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Advanced vs simplified design approaches for monopiles in seismic areas

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ABSTRACT: As part of a rapid global wind energy growth, offshore wind farms are being developed in moderate to high seismic active areas. The geotechnical design of monopiles, in non-seismic environments, is now typically based on detailed 3D finite element analysis (FEA) for the optimisation of foundation geometry and provision of required soil reaction curves (SRC). Despite this advanced design philosophy being well-established, simplified but accurate approaches for seismic input definition and soil-structure interaction for seismic design during early stages of developments are limited to date. This paper aims at presenting a simplified approach accounting for kinematic soil-structure interaction during earthquake loading, that could be used for the design of next generation 20 MW wind turbines founded on large diameter monopiles. The simplified approach is compared against an advanced one, to establish its performance. The advanced approach considered in this paper includes 3D FE time-domain modelling of the monopile in linear and non-linear soil materials subject to different real earthquake time histories. The simplified approach consists of a 1D soil column propagating earthquake time histories and connected to a stick model of the monopile through springs and dashpots. Results of the two approaches are compared and a sound yet efficient way to define an equivalent uniform ground motion input including kinematic soil-structure interaction is described.

Keywords: Seismic, Monopile, FEA, Earthquake

1 INTRODUCTION

Bottom-fixed offshore wind farms are being designed and installed in seismic active areas around the world (e.g. Taiwan, Japan, etc.). Seismic design of monopile foundations typically involves the following:

- Free-field site response analysis (SRA) with ground motions defined by PSHA/DSHA study for the area of interest and for postulated stiff soil/rock conditions;
- Evaluation of free-field liquefaction extent and pore pressures profiles;
- Definition of soil reaction curves (e.g. p-y, t-z and Q-z) for soil-structure interaction of 1D pile models being able to capture soil hysteretic behaviour, radiation damping, etc.;
- Geotechnical verifications of monopiles (axial and lateral) for seismic loading.

Different approaches may be used for each of the above activities, also depending on project phase (e.g. concept/preliminary/FEED/detailed).

Main scope of this paper is to describe and evaluate the performance of a novel simplified approach that may be used to assess the monopile seismic response taking into account both kinematic soil-structure interaction and (simplified) inertial loading.

2 METHODOLOGY

The following two sections briefly describe the 3D FE model (OpenSees – OS in the following) and the proposed simplified model (KEOPE) considered in this study.

2.1 Advanced Model (OS)

A fully coupled 3D FE model of the soil and foundation is developed using OpenSees software (McKenna, 2011).

The modelling approach initially proposed by Corciulo et al. (2017) has been modified to perform time-domain seismic analysis of monopiles. An advanced soil constitutive model is adopted to capture the interplay of cyclic effects and hydro-mechanical (HM) coupling in soil-monopile dynamic interaction during seismic shaking.

The dynamic HM coupled response of the soil is described by means of the well-known u-p formulation which relies upon the assumption of negligible soil-fluid relative acceleration. This approximation is widely recognized to suit well earthquake engineering problems.

Since a single direction seismic excitation is considered in the analysis, geometrical and loading symmetries are exploited to reduce the size of the 3D model into half, thus reducing the computational requirements. A conceptual representation of the FE model is shown in Figure 1. The soil domain is discretized by means of approximately 2000, 8-node, two-phase brick u-p elements, implemented in OpenSees for simulating dynamic response of solid-fluid fully coupled materials. Conversely, the steel monopile is modelled with standard one-phase brick elements. The FE mesh is shown in Figure 1.

The so-called "shear beam" boundary condition is applied to the lateral boundaries of the model by enforcing corresponding front and back nodes at any depth to move together. These boundary conditions, together with a large enough model, have been demonstrated to provide satisfactory results using OpenSees (e.g. Qui et al., 2019; Soler-Sandoval et al., 2019). At the base of the model, a non-reflecting boundary is included introducing at each node a viscous dashpot to reproduce the impedance of the elastic half-space underneath the soil domain. Earthquake acceleration records are applied at the base of the model as force time histories, evaluated by multiplying the properly calibrated viscous coefficient of each dashpot by the input velocity related to the seismic event. An implicit Newmark algorithm (β = 0.6, $\gamma = (\beta+0.5)2/4$) is adopted for time discretization in combination with explicit forward Euler integration of soil constitutive equations.

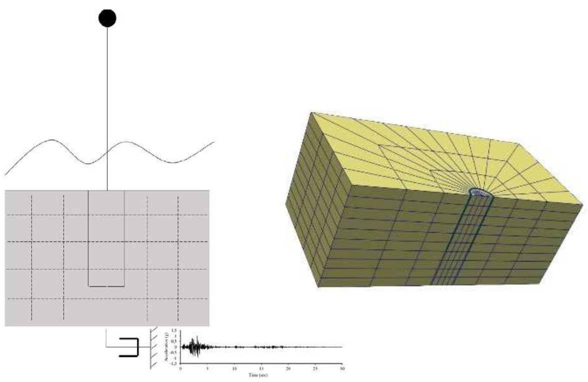

Figure 1. Conceptual representation of the FE model (left) and 3D view of the mesh (right)

Since a sandy deposit will be considered in the application case, cyclic soil behaviour is simulated via the UCSD08 multi-surface plasticity model (Yang and Elgamal, 2008), capable of reproducing pressure-dependence, volumetric-deviatoric coupling and cyclic hysteresis of saturated sands.

For simplicity, the superstructure (e.g. portion of the monopile above the mudline together with tower and nacelle) is modelled as a single degree of freedom (SDOF) model. The model uses a truss element embedding parallel spring and dashpot uniaxial materials that connect the equivalent lumped mass to the top of the monopile at mudline level. The lumped mass includes all the structural masses resulting from primary and secondary tower steel, transition piece and nacelle/blades together with mass of water entrapped in the monopile section. Added masses of the sea water surrounding the support structure is not considered in the analyses.

2.2 Simplified Model (KEOPE)

The KEOPE (Kinematic Effect On Pile during Earthquake) software was developed by the Department of Structural Engineering of the Politecnico di Milano (Ceci and Forcolin, 2006) to model in a simplified way the inertial and kinematic actions on single piles or conductors under earthquake loading. The software is the result of coupling two codes:

- STRATISH: 1D linear or equivalent linear site response analysis (SRA);
- CASING: 1D dynamic FE structural model for piles.

The program deals sequentially with the accelerograms given as input at the base of the soil column, its propagation within the soil and, by means of a finite element model, it analyses the pile-soil interaction, until the value of the internal actions of the pile is obtained. Although only vertically propagating S-waves in a single direction are considered in this study, KEOPE can manage 3D seismic input motions including vertical P-waves propagation.

The computational code STRATISH solves the 1D propagation of seismic waves assuming a linear or equivalent-linear soil behaviour.

The CASING code solves the structural problem of a beam (representing the pile) resting on pairs of spring-dampers (representing the pile-soil interaction parameters) loaded by time histories of the 3D free field ground displacements resulting from STRATISH. Specifically, the pile-soil spring-dampers are based on the Makris and Gazetas (1992) formulations with soil stiffness parameters being updated in agreement with stiffness reduction resulting from seismic waves propagation in STRATISH. Output from CASING are internal forces in the beam and associated accelerations, velocities and displacements.

To account for the presence of the superstructure on top of the beam, a SDOF system is modelled in KEOPE with a similar approach as described for OpenSees (see Figure 2).

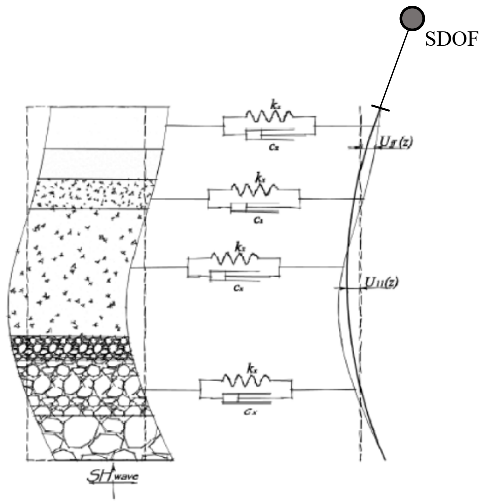

Figure 2. KEOPE conceptual schematization

3 APPLICATION CASE

The performance of the simplified model (KEOPE) is assessed on a real design case study consisting of a wind turbine founded on a monopile at a site of about 49 m LAT water depth. It is noted that the monopile was designed for ULS, ALS and SLS loading conditions without considering any seismic loading (not required for the real case location) and as such the seismic analyses presented in this paper should be considered as “a-posteriori” verifications.

Soil conditions, structure characteristics and seismic loading considered in this paper are provided in the following sections.

3.1 Soil conditions

Soil conditions considered for this study consist of dense to very dense sands from mudline to the depth of interest (i.e. about 40 m depth). Average unit weight of the sands is 20 kN/m^3. Measured average friction angle for this material is about 40°.

The first meter below seabed shows cone tip resistance q_c of approximately 10 MPa increasing to about 20 MPa from 1 to 5 m depth, while approximately 40 MPa are found from 5 m down to 40 m depth. G_{max} profile shows a roughly linear increase with depth from about 15 MPa at mudline to about 260 MPa at 40 m depth.

Stiffness reduction and associated damping curves were defined based on resonant column (RC) data available for the project. Since negligible variations with depth was appreciated in RC data, the same stiffness and damping curves were considered for the whole soil profile in KEOPE whilst the G/G_{max} varies with confinement pressure according to UCSD08 constitutive model in OS modelling. Considered G/G_{max} and damping curves used in this paper are shown in Figure 3 (note that curves for OS are extracted at mid depth of the model).

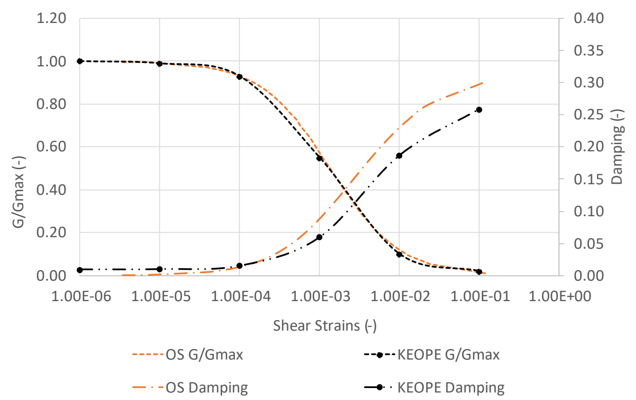

Figure 3. Shear stiffness reduction and damping curves

3.2 WTG structural data

A 20 MW turbine is considered in the analyses with the following structural characteristics:

- Rotor diameter: 285 m
- Hub elevation: 168 m above sea level
- Total nacelle + rotor mass: ~1100 t
- Tower bottom elevation: 18 m LAT
- Tower top diameter: 7 m
- Tower bottom diameter: 10 m
- Transition piece diameter: 10 m
- Monopile top diameter: 10 m
- Monopile bottom diameter 11.5 m
- Monopile length: 86 m
- Monopile embedment: 31 m
- Transition piece mass: 380 t
- Tower mass: ~1550 t
- Monopile mass: ~2000 t

Based on detailed eigenfrequency analyses conducted for the design of the structure, the first mode of vibration (swaying) of the structure has a frequency of 0.16 Hz (6.25 s). This frequency, together with the equivalent lumped mass of the structure above seabed, has been used to define stiffness and damping parameters of the equivalent SDOF for both KEOPE and OS models. It should be noted that the use of a

SDOF to represent the whole structure above mudline is a simplification required by KEOPE modelling limitations. This simplification does not allow to capture higher bending modes and eigenfrequencies of the structure above mudline.

3.3 Seismic input

As anticipated, seismic conditions were not considered in the real case design. For the purpose of this paper, the horizontal seismic input is taken from another location in North Adriatic Sea as described in Soler et al. (2019). Vertical input motion was not considered in the analyses.

Specifically, the assumed seismic spectrum is representative of a 475 years return period event on ISO site class C (Vs = 450 m/s). Given the seismic environment of the area and based on the deaggregation results, time histories having moment magnitude in the range 5 to 6.5 with epicentral distances of about 20 km were selected (see Table 1). Time histories were spectrally matched to target UHS before being used in the analyses.

Table 1. Selected ground motion time histories

ID	Event	Station	Mw (-)	Re (km)	PGA (g)
1	Mid Niigata	Tohokamachi	6.2	20.6	0.251
2	South Iceland	Solheimar	6.5	17.3	0.240
3	Izmit After.	Sakarya	5.6	11.2	0.202
4	South Iceland	Hella	6.5	14.5	0.211
5	L'Aquila Main.	Gran Sasso	6.3	18.0	0.149
6	Christchurch	Christchurch	6.2	19.3	0.185
7	South-Iceland	Hella	6.4	21.3	0.168

4 RESULTS

Comparison of results obtained with OS and KEOPE for the application case described above are provided in the following sections assuming the soil as a linear elastic material and as non-linear elasto-plastic material.

4.1 Linear elastic analyses

4.1.1 KEOPE vs OS

A first assessment of the results from KEOPE vs OS model is carried out considering linear elastic soil properties. Results are provided in the following figures (Figure 4 to Figure 6) for time history ID 2 (see Table 1) in terms of: (i) acceleration response spectra of input motion, freefield mudline (FF) and monopile at mudline level (ML); (ii) monopile horizontal displacements at mudline level and (iii) monopile shear force at mudline level.

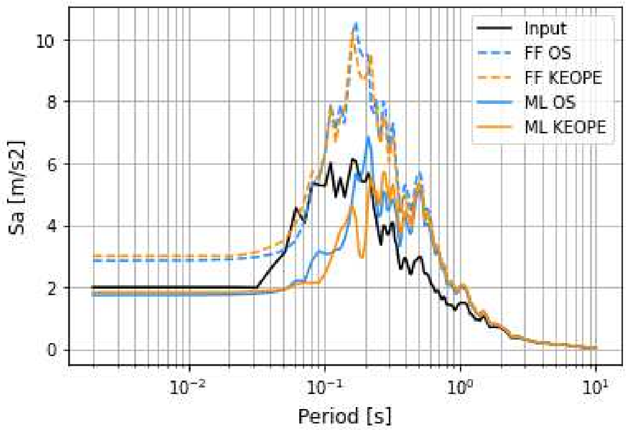

Figure 4. Acceleration response spectra - linear elastic soil

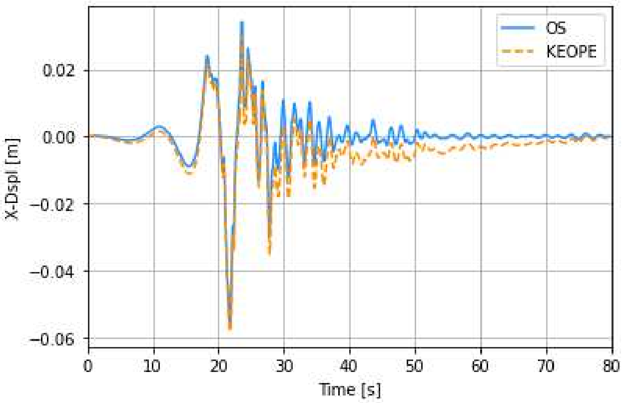

Figure 5. Monopile horizontal displacements at mudline level - linear elastic soil

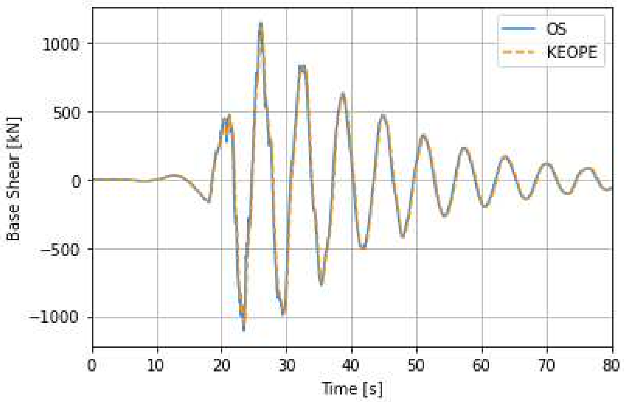

Figure 6. Monopile shear force at mudline level - linear elastic soil

Considering the different modelling approaches and assumptions, KEOPE and OS results are in very good agreement but it worths noting that KEOPE results can be obtained with a fraction of time and computation resources compared to a 3D FE model.

It should also be highlighted that the base shear at monopile mudline level is negligible in terms of magnitude. This is due to the limited energy content in earthquake time history at the natural frequency of the SDOF.

4.1.2 Kinematic Soil-Structure Interaction (KSSI)

The way the monopile modifies the seismic input compared to freefield conditions (e.g. the so-called kinematic soil-structure interaction effects) has also been investigated with both software. The KSSI can be easily identified by computing the spectral amplification ratio (SAR) between the acceleration response spectra at monopile mudline level (without any superstructure on top of it) and the ground surface response spectrum at freefield.

Results for linear soil behaviour, time history ID 2, are provided in Figure 7 and show that the presence of the foundation results in significant deamplification (roughly half) of the free-field motion at the mudline level for structural periods below 0.5 s.

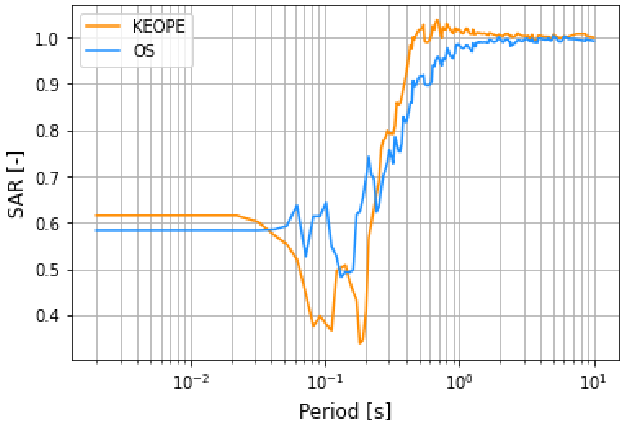

Figure 7. Spectral amplification ratio showing KSSI effects - linear elastic soil

4.2 Non-linear analyses

4.2.1 KEOPE vs OS

The same comparison carried out for the linear elastic case is provided also for the non-linear soil material as shown in Figure 9 to Figure 11 using as input the time history ID 2 of Table 1.

In general, impact of soil non-linearity on results, although present, is not too evident. This can be appreciated from Figure 8 showing shear strains vs depth for linear and equivalent linear KEOPE modelling. Main reasons for these results are the relatively dense sands being considered and the medium severity of the seismic excitation.

It is interesting to note how the simplified model KEOPE can provide comparable results to a far more advanced fully coupled 3D FE numerical model.

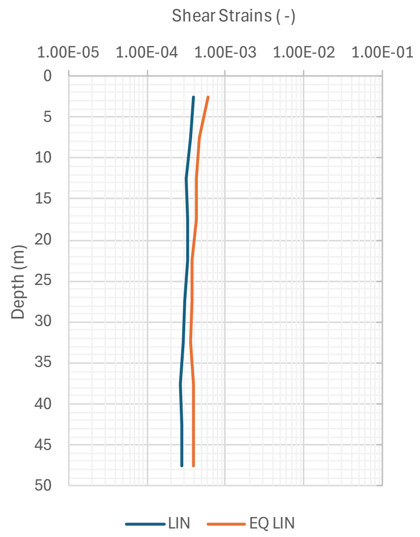

Figure 8. Shear strains from linear and equivalent linear KEOPE analyses

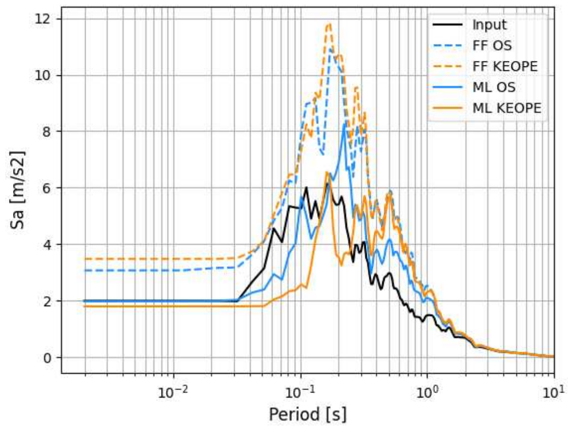

Figure 9. Acceleration response spectra - non-linear soil

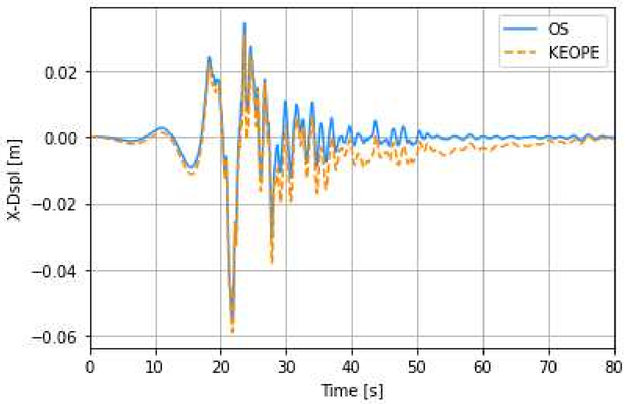

Figure 10. Monopile horizontal displacements at mudline level - non-linear soil

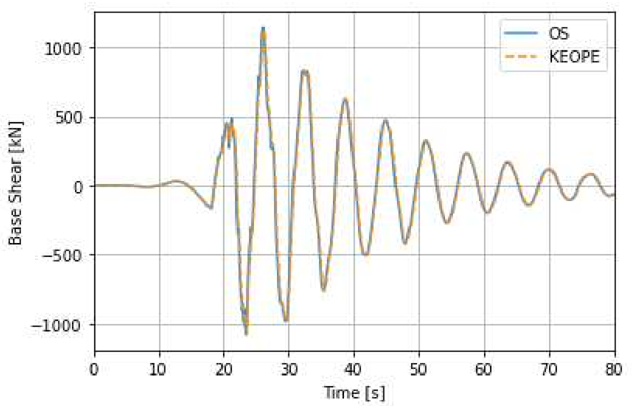

Figure 11. Monopile horizontal shear force at mudline level - non-linear soil

4.2.2 Kinematic Soil-Structure Interaction (KSSI)

In terms of KSSI, similarly to the linear case, a quite significant de-amplification is found at short periods but it is interesting to note that deamplifications are slightly larger compared to the linear case (Figure 12).

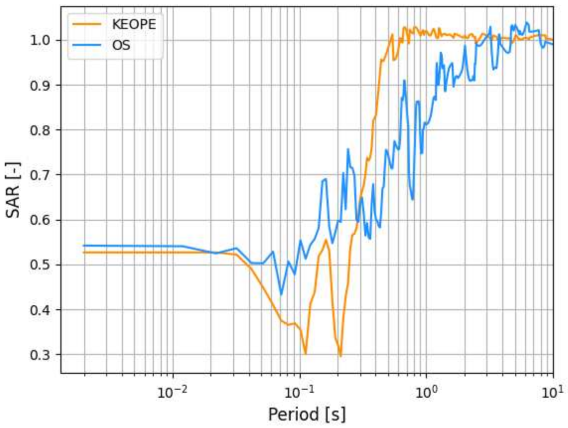

Figure 12. Spectral amplification ratio showing KSSI - non-linear soil

While the broad picture is congruent, some discrepancies between KEOPE and OS results are noticed with KEOPE providing higher SAR compared to OS for periods longer than 0.3 s. Reasons for these discrepancies can likely be explained by the different approaches to solve the non-linear problem (i.e. equivalent linear for KEOPE, fully non-linear with hydro-mechanical coupling for OS).

Considering the importance for deep foundations, the KSSI effects have been calculated for the seven time histories (Table 1) using both KEOPE and OS for non-linear soil response (Figure 13). Average results show that KSSI effects from KEOPE are generally in line with results from OS modelling with KEOPE predicting larger deamplifications for periods shorter than 0.4s and smaller for longer periods (0.4 to 2.0 s). Finally, it is of interest to note that KEOPE (and to a lesser extent OS) results are generally in line with results provided by Day (1977) for a rigid cylindrical foundation embedded in linear elastic soil (although Day considers foundations with lower embedment (L) to diameter (D) ratio).

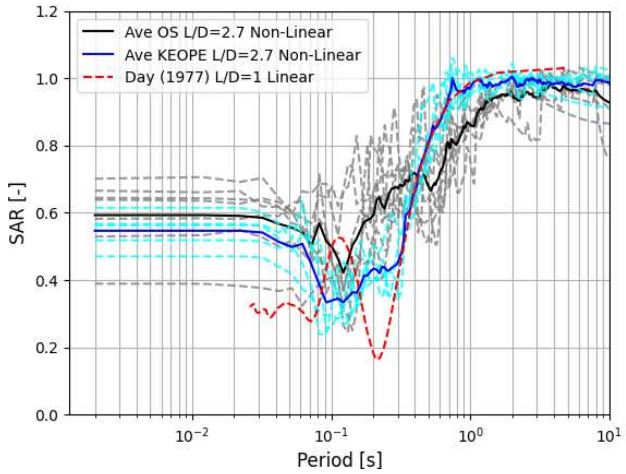

Figure 13. KSSI effects for non-linear soil. KEOPE (blue), OS (black) and Day, 1977 (red) results

5 POTENTIAL APPLICATIONS TO INTEGRATED LOAD ANALYSIS

As reported by DNV-RP-0585 (DNV, 2021), seismic modelling of offshore wind turbines requires the use of time domain analyses. Response spectrum analysis method, accepted for O&G offshore structures for ELE load level, is only permitted for very low seismic areas or onshore wind turbines.

Time domain analysis for wind turbines can be carried out with a fully integrated analysis or following a superelement approach. In case of fully integrated analysis, the entire structure (from rotor-nacelle assembly to foundations) is modelled with the wind turbine load calculation code. Considering that commercial wind turbine load calculation software used in a fully integrated approach may lack details in modelling the sub-structure and KSSI, tools like KEOPE or OS can be used as independent check of the structural response arising from the fully integrated seismic analysis, above all if the latter is based on linear soil reaction spring elements.

If a superelement approach is considered, e.g. in the case where the sub-structure is designed separately form the tower and rotor-nacelle assembly, care should be taken to properly account for non-linear seismic behaviour since the superelement is, by definition, linear. Similarly to the fully integrated analysis approach, the tools described in this paper can provide a valuable benchmark for the monopile superelement seismic performances.

Looking towards other types of sub-structures (e.g. piled jackets) and following DNV-RP-0585 (DNV, 2021) recommendations, KEOPE may also be efficiently used to provide time domain seismic input considering KSSI effects to either a normal superelement (if piles are not directly included in it) or to a seismic superelement (that is a superelement approach that uses multiple interface nodes - one interface node at tower bottom interface and seismic interface nodes for the application of seismic input).

Furthermore, when it is considered applicable (e.g. for low seismicity), a tool like KEOPE may be used to provide response spectra at mudline level including KSSI of deep foundations.

Finally, although not shown in this paper, KEOPE can simulate the vertical propagation of P-waves in a soil column and provide the vertical seismic response of a monopile. Given the sensitivity of some component of the wind turbines to vertical excitations, KEOPE could be again a useful tool for seismic design verifications.

6 CONCLUSIONS

This paper provides a comparison between simplified and advanced numerical solutions for seismic analyses of a monopile embedded in dense to very dense sands with linearly increasing G_{max} with depth.

Acknowledging that the case study presented in this paper is limited to medium seismic intensities (e.g. PGA = 2 m/s on stiff soil conditions), a homogeneous soil stratigraphy and a monopile having a L/D of about 2.7, the following key outcomes can be highlighted: (1) the simplified KEOPE model provides satisfactory results when compared to advanced 3D FE modelling; (2) simplified solutions can be a time and cost effective option particularly during early design stages and (3) KEOPE simplified model can be used to assess KSSI effects and define input motion allowing for a reduction of the seismic demand in the medium to short periods range compared to free field seismic demand.

Next steps for a more thorough investigation of KEOPE capabilities should include the investigation of more complex soil profiles and more demanding seismic inputs. Additionally, the impact of modelling the superstructure as a SDOF vs a complete tower and nacelle model should be investigated.

AUTHOR CONTRIBUTION STATEMENT

O. Zanoli: Conceptualization, Methodology, Formal Analysis, Writing- Original draft. **C. Piatti**: Formal Analysis, Software, Writing- Editing. **R. Paolucci**: Software, Supervision.

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