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Design Framework for Suction Bucket Jacket Foundations of Offshore Wind Turbines

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Abstract: Foundations for offshore wind turbines (OWT) are designed to withstand dynamic environmental loads from wind and waves, considering effects of resulting OWT motion and soil-structure interaction. The design approach typically consists of an iterative process including aero-elastic modelling and finite element analyses of structural details with complex geometry. In view of the growing focus on jacket support structures for offshore wind farms, this paper outlines an efficient jacket design framework developed by Ramboll.

1 Introduction

Offshore wind energy is of major importance to achieve the targets of the EU Green Deal towards climate neutrality by 2050. The German government has set ambitious expansion targets for offshore wind energy, aiming for 30 GW of installed capacity by 2030, 40 GW by 2035 and 70 GW by 2045, see [1]. In addition, 9 countries including Germany have committed to join forces in the Ostend Declaration to develop the North Sea as Europe's largest green power plant, with a total capacity of 300 GW by 2050. By the end of 2022, 8.1 GW have been installed, see [1].

Schaumann et al. (2021) [2] summarize the most common support structures developed for offshore wind turbines (OWT) in recent years. Monopiles are currently the most frequent support structures – in particular for locations with relatively shallow water depths (< 30 m) and favorable soil properties – due to their simple geometry for design and fabrication, enabling a serial production by utilizing highly automated submerged arc welding.

In the past three decades, 75 % of the commissioned wind farms were installed in shallow water below 30 m according to a study carried out by Rystad Energy in 2020, see [3]. However, according to the International Energy Agency [4], future bottom-fixed offshore wind farms will be located further away from shore and in greater water depths with more than 60 m to reach the ambitious expansion targets. For these locations, lattice supporting structures such as jacket foundations are a reasonable alternative, see Figure 1.

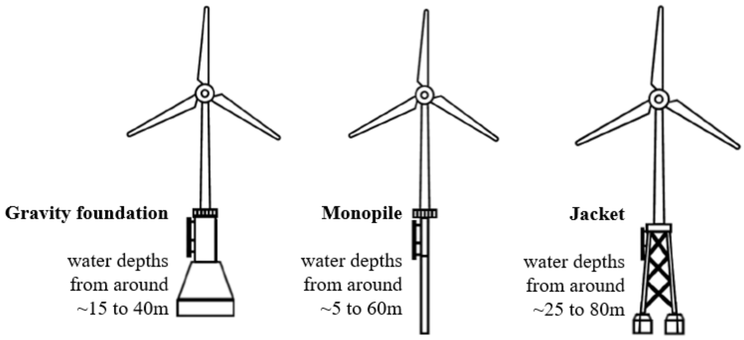

Figure 1: Support structure design types for OWT and application for different water depths

2 Design framework for jacket support structures

2.1 Support structure and foundation definitions

Jackets are lattice hollow-section frameworks similar to structures of oil and gas platforms, characterized by high rigidity with comparatively low material input. The interface to the OWT tower is established by a transition piece that includes a working platform and equipment for the turbine’s operation. The hollow-section components along the jacket are assembled by welded tubular joint variants defined as double-K- (DK-), X- and double-Y-joints, see Figure 2 (right). Jackets are designed with three or four-legs and are fixed to the seabed through driven piles, connected to the jacket legs by a grouted connection.

An alternative to the pile foundation is the suction caisson (also called suction bucket), which consists of a large steel cylinder (or “skirt”) with an open-end at the bottom and a closed-end top circular plate stiffened by girders to form the caisson lid at the connection to the jacket leg, see Figure 2 (right). A cylinder runs from the caisson lid plate vertically for connection with the leg of the jacket structure. The lid geometry is generally symmetrical, but not necessarily centric, about the jacket leg for each caisson apart from some cut outs provided for the installation equipment attachments.

Though used in the oil and gas (O&G) industry for decades, suction caissons are less common in offshore wind, where the loads on the foundation differ significantly and the design is to be optimized for a large quantity in comparison to single structures for O&G platforms. Still, suction caisson jackets (SCJ) have been increasingly deployed in the last decade from first demonstrator to full scale commercial offshore wind farm.

In particular at sites where soil conditions might impose challenges to driving the piles and where strict requirements regarding noise emissions apply, the SCJ have the benefit of a relatively shallow embedment depth into the soil as well as a quick and silent installation. The installation of the suction caissons relies on the initial self-weight penetration followed by a suction assisted installation phase, in which pumps extract water from inside the caissons and therefore generate a suction pressure underneath the caisson’s lid that is driving the caisson further into the soil. It is noted that suction caissons are not suitable for very shallow water depth and depending on the ground conditions, the installation process may be challenging with multiple refusal mechanisms. However, industry experience currently builds up and the development of ground risk mitigation measures is ongoing [5].

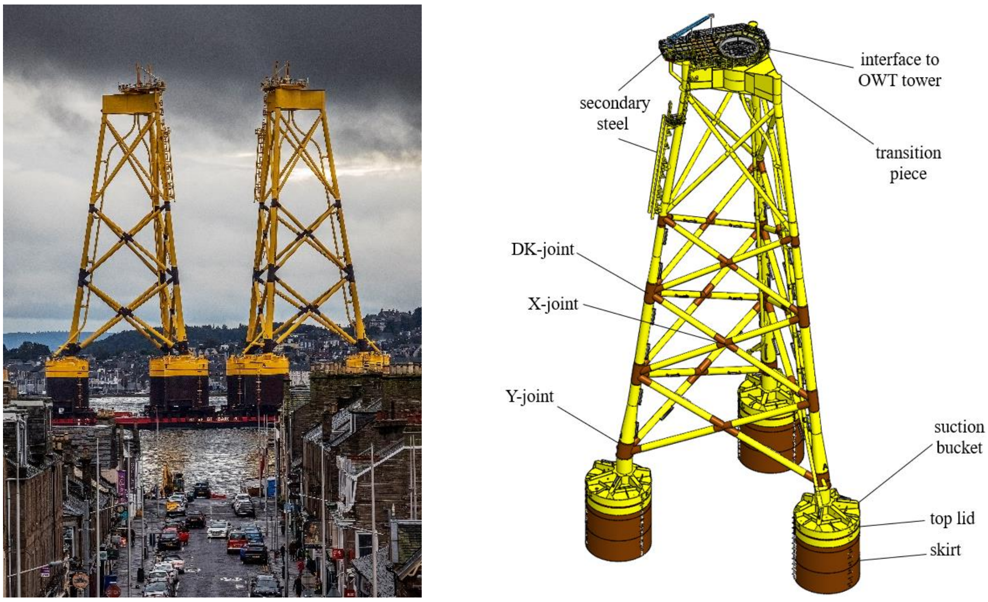

Figure 2: Left: loadout of suction caisson jacket for Seagreen Wind Energy (SSE Renewables); right: exemplary sketch of key structural components

Foundations for OWT are designed to withstand dynamic environmental loads from wind and waves according to the requirements prescribed in standards and recommended practices prepared by authorities such as DNV, the European Committee for Standardization, Standards Norway, the International Electrotechnical Commission or the American Petroleum Institute. In Germany, offshore support structures should also comply with the regulations of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie - BSH), which have been prepared by governmental agencies alongside certification bodies, industry representants and research facilities. The requirements of BSH may have several implications on the design of the support structures when compared to projects in other countries, especially for the design of axially loaded piles, grouted connections, and gravity-based foundations.

2.2 Structural analysis methodology and computational modelling

To properly represent the dynamic loads and structural response, the analyses for the design of the support structures are performed in the time domain. The Ultimate Limit State rarely drives the design of jackets, and it is rather the Fatigue Limit State that usually provides the governing load conditions, defined by several thousands of load cases prescribed by the relevant standards, such as IEC61400-3 [6] and DNV-ST-0126 [7].

The detailed assessment of complex structural elements such as tubular joints, critical hot-spots at the transition piece, the grouted connections to the driven piles or the suction caisson requires detailed shell or solid finite-element (FE) models. Especially with regard to the large number of design load cases (DLCs) to be considered for the fatigue analysis of a jacket structure, the consideration of such detailed FE-models is challenging with respect to the computational effort.

Figure 3 presents an overview of Ramboll's state-of-the-art design framework. It consists of a hybrid structural model combining a comprehensive Timoshenko beam formulation with the detailed FE-representations of non-trivial structural components like tubular joints, TP and suctions caissons. By applying this framework as part of Ramboll's in-house Offshore Structural Analysis Programs (ROSAP), the computational challenges can be overcome as it enables a parallel computing for the execution of multiple repetitive analyses.

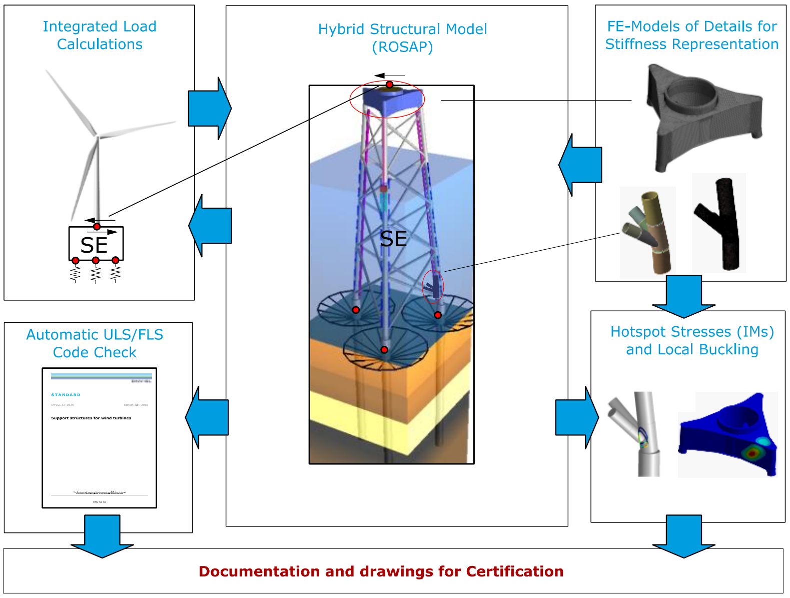

Figure 3: ROSAP design framework for jacket structures according to Nielsen et al. (2019) [8]

The computational model setup is fully parametric and thus allows for an efficient assessment of a wide range of configurations with, e.g., varying geometry, soil profiles, water depths etc., especially when combined with Ramboll's cloud computation setup. All load case definitions and their parametrizations are maintained in detailed load case tables. They form the interface to the load integrated analysis, which is either carried out by Ramboll in-house or by the turbine vendor.

The core of the structural design framework is a global beam model of the foundation in ROSAP. Such a beam-based model is sufficient for representing the overall geometry and stiffness properties accurately. For most practical applications, relevant secondary steel structures such as boat landing, J-tubes, ladders and platforms can be represented by mass and area appurtenances as illustrated in Figure 4 (left) to account for their contributions to the dynamic structural mass and the external loading. However, detailed models of these components may be included if required.

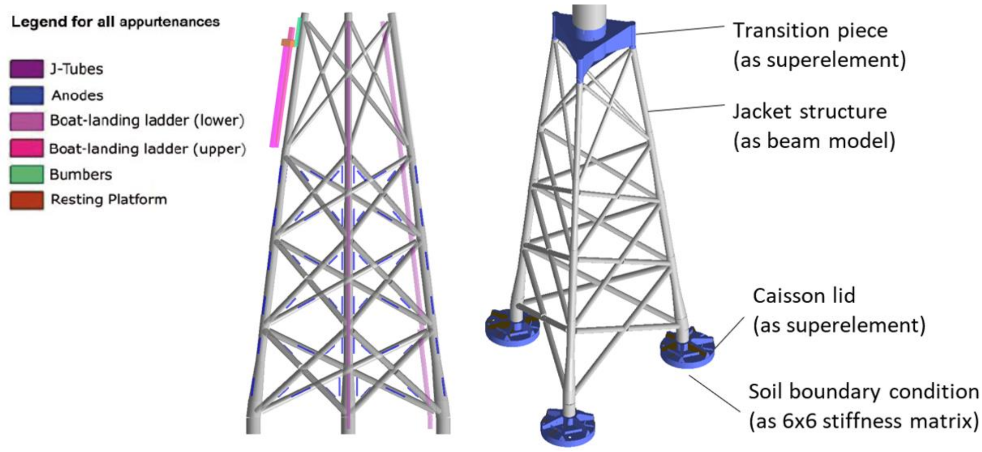

Figure 4: Global beam-based model in ROSA including distributed appurtenances for secondary steel structures (left) and superelements for structural components with complex geometry (right), modelled with the aid of shell or solid finite-element

Non-trivial structural details such as the TP, tubular joints, grouted connections and suction buckets are modelled in special purpose FE software such as ANSYS, which can accurately account for the three-dimensional spatial extent, material variation and mass and stiffness distribution. The detailed FE model representations can then be included directly in the global hybrid model by replacing the relevant geometry with a superelement, see Figure 4 (right). The method of transferring the structural behaviour of the TP and the buckets from an advanced 3D model to a beam model by using the so-called superelements is also often referred to as substructuring or Guyan reduction, see [9]. Further details can be found in [8]. To validate the implementation of these superelements, displacements under unit loads are compared between the detailed FE solid or shell model (in e.g. ANSYS) and the superelement included in ROSAP.

The embedded suction bucket as foundation for the jacket is represented in ROSAP by a 6x6 stiffness matrix, which describes the suction caisson's response to a certain load. Such a stiffness matrix is representative for a characteristic vertical, horizontal and moment (VHM) load combination. Since the suction caisson's bearing behavior is non-linear, iterations within a geotechnical 3D FE model defined in PLAXIS (see Figure 5) and a substructure model in ROSA (see Figure 4) are carried out. A convergence criterion is defined to ensure accuracy of the solution.

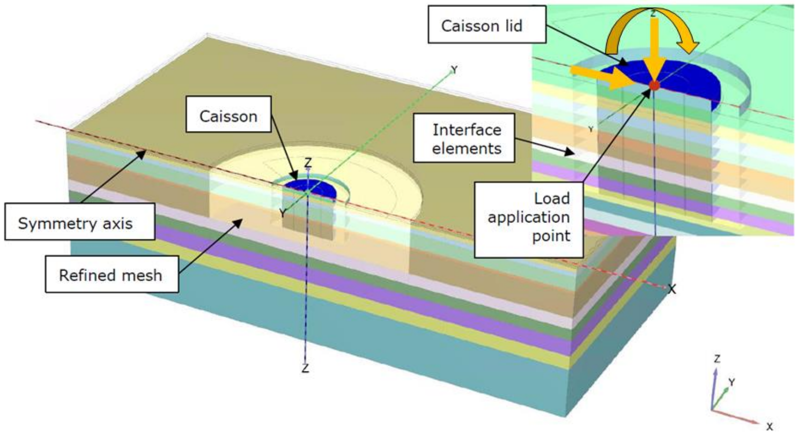

Figure 5: Geotechnical FE model in PLAXIS 3D to calculate the suction caisson's stiffness matrix representing the response to characteristic VHM load condition

The main load direction on the individual foundations is axial with limited shear loads and overturning moments correlating with the stiff connection to the jacket leg. For a simple qualitative discussion, only the axial load component is considered in here. In general, the bearing behavior under compression is stiffer and has a higher capacity in comparison to tension, which is the reason why tensile loads on suction caissons are often driving the design. In addition, the tensile bearing behavior also depends on the load's rate and period and hence the geotechnical design needs to cover high load magnitudes under relatively short load periods (partially drained to undrained response under e.g. single waves within a storm) as well as sustained tensile loads with lower magnitude (evoking drained resistance under e.g. continuous wind load in operation). While the drained tensile resistance is limited to the shaft friction along the caisson's skirt and is thus often relatively small, the partially drained to undrained behavior mobilizes passive suction pressure underneath the caissons lid and results in larger resistances. Both cases are covered by appropriate calculation models.

2.3 Integrated load iteration

Since the design of both the wind turbine and the tower is typically outside the scope of the foundation designer, the calculation of representative design loads accounting for the indirect excitations associated with wind loading is performed in collaboration with the wind turbine designer. The integrated load calculation process between the foundation designer and the turbine vendor is depicted in Figure 6 and the steps can be summarized as follows:

1. A hybrid structural model of the foundation is prepared by the foundation designer.

2. For each load case, the foundation model along with the associated wave load time series are condensed into a so-called superelement (SE). This is typically based on the Craig-Bampton approach (1967) [10], see [8]. The obtained superelement represents stiffness, mass and damping of the foundation and soil system in the aero-elastic analysis performed by the turbine vendor.

3. The turbine designer performs the aero-elastic simulation in the time domain for combined wind, wave and other environmental loads and delivers load-time series extracted at the tower base. The tower base usually serves as the common interface between the turbine vendor and the foundation designer.

4. The foundation designer then applies the interface load-time series to the hybrid structural foundation only model and recovers the response of the structure in a dynamic time domain analysis, which forms the basis for the subsequent foundation design. This approach is commonly referred to as a force-controlled recovery run.

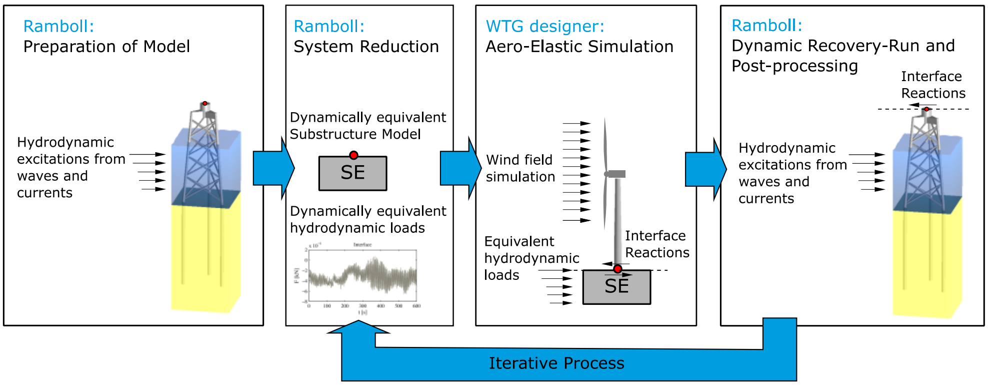

Figure 6: Process of the integrated load iteration between the foundation designer and the turbine vendor according to Nielsen et al. (2019) [8]

The force-controlled and dynamic recovery-run yields highly accurate results as validated in van der Valk et al. (2015) [11] and Nielsen et al. (2016) [12] as long as the superelement SE accurately represents the spectral properties of the underlying foundation model and thereby its interaction with the superstructure. Further information on the integrated load iteration is given in [8].

3 Conclusion

This paper describes how the design of a complex structure can be streamlined into an efficient and accurate process – in this example, the suction bucket jacket substructure for an offshore wind turbine. The framework presented here has been used on numerous commercial projects in accordance with the relevant codes and standards and has been successfully validated by certifying agencies such as DNV, Lloyds and Bureau Veritas.

A fully parametric computational model setup enables the analysis of a wide range of configurations. The application of superelements provides detailed representation of the structure's geometry and stress distributions where relevant, while still minimizing computational effort for the simulation of the whole structure.

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