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Soil modelling impact on the natural frequency of offshore wind turbines with reference to in-field measurements

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ABSTRACT: The natural frequency of the first bending mode of monopile-founded offshore wind turbines (OWTs) is decreasing along with the general trend of increasing turbine size. In addition, it is observed that in some cases the natural frequency starts to approach the rotor 1P frequency, which may trigger an increase in (wind) fatigue loading due to resonance effects. To mitigate this risk there are various options such as adjusting the support structure design by increasing the diameter and/or wall thickness, but this has a direct impact on the Capital Expenditures (CAPEX). Alternatively, enhancing soil-stiffness in engineering models allows to minimise the reliance on additional steel in the design. Evaluation of in-field frequency measurements from various offshore wind farms indicates a consistent trend: natural frequencies estimated during the design phase are often lower than the frequencies measured under in-situ conditions. A portion of observed “frequency gap” can be attributed to uncertainties and conservative assumptions in geotechnical design aspects, such as soil interpretation, soil-structure interaction modelling methods, presence of a scour protection system, installation and pile-soil interface ageing effects. Using measurements from several installed OWTs, this study demonstrates how addressing these factors during the design process can help bridge the frequency gap. Furthermore, this paper aims to feed a community-wide discussion on the extent to which the reported findings can be incorporated in the design phase of offshore wind support structures. The overarching goal is to achieve more accurate estimate of the natural frequency, reducing design conservatism, optimising steel usage, and minimising associated project costs.

Keywords: Monopile; Measurement; Natural frequency; Design optimization

1 INTRODUCTION

As Original Equipment Manufacturer (OEM) Siemens Gamesa Renewable Energy (SGRE) has access to in-field measurement data of the Offshore Wind Turbines (OWTs) resonance frequency over a large range of projects, covering various geographical locations, soil types, turbine types, water depths etc. This paper presents a comparison between in-field measured frequencies and the design natural frequencies. A consistent trend of underestimating the natural frequency in the design phase of an OWT, i.e., a “frequency gap” relative to the in-place measured frequency, can be seen from this comparison. Similar work has been done previously on a project-specific basis (e.g. Andersen et al., 2020; Sastre Jurado et al., 2022).

Understanding the factors that control the accuracy of estimating the OWT’s first (and second) frequency in design is relevant for several reasons:

- The natural frequency and other modal properties (such as mode shape) play a key role in the OWT loads and hence design. Improving the accuracy may result in a reduction of conservatism while maintaining a robust design.
- In case the first natural frequency approaches the rotor 1P nominal rotational frequency there is a risk for increased resonance and subsequent increase in Fatigue Limit State wind loads. To mitigate this risk, often the design is stiffened up by increasing diameter and/or wall thickness of the support structure.
- The natural frequency is also a key parameter in relation to the dominant frequency of a wave spectrum. Uncertainties around it may lead to either conservatively high wave loads or even a non-conservative underestimation of wave loading.

While it is recognized that there may be multiple sources for this frequency gap, this paper introduces an approach to evaluate the impact of a set of geotechnical effects that may impact the soil stiffness via a "p-multiplier" on the design p-y curve. This set of geotechnical effects are:

- Upper bound (UB) soil stiffness
- Scour protection system (SPS)
- Installation effects

Although accounting for these effects reduces the frequency gap, it is also observed that geotechnical effects alone are not likely to be the only contribution to this frequency gap and other sources play a role.

This paper is meant to feed a community-wide discussion on to what extend some of the reported findings can already be considered in the design phase of offshore wind support structures to provide a more realistic estimate of the natural frequency, reducing the need of extensive structural steel to stiffen-up these structures. Section 2 discusses the comparison between measured and as-designed first bending mode frequencies. Section 3 analyses the key factors influencing the system's computed natural frequency and presents a comprehensive approach to assess the effect of geotechnical factors among various projects. Lastly, Sections 4 and 5 outline the study's outlook and conclusions.

2 NATURAL FREQUENCY EVALUATION

2.1 SCADA measurements & eigenfrequency estimation

In the offshore wind industry, all turbines are typically equipped with a Supervisory Control and Data Acquisition (SCADA) system. The system measures signals which are relevant for the turbine controller and involve power, rotor speed, pitch angle, nacelle direction as well as ambient data like wind speed and wind direction. In addition, vibrations at the nacelle frame of reference (i.e. along and perpendicular to the main wind direction) are recorded with accelerometers located at the nacelle bedframe. The first bending mode frequency is estimated based on discrete Fourier transformation of the notch-filtered nacelle-based acceleration signal to compensate for the harmonic content. The frequency estimator is used for multiple control operations and field validation of the feature has been performed and benchmarked (Guntur et al., 2017).

2.2 1D beam-spring model description

For comparison with the measured frequencies, in-house design tools and numerical models have been employed. The primary steel structure is modelled with one-dimensional (1D) Timoshenko beam elements, with the stiffness and mass being determined by the diameter and wall thickness variation along the support structure. Secondary structures, attachments and marine growth are modelled as point or distributed masses. The rotor-nacelle assembly (RNA) is modelled as a concentrated mass with mass moment of inertia. Entrained and displaced water are considered as additional masses as well as the soil plug inside the monopile. The gravity of the RNA and resulting secondary moment ("P-Delta effects") are also accounted for.

Soil-structure interaction is modelled via lateral soil reaction curves under the Beam-on-Winkler-Foundation (BWF) framework. The monopile is connected to the surrounding soil through lateral load-displacement springs ('p-y' along the pile shaft), as depicted in Figure 1. Each spring describes the local lateral soil reaction upon a local pile lateral deflection. This is not the case for clamped models in which the structure is treated as a cantilever beam, clamped at mudline.

The assessed support structures' dimensions and characteristics are based on data used in the final design verification load iterations and, in some cases, as-built material, such as drawings. Therefore, the models represent the best of current knowledge for the systems as-built.

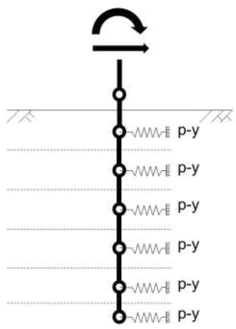

Figure 1: Impression of the 1D FE model employed in this study.

2.3 Result overview

The main characteristics of the dataset employed for the frequency comparison are outlined in Table 1. This dataset encompasses a representative array of contemporary turbine types, typical water depth ranges and monopile mudline diameters pertinent to SGRE's primary offshore market regions. For the purpose of analysing solely the impact of geotechnical factors (by means of soil springs modifications) on the design frequency, a selected subset of the studied cases is utilised.

Table 1. Overview of evaluated cases.

	Full database of final design cases	**Selected subset with soil spring modifications**
No. of OWT locations	47	37
No. of projects	22	15
Continents	Europe, Asia, North America	Europe, Asia
Turbine types	6 to 14 MW platforms	
Water depths [m]	18.5 - 47.6	
Monopile mudline diameters [m]	6.5 - 10	

A comparison of the measured frequency ($f_{measured}$) with the design frequency (f_{design}) for the full dataset (47 OWT locations, depicted by the Location Index) is shown in Figure 2. Note that the median measured value is used as reference, while the lower and upper quartile values are also provided. It is observed that the measured frequency is higher than the design frequency in all cases. Similar comparisons have been conducted for single design positions at selected wind-farm projects (Andersen et al., 2020) (Sastre Jurado et al., 2022).

The frequencies (design or clamped) are compared by the means of a relative error (ϵ_{rel}) to the median of the measured frequency in production (Eq. 1).

$$\epsilon_{rel} = \frac{f_{design}}{f_{median\ measured}} \qquad (1)$$

With: f_{design}: Natural frequency of the first bending mode applying the static model described in Section 2.2; $f_{median\ measured}$: Median value of the first bending mode frequency derived as described in Section 2.1.

As a result from the dataset comparison, there is a systematic underestimation of the natural frequency in the design phase. Design frequencies reach between approx. 85 and 97 % of the measured values in the dataset. Though this error (both in percentage as well as in mHz) appears small, the impact on fatigue loads may be significant.

Potential reasons for differences might be attributed to general project-specific level of conservatism, project-specific soil conditions, approach on soil interpretation and soil spring calibration (e.g. codified method vs. 3D FE calibrated method), applicability of scour protection systems, installation-related parameters, wind turbine type. Hence, a notable share of the observed frequency gap may arise from uncertainty and conservative assumptions in geotechnical design.

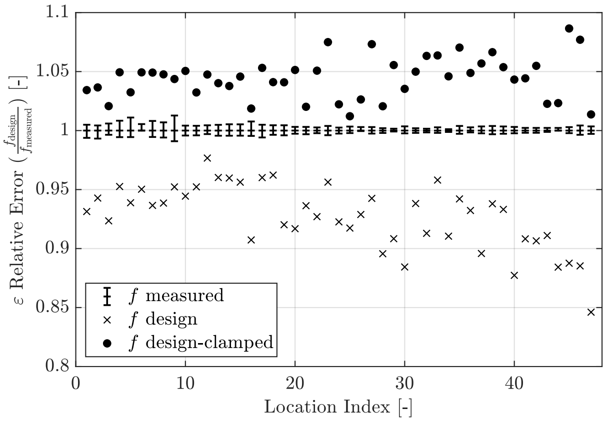

Figure 2: Overview of relative error of design to measured natural frequency of the first bending mode over Location Indices

A way to check the sensitivity on soil-impact is to focus on the frequency of the models that are clamped at mudline ($f_{design\text{-}clamped}$). This is a theoretical extreme case in which the soil is assumed to be infinitely stiff. The comparison of measured frequency ($f_{measured}$) with clamped frequency in Figure 2 reveals that the measured frequencies are systematically lower than the clamped frequencies. The proximity of the clamped frequency to the measured frequency indicates how likely it is to bridge the "frequency gap" with geotechnical optimisations alone. For instance, $f_{design\text{-}clamped}$ is closer to $f_{measured}$ for the Location Indices 3 than 4. This might be an indication that purely soil-related enhancements are not sufficient to bridge the 'frequency gap' and other factors may play a crucial role (see Section 3.1) to reach the $f_{measured}$ for Location Index 3, since the clamped frequency, that represents the extreme case in terms of soil stiffness, is close to the measured frequency. Additionally, the difference between clamped ($f_{design\text{-}clamped}$) and design ($f_{design}$) frequency can directly be related to the soil stiffness: if the difference is small (e.g. Location Index 2), the soil is rather stiff and hence less optimisation on the soil-side is to be expected.

The spread of the frequency discrepancy in a single wind farm, as depicted in Figure 3, suggests that the frequency mismatch cannot only be attributed to factors that are uniform across a project, for example design assumptions and modelling approach. The observed spread in the two exemplary wind farms points to position-specific impact factors such as: the variability in local soil conditions and their interpretation, the geometry of the as-placed SPS or installation-related variations.

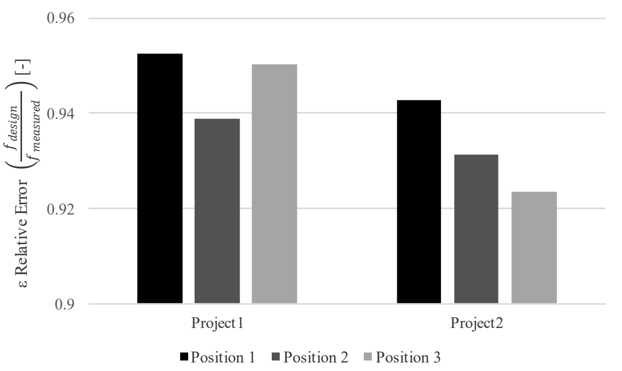

Figure 3: Frequency gap variation across three positions within two exemplary projects

3 INFLUENCE FACTORS ON SYSTEM FREQUENCY

To gain more insights into the sensitivity of design frequency, impact factors on the natural frequency are gathered and evaluated for a selected subset of projects (Table 1).

3.1 Potential impact factors

Potential impact factors that can influence the eigenfrequency are listed below. These factors can be categorized into geotechnical-related factors, which are the primary focus of this study, as well as additional factors associated with the support structure, hydro-related influences, and modelling considerations.

Geotechnical-related factors:
- Soil interpretation
- Scour protection system (if applicable)
- Installation method
- Long-term / ageing effects
- Soil structure interaction / soil spring calibration

Structural-related factors:
- Mass & inertia of the Rotor Nacelle Assembly
- Structural mass / plate thickness (tower and foundation)
- Stiffness of structure and connections
- Secondary structures (e.g., dampers, boat landing)

Hydro-related factors:
- Water level / depth variation
- Marine growth

Modelling-related factors:
- Added soil and water mass
- P-delta effects

For the geotechnical impact, the soil interpretation is by definition dealing with uncertainties related to local variation of the soil characteristics or the employed testing method. Typically, a (cautious) best estimate interpretation is used for assessing the natural frequency. More progressive interpretations, specifically for the small strain shear modulus G_0 (e.g. based on insitu tests like seismic CPT or PS logging techniques) can increase the design frequency.

Scour protection systems are widely used offshore and can have an effect on the overburden pressure as well as a stiffening effect if they are directly in contact with the pile and allow for transmitting loads (Mayall, 2019), (Winkler et al., 2023). However, due to the inability to guarantee the presence these effects over the entire service life of the structure, they are typically not incorporated into the design process. Nevertheless, these factors may still influence the measured frequencies.

Similar considerations apply to installation as well as long-term and ageing effects. A densification of the soil around a driven pile would increase the lateral stiffness of the system (Pisanò et al., 2024) and therefore its natural frequency, but this effect may deteriorate over the lifetime. Furthermore, ageing effects at the monopile-soil interface may develop over lifetime and could also lead to higher frequencies (Jardine, 2023). Ultimately, modelling the soil-structure interaction using BWF (see Section 2.2) for conventional engineering purposes may introduce a conservative bias. Utilizing advanced three-dimensional (3D) finite element (FE) models and calibrating the lateral soil reaction based on these models can partially alleviate this conservatism. However, even with 3D-FE-calibrated springs, the initial stiffness characteristics of the monopile-soil system may not be accurately represented by the 1D beam-spring model.

3.2 Assessment of selected projects

The influence of the geotechnical-related components is assessed for several design positions across five selected projects. The objective is to quantify the effects and generalize the findings to a broader range of projects. This methodology allows for an approximate estimation of the potential soil impact on the discrepancies between measured and design frequencies.

The geotechnical-related factors mentioned in Section 3.1 are modelled via 3D-FE using PLAXIS 3D. The latter are used to calibrate the 1D beam-spring models (see Section 2.2). Emphasis is put on the accurate calibration of the system's initial stiffness.

To ensure comparability and facilitate easy application to other projects, the calibrated lateral soil reaction is matched by an equivalent soil stiffness multiplier. For this purpose, the distributed lateral soil reactions curves are multiplied with a depth-independent "p-multiplier" as depicted in Figure 4. The multiplier is selected to match the natural frequency of the 1D model, calibrated based on the 3D FE model, with that of the 1D system using the "equivalent" soil reaction. In principle, there is no need to adapt the entire soil reaction curve, but only the initial part. Nevertheless, a "p-multiplier" is a simple method that can easily be applied on any kind of monotonic soil reaction curve. It must also be noted that the impact of this is reduced slightly if design springs include tip springs or rotational springs, although the lateral distributed py-spring is typically still the most dominant one for the overall pile-soil response in the integrated load analysis (ILA) design process.

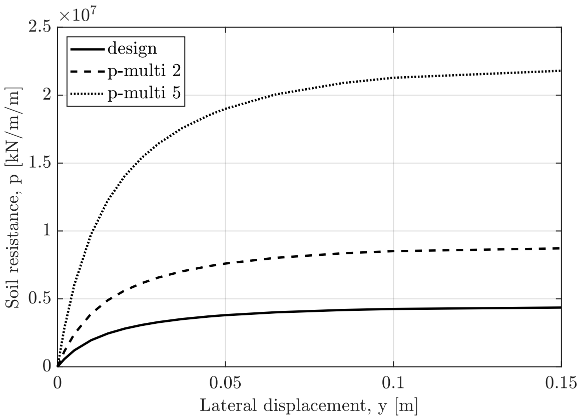

Figure 4: Example for the application of p-multipliers, equal to 2 and 5, on the design p-y curve

Figure 5 presents the selected values of the "p-multiplier" for upper bound or high estimate soil interpretation, modelling SPS and installation effects. Additionally, it shows the multipliers for a case lumping all or selected of these effects in a model. The data suggest that there is variability in the effect between the individual impact parameters as well as between the analysed cases per single impact parameter. Especially for the lumped set, the p-multiplier varies between 2 and 10 depending on the project and position specific conditions. For the impact parameters, both UB soil interpretation and installation effects lead to similar multipliers, up to 2. The impact of the SPS depicts a larger spread between approximately 2 to 4 reflecting a wide range of geometry, material parameters and employed modelling techniques. Although detailed information on these aspects is not provided due to space constraints, the authors suggest that the key factor is the variability in the "p-multiplier" values. The observed range highlights the influence of the SPS on the system's stiffness and computed natural frequency (refer to Section 3.4).

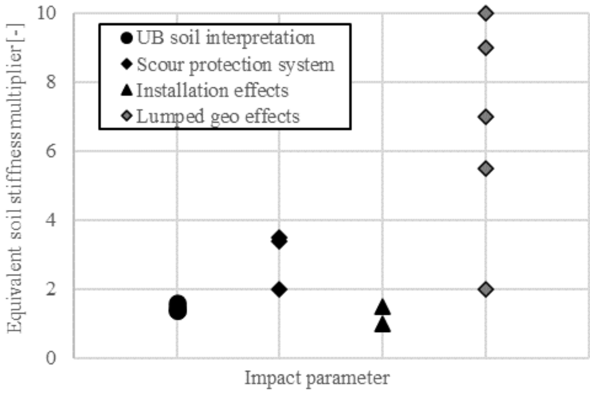

Figure 5: Equivalent soil stiffness multipliers derived for selected design positions. Lumped multipliers combine effects.

3.3 Identification of representative soil spring multipliers

For the generalisation of the findings from Section 3.2 (frequency impact on individual positions) to the reduced dataset (right column in Table 1), soil spring multipliers are selected as an indicative proxy as outlined in Section 3.2.

Detailed information and background (e.g. as-built geometry, SPS geometry, soil data) are often not completely available or known during design stages; simplified assumptions are applied on the dataset for a general indication and sensitivity.

In this sense, a p-multiplier of 1.0 corresponds with the current industry practice for design, which includes best estimate soil interpretation with 3D-FE calibrated springs, but without consideration of the geotechnical-related effects analyse in Section 3.2.

A 'high geo scenario' is represented by a p-multiplier of 2.0 which resembles a limited extend of the impacts described in Section 3.2. Considering the fully lumped effects as an 'upper bound geo scenario' can be generalized with a p-multiplier of 10.0.

Note that application of the multipliers on the selected subset of design cases (Table 1) neglects the sensitivity of the multiplier on project and position specific features.

3.4 Impact of geotechnical adaptions

Application of the p-multipliers on the selected subset of design cases (Table 1) yields the result shown in Figure 6. In all cases, the design frequency with the highest p-multiplier of 10 is below the measured frequency. This suggests that by only considering the geotechnical-related factors discussed in Section 3.1 the frequency gap cannot be bridged. Therefore, a conclusion is that it is very unlikely to associate the mismatch between design and measured frequency to only geo-related uncertainties.

The individual impact of the soil stiffness multipliers varies across different locations. However, a general trend is observed: when the relative error between the design and measured frequencies is originally small, the benefit of applying the p-multiplier is also limited (e.g., compare location indices 4 and 20 in Figure 6). On the other hand, it also becomes evident, that increasing the soil stiffness in a reasonable range as explained in Section 3.2 significantly reduces the observed relative error.

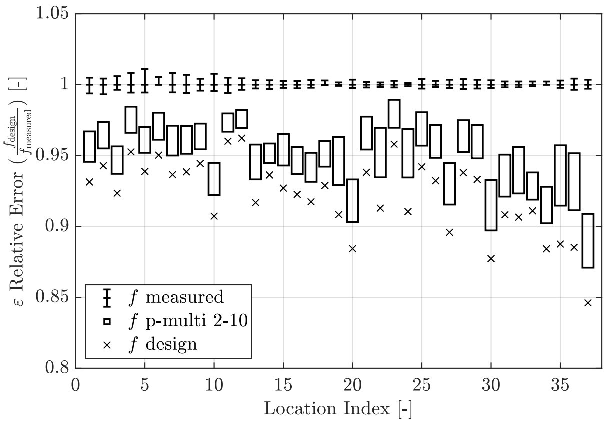

Figure 6: Comparison of design frequency including p-multipliers with measured natural frequencies

A sensitivity study on the p-multiplier for an indicative case of a relative error equal to roughly 6% can be found in Figure 7. The figure shows that the increase of the design frequency (f p-multi x) with increasing p-multiplier follows an asymptotic curve: the larger the multiplier the smaller the increase of the design frequency. Even with an (unrealistic) stiffness multiplier of 1000, the measured frequency is not reached. This further underlines the notion that the soil sensitivity, or soil-structure relative stiffness, may be a relevant contributor to the gap between design and measured frequency, but that the observed gap cannot be solely explained by geotechnical-related effects.

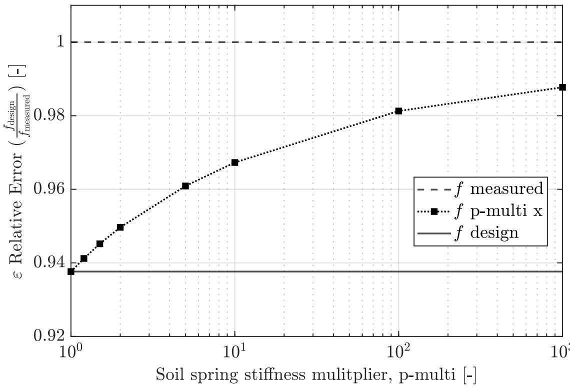

Figure 7: Influence of soil spring stiffness multiplier on the relative error between design and measured frequencies

4 OUTLOOK

Given that only part of the frequency discrepancy between modelled and measured data can be attributed to soil uncertainties, the subsequent step is to investigate the other impact parameters detailed in Section 3.1. Specifically structural parameters, including the RNA mass and the actual stiffness of plates - determined by thickness tolerances and variations in Young's modulus - also contribute to under-prediction of the measured frequency.

Since this study is focussing on the natural frequency of the first bending mode, using the database for higher modes can also enhance the understanding of differences between the measured in-field behaviour and the modelled structures.

5 SUMMARY & CONCLUSIONS

Measured 1st bending mode frequencies are compared with as-designed cases for a representative dataset of 47 OWT locations covering old to latest turbine types, typical water depth variation and MP diameters.

In all assessed cases measured frequencies exceeded the design frequencies indicating a stiffer system behaviour than modelled. Potential scour protection system, soil interpretation and installation / ageing effects are identified as main geotechnical-related influence factors. A simplified method using soil springs modified with equivalent soil stiffness multipliers is applied to assess these factors on a representative subset of design cases.

The analyses demonstrate that geotechnical effects can significantly affect the design frequency. Nevertheless, the results indicate that the observed frequency discrepancies cannot be entirely attributed to geotechnical parameters. Consequently, it is necessary to further evaluate structural, hydro, and model-related parameters to achieve an optimized integrated support structure design.

AUTHOR CONTRIBUTION STATEMENT

A. Nernheim, P. Voges-Espelage, S. Panagoulias: Conceptualization, Methodology, Data curation, Formal Analysis, Writing- Original draft. **C. H. Wilsch**: Software, Data curation, Visualization. **A. Iliopoulos, S. J. Hermans, P. Versteijlen**: Supervision, Writing- Reviewing and Editing

REFERENCES

Andersen, K. W., Duroska, P., Brown, C., Andrade, M.P. & Harte, M. (2020). Modal analysis of OWTS in sand – comparison between measured and predicted values. *Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics (ISFOG)*, 2020.

Guntur, S., (2017). A validation and code-to-code verification of FAST for a megawatt-scale wind turbine with aeroelastically tailored blades. *Wind Energy Science, 2, 443-468.* https://doi.org/10.5194/wes-2-443-2017.

Jardine, R. (2023). Time-dependent vertical bearing behaviour of shallow foundations and driven piles. ISSMGE McClelland Lecture. *Proceedings of the 9th International SUT Offshore Site Investigation and Geotechnics Conference (OSIG)*, 2023.

Mayall, R. (2019). *Monopile Response to Scour and Scour Protection*. PhD thesis, University of Oxford.

Pisanò, F., Del Brocco, I., Ho, H. M. & Brasile, S.. (2024): 3D FE simulation of PISA monopile field tests at Dunkirk using SANISAND MS. *Géotechnique Letters 14,* 1-11. https://doi.org/10.1680/jgele.23.00073.

Sastre Jurado, C., Stuyts, B., Weijtjens, W. & Devriendt, C. (2022). Impact of calibrated soil-monopile-interaction model on resonance frequencies. *J. of Physics: Conference Series*, 2265 032098. doi:10.1088/1742-6596/2265/3/032098

Winkler, K. Weil, M., Sastre Jurado, C., Weijtjens, W. & Devriendt, C. (2023). Quantifying the effect of rock armour scour protection on eigenfrequencies of a monopile supported OHVS. *J. of Physics: Conference Series*, 2626 012039. doi:10.1088/1742-6596/2626/1/012039