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Pile-grid foundations of onshore wind turbines considering soil-structure-interaction under seismic loading

Philipp Michel[a,b,*], Christoph Butenweg[b], Sven Klinkel[a,b]

[a] Chair of Structural Analysis and Dynamics, RWTH Aachen University, Mies-van-der-Rohe Strasse 1, 52074 Aachen, Germany
[b] Center for Wind and Earthquake Engineering, RWTH Aachen University, Mies-van-der-Rohe Strasse 1, 52074 Aachen, Germany

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ABSTRACT

In recent years, many onshore wind turbines are erected in seismic active regions and on soils with poor load bearing capacity, where pile grids are inevitable to transfer the loads into the ground. In this contribution, a realistic multi pile grid is designed to analyze the dynamics of a wind turbine tower including frequency dependent soil-structure-interaction. It turns out that different foundations on varying soil configurations heavily influence the vibration response. While the vibration amplitude is mostly attenuated, certain unfavorable combinations of structure and soil parameters lead to amplification in the range of the system's natural frequencies. This testifies the need for overall dynamic analysis in the assessment of the dynamic stability and the holistic frequency tuning of the turbines.

1. Introduction

1.1. Motivation

While the request for renewable energy is still growing, many sites with suiting wind characteristic are already in use. This leads to tower and turbine design for sites with slower winds, increasing the tower and the rotor size. In addition, the sites may provide poor load bearing capacity or may be in a seismically active region or both, which requires a sophisticated dynamic analysis of the structure. Additionally, to increase the sustainability and the efficiency of the overall turbine, progressing research is carried out.

In a joint project group consisting of mechanical and structural engineers research is carried out, regarding the holistic wind turbine design to minimize friction at the interfaces of the different engineering specialties. The group aims to increase the life span of multi megawatt onshore turbines. The drive train has to be designed for best performance, the tower design is optimized in terms of fatigue design. During the project a reference turbine is designed using established design codes to identify and quantify the different influences of compliant soil, a three-dimensional wind field and the control technology on the turbine behavior. Frequency tuning of the overall system is necessary for the optimization of the turbine. This requires sophisticated studies of the foundation-soil structure, as the presence of the compliant soil alters the dynamic behavior of the structure. Established design codes [1–3] demand the consideration of dynamic soil-structure-interaction (SSI) effects in the design of wind turbines. SSI effects affect especially slender structures like the towers of wind turbines [4]. Depending on the dynamic stiffness of the soil, the eigenfrequency of the wind turbine tower changes [5,6] and different soil constellations alter the response of the turbine tower [7]. These effects play a major role in the frequency tuning of the turbine. Accordingly, the SSI effects have a vast influence on the seismic response of the wind turbine. Onshore wind turbines settle on shallow foundations or pile foundations. Latter often use multi pile grids with a high number of piles. Commonly, pile-foundations are used to minimize settlements in soils with low load bearing capacity. However, they also influence the dynamics of the system regarding the SSI effects. This influence has been quantified in the literature [8,9] for different pile parameters using small pile grids.

The present contribution deals with the foundation design, and the influence of both the foundation and the soil-structure-interaction on the behavior of the overall structure, focusing on foundations with multiple piles. The present work extents the earlier findings for small pile groups to large pile grids of modern onshore wind turbines.

1.2. State of the art

Early SSI studies address the vibrations of machine foundations on elastic half space [10]. A major advantage in the understanding of the SSI effects was the incorporation of the dynamic impedance functions in SSI analysis [11]. The most important step towards practical applications was the shift from analytical investigations to numerical

* Corresponding author at: Chair of Structural Analysis and Dynamics, RWTH Aachen University, Mies-van-der-Rohe Strasse 1, 52074 Aachen, Germany.
E-mail addresses: michel@lbb.rwth-aachen.de (P. Michel), butenweg@cwe.rwth-aachen.de (C. Butenweg), klinkel@lbb.rwth-aachen.de (S. Klinkel).

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approaches, which allows the study of complex systems with arbitrary shaped flexible foundations, embedded foundations and piles, as well as inhomogeneous, layered soil. A complete review of the SSI development over time can be found in [12]. The Boundary-Element-Method (BEM) is used to model the infinite soil model and can be coupled with the Finite-Element-Method (FEM) considering realistic soil compositions as well as complex structures [13]. The cone model as introduced by Wolf [14] is a simplified analytical approach to simulate SSI effects. The lumped-parameter-model (LPM) is another simplified analytical approach, which allows efficient SSI calculations in the time domain for both shallow and pile foundations [15]. The LPM model has to be fitted to a rigorous model or experimental results for accuracy.

In the early works of Kaynia and Kausel [9,16] the dynamic behavior of pile groups is analyzed. Square foundations with up to 16 piles are investigated. Garcia [8] used FEM-BEM coupling via the software SASSIG that employs the Thin-Layer-Method [17] to calculate the flexibility of the soil model. He used up to nine piles to reduce seismically induced loads, investigating the influence of pile spacing and inclination on the seismic response of an example structure.

Bazeos et al. [5] were among the first to describe the alternation of a wind turbine's natural frequency by compliant soils. Taddei et al. [7] applied FEM-BEM coupling to study SSI effects on a wind turbine based on a shallow foundation on layered soil. This research is in alignment with other recent studies, which fulfil the need for SSI investigations in wind turbine design as demanded by the codes. Andersen [15] employed the LPM to show how the SSI effects alter the resonance frequencies of the wind turbine, which are dependent on stiffness and depth of the soil layer. The second and higher modes of the wind turbine tower are damped by the energy transmission into the ground. The damping is also dependent on the soil properties. As the first eigenfrequency of the first tower mode lies below the cut-on frequency of the soil system, damping effects are not activated by the first tower mode. Harte et al. [6] used the cone model in the time domain to prove that the frequency content in the response time history is altered by the influence of a weak homogenous soil. Ghaemmaghami et al. [18] present transfer functions and response spectra of a wind turbine on a shallow foundation, which show the influence of the SSI effects on the seismic demand on the tower. Taddei [7] expanded these investigations to layered soil, showing the important influence of the relative stiffness of structure and soil. Further, it is pointed out that the stiffness ratio of different soil layers plays an important role.

The studies of SSI effects on wind turbines are not limited to shallow foundations. Zania [19] examined slender structures on monopiles, using analytical solutions to investigate the influence of the dynamic soil-pile interaction on the natural frequencies and the damping of offshore wind turbines. Offshore wind turbines on mono piles are also in the focus of Damgaard, et al. [20]. They used an LPM model of pile foundations to study the response of the structure under wind load in both frequency and time domain. Further research on multiple piles is carried out by Medina [21] who employed FEM-BEM coupling to investigate deep foundations with inclined piles. The results show, that the number of piles and different rake angles influence the dynamic behavior. Dezi et al. [22] introduce numerical models of the foundation, where the pile-soil-interaction is modelled using two-dimensional Green's function. Transfer functions and impedance functions are presented showing the impact of pile geometry and spacing on the dynamics of a 2×2 pile group. Gonzalez and Padron [23] used a LPM for the computation of 3×3 pile groups, investigating impedance function and earthquake time histories. The LPM model is fitted to FEM-BEM calculations. Santangelo et al. [24] investigated the time dependent behavior of the turbine tower under earthquake and wind load. Including square shallow foundations as well as a square foundation with four piles and simplified SSI modelling, Santangelo et al. show the possibility to consider both load cases via the combination of two uncoupled calculations [24].

1.3. Goals and outline

While the dynamic behavior of small pile groups is well investigated, the question remains, if the findings can be generalized to multi-pile grids, which are widely used in the construction of onshore wind turbines. Dynamic SSI effects determine the seismic response of slender structures, which underlines the necessity for the dynamic analysis of a turbine tower on a multi-pile grid. Consequently, three major questions arise:

i) Do the dynamics of a multi-pile grid resemble the dynamics of smaller pile groups?
ii) How does a multi-pile foundation of a wind turbine react to seismic loading?
iii) Does the use of multi-pile foundations increase the dynamic stability as much as the static stability?

These questions are addressed in the present work. The first step is to carry out the pre-design for a realistic multi-pile grid to create a useful reference foundation for further dynamic investigations on a reference turbine. This multi-pile grid is modelled using established methods and programs to analyze its dynamic behavior. Subsequently the results of the dynamic analysis are compared to findings in the literature concerning small pile groups to identify the SSI effects. Afterwards holistic seismic investigations of the wind turbine tower on the multi-pile grid are carried out. Due to the frequency dependency of the soil system the answer might vary for different soil conditions and frequency ranges of the investigation.

2. Foundations under dynamic loads

2.1. Static pre-design of wind turbine foundations

2.1.1. Procedure

The purpose of the foundation is to distribute all loads acting on the wind turbine structure into the underlying ground. The shallow or surface foundation is grounded on soils with good load bearing capacity, where the proof against overturning has the most significant influence on the foundation size of the shallow foundation. If the load bearing capacity diminishes, pile foundations are used to minimize unwanted settlements of the structure. To classify the soil for the placement of wind turbines, geological, geophysical and geotechnical examinations have to be carried out [2]. Information is required on the layering of the soil, the different rock and soil types, their density and stability. In the construction of wind turbine foundations driven piles or drilled piles are mostly used, the selection is depending on multiple practical considerations. The piles are connected to the foundation via the pile caps, which distribute the load acting on the foundation into the piles. The design of the slab and the check for the inner load bearing capacity of the piles is not part of this investigation; the preliminary design is following the current codes and guidelines and is carried out for the ultimate limit state and the service limit state. The loads consist of permanent action such as dead self-weight and earth pressure and variable loads such as wind loads.

The mechanical system of a wind turbine's pile grid is highly statically indeterminate, so the distribution of the stress from the pile cap into the piles is done via Schiel's method [25]. It allows a matrix based calculation of the pile forces of a system under the following conditions:

1. The pile cap acts as a rigid block, and in comparison with the piles, is not subjected to any shape and length variations.
2. The piles are slender enough and the dislocation of the block is small enough, to be able to neglect the passive earth pressure and the pile moment resulting from the dislocation. This means, the piles behave as if they were connected to both the block and the underlying bedrock via joints.