Optimization of monopiles for offshore wind turbines

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The offshore wind industry currently relies on subsidy schemes to be competitive with fossil-fuel-based energy sources. For the wind industry to survive, it is vital that costs are significantly reduced for future projects. This can be partly achieved by introducing new technologies and partly through optimization of existing technologies and design methods. One of the areas where costs can be reduced is in the support structure, where better designs, cheaper fabrication and quicker installation might all be possible. The prevailing support structure design is the monopile structure, where the simple design is well suited to mass-fabrication, and the installation approach, based on conventional impact driving, is relatively low-risk and robust for most soil conditions. The range of application of the monopile for future wind farms can be extended by using more accurate engineering design methods, specifically tailored to offshore wind industry design. This paper describes how state-of-the-art optimization approaches are applied to the design of current wind farms and monopile support structures and identifies the main drivers where more accurate engineering methods could impact on a next generation of highly optimized monopiles.

1. Introduction

Over the past 10 years, offshore wind farms have been installed in the North Sea, Baltic Sea and Irish Sea. As of 2013, 6.6 GW of offshore wind was connected to the grid [1], with the pipeline of offshore wind projects being considerable across Europe, as well as
Figure 1. Some typical foundation concepts and their respective share on commercial projects as of December 2012 [3].

(a) Gravity-based foundation (16%), (b) monopile foundation (74%), (c) caisson foundation (0%), (d) multipile foundation (5%), (e) multi caisson foundation (0%) and (f) jacket foundation (5%).

Further afield. For example, the UK’s ambition is to increase the installed capacity over the next decade by three to eight times the current level. At the same time, the cost of energy, a combined index of energy production from the wind farm, capital expenditure and operational expenditure, must be reduced by 40% to enable wind to be more commercially viable [2]. These plans require the introduction of new and more cost-effective technologies along with the optimization of current technologies and design methods.

An offshore wind turbine consists of a wind turbine installed on top of a support structure and foundation. The foundation and structures currently employed commercially and/or considered by the industry, along with their respective market shares, are shown in figure 1. The monopile structure is by far the most common foundation concept, owing to the simple yet robust design by comparison with other foundation concepts; it is well suited to mass-fabrication and the installation method, based on conventional impact driving, is robust in most soil conditions. The majority of current developments have taken place in relatively shallow water, where the monopile is clearly suited, both commercially and technically. A key issue is the water depth at which other foundation and structure types begin to be preferred over the monopile. Many of the newly licensed wind farms in both the German sector and in the UK Round 3, to be developed before 2020, are below 40 m water depth. For example, 90% of the 9 GW Dogger Bank development is below 35 m [4] and about 50% of the 4 GW Hornsea development is below 40 m water depth (as shown in figure 2). Based on experiences from full-scale measurements [5,6], results of advanced finite-element modelling and the development of new more highly optimized design methods, it is possible that monopiles supporting 6–8 MW wind turbines could be installed within the majority of these sites. As of today, monopiles supporting 6 MW wind turbines have been designed for water depth up to 35 m, including those recently constructed for the Gode Wind Offshore Wind Farm and shown in figure 3. This monopile is 7.5 m in diameter. Monopiles, with diameters up to 10 m, are claimed to be feasible in water depths up to 60 m [7]. However, larger turbines and deeper water will challenge the technical feasibility of the monopile, particularly as wave action will increasingly interfere with the dynamics of the turbine structure.

If monopile foundations could be employed in future projects, there would be a positive benefit in further developing the existing well-resourced supply chain for fabrication, as opposed to developing new supply chains for other more complex structural concepts, such as jacket structures [2]. The monopile allows a high degree of standardization leading to improved scale
Figure 2. Water depth distribution for the Hornsea development.

Figure 3. A 7.5 m diameter monopile for Gode Wind Offshore Wind Farm. DONG Energy. (Online version in colour.)

and productivity in the supply chain. This is an area that is still to be fully optimized. In addition, installation vessels and installation methods could be tailored for larger monopiles. An example is the development of vibratory driving methods, currently being investigated in a joint industry research project [8]. Finally, the track record of monopile installations over the past 10 years, and subsequent foundation performance assessment, provides a degree of confidence in the concept, as compared with the other more novel concepts.

The aim of this paper is to describe how the current state-of-the-art is applied to the design of monopiles, demonstrated by a number of case studies. The paper then identifies how optimization using more accurate design methods, and more intelligent engineering approaches, could impact on the next generation of monopile foundations.
2. Overall optimization of wind farms

(a) Wind farm grid layout optimization

Typically, an offshore wind farm consists of 50–150 structures and so an optimization of the entire wind farm grid must be initially considered. The average power production of a wind turbine within a wind farm can be 5–20% lower than that of a stand-alone turbine, principally due to the effects of shadowing where a wind turbine is located downstream of another [9,10]. However, it is not always possible to achieve the most optimal wind farm layout due to consented area constraints and/or environmental constraints. The optimization must consider the overall power production against total estimated costs, and so must use an approximate and holistic model. The costs are likely to be reduced by, for example, limiting electrical cable lengths, favouring positions with attractive soil conditions, and by minimizing water depths. As an indication, it has been found that 4–5% cost reduction in total support structure costs balances 1% loss in energy yield [11]. Advanced layout algorithms for optimization of grids to lower the cost of energy, as proposed by, for example, Elkinton et al. [12], are commercially used and also under continuous development by wind farm developers.

Anholt Offshore Wind Farm is an example where an efficient layout was developed during the design phase. The wind farm consists of 111 3.6 MW wind turbines on monopile support structures. The optimization took account of the actual seabed conditions, a position-specific pile design and the prevailing wind direction. This process resulted in the layout shown in figure 4a. The layout was governed by the west–southwest dominating wind direction, as well as a layer of thick soft clay (more than 30 m deep), making the installation of turbines less feasible in the northern area of the wind farm [13]. Another example is the layout for West of Duddon Sands Offshore Wind Farm, shown in figure 4b. This wind farm consists of 108 3.6 MW wind turbines on monopile support structures. The layout was governed by areas with shallow depth from seabed to bedrock in the southern part of the site, making the installation of large diameter monopiles infeasible [14]. These two examples illustrate that overall optimization of the layout of an offshore wind farm is an integrated task, where knowledge of the environmental conditions at the site is essential.

(b) Position-specific designs

Owing to the possibility of large variations in soil conditions and water depths across a wind farm site, individually optimized designs for each turbine position will significantly reduce the amount of steel required for the monopiles. There are three main variables: wall thickness variations along the pile, embedded pile lengths and position-specific pile diameters. Across a site, pile diameters are typically fixed in one or two categories, principally due to limitations arising from installation and transportation equipment. Therefore, optimization based on embedded pile lengths and wall thickness is important.

An example of where individual pile optimization has been completed is at the Westermost Rough Offshore Wind Farm. A cross section through the geological model is shown in figure 5. The seabed at this site consists of a number of different soil units, including Holocene Surface Deposits, the Botney Cut Formation, the Bolders Bank Formation, the Swarte Bank Formation and chalk. Shown in the figure are examples of the final location of the turbines along the cross section. The mass and embedded length of the monopiles, relative to the heaviest and longest pile, have been included in table 1. For these structures, the foundation mass varies by up to 40% and the length varies by up to 30%, illustrating clearly the importance of position-specific designs.

3. Requirements for monopile design

The design of a monopile support structure is driven by requirements for installation, turbine operation, maintenance and lifetime. The conventional monopile support structure consists of
Figure 4. (a) Layout of the Danish Anholt Offshore Wind Farm, coordinates according to WGS84 UTM32N. (b) Layout of the British West of Duddon Sands Offshore Wind Farm, coordinates according to WGS84 UTM30N. Each dot represents a turbine position within the marked wind farm area.

Figure 5. Cross section through the geological model for Westermost Rough Offshore Wind Farm. 1–5: monopile positions. Hc, Holocene Surface Deposits; BC, Botney Cut Formation; Bo, Boulders Bank Formation; Sw, Swarte Bank Formation; Ch, chalk grade Dm becoming A1 with depth.

Table 1. Mass and length of monopiles for the five structures at Westermost Rough Offshore Wind Farm shown in figure 5.

<table>
<thead>
<tr>
<th>position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of monopile, relative to heaviest pile</td>
<td>0.63</td>
<td>0.61</td>
<td>0.67</td>
<td>0.78</td>
<td>1.00</td>
</tr>
<tr>
<td>embedded pile length, relative to longest pile</td>
<td>0.87</td>
<td>0.69</td>
<td>0.77</td>
<td>0.95</td>
<td>1.00</td>
</tr>
</tbody>
</table>

the pile (figure 3) as well as the transition piece (figure 6) that connects the pile to the tower structure. The monopile is typically driven into the seabed with a large hydraulic hammer, with the transition piece grouted or bolted to the top of the monopile following installation. This connection allows levelling of the wind turbine structure should the foundations be installed with a minor inclination. In addition, the transition piece houses all secondary structures to meet
the requirements of the installation contractor and operation and maintenance contractor such as access ways, working and inspection platforms.

Monopile support structures are relatively simple, with only a few degrees of freedom: embedded pile length, diameter and thickness of the tubular sections, welding details, level of grouted or bolted connection, conical section and interface, and the location of secondary steel items. The length of the monopile is typically governed by the overturning capacity under extreme conditions, or the maximum allowable tilt of the turbine over its lifetime due to accumulated rotations from cyclic loading [15]. The diameter of the monopile is typically driven by requirements for the fundamental frequency of the turbine, and this is closely linked to the stiffness response of the soil. Finally, the wall thickness is typically governed by either fatigue loads or shell buckling during installation and/or extreme events. Fatigue loads are most severe in areas with welded attachments or cut-outs, and special consideration must be paid to these details in design.

(a) Governing dynamic interaction

Offshore wind turbines are dynamically loaded structures, with loads arising from the wind, waves and the rotor excitations, as illustrated in figure 7. The response of the structure depends closely on the fundamental frequency $f_0$ (the first tower bending frequency) and the dynamic interaction with the external loads. Offshore wind turbines supported by monopile foundations are typically designed as soft–stiff structures. This is where $f_0$ is above the rotational frequency of the rotor, $f_{1P}$, which arises due to rotor imbalances, but below the blade-passing frequency,
Wave loads are treated as stochastic loads with a spectral density of surface elevation usually approximated by either the JONSWAP spectrum [17] or Pierson–Moskowitz spectrum [18]. The spectral peak frequency of waves is between 0.1 and 0.3 Hz depending on the wind speed and site conditions.

For smaller turbines, $f_0$ is usually towards the top end of the wave frequencies; however for larger and more novel turbines this will not always be the case. For a 6–8 MW offshore wind turbine on a monopile, designed for the soft–stiff frequency range, $f_0$ would be around 0.20–0.23 Hz. In this frequency range, the fundamental mode of the structure would resonate with the waves at low wind speeds and be exposed to high spectral energy of waves during higher wind speeds. The response of the fundamental mode of vibration due to loading acting orthogonal to the rotor plane is low during operation of the turbine, as a rotor in operation provides a high degree of aerodynamic damping. However, misaligned wave loading, i.e. wave loading acting parallel to the rotor plane, can cause very high dynamic excitation of the side–side response and be a dominant component of fatigue loading. Furthermore, fatigue loading during stand-still periods of the turbine can become very severe, as the aerodynamic rotor damping does not contribute. This will be an important driver in future designs.

The impact of wave loads on the response of the fundamental mode of vibration can be assessed through a frequency response analysis to the wave input. This will be representative for the side–side response of the structure or during stand-still. Tarp-Johansen [19] demonstrated that the dynamic loads $\Delta\sigma$ approximately correlate with the mode shape displacement in the wave exposed part of the pile $\varphi$, the damping ratio $\zeta$ of the fundamental mode of vibration $f_0$, and the significant wave height $H_s$ in the following way:

$$\Delta\sigma \propto \varphi \cdot \sqrt{\frac{1}{\zeta f_0^2}} H_s.$$  

Owing to the large sensitivity of the structural response to variations in dynamic properties, it is of importance to be able to accurately predict all four parameters if optimization of monopile foundations is to be successful.

4. State-of-the-art design of support structure and tower

(a) Modelling of offshore wind turbines

Offshore wind turbine design is typically completed using two models. The first model comprises the turbine and tower structure and is developed by the turbine manufacturer. The second
model is of the support structure, including the foundation, and is developed by the foundation designer. The interface between the two models is located perhaps at 20 m above sea level. The interaction between the two models is represented by a cold link, containing loads, stiffness or equivalences. Owing to the dynamic interaction between the two models, often two to three load iterations are required to achieve convergence for a single structure. A fully optimized design may require 50 or more geometry iterations per position, within each load iteration, considering wall thickness variations, embedded pile length and pile diameter. This leads to a significant number of calculations for the complete wind farm design.

This approach is derived from onshore wind turbine design where the response of the support structure can usually be approximated as either rigid or linear elastic. Adoption of this method for offshore design is commercially attractive due to the speed at which geometry iterations can be undertaken. It is also felt to be technically acceptable for shallow water structures. However, in deeper water, the support structure is a larger proportion of the total structure, with a considerable effect on the integrated response of the structure. In addition, the optimization of design methods will involve a better representation of the foundation response incorporating a larger degree of nonlinearity. It would therefore be technically more robust and potentially more cost effective if the entire structure was optimized by considering an integrated response model, in which the entire structure and loads are considered in one model, rather than two. This could allow a more optimal distribution of material throughout the entire structure, as well as permit the development of new ideas such as control algorithms for the rotor nacelle assembly that could assist in minimizing the dynamic response of the structure [11]. Analyses performed by Fischer & Vries [20] and Haghi [21] suggest that integrated design has the potential to reduce structural weights by up to 15%, although the actual realization will clearly depend on the optimization potential of the two-model approach, in addition to site-specific conditions. Currently, integrated design methods are rarely used, as they present a number of interface problems as both the wind turbine manufacturer and the foundation designer would need to work in the same model. An integrated design philosophy therefore represents an aim rather than a current reality.

Given the large number of iterations required during design and the large number of turbines in a wind farm, the industry favours automated design processes for the primary structure. These are usually based upon simple engineering models over more complex, time consuming, but more accurate (numerical) analyses. Smaller more intricate details, such as connection details, are typically modelled separately using more complex models. A typical pile support structure is usually modelled as an elastic beam, with either Bernoulli–Euler or Timoshenko beam elements. The pile–soil response is represented by a set of uncoupled nonlinear springs acting along the embedded part of the pile. Such a model is shown in figure 8. The nonlinear springs, representing the pile–soil response, are commonly referred to as p–y springs, and these describe the relation between the lateral soil resistance \( p \) and the lateral displacement \( y \) (see recommendations by DNV [22]). In addition, a shear spring to simulate the toe shear resistance \( S \) could be implemented as suggested by LeBlanc et al. [15], but this is not a standard approach in current offshore design.

Two of the design drivers for the pile diameter and wall thickness relate to shell buckling and fatigue damage. The shell buckling stability is critical during installation and extreme events, whereas the fatigue damage is caused by cyclic loads throughout the lifetime of the structure. Shell buckling and fatigue damage are assessed at each step in the geometry iteration process, and therefore guidelines applicable to simple engineering models are applied. Shell buckling is considered according to the stress design approach [23], whereas fatigue damage is obtained by applying a rainflow counting algorithm to the time series and summing up using the Palmgren–Miners rule and an appropriate S–N curve [24].

(b) Introducing full-scale measurements in the design

The use of full-scale performance monitoring in foundation design is steadily increasing as a method for validating design approaches, as well as for developing them further. For offshore
Figure 8. Example of an engineering model applied in the design of monopile foundations. $H_{wtg}$, horizontal load from wind turbine generator; $M_{wtg}$, overturning moment; $F_{wa}$, wave load; $EI$, bending stiffness; $m$, distributed mass.

Wind turbines, this ‘observational method’ could be a substantial benefit because many turbines have already been installed, and many more will be installed; it makes sense to learn from experience. A turbine monitoring programme could consider loads, response, settlements, changes of the scour/scour protection, corrosion protections, etc. For the majority of turbines, some monitoring data are already obtained from the turbines’ control and monitoring systems placed in the rotor–nacelle assembly. For example, this dataset often includes acceleration measurements on which $f_0$ can be evaluated. Figure 9 shows a comparison of measured and designed values of $f_0$ for 400 offshore wind turbine structures supported by monopiles and founded within different soil conditions, illustrating that $f_0$ has generally been under-predicted by designers. The implication of this is reduced dynamic interaction for the installed structures, and thereby reduced loads, giving a greater life expectancy, along with a potential for further optimization of future structures.

A sensitivity study of design parameters influencing $f_0$ has been carried out for a turbine structure, in 25 m mean water depth, at the Walney Offshore Wind Farm. The results of this study are shown in Table 2, clearly demonstrating that the $f_0$ predictions are very sensitive to an accurate evaluation of the pile–soil stiffness, as well as the degree of fixity provided by possible scour protection measures. The other uncertainties comprise approximately 1%. This is further supported by detailed measurements of the moment distributions through the embedded part of the pile which have identified that the pile–soil response has been under-predicted in design by up to 30–50% during operational conditions [5]. Furthermore, unpublished observations indicate that the scour protection can have a significant effect on the fundamental frequency. These observations imply a greater degree of fixity of the foundation, compared with design, reducing the deflection levels and the mode shape deflections in sea level ($\varphi$), with a consequent
**Figure 9.** Measured first tower bending frequency ($f_{\text{meas}}$) compared to the design frequency ($f_{\text{design}}$) for 400 offshore wind turbines. Dark grey, West of Duddon Sands Offshore Wind Farm; light grey, other offshore wind farms.

**Table 2.** Sensitivity study of design parameters for a turbine within Walney Offshore Wind Farm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Range of Variation</th>
<th>Sensitivity on Fundamental Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lower</td>
<td>mean</td>
</tr>
<tr>
<td>corrosion allowance in splash zone</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>total pile–soil stiffness ($K$) in comparison with current design approach ($K = 1$)</td>
<td>1/5</td>
<td>1</td>
</tr>
<tr>
<td>height of scour protection</td>
<td>0 m</td>
<td>1 m</td>
</tr>
<tr>
<td>wall thickness deviation due to production tolerances</td>
<td>0 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>marine growth contained and added mass of water column</td>
<td>$C_M = 1.0$</td>
<td>$C_M = 1.5$</td>
</tr>
<tr>
<td>distributed mass in the structure</td>
<td>0 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td>height of the nacelle</td>
<td>−0.2 m</td>
<td>0 m</td>
</tr>
</tbody>
</table>
Table 3. Comparison of frequency and lifetime predictions for a structure within Walney Offshore Wind Farm.

<table>
<thead>
<tr>
<th></th>
<th>frequency</th>
<th>lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>design</td>
<td>0.302 Hz</td>
<td>25 years</td>
</tr>
<tr>
<td>reassessment</td>
<td>0.330 Hz</td>
<td>47 years</td>
</tr>
<tr>
<td>reassessment/design</td>
<td>1.1</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 4. Realized savings on West of Duddon Sands Offshore Wind Farm.

<table>
<thead>
<tr>
<th>initiative</th>
<th>reduction of steel tonnage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>improved load calculation</td>
<td>~8–10</td>
</tr>
<tr>
<td>accurate frequency prediction</td>
<td>~6–8</td>
</tr>
<tr>
<td>automated structural geometry optimization</td>
<td>~6–8</td>
</tr>
<tr>
<td>total</td>
<td>20–25</td>
</tr>
</tbody>
</table>

reduction of dynamic pile–wave interaction. These measurements identify that better assessment of pile–soil stiffness could lead to more cost-effective designs.

(i) Lifetime extension using measurements

A reassessment of the fatigue life of one monopile support structure within the Walney Offshore Wind Farm was undertaken after commissioning of the wind turbine. The reassessment considered a revised load calculation based upon a structural model tuned to the measured \( f_0 \) and a reassessment of wave loads. Otherwise equivalent design assumptions, fatigue details and S–N curves, as applied in the original design, were used. The fatigue lifetimes of the structure in both the original design and reassessment were calculated according to DNV-RP-C203 [24]. Table 3 shows \( f_0 \) and the lifetime of the support structure as determined in the design and in the reassessment. It demonstrates that for this particular structure, there is a potential to extend the lifetime by 88%. The analysis showed that this increase was equally due to the under-prediction of the fundamental frequency (by 10%), giving a larger degree of fixity at the foundation, as well as due to the reassessment of wave loads. Evidence, such as that shown in figure 7, indicates that extension of lifetimes might be possible for other turbines depending on the site-specific conditions, if design assumptions are not violated during the lifetime of the structures.

(ii) Design improvements using measurements

West of Duddon Sands Offshore Wind Farm was the first wind farm designed by DONG Energy using an automated design process, leading to more highly optimized monopile foundations. The design was based upon the current state-of-the-art engineering methods for design resistance and for the evaluation of loads. Furthermore, a site-specific pile–soil response formulation was tuned using full-scale measurements from the nearby Walney Offshore Wind Farm. The reduced steel requirements due to these initiatives are illustrated in table 4. Following the installation of the West of Duddon Sands Offshore Wind Farm full-scale measurements have demonstrated an as-built \( f_0 \) within ±2% of the predicted frequency (figure 9). The design has performed to expectations. The monopile support structures at West of Duddon Sands demonstrate the potential for more optimal foundation design.

5. Discussion

The case studies described above illustrate that an accurate interpretation of the external loads and the dynamic properties of the wind turbine structure are important technical levers for
optimizing monopiles. However, most of the optimization achieved was due to engineering for site-specific conditions, rather than the application of more wide-ranging design guidelines. Within the context of this work, four areas have been identified where conservatism in design could be eliminated, to allow a higher degree of optimization of monopile foundations: (a) more accurate models for the soil response, (b) more robust assessment of damping, (c) better fatigue damage evaluation, and (d) more precise estimation of shell buckling capacity.

(a) Accurate modelling of soil–structure interaction

There is an embedded uncertainty in many of the characteristic soil parameters derived from geotechnical site investigations, from both \textit{in situ} testing as well as laboratory tests. Taking the case of laboratory testing, this uncertainty can be derived from sample disturbance or from the method by which the samples are prepared for testing. Sample disturbance can be significant for most soils, as samples cannot usually be collected in a representative \textit{in situ} state. Caution must therefore be applied in interpreting the results from the laboratory testing. For example, uncertainties and errors in fairly simple classification tests for the minimum and maximum dry density of sand have been identified as a cause of up to 5\% differences in the requirements for monopile steel. The industry therefore needs to work together to ensure methods for deriving soil parameters are robust and according to state-of-the-art practice.

The conventional \(p-y\) formulations representing soil–pile interaction were originally developed to evaluate ‘envelope curves’ that would capture the response of a jacket pile loaded monotonically at the end of an extreme storm \cite{25}. The accuracy and validity of these \(p-y\) curves, when applied to the soil–pile response of a large diameter monopile, are questionable. As a consequence, the joint industry project Pile Soil Analysis (PISA) was launched to investigate and develop improved design methods for laterally loaded piles, specifically tailored to the offshore wind sector. The work uses state-of-the-art three-dimensional finite-element analyses, complemented by field testing, to provide a basis for improved design methods. Early results of the project have already indicated a significant possibility for improving the assessment of the pile–soil stiffness and the pile capacity. This is likely to lead to reduction of pile lengths and smaller overall geometries compared with current approaches to design. There are a number of aspects of pile–soil interaction that will not be captured by numerical analysis or field testing, such as the effects of scale, drainage, ageing and cyclic loads. The new methods will therefore need to be validated against measurements from full-scale monopiles in various soil conditions before being applied to full-scale design. These types of initiatives are an important step towards developing a better evaluation of the pile–soil response and therefore a more optimal design.

(b) Damping

The overall structural damping, defined as the total damping less the aerodynamic damping, for an installed offshore wind turbine is of high uncertainty. Not only is it difficult to accurately quantify the individual contributions to the overall damping, e.g. soil damping, hydrodynamic damping or structural damping, but the overall structural damping is very difficult to measure during operational conditions. In the literature, values reported for damping have been between 1 and 4\% of critical damping \cite{26–30}, with typical design values being 0.9–1.2\% \cite{31}. To allow optimization of the turbines and to add more confidence to the design calculations a better assessment of the overall structural damping is needed.

(c) Fatigue damage assessment

Tests that underpin the current S–N curves used for assessing fatigue damage include up to 10\% of the wall thickness in misalignment when two plate sections are welded together \cite{24}. For monopiles, with relatively large wall thicknesses (50–150 mm), this is considerably more than can be achieved in the fabrication process. The Structural Lifecycle Industry Collaboration
(SLIC) project is currently ongoing where fatigue tests are carried out with near-perfect geometry allowing misalignment to be accounted for in calculation models. It is expected that this will ensure a more accurate prediction of fatigue life and less conservative designs.

Recent studies have also indicated that the thickness effect included in current S–N curves depends on the weld geometry [32]. Considering the calculations for Walney Offshore Wind Farm, it has been assessed that depending on the actual structural detail, there may be a further potential to extend the lifetime by up to 40%, or equivalently reduce the mass of fatigue driven parts of the pile in future designs. Improving weld geometry could be an effective way to reduce foundation costs.

(d) Shell buckling

Finally, for shell buckling, the imperfection shape and size is significant for calculating capacity [33]. The fabrication tolerance class is used to link actual imperfections to design in the governing standards. Point cloud measurements of fabricated foundations have indicated that imperfections do not necessarily fit smoothly with the available tolerance quality classes, so there is potential for improving this aspect of design. However, imperfections are difficult to measure reliably during fabrication. Better tools and procedures are needed to ensure consistency between design assumptions and the fabricated foundation, in order to capitalize on the effect of improved imperfection classification.

6. Conclusion

This paper demonstrates that there is a potential for further optimization of monopile support structures, compared with current state-of-practice across the industry. The overall reduction of steel tonnage, which is closely linked to costs, will depend very much on site conditions, but savings in the region of 10–25% may not be unreasonable, compared to current assessments. The experience from West of Duddon Sands Offshore Wind Farm highlights the potential for this optimization. Improved design methods will allow the monopile to be used in deeper water, and for larger turbines, than hitherto. The continued use of monopile support structures for future projects will allow the entire monopile supply chain to further mature, providing additional benefits. This could make monopile support structures technically feasible for the majority of the sites to be designed before 2020. In addition, a better understanding of the engineering response of monopile structures may result in extensions of lifetime for currently installed support structures, assuming that design assumptions are not violated. The extension of life assessment will become increasingly important going forward for the earlier generations of wind farms. The optimization methods described in this paper are an important part of meeting the cost-reduction targets targeted by the industry, if the industry is to develop as the ambition requires it to.

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