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# DYNAMIC RESPONSE OF OFFSHORE FOUNDATIONS – FROM PILE INSTALLATION TO SEISMIC PERFORMANCE

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**Abstract**: *Dynamic analysis has an important role to play in the rapid expansion of offshore wind installations worldwide, as it affects multiple design stages. This paper highlights the use of dynamic analysis in two distinct aspects of offshore geotechnics. It first gives examples from recent Joint Industry Projects where consistent procedures for wave propagation analysis based on impact pile driving and restrike data were established, ultimately resulting in the development of more reliable tools for the assessment of axial capacity of piles supporting jacket structures. Following the rapid expansion of offshore wind farms in seismic areas, the second part of the paper discusses some of the challenges in transferring some of the existing seismic assessment procedures, which were established for conventional onshore structures, to offshore structures. This includes the assessment of liquefaction offshore at large depths and its consequences on the response of offshore wind turbines supported by monopile foundations.*

## Introduction

Climate and sustainability targets have led to a rapid increase in the demand for renewable energy over the last two decades, with the offshore wind energy sector being in the forefront of these developments. There is a worldwide expansion of offshore wind installations in deeper waters and in areas of medium to high seismicity (e.g. Taiwan, China, Japan, USA) with structures of higher energy capacity. Wave propagation and dynamic analysis are key elements of such developments affecting different stages of the design process, ranging for pile installation and pile axial capacity assessment, to the turbine tower and foundation response to environmental and seismic loading. The first part of this paper highlights examples from recent Joint Industry Projects (Buckely et al 2020, Cathie et al 2022) in which dynamic analysis of pile driving and restrike data of steel, tubular piles were successfully used to estimate pile axial capacity at different stages since installation and for different geomaterials (mainly chalk and sand). The second part of the paper draws the attention to seismic design matters, focusing on the challenges encountered when assessing liquefaction offshore and highlights the impact of liquefaction on the overall response of an Offshore Wind Turbine (OWT) supported by monopile foundations (Möller et al 2020 and Möller et al 2023).

## Dynamic Pile Analysis based on Driving and Restrike Data

### *Background*

Foundations are an important component of OWTs which can comprise 25 to 30% of the overall capital costs, while any uncertainty over the foundations can restrict or even block the development of a new offshore wind farm. The construction of a typical offshore windfarm involves the installation of tens to hundreds of piles, covering large areas which exhibit geospatial variability in terms of the encountered geotechnical units, their properties, and their stratigraphy. This spatial variability and the associated difficulties in geotechnical site characterisation pose challenges for the reliable design of piled foundations, with one of the key aspects of pile design being the reliable estimation of their long-term static axial capacity.

Dynamic pile testing (DPT) is used routinely as a relatively economical means of gaining indicative information on static axial pile capacity. It is typically performed on a representative number of piles at carefully selected locations, first during pile installation and for some locations

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DPT is repeated several days (or even weeks) after installation, aiming to establish trends of changes in static capacity with time.

DPT comprises monitoring of strain and acceleration using transducers attached to the pile shaft above ground, near the pile head during blows applied by impact hammers or large drop-weights. Using the measured time histories one can infer the soil resistance during pile driving (SRD) and/or during subsequent restrike blows. The raw data time histories are converted to force (F) time histories by multiplying the measured strain by the cross-sectional rigidity EA of the pile (where E is the Young’s modulus and A is the area of the pile cross-section) and velocity (v) time histories by integrating the acceleration signal.

Pile capacity can then be obtained by idealising the response as a one-dimensional (1D) wave propagation problem. ‘Signal matching' analyses may then be performed using the measured F or Zv (pile impedance Z times the velocity) signal as input boundary conditions, operators then aim to vary the resistance parameters applying over the pile shaft until they can generate an artificial returning upward force signal that matches the measured wave well. For the computation the pile-soil interaction is represented with the aid of rheological soil resistance models, typically consisting of sliders, dampers and springs. These simulate the pile-soil interface response at the pile shaft, the far-field radiation damping, as well as the pile base response. Signal matching consists of iteratively varying the profiles input into the adopted soil resistance model, until a good quality match is obtained. The solution is not unique, as there are many potential combinations of parameters that can lead to similarly good matches. Figure 1a illustrates an example of this process for an End of Driving blow (EoD) in which the measured force was used as an input boundary condition for the computation, while Figure 1b compares the resulting computed wave after multiple iterations with the measured one at the pile head.

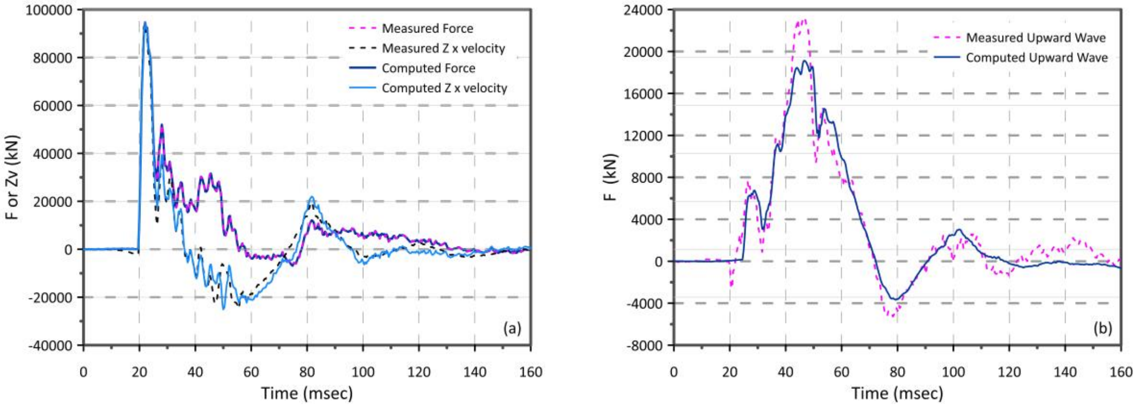


*Figure 1: Example of signal matching performed on an EOD blow using the measured force an input (a) force and Z x velocity (b) upward wave*

Pile driveability analysis can also be employed to back-analyse SRD using the hammer characteristics, driving records of transferred energy and blow counts as a reference, employing the same one-dimensional stress wave theory and soil resistance models. However, signal matching offers a more representative means of determining profiles of resistance with depth applying at particular stages during pile installation from single blows than driveability analyses, where the blow count profiles can only be used estimate the total pile resistances available at given stages of driving from the penetrations achieved per blow at that depth.

Given that multiple signal matching solutions exist for any given dynamic blow dataset, it is well accepted that static testing is the best way to verify dynamic pile tests (Svinkin, 2004). However, static testing is rarely feasible offshore due to its high costs and practical difficulties, making dynamic test interpretation an essential component of offshore pile design field monitoring. While dynamic testing is understood to be inherently more subjective and open to more variable outcomes than static pile testing, it is possible to reduce the potential spread of results by applying a standard, physically based, approach in all dynamic stress wave interpretations. Recent Joint Industry Projects (JIPs) have established suitable procedures for reducing the uncertainty in dynamic testing interpretation. Representative examples of such cases are presented and discussed in this paper.

*Wikinger Windfarm*

The development of the Wikinger windfarm in the German Baltic, involved novel static and dynamic testing which facilitated the design of seventy 5MW Wind-Turbine Generators (WTGs) and an Offshore Substation (OSS) that were installed in 2017, as detailed in Buckley et al (2020). Each WTG's jacket structure is founded on four 2.7m outside diameter, D, tubular driven steel piles, while the OSS relies on six 3.7m diameter piles. The piles penetrate through stiff/dense sandy and clay glacial tills over low-medium density chalk and in some cases, limestone (Barbosa et al., 2015a, Barbosa et al., 2015b). A joint industry project (JIP) involving the project developer Iberdrola, Imperial College and Geotechnical Consulting Group (GCG) supported the offshore research under the auspices of a UK Innovate research project, with parallel onshore pile experiments in chalk at St. Nicholas-at-Wade (SNW) in NE Kent, UK (Buckley et al. 2018a, Buckley et al. 2018b).

Field trials and testing, conducted before finalising the main project's pile design, advanced at Wikinger in two phases. The first 'pre-construction' piling campaign involved three locations where three 1.37m outside diameter steel tubular piles were driven using a Menck MHU 800S hammer. At each location, pile 1 was subjected to dynamic testing only, pile 2 was subjected to a static tension test and pile 3 was an un-failed reaction pile. Strain gauges and accelerometers were attached to piles 1 and 2. The second phase of testing involved instrumented dynamic driving of 2.7 to 3.7m diameter tubular steel production piles. Barbosa et al. (2015a) discussed the systems developed to meet the challenges of conducting the first remotely-controlled, full-scale, seabed offshore load tests, while Buckley et al. (2020) give a detailed account of the entire Wikinger testing programme.

The back analyses undertaken for blows recorded at different stages of pile installation at Wikinger, where performed with the research-oriented signal matching software IMPACT (Randolph, 2008). While the common practice in signal matching analysis is to examine only the End of Driving (EoD) blow, cases were considered that covered blows applied after operational driving pauses, Beginning of Restrike (BoR) blows after extended ageing periods, as well as continuous penetration for piles of different dimensions. A rigorous approach was developed for the analyses of the blows aimed at reducing the uncertainty associated with the signal matching analysis, which involved (i) selection of a consistent initial profile for the iteration process, computed with a CPT-based driveability method (ii) use of resistance models which are predominantly linked to measurable soil properties (iii) consistency checks for the employed parameters and the results between multiple adjacent blows as well between EoD and BoR blows (iv) checks for user and software variability.

The extensive dataset and related analysis of DPTs in Wikinger allowed to estimate the gains in pile capacity with time. Such gains were previously seen for piles driven in sands (e.g. Jardine et al 2006), but the signal matching analysis of the Wikinger data allowed assessment, for the first time, of how large driven piles set-up in chalk. Figure 2 shows an example of an increase in shaft resistance for a Wikinger chalk-dominated profile during an operational pause and the subsequent changes in shaft resistance with further driving blows. Furthermore, the back analysis through signal matching of the Wikinger data and of the parallel SNW campaign led to the new pile driveability prediction method for Chalk detailed in Buckley et al (2021), which was recently updated with the ALPACA and ALPACA Plus findings in Jardine et al (2023). The new driveability method gives estimates local radial effective stresses and short-term shaft resistances during continuous driving in chalk, as a function of local CPT cone resistances, the relative depth of the pile tip and the interface shearing angle.

Overall, the Wikinger JIP findings assisted the challenging design of the piles driven in chalk formations supporting the jacket structures, leading to considerable savings through elimination of project risks and reductions of the total pile lengths by an estimated 3km, with obvious associated savings in steel and CO2 emissions (Barbosa et al 2017).

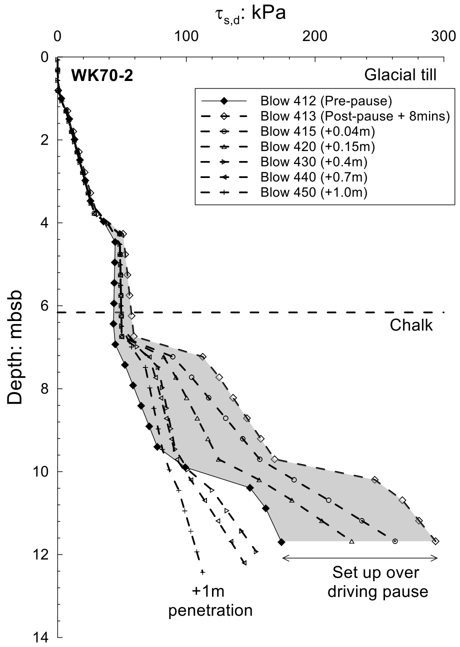


*Figure 2: Change in shaft resistance immediately following a driving pause and with subsequent driving adapted from Buckley et al (2020)*

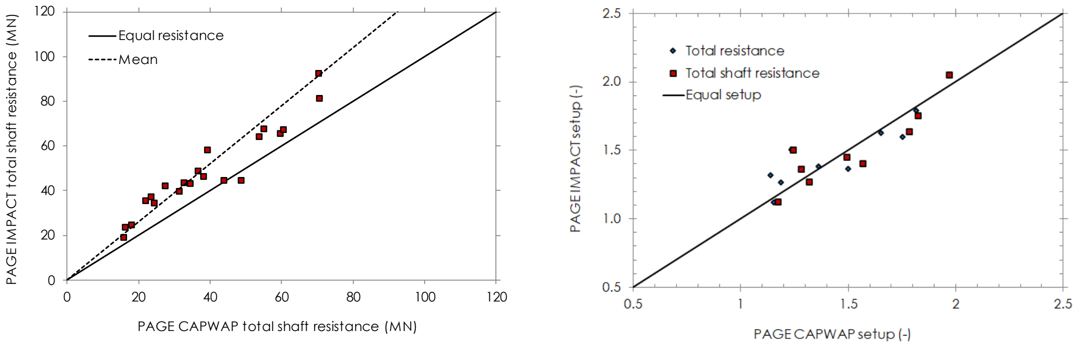
The Wikinger campaign is one of the scare offshore cases for which DPTs were conducted at the same time as parallel tension static load tests on identical 'virgin' piles. The resulting correspondence between the signal matching and the static testing was encouraging (Buckley et al. 2020), and was further explored in the subsequent ALPACA and ALPACA Plus JIPs which involved further DPTs and static tests onshore in chalk at SNW (Jardine et al 2023). Recently Wen (2023) developed a machine learning model which was trained on a database he compiled of 82 dynamic testing signals recorded on 52 tubular open-ended steel piles driven in chalk, including those driven at Wikinger and SNW, as well as three other chalk dominated sites. Wen (2023)'s model allows the estimation SRD for piles driven in chalk as a function of pile characteristics, soil properties and measured driving dynamic stress wave forms showing the potential in the application of machine learning in DPTs.

### *Pile setup in sand – the "PAGE" joint industry project*

The design reliability of offshore piles supporting jacket structures depends crucially on predictions of their long-term axial capacity. Although greater effort has been made over the years in to develop design procedures for piles driven in sands than, for example, in chalk which was only recently investigated, current databases of static load tests include only two entries of piles of with diameters D greater than 1m and none >2m (Cathie et al 2022). Also, most of the available tests were conducted at relatively early ages after driving. The **Pile** **Age**ing (PAGE) JIP (Cathie et al 2022) involved Cathie, GCG and Imperial College with funding from 8 industrial sponsors. The project's aim was to address this knowledge gap by collating a database of offshore dynamic tests on open, steel driven piles applying strict quality assurance and systematic, consistent, numerical re-analysis. The main outcome of the project is the establishment of trends for overall shaft resistance and total resistance setup, with the latter defined as the ratio of the BoR to EoD resistances based on 25 offshore piles with 1.6 to 3.4m outside diameters and covering periods of 1h and 1 year after driving.

A high-quality database was developed by assuring a) that the necessary pile details were known, b) the dynamic data quality was sufficiently high, and c) ground conditions were sufficiently well-characterised to facilitate reliable signal matching analysis. Systematic signal matching was performed with two independent codes that applied different soil models and the outcomes were compared with predictions from modern CPT-based static capacity design methods. The offshore pile study was complemented with re-analysis of data from two onshore research sites, and one nearshore site (Wen et al 2023), where both dynamic impact and static testing was conducted on comparable piles.

The analysis approach that was first established in the Wikinger project (Buckley et al 2020, 2021) was further developed in PAGE aiming to increase the reliability of signal matching predictions. After carefully assessing input data quality and rigorous checking of how the various dynamic analysis parameters affect the results obtained, standardised procedures were applied for all signal matching analyses. The shaft and bases SRD profiles were restricted to physically reasonable distributions, keeping all dynamic parameters within published recommended limits. To address model uncertainty one team employed the well-known CAPWAP (PDI, 2006) package exploring pile-soil models with and without radiation damping, while the other team adopted the research orientated code IMPACT (Randolph, 2008) which employs the Randolph and Simons (1986) shaft resistance model and the Deeks and Randolph (1995) base model.



(a) (b)

*Figure 3: Comparison of CAPWAP and IMPACT (a) total (internal and external) shaft resistance (b) setup factors (adapted from Cathie et al 2022)*

Figure 3 shows a comparison of the results obtained by both CAPWAP and IMPACT in terms of total (sum of inside and outside) shaft capacity and setup factors. The results indicate a consistent shaft resistance bias (Figure 3a) which is not apparent when considering the setup factors (Figure 3b). This demonstrates that setup is not as sensitive to the pile-soil interaction model adopted. The comparison also highlighted the higher uncertainty in the base predictions than in the shaft predictions which is due to mainly insufficient displacements to mobilise the pile's end bearing capacity during driving or restrike (Randolph 2003; Salgado et al. 2015). Cathie et al (2022) discusses the systematic differences in the derived resistances between the two codes (CAPWAP and IMPACT) and how these are linked to the different soil response models. Comparisons between static pile test axial resistance and CAPWAP/IMPACT did not indicate any clear superiority between the two and therefore both approaches were given equal weight for the derivation of the final setup trends. However, when the set was low (< 2.5mm), mainly in BoR cases, the IMPACT results were often significantly higher than CAPWAP and gave more plausible indicators of pile resistance. This probably derives from the more rigorous modelling of the energy dissipation into the soil mass in the continuum formulation used in IMPACT.

Overall, the careful re-analysis through signal matching of the collated 25 high-quality offshore cases provided the first database of pile capacity setup factors for large diameter offshore piles, for which no static pile test data is currently available, following a process that improved the reliability of signal matching predictions.

## Offshore foundations in seismic areas

### *Background*

The growing demand for renewable energy has resulted in a rapid, worldwide expansion of offshore wind installations in deeper waters and in areas of medium to high seismicity (e.g. Taiwan, China, Japan, USA) with structures of higher energy capacity. The first generation of offshore wind farms were located in areas of low seismicity, mainly in northern Europe, and therefore there is limited experience worldwide on how this type of structure would respond to seismic loading or to combined environmental and seismic loading.

Design performance requirements and code provisions with explicit reference to offshore structures under seismic loading conditions are under development, and only recently DNV-RP-

0585 published the first dedicated guidance for the seismic design of wind power plants. Due to the scarcity of offshore wind specific guidelines and of relevant past performance experience through historic seismic events, the existing seismic design guidance for other types of structures (e.g. buildings) or for onshore foundations is often adopted, although this is not always transferable to offshore conditions.

To avoid resonance under operational and environmental loading, wind turbine systems are normally designed to ensure that the first turbine tower frequencies are not excited by dynamic loads originating from the movement of the rotor (1P), the passing of the blades (3P) and environmental loads. These design considerations result in OWTs of rather low natural frequencies; for example Arany et al (2016) report for monopile-supported OWTs first vibration modes between 0.25-0.78Hz. While the exact frequency values are bound to vary depending on the turbine model and foundation type, these values indicate a frequency range that is not vulnerable to horizontal ground shaking of low intensity earthquakes. However, the local soil conditions under high intensity shaking can swift dramatically the system response to the frequency range in which horizontal ground motion is dominant (De Risi et al (2018), Möller et al (2023)). Such an example is shown herein for the case of a monopile-supported OWT within a liquefiable deposit based on work of Möller (2022) and Möller et al (2023). Furthermore, the natural frequency of OWTs in the vertical direction is much higher, (in the range of 4 – 7 Hz (Kaynia 2019), falling within the typical frequency spectrum of the vertical motion. Tsaparli et al (2020a) have also shown how resonance phenomena in the vertical ground motion can lead to large amplification at mudline level in a frequency range that is relevant to the vertical response of OWTs and of their components (e.g. nacelle). When considering the site response for the vertical component in an offshore environment, the water column as well as the full depth of soil profile to the engineering bedrock level should be considered to represent accurately the natural frequency of the soil-water system. In that respect, the potentially beneficial effect of de-amplification noted in offshore vertical ground motions for frequencies close to the natural frequency of the water column for P-waves should also be taken into account to avoid over-conservatism in the design (see Tsaparli et al 2020a).

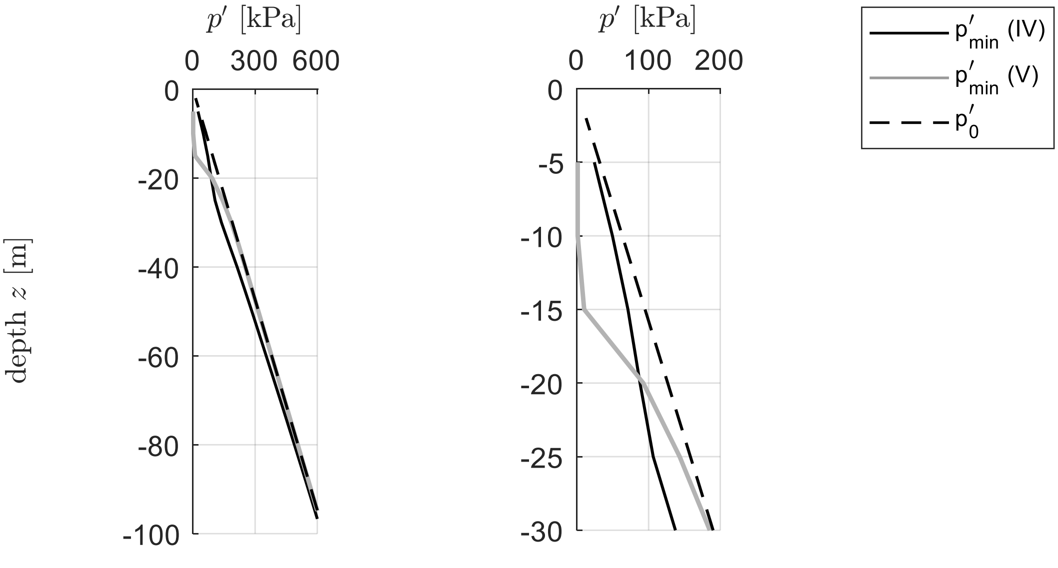
In terms of analysis methods, the time domain fully integrated analysis approach, in which the entire structure of the rotor-nacelle assembly, tower sub-structure and foundation are simulated within one model, is the most comprehensive one, but also rather cumbersome computationally. This approach is also technically challenging, as it requires combined expertise in structural and geotechnical modelling. Therefore, it is more common in practice to perform a sub-structuring analysis in which the turbine and the foundation are modelled separately, with the overall response simulated through iterations between the structural and geotechnical teams. In such cases, in the structural model of the tower, the foundation is typically represented by nonlinear springs or macro-elements (Kaynia 2019). The two major challenges in this type of macro-element-based models are (a) the realistic representation of damping (hysteretic and radiation) and (b) the definition of appropriate, multi-directional ground motions at the base of the structural model (mudline level) which encompass the influence of site effects. A further limitation of the sub-structuring approach is that liquefaction related phenomena and the associated soil-structure interaction cannot be captured accurately. Soil liquefaction is an important consideration for the safe design of OWT, which can be triggered by earthquakes, by impact pile driving resulting in ‘pile runs’ (e.g. Kourelis et al 2022) and in some cases by wave action (Ishihara & Yamazaki 1984). The consequences of liquefaction related to foundations range from loss of bearing capacity and excessive settlements, to loss of lateral stiffness and capacity with an associated modification of the dynamic characteristics of the entire SSI system; the latter is particularly relevant to monopile foundations and is discussed further herein.

### *Liquefaction at offshore sites*

Liquefaction is a major hazard for offshore wind farms, potentially affecting the OWTs’ foundations as well as the offshore power cables. The susceptibility assessment is mainly performed with the so-called stress-based methods, in which the factor of safety against liquefaction is defined as the ratio of the Cyclic Resistance Ratio (CRR) and the Cyclic Stress Ratio (CSR). The latter can be estimated through a simplified expression employing either the shear mass participation factor or through drained Site Response Analyses (SRAs). The shear mass participation factor $r_d$, is only valid for a maximum depth of 20 m (Idriss and Boulanger, 2008), which is a severe limitation for OWTs founded on jackets or monopiles where the foundation depths can reach 60-80m. Therefore, for such cases SRA is required for the estimation of CSR. Within the stress-based assessment method, the SRA should be conducted assuming drained conditions, while DNV-RP-

0585 suggests either equivalent linear or nonlinear SRA depending on the available data and expertise.

In the conventional liquefaction assessment framework, the CRR is estimated based on correlations of in-situ measurements (in terms of either SPT, CPT or Vs data) and the critical shear stresses known to have caused liquefaction during past earthquakes. Essentially, liquefaction resistance is depicted from case histories of surface manifestation of liquefaction at onshore sites which relate to liquefaction of soil layers close to the ground surface onshore. Currently there is limited field information and evidence regarding subsea liquefaction and/or liquefaction at large depths. Therefore, for offshore sites it is important to assess CRR based on laboratory tests (cyclic simple shear, cyclic triaxial) despite the difficulties encountered in sampling undisturbed sand samples.



(a) (b)

*Figure 4: Minimum mean effective stress $\boldsymbol{p'_{min}}$ and initial mean effective stress $\boldsymbol{p'_0}$ for Analyses IV (BSPM only) and V (BSPM + cyclic nonlinear) (a) full profile (b) zoomed in upper 30m (modified from Möller et al 2020)*

Alternatively, the liquefaction assessment can be based on SRA employing a fully coupled dynamic finite element formulation and adopting appropriate and well-calibrated constitutive models for the simulation of the various strata. This type of approach can give a better physical insight of the response and has general applicability, but it requires extensive laboratory characterisation and expertise for the model calibration and use. Möller et al (2020) investigated numerically the occurrence of liquefaction for profiles of large depths and note the importance of choosing an appropriate constitutive model for such SRA. They showed that bounding surface plasticity models (BSPM), which are widely used for the simulation of liquefaction, can suffer from overestimation of the dissipated energy when used in site response analyses of deep deposits. This leads to non-conservative predictions with an underestimation of the liquefaction depth. An example of the findings of Möller et al 2020 is shown Figure 4, which plots the mean effective stress profiles (initial $\boldsymbol{p'_0}$ and minimum $\boldsymbol{p'_{min}}$ recorded during the analysis) computed with a fully coupled SRA for a deep stratigraphy of 100m of Nevada sand. For the considered case herein rhe profile was subjected to a seismic record from the Lotung 1986 $M_L$ 6.5 earthquake. Analysis IV was conducted with a BSPM (Tsaparli 2017, Tsaparli et al 2020b) for the entire profile, whereas for analysis V only the upper 20m were simulated with the BSPM, while the remaining 80m were simulated with a cyclic nonlinear model of Taborda & Zdravkovic (2012). The latter model can depict well hysteretic behaviour, but it cannot simulate liquefaction related phenomena. Cleary no liquefaction is observed in analysis IV using only the BSPM, while the top 10 m of sand are fully liquefied ($\boldsymbol{p'_{min}} = 0$) when the cyclic nonlinear model is employed for part of the deposit (i.e. Analysis V). These differences stem from the overestimation of the dissipated energy in the deeper layers by the BSPM which leads to lower stresses close the surface layers. In such cases a careful combination of constitutive models is needed, for example with a selection of a model that can simulate well hysteretic response (e.g. Taborda & Zdravkovic 2012) for the deeper layers and a BSPM type of model (e.g. Taborda et al 2014) for the simulation of liquefaction of any remaining layers.

*Monopile analysis in liquefiable deposits*

As previously discussed, under high intensity shaking the local soil conditions can swift dramatically the entire system response to a frequency range in which horizontal ground motion is dominant. Möller et al (2023) demonstrated the impact of low frequency amplification in liquefiable deposits employing as an example a 5 MW reference turbine (Jonkman et al. 2009), supported by a transition piece and monopile foundation (Figure 5). The geometry of the turbine and transition piece were simplified, while the ground stratigraphy of 100m depth includes a layer of Fraser River sand (40m of two distinct densities) over a bottom layer of a stiff marine clay (60m thickness). The sand layer was simulated with a BSPM (Tsaparli 2017, Tsaparli et al 2020b), while the clay was simulated using an enhanced modified Cam Clay model with a Hvorslev surface (Tsiampousi et al. 2013) in combination with a cyclic nonlinear elastic model (Taborda & Zdravkovic 2012). Fully-coupled dynamic finite element analyses were performed for six carefully selected motions, aiming to represent seismic areas where wind farm developments may be potentially located (Taiwan, USA, Canada and Japan). More details about the numerical model arrangements can be found in Möller (2022) and Möller et al (2023).

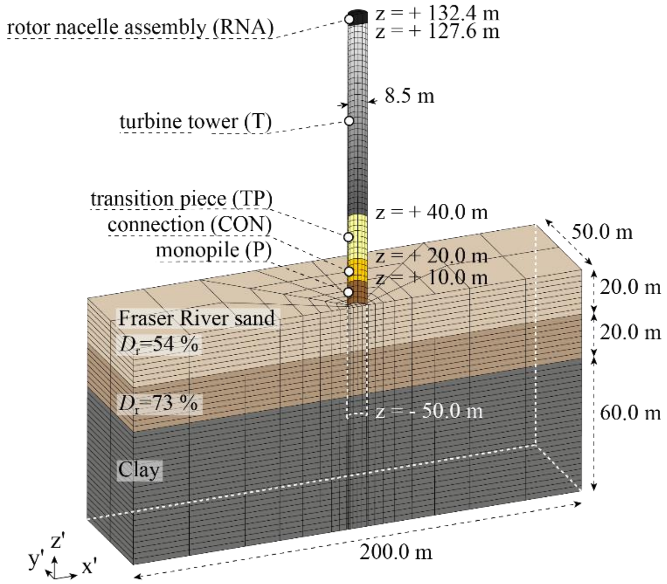
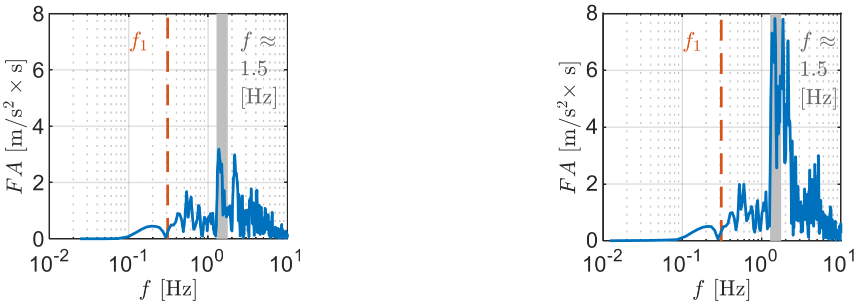


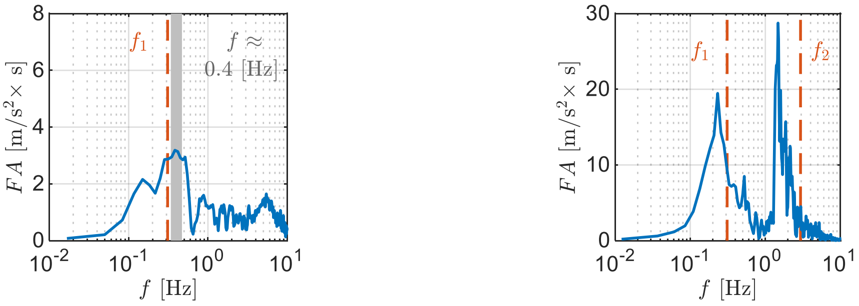
Figure 5: Simplified turbine substructure system: geometry, ground stratigraphy and finite element mesh (from Möller et al 2023)

For the analysis considered herein the system was subjected to a record from the1995 Kobe earthquake, with response indicating full liquefaction of the top 40 m of the deposit. Figure 6 (a,b,c) plots the free-field accelerations obtained from the left-hand side mesh boundary at various depths, with their predominant frequencies indicated in grey. From the base excitation shown in Figure 6(a) to the top of the stiff clay strata at $z = -40.0$ m (Figure 6b), the motion is strongly amplified near the peak input frequency of 1.5 Hz. Further up into the liquefied sand layers there is a gradual shift to lower frequencies (not shown herein for brevity), while near the soil surface at $z = -2.5$ m, the motion is highly dissipated and is dominated by frequency components near 0.4Hz. Included for comparison is the first fixed-base turbine tower frequency $f_1$ of the side-side vibration mode, which lies close to this peak at 0.31Hz, Jonkman et al. (2009). Figure 6d plots the corresponding Fourier acceleration spectrum of the RNA mass at the top of the wind turbine tower. Compared to the fixed-base turbine tower frequencies of the 1st and 2nd modes of vibration after Jonkman et al. (2009), a period elongation is depicted due to the compliance of the soil-foundation system. Overall the results show an excitation of the second vibration mode, as well as a strong response near the first resonance frequency of the turbine tower.



(a) z=-100.0m

(b) z=-40.0m



(c) z=-2.5m

(d) turbine tower

*Figure 6: Fourier amplitude spectra against first ($f_1 = 0.31$ Hz) and second ($f_2 = 2.94$ Hz) fixed-based tower frequencies of the reference turbine; (a,b,c) free-field response at various depths (d) turbine tower response (modified from Möller et al 2023)*

## Concluding Remarks

Dynamic analysis plays an important role in various design aspects of offshore wind installations worldwide. Focusing on offshore geotechnical applications and recent experience from JIPs, it was shown that the uncertainties in dynamic pile testing interpretation can be reduced when adopting consistent analysis processes leading to more reliable estimates of static axial pile capacity for the design of jacket structures. This was first shown for the case of the Wikinger OWTs, where an extensive dataset and related analysis of DPTs allowed to estimate the gains in pile capacity with time in challenging ground conditions of chalk dominated profiles.

The processes established in Wikinger were further developed in the PAGE JIP which collated a database of offshore dynamic tests on open, steel driven piles in sands applying strict quality assurance and systematic, numerical re-analysis. The careful re-analysis through signal matching of the collated 25 high-quality offshore cases provided the first database of pile capacity setup factors for large diameter offshore piles in sands, for which no static pile test data is currently available, following a process that improved the reliability of signal matching predictions.

Turning into the development of OWTs in seismic areas, it becomes apparent that there is a lack of guidance for their design performance requirements, and limited experience worldwide on how this type of structures would respond to seismic loading or to combined environmental and seismic loading. Focusing on the geotechnical aspects, the empirical liquefaction assessment methodologies which are well-established for shallow onshore profiles have limited applicability at the deep profiles encountered in offshore pile design. While some adjustments are possible through site-specific laboratory testing, advanced numerical analysis offers a rigorous alternative for the liquefaction assessment in such conditions. It was shown though that a careful combination of constitutive models is needed, for example with a selection of a model that can simulate well hysteretic response for the deeper layers and a BSPM type of model for the simulation of liquefaction of any remaining layers to avoid issues of overestimation of the dissipated energy which is associated with an underestimation of the extent of liquefaction.

An important consequence of soil liquefaction for OWTs was also highlighted as it was shown that low frequency components of seismic shear waves propagating through deep deposits can be amplified through soil liquefaction, resulting in a significant frequency swift of the entire OWT system. The dynamic finite element analyses showed that the resonant frequencies of the analysed OWT were excited for the Kobe earthquake ground motion, inducing significant nonlinearity in the soil surrounding monopile foundations. These findings highlight the potential vulnerability to seismic shaking of OWTs in liquefiable deposits through excitation of their resonance frequencies.

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## References

Arany L., Bhattacharya S., Macdonald J.H.G., Hogan S.J. (2016) Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI, Soil Dynamics & Earthquake Engineering, Vol. 83,pp.18-32 https://doi.org/10.1016/j.soildyn.2015.12.011.

Barbosa P. M., Geduhn, M., Jardine, R. J. & Schroeder, F. C. (2017). Large scale offshore static pile tests-practicality and benefits. Proc. 8th Int. Conf. on Offshore Site Investigation and Geotechnics, London, UK: 644-651

Barbosa P., Geduhn, M., Jardine, R. J. & Schroeder, F. C. (2015b). Full scale offshore verification of axial pile design in chalk. Proc. Frontiers in Offshore Geotechnics III, Oslo, Norway: 516-520

Barbosa P., Geduhn, M., Jardine, R. J., Schroeder, F. C. & Horn, M. (2015a). Offshore pile load tests in chalk. Proc. 16th Eur. Conf. Soil Mech. Geotech. Eng., Edinburgh, Scotland: 2885-2890

Buckley R. M., Jardine, R. J., Kontoe, S. & Lehane, B. M. (2018a). Effective stress regime around a jacked steel pile during installation ageing and load testing in chalk. Can. Geotech. J., 55, No. 11: 1577-1591.

Buckley R. M., Jardine, R. J., Kontoe, S., Barbosa, P. & Schroeder, F. C. (2020). Full-scale observations of dynamic and static axial responses of offshore piles driven in chalk and tills, Géotechnique Vol. 70, 657–681. https://doi.org/10.1680/jgeot.19.TI.001.

Buckley R. M., Jardine, R. J., Kontoe, S., Parker, D. & Schroeder, F. C. (2018b). Ageing and cyclic behaviour of axially loaded piles driven in chalk. Géotechnique, 68, No. 2: 146-161.

Buckley, R., Kontoe, S., Jardine, R. J., Barbosa, P., & Schroeder, F. (2021) Pile driveability in low-to-medium density chalk. Canadian Geotechnical Journal. Vol. 58(5), pp. 650-665. doi:10.1139/cgj-2019-0703.

Cathie, D., Jardine, R. J, Silvano, R., Kontoe, S. & Schroeder, F. (2022). Pile setup in sand – the "PAGE" joint industry project. Keynote paper. Proc. 11th International Conference on Stress Wave Theory and Design and Testing Methods for Deep Foundations, Rotterdam, September.

De Risi R., Bhattacharya S. & Goda K. (2018) Seismic performance assessment of monopile-supported offshore wind turbines using unscaled natural earthquake records, Soil Dynamics and Earthquake Engineering, Vol. 109, pp.154-172, https://doi.org/10.1016/j.soildyn.2018.03.015.

Deeks A. J. & Randolph, M. F. (1995). A simple model for inelastic footing response to transient loading. Int. J. Num. Meth. Geotech. Eng., 19, No. 5: 307-329.

DNV-RP-0585 (2021) Seismic design of wind power plants. August 2021 Edition.

Idriss, I.M., Boulanger, R.W., 2008. Soil liquefaction during earthquakes. Earthquake Engineering Research Institute, Oakland, CA.

Ishihara K. & Yamazaki A. (1984) Analysis of wave induced liquefaction in seabed deposits of sand, Soils & Foundations, Vol. 24 (3), pp.85-100.

Jardine, R., Buckley, R., Liu, T., Andolfsson, T., Byrne, B., Kontoe, S., McAdam, R. A. Vinck, K. , Schranz, F. (2023). The axial behaviour of piles driven in chalk. Accepted for publication in Geotechnique.

Jardine, R.J., Standing, J.R., Chow, F.C., 2006. Some observations of the effects of time on the capacity of piles driven in sand. Géotechnique 56, 227–244.

Jonkman, J., Butterfield, S., Musial, W., Scott, G. (2009). Definition of a 5-MW Reference Wind Turbine for Offshore System Development (No. NREL/TP-500-38060, 947422).

Kaynia, A.M. 2018. Seismic considerations in design of offshore wind turbines. *Soil Dynamics and Earthquake Engineering* **124**, 399–407.

Kourelis, I., Kontoe, S., Buckley, R., & Galbraith, A. (2022) An assessment of pile driveability analyses for monopile foundations. In Proceedings of the 11th International Conference on Stress Wave Theory and Design and Testing Methods for Deep Foundations (SW2022),. Rotterdam, The Netherlands. doi:10.5281/zenodo.7148970.

Möeller, J. K., Kontoe, S., Taborda, D., & Potts, D. (2020) “Maximum depth of liquefaction based on fully-coupled time domain site response analysis” 4th International Symposium on Frontiers in Offshore Geotechnics. Austin, Texas.

Möller J., Kontoe S., Taborda D. & Potts D. (2023), Resonance in offshore wind turbine systems due to seismic loading and extensive soil liquefaction, Proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering, 26-28 June 2023, London, UK. doi: 10.53243/NUMGE2023-126

Möller, J.K. (2022) Seismic response of monopile foundations for offshore wind turbines in liquefiable deposits (PhD thesis). Imperial College London.

PDI (2006). CAPWAP-Case pile wave analysis program.

Randolph M. F. & Simons, H. A. (1986). An improved soil model for one-dimensional pile driving analysis. Proc. 3rd Intl. Conf. Numerical Methods in Offshore Piling, Nantes, France: 3-17.

Randolph, M.F. (2003). Science and empiricism in pile foundation design. Geotechnique 53, 847–875.

Randolph, M.F., 2008. IMPACT - Dynamic analysis of impact driving - User manual for version 4.2 (Feb 2003 release).

Salgado, R., Loukidis, D., Abou-Jaoude, G., Zhang, Y. (2015) The role of soil stiffness non-linearity in 1D pile driving simulations, Géotechnique, Vol. 65 (3), pp. 169-187. doi :10.1680/geot.13.P.124.

Svinkin, M. R. (2004). Some uncertainties in high-strain dynamic pile testing. Proc. Geo Trans 2004, Los Angeles, California, pp. 705-714.

Taborda, D.M.G., Zdravkovic, L. (2012). Application of a Hill-Climbing technique to the formulation of a new cyclic nonlinear elastic constitutive model. Computers and Geotechnics 43, 80–91.

Taborda, D.M.G., Zdravković, L., Kontoe, S., Potts, D.M. (2014). Computational study on the modification of a bounding surface plasticity model for sands. Comput. Geotech. 59, 145–160.

Tsaparli, V. 2017. Numerical modelling of earthquake-induced liquefaction under irregular and multi-directional loading (PhD thesis). Imperial College London.

Tsaparli, V. V., Kontoe, S., Taborda, D. M. G., & Potts, D. M. (2020b) “A case study of liquefaction: demonstrating the application of an advanced model and understanding the pitfalls of the simplified procedure”, Géotechnique, Vol. 70 (6), pp. 538-558, doi:10.1680/jgeot.18.p.263.

Tsaparli, V., Kontoe, S., Taborda, D., & Potts, D. (2020a). “Resonance as the source of high vertical accelerations: field demonstration and impact on offshore wind turbines” 4th International Symposium on Frontiers in Offshore Geotechnics. Austin, Texas.

Tsiampousi, A., Zdravković, L., Potts, D.M. (2013). A new Hvorslev surface for critical state type unsaturated and saturated constitutive models. Computers and Geotechnics 48, 156–166.

Wen K. (2023) Dynamic and Monotonic Axial Loading Responses of Pile Driven for Offshore Wind Turbines, PhD thesis, submitted, Imperial College London, UK.

Wen, K., Kontoe, S., Jardine, R.J., Liu, T., Cathie, D., Silvano, R. , Prearo C., Wei, S. , Schroeder, F.C. , Po, Stanislas (2023). Assessment of time effects on capacities of large-scale piles driven in dense sands. Canadian Geotechnical Journal, https://doi.org/10.1139/cgj-2022-0060.