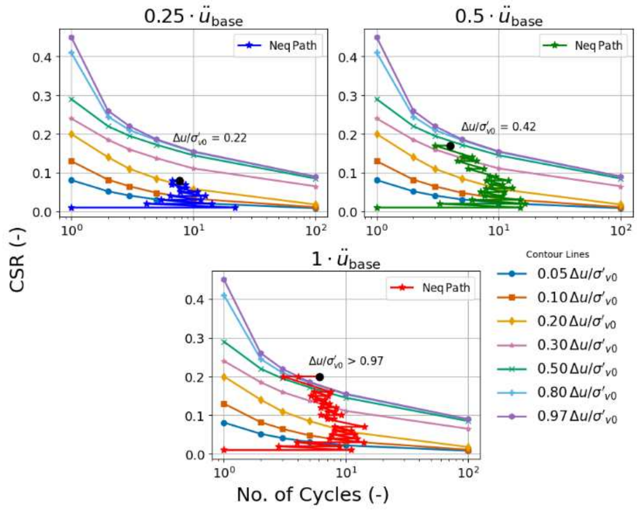


Figure 5. Predicted $\Delta u/\sigma'_{v0}$ using the proposed seismic pore pressure accumulation method.

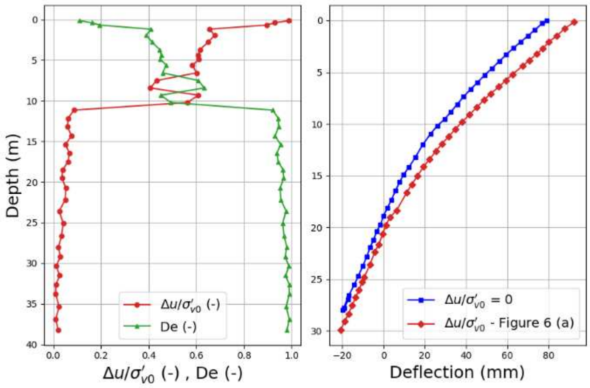
Employing the proposed framework, Figure 6a illustrates that full liquefaction occurs in the top 1 m of the soil column, where $\Delta u/\sigma'_{v0} = 1$. At depths between 1 and 10 m, excess pore pressure ratios are approximately 0.6, while below 10 m, they are nearly zero. These calculated excess pore pressure levels are then used to degrade the ultimate strength—and, by extension, the stiffness—of the monotonic soil reaction curves through a degradation factor defined as $De = 1 - 0.9(\Delta u/\sigma'_{vo})$ (Boulanger et al., 2003; Japanese Road Association, 2002). (a)

(b)

Figure 6b illustrates the measurable increase in lateral deflection when accounting for the soil reaction degradation in the design under ULS loading. The effect of $\Delta u/\sigma'_{v0}$ on monopile embedment depth is evaluated under ultimate limit state (ULS) conditions at the mudline. The embedment depth is increased until lateral displacement is within 0.1D. For the reference case – no seismic input, the required embedment is 28.3 m. Under the hypothetical seismic scenario, accounting for degraded soil properties, the embedment increases by 2.1 m (approximately 7%). Note that the employed soil reaction curves do not account for stiffness degradation due to cyclic environmental loading, which would necessitate an even greater embedment depth.

5 CONCLUSIONS

This study proposes a method to evaluate excess pore water pressure accumulation during earthquakes by combining site response analyses, with the pore pressure accumulation procedure and the contour diagram framework by Andersen (2015). The method's performance is assessed by comparing its $\Delta u/\sigma'_{v0}$ predictions for a soil column subjected to the Loma Prieta earthquake against detailed PLAXIS 2D results. The input motion is scaled by factors of 0.25, 0.5 and 1.0 to examine seismic intensity effects.



(a) (b)

Figure 6. (a) Excess pore pressure ratio and shear strength degradation factor (De) depth profiles. (b) Monopile lateral deflection using p-y soil reaction curves.

The method performs well in predicting liquefaction onset and $\Delta u/\sigma'_{v0}$ during mild shaking but is found to overestimate $\Delta u/\sigma'_{v0}$ predictions for medium intensity seismic inputs, potentially leading to conservative Δu predictions. Unlike conventional methods for seismic pore pressure effects, the proposed approach can provide insights into soil column shaking, and excess pore water pressure build-up without requiring advanced numerical analysis or commercial software. Moreover, $\Delta u/\sigma'_{v0}$ contour graphs are nowadays frequently part of the project data, making the proposed method easier to apply. Overall, the proposed method has the potential to support industry practice for assessing liquefaction and pore pressure development during the design phase of offshore wind turbine foundations in seismic areas.

AUTHOR CONTRIBUTION STATEMENT

A. Stamou: Software, Data curation, Formal Analysis, Writing- Original draft. **S. Panagoulias, P. Voges-Espelage, A. Nernheim**: Software, Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing **E. Kementzetzidis**: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.

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