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Influence of soil and structural stiffness on the design of jacket type substructures

The detailed design of jacket type substructures for offshore wind turbines involves an iterative load calculation process in which structural properties and loads are exchanged between the turbine vendor and the substructure designer. Structural and soil stiffness in particular play an important role as they directly influence the magnitude of loads in the ultimate and fatigue limit state. The well established procedures for monopiles cannot be directly adopted for jackets. Ramboll has conducted extensive sensitivity studies on how global and local loads change when stiffness is adjusted during the design process. The main findings are presented in this paper. These form the basis for some recommendations on how the design and load iteration process for jackets can be planned in order to achieve an optimal substructure design with a limited number of full load iterations. So-called "Mini-Load-Iterations", in which only a reduced number of time series is simulated, play an important role in this process.

Zum Einfluss der Boden- und Struktursteifigkeit auf die Bemessung von Jacket-Gründungen. *In der Ausführungsplanung von Jacket-Gründungen für Offshore-Windenergieanlagen spielen die Lastiterationen, in denen Strukturdaten und Lasten zwischen dem Turbinenlieferanten und dem Fundamentplaner ausgetauscht werden, eine entscheidende Rolle. Insbesondere die Steifigkeiten der Struktur und des Bodens haben einen direkten Einfluss auf die Größe der Lasten in den unterschiedlichen Komponenten der Struktur – sowohl im Grenzzustand der Tragfähigkeit als auch für den Betriebsfestigkeitsnachweis. Ein etabliertes und funktionierendes Verfahren der iterativen Lastberechnung existiert für Monopile-Gründung. Es ist jedoch nicht direkt auf Jacket-Gründungen übertragbar. Ramboll hat eine Vielzahl an Sensitivitätsstudien durchgeführt, um den Einfluss sich während des Bemessungsprozesses ändernder Steifigkeiten auf globale und lokale Lasten zu untersuchen. Die wesentlichen Ergebnisse sind in diesem Beitrag zusammengestellt und dienen als Basis für Empfehlungen, wie die Bemessung und die Lastiterationen geplant werden sollten, um am Ende ein optimales Fundament zu erhalten bei einer möglichst geringen Anzahl von vollen Lastiterationen. Sogenannte Mini-Lastiterationen, bei denen nur wenige Lastfälle simuliert werden, spielen hierbei eine entscheidende Rolle.*

1 Introduction

Offshore wind energy is one of the main pillars of renewable energy to reduce carbon emissions. Several offshore wind farms have already been installed across Europe and significantly more are being planned for the next decades. Most of the already installed wind turbines are supported by monopile substructures, but future projects will be situated more often in deeper waters, where jacket type substructures are a very reasonable alternative solution; e. g. the offshore wind farms Wikinger, Borkum Riffgrund 2 (both in German waters) and East Anglia One (UK) have different jacket types as the preferred substructure type. Wikinger has a 4-legged jacket on pre-installed piles, East Anglia One plans are with a 3-legged jacket on pre-installed piles, while Borkum Riffgrund 2 will be installed on 3-legged jackets supported by suction buckets (so-called suction bucket jacket, see Fig. 1).

The competitive energy market demands that the cost for offshore wind energy is reduced. Cost reduction can be achieved by optimization of substructures in order to save on steel and fabrication effort. One key element of this process is to get a thorough understanding of the loads in the time domain which influence the ultimate capacity as well as the fatigue life of the structure. For monopiles, the industry has gained valuable experience throughout the last years in regard to how structural stiffness influences the loads, e.g. softer substructures result in higher loads. Those effects are analysed in an integrated model of the substructure, tower and turbine, which reflects the non-linearities of the soil, dynamics of the superstructure and damping effects. Procedures have been developed to accurately reflect the site conditions and

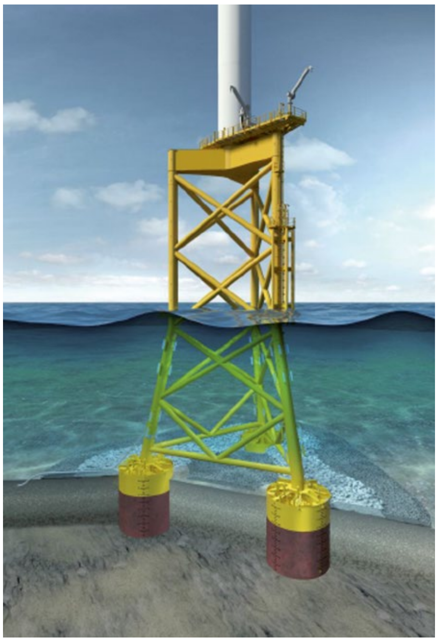

Fig. 1. Example of a suction bucket jacket (source: Ramboll)
Bild 1. Beispiel eines Suction-Bucket-Jackets

turbine characteristics and by that substructure loads could be reduced leading to a more optimized pile design, see for example [1], [9] and [10].

For jacket type substructures the analyses are significantly more complex, because the system reacts far more sensitively to changes in the stiffness of individual structural members. Furthermore, the fundamental natural frequencies for a truss-like jacket layout are fairly closely spaced compared to uniform monopiles, hence jacket substructures are potentially more vulnerable to dynamic couplings with the turbine structure over all wider frequency ranges. Findings that have been developed for monopile structures may not be valid for jacket substructures. Therefore, a thorough understanding of the influence of structural and soil stiffness on the load determination is essential to identify the relevant dependencies and to avoid unnecessary and time consuming extra load iterations between substructure designer and turbine vendor. The complexity of the stiffness/load interaction is demonstrated by means of a few comparisons in the following sections.

2 General procedures in the design of jacket substructures

Typically the design of jacket substructures for offshore wind turbines is performed in a sequential approach where the wind turbine vendor is responsible for the design of the tower and rotor-nacelle-assembly (RNA) as well as performing aero-elastic simulations of the integrated structure, while a separate substructure designer carries out the detailed design of the jacket.

The procedure can be briefly summarized as follows:

Substructure model: A detailed substructure model accounting for all relevant primary and secondary steel structures, local joint flexibility, pile-soil interaction, etc. is prepared by the substructure designer. At Ramboll this is performed in the in-house software package for structural analysis of offshore structures ROSA which includes state-of-the-art numerical procedures for performing all steps from initial model setup to detailed design of individual members in accordance to relevant design standards.

Reduced model: The detailed substructure model including relevant hydrodynamic load time series associated with waves and currents are then imported into a suitable aero-elastic code (see Fig. 2). This may be either in full format or in terms of so-called superelements e. g. based on *Craig* and *Bampton* [3] system reduction along with compatible condensed load vectors. The latter format is usually preferred, as this significantly reduces the size of the combined aero-elastic model and thereby the analysis time without sacrificing the accuracy of the dynamic behaviour.

Aero-elastic simulations: The aero-elastic simulations are then performed on the coupled model consisting of a high-fidelity representation of the rotor blades, nacelle structure, tower and substructure – possibly represented by a superelement (see Fig. 3).

Recovery-run: Subsequently, the substructure designer can reproduce

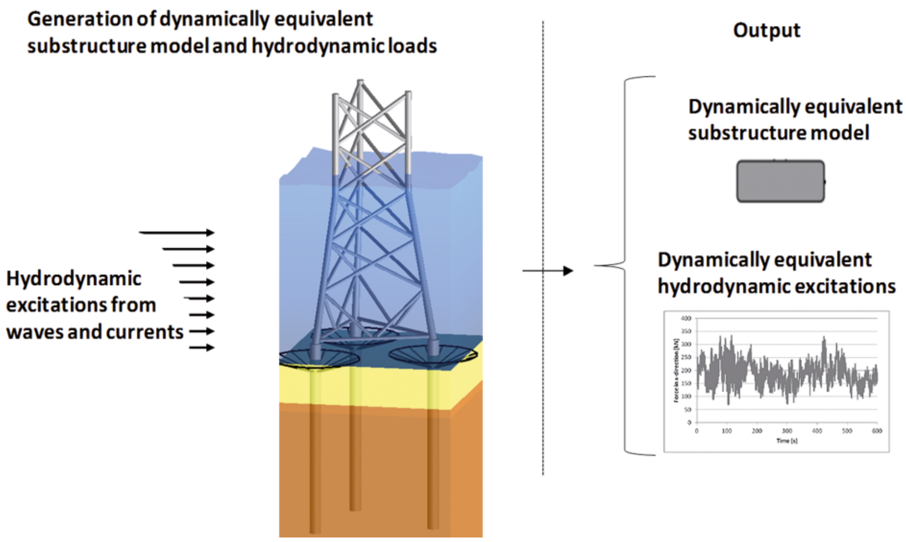

Fig. 2. Generation of dynamically equivalent model and hydrodynamic loads
Bild 2. Generierung eines dynamisch äquivalenten Modells und hydrodynamischer Lasten

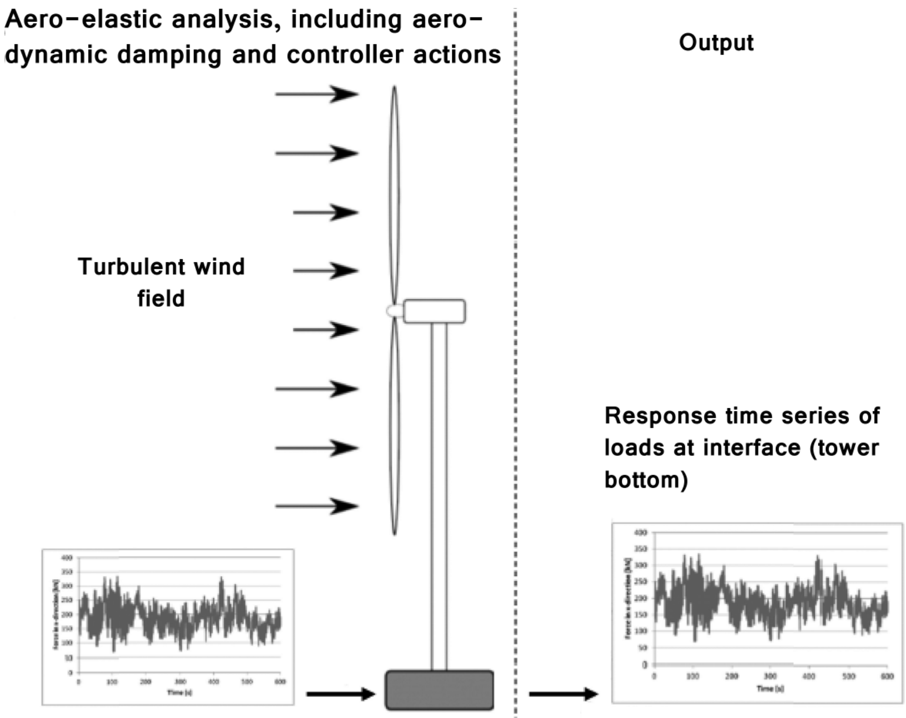

Fig. 3. Aero-elastic analysis
Bild 3. Aero-elastische Analyse

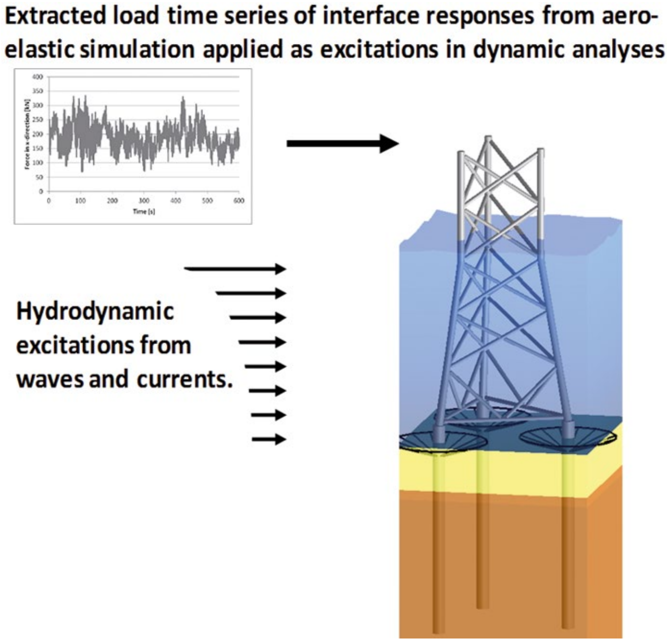

Fig. 4. Application of load time-series and hydrodynamic loads in a dynamic analysis (Recovery-run)
Bild 4. Aufbringung der Last-Zeitreihen und der hydrodynamischen Lasten

the detailed response of the full (non-reduced) substructure model by applying the time series of the interface forces from the coupled aero-elastic analysis along with synchronized hydrodynamics load time series to the initial full substructure model described above (see Fig. 4). The so-called recovery-run hereby forms the basis for detailed design of individual members and joints.

For load determination in connection with preliminary substructure design, Ramboll is able to perform the necessary load iterations internally by using the in-house developed aero-elastic code LACFLEX (based on FLEX5 core).

Mathematically the sequential approach described above can be expressed in the dual format, [2]:

$$M_s\ddot{u}_s + C_s\dot{u}_s + K_s u_s = f_s - g_s(u)$$

$$M_f\ddot{u}_f + C_f\dot{u}_f + K_f u_f = f_f - g_f(u)$$

$$G(u) = 0$$

where the first equation with subscript s is the dynamic equation of motion for the superstructure representing the tower and RNA and the second with subscript f is associated with the substructure. The equations of motion for the two subsystems are kinematically coupled via the constraint condition G(u). This enforces compatibility at the interface – typically a single node – and as a consequence introduces the interaction forces exchanged between the two substructures and in the equations for the superstructure and the substructure respectively. The aero-elastic simulations of the integrated structure amount to solving the coupled set of equations in a time domain, while the recover-run corresponds to solving the second equation only subject to hydrodynamic loads along with the interface reaction forces which are readily available from the aero-elastic simulations.

It should be noted that the sequential approach expressed in the dual format above is only exact when a full (non-reduced) substructure model is applied in both the coupled aero-elastic simulations and the subsequent recovery-run. However, if a properly converged substructure superelement, i.e. a reduced model that represents the spectral properties of the substructure to well above the governing excitation frequencies, the error is negligible.

3 Influence of structural details on the load determination

A crucial aspect that may seem obvious but which is often violated in practical design is that the above described sequential approach is only applicable when the same structural models are used in all design steps. Ideally the recovery-run should only be used as a final design check, i.e. for determining section forces (and stresses) that are used for validation according to relevant design codes. Whilst it might be tempting to use the recovery-run to perform further design optimizations such as increasing or reducing thicknesses or diameters of selected members in certain areas with high or low utilization, such subsequent modifications require extensive experience in order to ensure that the changes have the desired effect.

Consider the case where a part of a jacket structure is stiffened e.g. by increasing the brace or chord thickness in a tubular joint. Intuitively, this will be beneficial for lowering the local stresses. However, due to the statically indeterminate nature of typical jacket structures, local stiffening will lead to redistribution of forces such that larger forces may be transferred through the joint. Furthermore, the effect also depends highly on how the structural changes influence the local joint flexibility [6] and the local stress concentration factors (SCFs) [5], which is not straight forward to predict. Finally, it should be noted that if the structural changes have a significant effect on the overall structural properties of the jacket and thereby its interaction with the tower and RNA structure in the coupled aero-elastic simulations, the interface forces that serve as input for the final recovery-run are also changed. In particular in connection with analysis in fatigue limit state (FLS), where not only the load level, but also the load frequency content is important, structural changes that may seem insignificant can have a huge effect on the fatigue performance of the structure.

In the following a few guidelines based on extensive studies from both commercial projects and generic models are presented. In order to categorize to what extend structural modification are expected to influence the structure, these are divided into global and local changes.

Global changes: These are defined as modifications that affect the structure in a global sense and thereby are expected to lead to large differences between results from a consistent recovery-run, i.e. based on the original structural model, and the results where a modified structure is subject to the initial interface forces. Obviously overall concept changes such as number of legs and number of brace levels will have a large global impact on the jacket that will likely completely invalidate the interface loads from an inconsistent aero-elastic analysis. Similarly, a high sensitivity is found with changes in the footprint or the soil conditions as these serve as boundary conditions for the structure and thus determines its global dynamic behaviour.

It is not trivial to determine whether these are conservative or not for all parts of the structure as these will significantly change the overall stiffness of the structure and thereby the dynamic interaction with the tower/RNA. Therefore, if modifications of this type are introduced in the recovery-run, a new load iteration must be performed to ensure that the interface loads are still consistent.

Local changes: These changes will mainly have a local effect, as they do not change the overall dynamic properties of the substructure and thereby its interaction with the superstructure. This could mean exclusive changes to tube dimensions of braces or legs, brace angles or offsets.

In general it has been found that structural changes in the recovery-run based on initial interface forces will not exhibit the full effect as if consistent (updated) interface forces were used. This means that a local stiffening in general is conservative as the increased resistance e.g. in terms of fatigue life seen immediately will further improve if consistent interface loads from an updated aero-elastic simulation are used. On the other hand, the structural capacity predicted for stiffness reduction may be underestimated if not based on consistent interface loads. This is non-conservative, and thus care must be taken.

Even though the effect on the global structure is limited, local structural changes such as leg and brace modifications may have a significant effect on the local joint flexibility and SCFs at tubular joints, where the critical hotspots with respect to fatigue damage are typical found. In particular, it is important to realize that neither the SCFs nor the local joint flexibility necessarily scale linearly with geometrical changes. As illustrated in Fig. 5, the SCFs at 36 hotspots along the circumferential of a tubular K-joint do not exhibit the same changes in the saddle and crown points for a change in chord thickness. While the effect on the crown points (17 and 35) is rather limited – especially at the lower point – a high influence is observed at the saddle points (8 and 27). The results are shown here for the chord side of the weld; however, similar non-uniform scaling is seen on the brace side. As a consequence a detailed assessment of the joint e.g. via a 3D FE-model must be performed rather than a simple scaling of stresses.

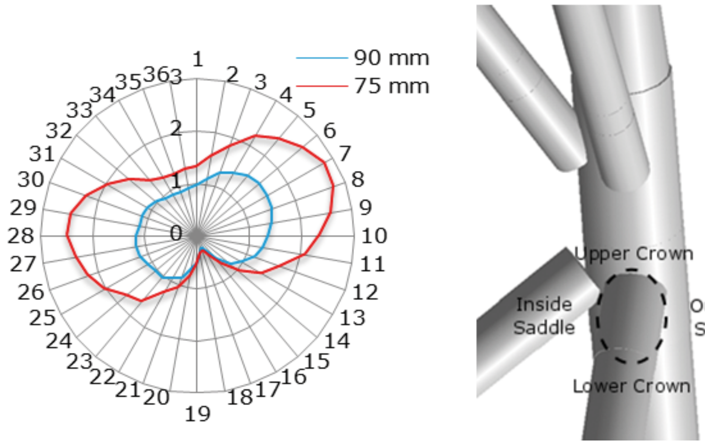

Fig. 5. Influence of chord thickness modification on local SCFs in a tubular joints
Bild 5. Einfluss einer Modifikation der Wanddicke auf lokale Spannungskonzentrationsfaktoren im Knoten

The jacket legs are mainly carrying axial forces as they serve to transfer the vertical forces associated with gravity as well as the overturning moment to the ground, e.g. via piles or suction buckets. Since the overall axial stiffness of the jacket is mainly governed by the soil conditions as discussed more in detailed in the next section, typical desired leg modifications do not change the overall behaviour to an extent that requires an update of the interface forces.

Braces are mainly used for transferring the overall shear forces as well as the torsional moment that typically come from the asymmetric time-dependent force resultant acting on the rotor. For larger turbines (> 5 MW) the latter contribution is typically dominating for the local fatigue life in joints as this introduces large axial forces in the braces varying with a frequency around three times the revolution or P-frequency. Additionally, significant out-of-plane motion of the braces may be introduced if local blade frequencies coincide with local brace modes that are likely to be excited by the turbulent wind field (see e.g. [4]). This is a highly dynamic excitation with frequencies around 2 to 3 Hz that can have a large impact on the fatigue life (see e.g. [9]).

It should be noted that if the braces are relatively stiff such that undesirable couplings with local blade motion are mitigated and the excitation can be regarded as quasi-static, local modifications have a fairly limited effect comparable to the geometric modification. However, if the structure is dynamically sensitive (or close to being dynamically sensitive), even small local changes that do not necessarily require an update of interface forces may have a huge effect on the fatigue life locally.

4 Influence of soil stiffness on the load determination

Soil-structure interaction is an important detail of the overall structural stiffness. In the detailed design a full model of the jacket including foundation elements (i.e. piles or suction caissons) is used to analyze stiffness and loads and to design the structural components. During load simulations soil-structure interaction may sometimes be simplified by means of super element matrices which break the complex non-linear interaction between pile/suction caisson and soil down into a set of spring stiffness for each degree of freedom. The stiffness matrices can be derived from a numerical model of the foundation in soil or by means of a simple beam on elastic foundation analysis (see e.g. [11]).

The foundation pile loads are determined on the complete structural model which is subjected to wind, metocean and turbine loads. Soil-pile interaction in this model is defined based on characteristic soil properties. The dynamic behavior of the overall structure therefore depends on a characteristic stiffness of pile reaction. The resulting loads at pile head level include partial safety factors and are afterwards transferred to a single pile model which is based on design soil resistance, i.e. including partial safety factors, to perform the geotechnical design checks and find sufficient pile dimensions. The principles are shown in Fig. 6.

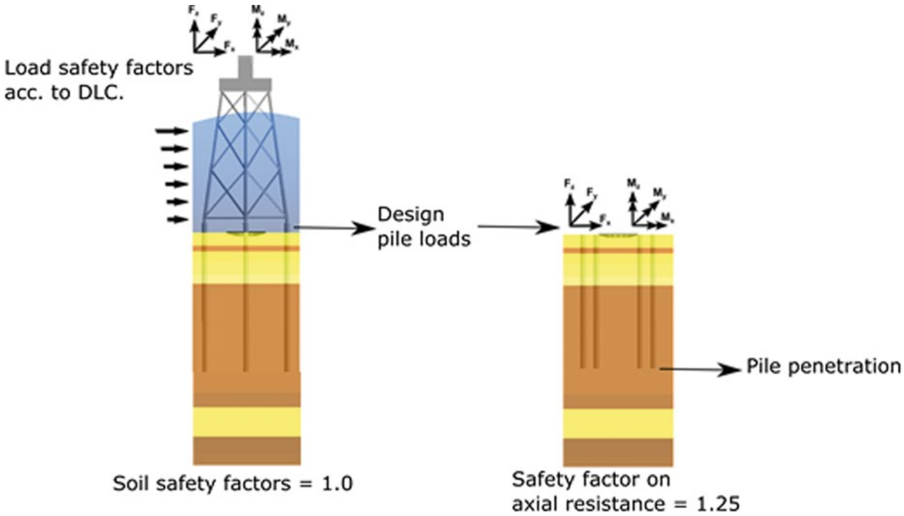

Fig. 6. Determination of pile head loads and pile penetration
Bild 6. Ermittlung von Pfahlkopflast und Pfahllänge

In case the pile dimensions change, the stiffness of the jacket fixation on the ground changes as well. This may have an influence on the pile head loads determined on the global modal. Stiff fixations usually attract more loads. Fig. 7 shows an example of how axial pile head loads change depending on the pile penetration and pile capacity. In this example from a British North Sea project, the water depth was 23 m, the jacket had four post-installed piles penetrating into stiff glacial till over chalk. The piles had a diameter of 96″ (2438.4 mm). When the pile penetration increases, the capacity and axial stiffness of the foundation pile increase as well. But this also results in an increase of axial compression load by approximately 16 %. The determination of pile loads and pile penetration is therefore an iterative procedure rather than a single static analysis.

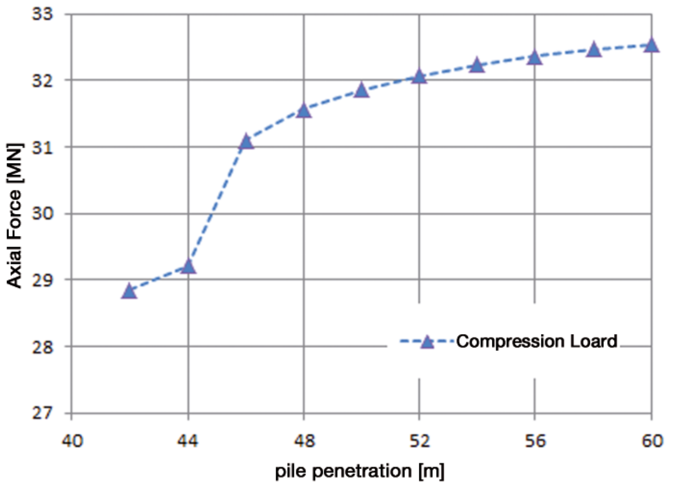

Fig. 7. Pile head load as a function of pile penetration
Bild 7. Axiale Pfahlkopflasten als Funktion der Einbindelänge

There are different design procedures available in standards and scientific papers to calculate the pile bearing capacity. The most commonly used API guideline [7] presents at least five different approaches, one being the so-called ‘main text method’ which has been best practice in Oil & Gas for decades, and four rather new methods based on the results of cone penetration tests (CPT). One of those is based on a publication by *Jardine* et al. [8] called ICP method. Besides the location specific CPT, it takes into account a more accurate stress state, installation effects, cyclic degradation and over-consolidation. In many cases the CPT based methods provide shorter pile lengths compared to the main text method.

Even though the ultimate resistance may be significantly different in the design approaches, the mobilization of resistance is comparable. This means that if a pile is designed for a certain axial load, the pile penetrations may be different depending on the chosen approach, but the calculated stiffness (and thereby the loads retrieved from the global model) should be well comparable.

This fact makes it quite complicated to decide on a load-iteration position within a wind farm which yields stiffest or softest foundation response. Looking at the soil conditions only is not conclusive, because a soft soil location will require a longer pile (which increases the axial pile stiffness), whereas a stiff soil requires a short one.

The approach used to calculate the pile capacity influences the calculated pile length. This effect is related to the overall design procedure and the geotechnical engineer should use the approach most reliable for the chosen pile type and site conditions. On the other hand, the approaches are also sensitive to some soil parameters.

Fig. 8 shows how the pile capacity and it components changes with increasing pile length for a pile in sand calculated with the ICP method [8]. The friction between the pile surface and the soil is a material parameter used in the model, expressed by the interface friction angle δ_v. Since this parameter has to be determined in

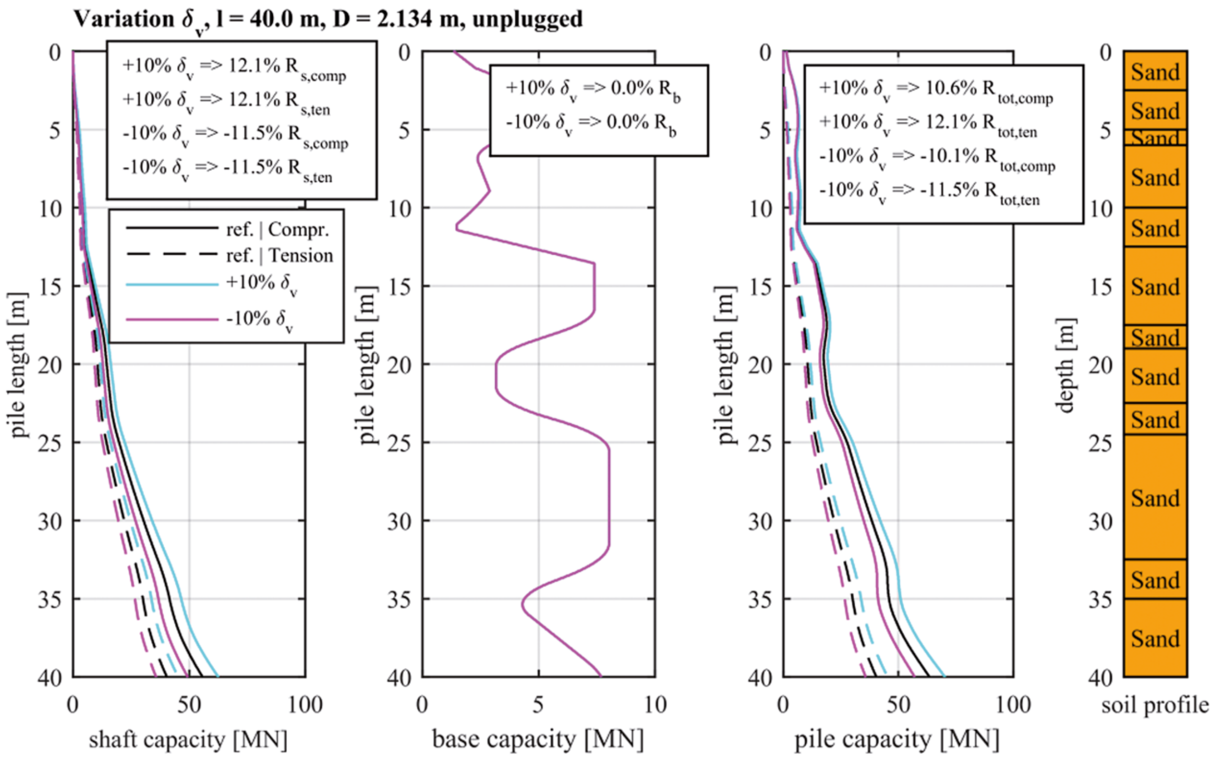

Fig. 8. Pile capacity as a function of pile penetration in sand and variation of the interface friction angle, calculated using the ICP method [8] $R_{s,comp}$ and $R_{s,ten}$ denote shaft capacities in compression and tension, respectively, R_b denotes the base capacity and $R_{tot,comp}$ and $R_{tot,ten}$ denote total capacities in compression and tension, respectively

Bild 8. Pfahltragfähigkeit in Abhängigkeit der Pfahllänge in Sand und Variation des Wandreibungswinkels, berechnet mit der ICP-Methode [8]. $R_{s,comp}$ und $R_{s,ten}$ bezeichnen die Mantelwiderstände bei Druck, bzw. Zug, R_b bezeichnet den Fußwiderstand und $R_{tot,comp}$ und $R_{tot,ten}$ die Gesamtwiderstände in Druck- bzw. Zugrichtung

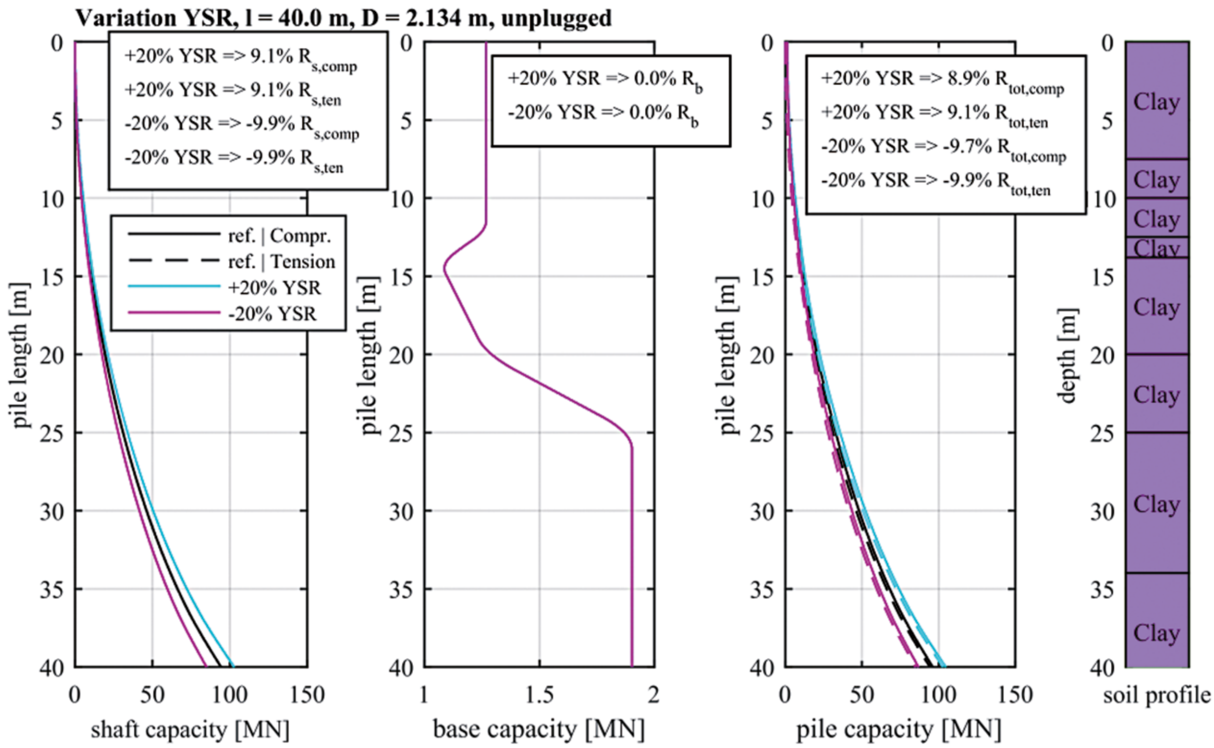

Fig. 9. Pile capacity as a function of pile penetration in clay with variation of the yield stress ratio (YSR), calculated using the ICP method [8]

Bild 9. Pfahltragfähigkeit in Abhängigkeit der Pfahllänge in Ton und Variation der yield stress ratio (YSR), berechnet mit der ICP-Methode [8] ring shear tests or estimated by the geotechnical engineer, a natural variation will occur. The influence of this variation on the pile capacity is shown in Fig. 8. A change of 10 % of the interface friction angle leads to a change of slightly more than 10 % of the pile capacity and therefore to a similar change of the pile stiffness for a given pile penetration. The interface friction angle is a parameter for sand and clay so its uncertainty affects both types of soil.

The influence of the yield stress ratio (YSR) on the pile bearing capacity is shown in Fig. 9. The yield stress ratio is often similar to the over consolidation ratio and therefore not easy to estimate accurately. A variation of 20 % leads to a change of about 10 % in pile capacity and hence pile stiffness.

These two examples show how sensitive the calculation of the pile capacity with the ICP method reacts to variations of some soil parameters, although the ICP method is based on a large database of pile tests. The geotechnical engineer who interprets the soil conditions and the soil parameters should be aware of the calculation method used in the design. The estimation of the soil parameters should be as accurate as possible since a too cautious estimate may lead to significant differences between the stiffness used for design and the stiffness occurring in the field resulting in unexpected dynamic behaviour and load distributions in the structure.

5 Recommendations for an optimized load iteration procedure

From the above statements the following recommendations can be derived for the design process of offshore wind jackets.

Any results based on structural modifications during the recovery-run should be treated with care. This is because structural modifications can result in a significantly modified dynamic jacket response and/or local stiffness changes. These modifications will influence interface forces and local force redistributions in the structure which subsequently will influence the Fatigue Limit (FLS) as well as the Ultimate Limit State (ULS) results. Consequently, the validity of the interface loads might be compromised which calls for a revised full load simulation.

In order to limit the workload associated with this, the optimization process of the jacket should be based on so-called "Mini-Load-Iterations" which only consider a few carefully selected time series yielding very similar results when compared to results based on the complete set of time series considered for full load iterations. While the complete set of time series for full load iterations usually comprises a few thousand time series, "Mini-Load-Iterations" only require a handful, e.g. 24 time series for FLS. This allows for consistent evaluation of different jacket layouts within a short period of time.

Especially in the beginning phase of a project, significant structural modifications are likely to occur and therefore the interface loads require updates accordingly. However, it is believed that time series derived from "Mini-Load-Iterations" provide a much better basis for the jacket optimisation than damage equivalent loads (DELs) which are until today the only wind-induced FLS load type available during the concept phase.

For the planning process and the project schedule the above indicates that "Mini-Load-Iterations" should be adequately incorporated and that full load-iterations should be scheduled whenever a sufficient degree of structural optimization has been reached. This guarantees that the time reserved for structural optimisation is used in an efficient manner. This procedure obviously deviates from the common approach initially established for detailed designs of monopile substructures where only full load-iterations are scheduled. For jacket substructures, however, it is realized more and more that this approach is insufficient and needs to be complemented by an adequate number of "Mini-Load-Iterations".

6 Conclusions

The results of the sensitivity studies presented in this paper as well experience from commercial projects show how structural adjustments in the substructure design may change the structural stiffness and thereby global and local substructure loads. Soil-pile (or soil-bucket) interaction has a direct influence on the pile head load. Stiff fixations of the jacket on the ground attract higher loads than soft ones, where a load distribution between the foundation piles can take place more easily. The orientation and number of braces, the diameter and wall thicknesses of any structural jacket member and the design of the transition piece directly influence the dynamic properties of the jacket. This has significant influence on e. g. the fatigue life of individual members and joints. Those influences can best be identified by so-called "Mini-Load-Iterations" incorporating only a few governing time series. It is therefore recommended to schedule more "Mini-Load-Iterations" during the concept phase as well as the detailed design of jacket substructures and thereby reduce the number of full load iterations. Experience gained in projects following this procedure show that lightweight and optimized jacket structures are achievable in a very efficient manner.

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