Pile installation fatigue damage from impact driving records – A case study of offshore monopiles

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ABSTRACT

Currently, impact pile driving is the preferred method of installation for offshore wind monopile foundations, thanks to the good stability of the foundation achieved after driving and fairly reliable driveability predictions possible for this installation method. Despite these benefits, a possible drawback of impact pile driving can be the high forces exerted on the foundation during installation. Since roughly 90% of steel structure failures during service life is due to fatigue or fracture, in order to promote circularity in the renewable energy sector and to allow a safe re-use of the wind turbine foundations, a correct estimation of the fatigue damage cumulated during the installation process is needed.

The purpose of this paper is to address the topic of cumulative fatigue damage of offshore monopiles installed by impact driving based on driveability prediction results and actual driving records. The paper shows that the monopile fatigue damage predicted in the design stage, often based on numerical models considering constant maximum impact energy, can be overly conservative when compared to the fatigue damage calculation performed based on the actual driving records. This conclusion demonstrates the need for appropriate piling strategies to be able to reduce the actual fatigue damage in the foundation.

Keywords: impact pile driving, fatigue, pile driving records

INTRODUCTION

The renewable energy sector has developed over the past decades to address the continuous demand for sustainable energy supply, with a prominent role for wind energy. Wind turbines are installed on land and offshore (at sea), with offshore installation being currently preferred due to the more favorable wind conditions and to limit the visual impact of the wind farms compared to onshore installations (Moulas et al. 2017). The outlook of installation of new offshore wind power is, under current investment plans and policies, an increase of 13% per year, passing 20 GW of additions per year by 2030 (IEA, 2019).

In the current offshore wind energy market, monopiles represent the most cost-effective solution for wind turbine foundations due to their relatively simple design compared to, for example, more complex jacket and tripod layouts (Köller et al. 2006). Generally, a monopile consists of a series of welded steel pipes, with both tubular and conical sections, which are usually installed by the means of impact hammers. Due to the large forces generated by impact pile driving, cyclically exerted on the monopile during every blow, fatigue damage will cumulate in the construction, having a negative impact on the in-service lifetime duration of the wind turbine itself.

Failure of steel structures by fatigue is responsible for 80% to 90% of the in-service failures (FADLESS, 2014). Therefore, reliable assessment methods are needed to avoid unexpected failures and to increase structural safety, while optimizing the amount of steel adopted in the construction to limit production costs. Apart from a cost perspective, optimizing the steel weight that is required to fulfil a determined structural performance is an important aspect with regard to the decarbonization of the wind energy sector, since producing a lighter monopile foundation will result in the least emissions. In addition to this, when promoting circularity in the renewable energy sector, a safe re-use of wind turbine foundation elements by, for example, re-installing them in less demanding locations for additional service life, will be possible only if a correct estimation of the fatigue damage experienced by the structure up to re-use is performed.

The purpose of this paper is to report and compare the outcome of sophisticated fatigue assessment methods on the remaining fatigue lifetime of a monopile foundation after installation by impact pile driving. By the application of these methods on a case study, it will be possible to draw conclusions about the extension of the foundation fatigue lifetime, also showing potential areas of improvement to achieve lighter, and therefore "greener", monopile designs which will help to decarbonize the offshore wind energy sector.

PILE DRIVING FATIGUE ASSESSMENTS

As described in Orlando et al. (2021), fatigue assessments are performed in the preliminary design stage of monopile foundations, for example, adopting mono-dimensional models and wave equation analyses, where the effects of soil-structure interaction can be considered. A typical output of this simplified analysis is the longitudinal stresses in the pile that are used in a stress-based fatigue calculation adopting the S-N curves of relevant standards, like the DNV-RP-C203 (DNV 2019) recommended practice.

However, analyses based on simple mono-dimensional elements cannot account for the effects of local bending and local vibration of the monopile top that are not negligible when analyzing piles with large diameters, e.g., outer diameters larger than 5 m. Therefore, improved methods are needed to provide more accurate stress evaluations for fatigue checks, such as the one presented by Ligthart (2022), where a novel impact modelling methodology based on a reduced order modelling (ROM) approach is described. Alternatively, when complex connection methods between the monopile and the transition piece/tower are present (such as a bolted flange connection), sophisticated finite element (FE) modelling approaches are required to correctly calculate local stresses.

In general, during pile driving the compression stress wave induced by the impact between ram and anvil travels downward through the pile. During this process the magnitude of the compression stress wave gradually decreases due to the friction between pile wall and soil, from which it follows that the downward traveling compression wave decreases gradually in magnitude when it moves downward through the soil. When the compression stress wave reaches a change in impedance, a change in external force or the pile tip, the compression stress wave reflects and moves upward again. The reflected stress wave depends on the tip resistance of the pile. In general, when the pile is not near refusal, the force in the pile wall due to the hammer impact is higher than the soil resistance. This means that the reflected stress wave from the pile tip is always a tensile stress wave.

In the FE analysis it is not possible to take the soil resistance accurately into account. For this reason, the soil resistance effects are typically neglected in the FE model and the pile tip is modelled as a free end. This means that the stress wave reflecting at the pile tip will be a tensile stress wave, just as in reality, however with a magnitude equal to the original downward travelling compression stress wave. The magnitude of the upward travelling tensile stress wave is thus larger than in reality due to lack of soil resistance. This is compensated for by decreasing the upward travelling stress wave amplitude with a scaling factor determined from the driveability study with mono-dimensional models and wave equation analysis.

In this paper, reference will be made to fatigue assessments at the pile top level based on results extracted from two-dimensional axisymmetric FE models. In the following sections, three different pile driving fatigue assessments will be described briefly, each of them based on different analysis assumptions.

Standard pile driving fatigue assessment

In the first stages of the monopile foundation design, it is standard practice to calculate the fatigue damage of the construction during installation based on the assumption that every required blow to bring the pile to depth will be executed at the maximum energy possible for the adopted impact hammer. The impact hammer is generally selected based on the results of conservative driveability predictions, e.g., the most challenging soil stratigraphy for the installation site in upper bound soil conditions. This calculation method can be expected to provide the most conservative results in terms of pile driving fatigue and it can be accepted in the early stages of the design as a preliminary tool to have an upper bound monopile design layout that must be further optimized to achieve better results.

Pile driving fatigue assessment from driving prediction

A more realistic and less conservative approach that can be executed in the early design stages of the monopile foundation consists of adopting the driveability predictions as a basis to define a fatigue spectrum for the installation of the analyzed monopile. By applying this method, every blow will be considered with the expected impact energy for each specific pile penetration depth, resulting in the best possible approximation of realistic pile driving fatigue damage prior to the actual foundation installation. Back-analysis of prior installations of nearby monopiles will increase the accuracy of the driveability analysis, thereby improving the accuracy of the fatigue assessment.

Pile driving fatigue assessment from driving records

Once the installation of the specific monopile is completed, driving records are available to the analyst for performing a back analysis based on the actual driving conditions, namely actual impact energy for every executed blow. Assuming that accurate soil model calibration will be possible for the analyzed driving location, using each pile driving record as a fatigue spectrum for the appropriate pile, will result in the best possible pile driving fatigue calculation for the specific foundation (at least in the case that no strain measurement data are available). However, this calculation method is only applicable once the installation has been completed, so it cannot be adopted in the design stages of the construction.

In the next sections it will be shown that a monopile fatigue calculation based on driveability analysis and driving record data shows reduced total cumulative fatigue damage, which is deemed a more precise account of the actual fatigue damage done to the pile, suggesting an increased remaining service life of a monopile foundation.

CASE STUDY

In this section, the three fatigue assessment methods that were previously presented are applied to a real case of a large diameter offshore monopile with a pile top outer diameter of 6.5 m driven in the Baltic Sea with the pile driving configuration reported in Table 1. For the investigated installation location, different soil layers were initially characterized by CPT analyses, forming the basis of preliminary driveability predictions for the hammer selection of Table 1.

Table 1. Pile driving configuration.

Hammer	4000 kJ (IQIP Hydrohammer IQ-4)
Pile Top Diameter	approx. 6.5 m

For the purposes of this paper, a butt weld connection between the first two monopile cans is assumed at 1 m below the pile top. The fatigue assessment is performed based on the methodology of DNV-RP-C203

(DNV 2019) only for the outer diameter location of this weld. The fatigue damage of the structure due to impact pile driving is determined based on the S-N fatigue approach under the assumption of linear cumulative damage (DNV 2019). According to this assumption, dividing the stress history of the assessed monopile location in a stress histogram with k constant stress range blocks, each with a number of stress repetitions n_i, the cumulative fatigue damage D can be expressed as:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

Here N_i is the number of cycles to failure at constant stress range $\Delta\sigma_i$ for stress block i. A fatigue damage value of 1 normally refers to the crack initiation point of the assessed location, without accounting for any safety factor.

The FE analysis methodology reported in Orlando et al. (2021), is used as a starting point for this investigation to generate numerical models able to accurately predict the pile stress at the location of interest. For the analyzed weld location in proximity of the pile top, it is assumed that the effects of soil-pile interaction on the reflected stress waves during installation will be negligible, and therefore for the purposes of the study these effects have not been considered.

Further details of the applied fatigue analysis methodology will not be described since the focus of this paper is to demonstrate the possibility of designing monopile foundations with increased service life, reducing the environmental impact of the offshore wind energy sector.

Standard pile driving fatigue assessment

Based on the initial driveability prediction of the pile considered in this case study, a total number of blows equal to 3648 was estimated for the analyzed pile and installation location. Based on this assumption, a 2D axisymmetric FE model has been developed in ANSYS Mechanical version 2022 R2 according to the adopted methodology as shown in Figure 1, with the ram component shown in cyan, the anvil in dark green and the monopile in light green. The main modelling assumptions adopted to build this model are listed below:

- It is assumed that the center line of the ram, anvil and pile are aligned, so no eccentricity is taken into account.
- The element types used for creating the model are Plane182 elements, i.e., a linear 4 node axisymmetric element type.
- Between the various components, contact elements have been modelled to transfer compression stresses from one component to the other, also allowing for separation of these components when tensile forces occur at the interfaces.
- At the center line of the axisymmetric model, symmetry constraints have been applied. The pile tip is unsupported and also no wall friction is taken into account, since the main focus of this case study is the weld location in proximity of the pile top, and therefore the effects of soil-pile interaction on the reflected stress waves during installation are negligible for this assessment.
- No gravity is included in the analysis, so only the dynamic stresses due to the ram impact are simulated.
- The standard material properties used for the linear-elastic material model adopted for the steel components are a modulus of elasticity $E = 2.1\ 10^{11}$ Pa, Poisson ratio $\nu = 0.3$ and material density $\rho = 7850$ kg/m^3.

The transient impact calculation executed at 4000 kJ impact energy resulted in the analyzed weld longitudinal stress of Figure 2, with a maximum absolute value of c.a. 160 MPa.

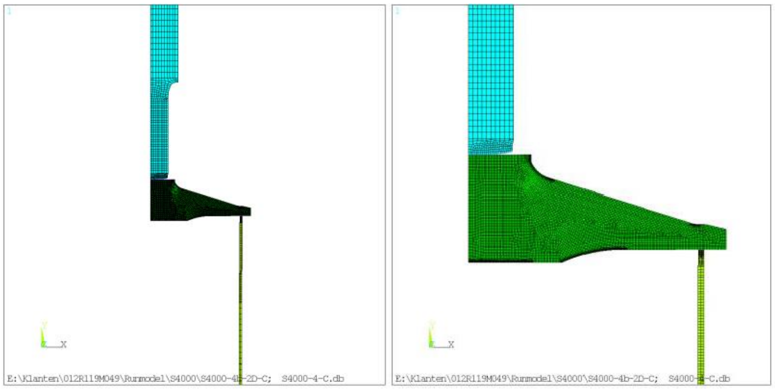

Fig. 1 Finite Element model and details of the mesh

The application of this fatigue assessment method, based on maximum-energy driving, results for this weld in a total damage for 3648 blows of: $D_{\text{max-energy}} = 0.0143$.

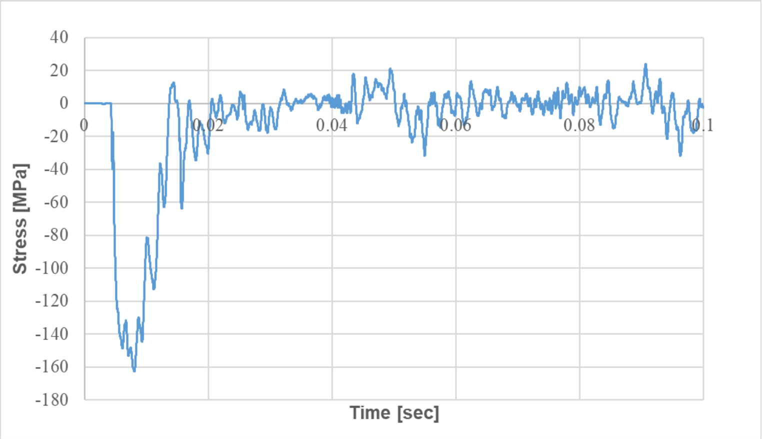

Fig. 2 Longitudinal stress at the weld located 1 m below pile top for impact energy of 4000 kJ

Pile driving fatigue assessment from driving prediction

As previously mentioned, preliminary driveability predictions were performed for the monopile installation of this considered case study to select the best driving configuration. A summary of the predicted energy spectrum for driving this pile to depth is reported in Figure 3.

From Figure 3 it results that very few blows, i.e., just 396, were expected with an impact energy between 3200 kJ and 4000 kJ, and most of the blows, i.e., 2165, were expected with impact energies between 2800 kJ and 3200 kJ. According to the fatigue spectrum of Figure 3 the resulting fatigue damage according to the driveability predictions for the analyzed weld is calculated as $D_{\text{predictions}} = 0.0053$.

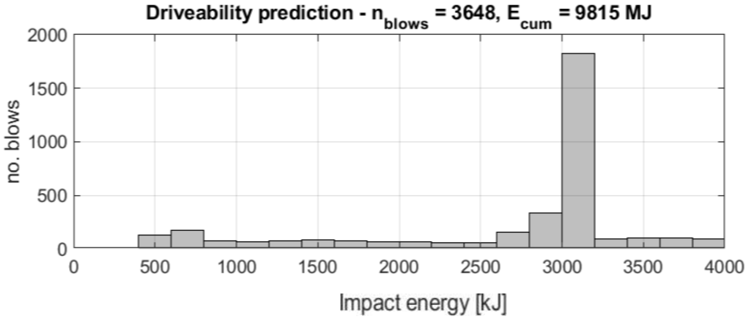

Fig. 3 Number of blows vs. impact energy according to driveability prediction

From this result, a reduction of the total fatigue damage of 63% is found when the fatigue spectrum from the driveability prediction is considered, $D_{\text{predictions}} = 0.0053$, instead of the default max-energy fatigue damage calculation ($D_{\text{max-energy}} = 0.0143$), under the assumptions of this study.

In Figure 4, the contribution to the fatigue damage is reported for each impact energy, showing that the highest damaging impact energy is indeed 3100 kJ, that accounts for c.a. 60% of the total damage.

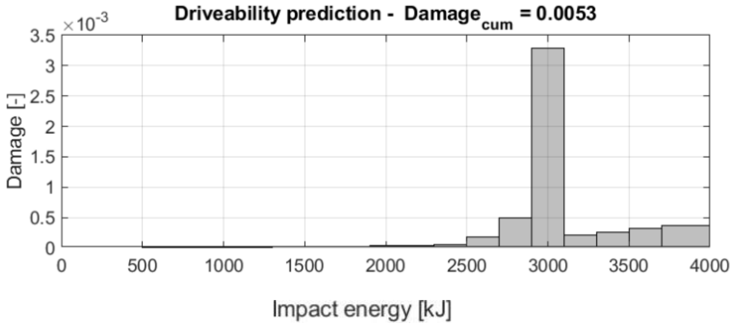

Fig. 4 Fatigue damage vs. impact energy according to driveability prediction

Pile driving fatigue assessment from driving records

Figure 5 presents the energy spectrum from the actual driving record for this particular pile.

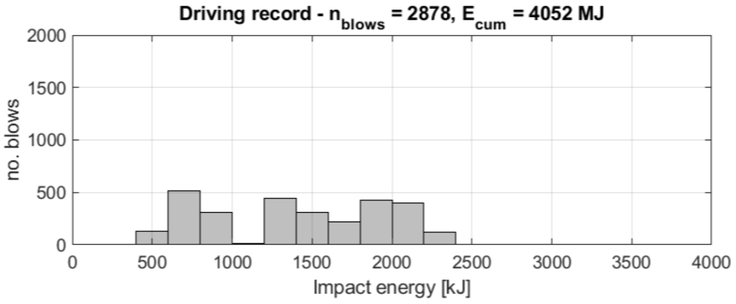

Fig. 5 Number of blows vs. impact energy according to driving records

It is immediately clear from Figure 5 that the driving record impact energy spectrum is much less damaging for the monopile compared to the energy spectrum from the preliminary driveability predictions as shown in Figure 3, due to the lower impact energy and lower number of blows required to drive the pile up to the desired depth. Back-analysis that were performed after the project have revealed that this fairly easy pile driving was a consequence of less demanding soil conditions than expected (bodies of glacial till and chalk as found in the Baltic Sea show high variation of strength due to the nature of the till, and variation in strength was found especially for the chalk when comparing to other regions with chalk). In this case, the cumulative fatigue damage for the analyzed weld according to the driving records is calculated as: $D_{\text{records}} = 0.0006$.

From this result, a staggering reduction of the total fatigue damage of 96% is found relative to the damage calculated according to the fatigue calculation based on driving every blow at maximum energy (i.e., $D_{\text{max-energy}} = 0.0143$). In Figure 6 the contribution to the total fatigue damage for the considered weld is reported for each impact energy of the driving records, showing very low damages across the load spectrum.

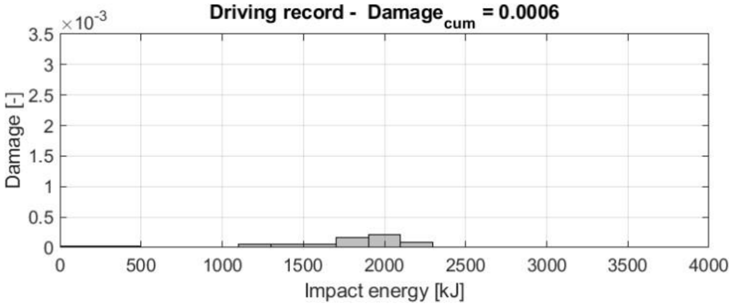

Fig. 6 Fatigue damage vs. impact energy according to driving records

CRITICAL REVIEW OF THE PROPOSED FATIGUE ASSESSMENT METHODS

In this section, the impact pile driving fatigue calculation results presented above for the analyzed weld and installation location are critically reviewed. With regards to the applicability of the energy spectrum based on preliminary driveability predictions, e.g., Figure 3, it must be mentioned that in practice driveability predictions could also turn out to be non-conservative compared to actual driving conditions. In particular, it is possible that the final driving record for a specific piling location will be more demanding than initially estimated. Such an example is shown in Figure 7 where predictions and driving records are compared for a monopile installation that was performed in the North Sea. The actual impact energy spectrum might result in higher fatigue damages than the preliminarily estimated impact energy spectrum.

This example shows that it is not certain that executing a fatigue damage calculation based on driveability predictions will always be conservative, and therefore it is important that a back-calculation on the soil conditions is executed to achieve a high degree of confidence on soil data and modelling of the soil resistance to driving, especially when considering pile elements that are close to the pile toe since the stress wave encountered by those elements is highly affected by the pile-soil interaction.

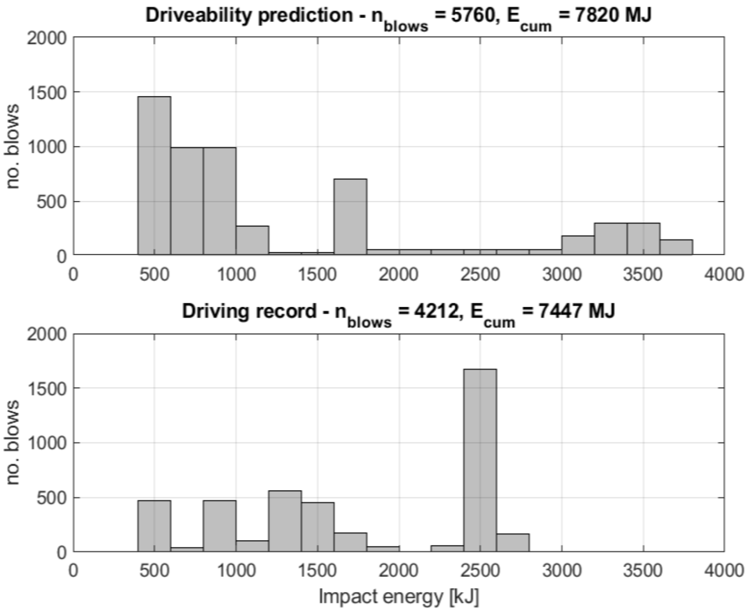

Fig. 7 Number of blows vs. impact energy according to driveability prediction and driving records for a different project in the North Sea region.

With regards to performing fatigue calculations based on driving records, it must be noted that this methodology will not lead to correct results unless accurate soil models are used to represent the soil-structure interaction, and especially when assessing parts of the pile closer to the pile toe instead of the pile top, particular attention should be placed on the soil resistance model to use when performing the model update based on experimental data, i.e., back analysis for soil characterization. In general, the calculation inaccuracies linked to the soil-structure interaction during pile driving are less relevant for the pile top locations since reflecting stress waves from the soil-pile interaction have less influence at the pile top compared to lower on the pile.

In addition to this, it must be considered that driving records can be affected by inaccuracies in the measurement system of the impact hammer (Orlando et al., 2022), although these errors are not expected to have a significant effect on the calculated cumulative fatigue damage of the monopile.

SUMMARY, EVALUATION AND CONCLUSIONS

In this paper three different fatigue assessment methods have been presented for calculating the cumulative fatigue damage in the construction due to impact pile driving:

- Standard fatigue assessment, based on maximum impact energy for every blow foreseen to drive the monopile to the desired depth;
- Pile driving fatigue assessment from driveability predictions, based on the impact energy spectrum derived from the preliminary driveability predictions, where every blow is analyzed with the expected impact energy for each penetration depth in either best estimate or upper bound soil conditions;
- Pile driving fatigue assessment from driving records, based on the energy spectrum derived from the final driving records, where the fatigue damage from every blow is analyzed with the measured impact energy for each penetration depth.

The aim of the paper was to present the fatigue-life safety margins that are assumed in the foundation design stage, to highlight the possibility via more refined analysis methods to optimize the use of steel in the wind energy sector in order to help the decarbonization of this industry.

In particular, results of an actual offshore pile installation that was executed in the Baltic Sea has shown a calculated fatigue damage reduction of 63% when fatigue damage calculations are performed according to the fatigue spectrum of the driveability predictions compared to the more standard approach based on maximum hammer energy for each blow. The cumulative fatigue damage was shown to have reduced with 96% for this particular case study compared to the standard approach based on maximum hammer energy for each blow. A summary of these results is reported in Figure 8 for clarity.

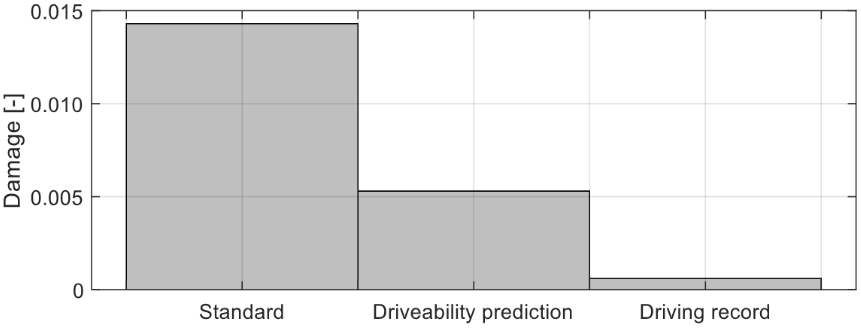

Fig. 8 Fatigue damages according to the different methods presented in this paper.

It is understood that the actual soil conditions at the site considered in this case study turned out to be significantly less demanding than expected. It must be understood that it can also occur that soil conditions are in reality more demanding than expected, therefore the pile fatigue damage could be underestimated in a case of performing the fatigue calculation based on the driveability prediction results only. Continuous improvement of the soil resistance to driving models is essential to have the most accurate driveability calculations and consequently the most accurate fatigue assessments prior to actually installing the foundation elements.

In spite of the potential benefits in terms of steel saving for the manufacturing of offshore monopile foundations for wind turbines, the proposed refined analysis methods must be adopted with caution since they can lead to non-conservative results and therefore unsafe working conditions for the considered wind turbine. Nevertheless, comparison of fatigue damages calculated with the standard maximum energy approach and the driveability-based approach could provide a realistic view on the level of conservatism of the pile design, the potential savings on steel, and the potential for re-use of the foundation. This exercise could be implemented in the foundation design process to have a pile design accommodating current and future use.

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