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Robust design and optimization procedure for piled-raft foundation to support tall wind turbine in clay and sand

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Abstract

A geotechnical design and optimization procedure for piled-raft foundations to support tall wind turbines in clayey and sandy soil are presented in this paper. From the conventional geotechnical design, it was found that the differential settlement controlled the final design and was considered as the response of concern in the optimization procedure. A parametric study was subsequently conducted to examine the effect of the soil shear strength parameters and wind speed (random variables) on the design parameters (number and length of piles and radius of raft). Finally, a robust design optimization procedure was conducted using a Genetic Algorithm coupled with a Monte Carlo simulation considering the total cost of the foundation and the standard deviation of differential settlement as the objectives. This procedure resulted in a set of acceptable designs forming a Pareto front which can be readily used to select the best design for given performance requirements and cost limitations.
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Keywords: Piled-raft foundation; Robust design; Optimization; Wind turbine; Renewable energy

1. Introduction

Wind energy, an alternative to conventional energy produced by burning fossil fuels, is a renewable and clean energy which produces no greenhouse gas emissions during operation, consumes no water, and uses only a little land. With the rapidly growing world population, it is essential to increase the production of energy using sustainable sources such as wind to meet the demand. One of the cost-effective ways to increase the production of wind energy is to build taller towers. Since a higher and steadier wind speed can be accessed at higher elevations, building taller towers can increase the wind energy production of a single turbine. The study of Lewin (2010) revealed that an increase in turbine elevation from 80 m to 100 m would result in a 4.6% higher wind speed which translates to a significant 14% increase in power output. A further increase in tower height from 80 m to 120 m would result in an 8.5% higher wind speed and a 28% increase in power output. It should also be noted that the higher initial construction cost and the lower operational cost of wind turbines make it economical to build a few taller towers rather than several normally sized towers to maximize the wind energy production.

Increase in tower height, however, leads to significant geotechnical engineering challenges because the foundation design loads (vertical load, horizontal load, and bending moment) increase with the increasing tower height. Larger loads not only result in the larger foundations demanding

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significant resources to be allocated for the design and construction of the foundations, but they also present challenges in choosing the appropriate type of foundation as well as the optimal design parameters. Among the many types of foundations used for supporting wind turbines, a piled-raft foundation is considered to be effective for supporting tall wind turbines, especially for improving serviceability requirements (Shrestha, 2015). The centrifuge model tests performed by Sawada and Takemura (2014) on three types of model foundations (piled-raft, pile group, and raft alone) subjected to vertical, lateral, and bending moment loads also show that the vertical bearing capacity of the piled-raft foundation is the largest among the three foundations considered. This may be due to the higher bearing capacity of the raft and the increase in pile capacity due to the increase in soil stiffness caused by the raft contact stress. The same study also concludes that the settlement due to various loads can be reduced by using a piled-raft foundation.

The geotechnical design of a piled-raft foundation is complicated, especially when the foundation is subjected to a larger horizontal load and bending moment. The complexity increases even further when uncertainties in the wind load and the soil parameters must be incorporated into the design process, to increase its robustness, while keeping the cost at the lowest possible value. The selection of suitable design variables, such as the number of piles, the length of the piles, and the radius of the raft, for given loading and soil conditions, is another challenge because of the existence of a large number of acceptable designs. Selecting the best design that suits the performance and cost limitations is not straightforward in the conventional design. In such situations, the robust design optimization technique can be used to produce a relationship between the measure of robustness and the total cost of the foundation enabling the easy selection of the best design for a given set of performance requirements and cost limitations.

It is well recognized that the uncertainties of the soil parameters and the loads are unavoidable in the design of foundations. In a deterministic design approach, engineers use a factor of safety (FS) to cope with the uncertainties in the entire solution process. Usually, a larger FS is used when the uncertainties of the soil parameters and the loads are higher. Although design optimization is performed in the day-to-day engineering profession, the traditional optimization procedure becomes inefficient for the design problem pursued in this study. This is because the pool of acceptable designs in the traditional optimization is small and the problem is simplified to reduce the number of random and design variables within a manageable range. To consider the uncertainties in a systematic and accurate manner, a reliability-based approach supported by automated computer algorithms must be considered. Researchers have proposed various methods that consider the uncertainties in the soil parameters explicitly for the design of geotechnical as well as other engineering systems (Duncan, 2000; Griffiths et al., 2002; Phoon et al., 2003a, b; Fenton and Griffiths, 2008; Schuster et al., 2008; Juang et al., 2009, 2011; Wang et al., 2011; Zhang et al., 2011). Recently, one of the authors and his colleagues developed a reliability-based robust design methodology for the design of an individual drilled shaft in sand considering the uncertainties of the soil parameters (Juang et al., 2013). Additional literature on the geotechnical design concept and the design optimization is presented in the optimization section.

This methodology is employed in the current study for the design of a piled-raft foundation considering not only the uncertainties of the soil parameters, but also of the wind speed which affects the horizontal load and the bending moment. The spatial variation in strength and stiffness properties is unavoidable especially when the foundation design is being made for the construction of a wind farm which covers a large area. Conducting a subsurface exploration to accurately determine the soil properties and to design a piled-raft foundation for each wind turbine would be expensive and is not recommended in practice. Therefore, it is necessary to develop a design procedure considering the possible variations in soil properties so that the design will be accurate. Similarly, the wind speed which affects the horizontal load and the bending moment at the base of each tower also varies with the location, height, and time. Therefore, the wind speed must also be considered as an uncertain parameter in the design. Both aforementioned uncertain parameters have a significant impact on the selection of an optimum design for given site conditions, performance requirements, and cost limitations. A systematic incorporation of multiple random variables in the design requires an advance optimization procedure with predefined objectives such as cost and performance limitations.

To demonstrate the procedure, a 130-m-tall onshore wind turbine in clayey and sandy soil is considered. In the design optimization, the wind speed, the undrained cohesion of the clayey soil, and the friction angle of the sandy soil are taken as the random variables, while the length of the piles, the number of piles, and the radius of the raft are taken as the design variables. The differential settlement of the piled-raft, which is an overall stability parameter critical to fulfilling the serviceability requirement, is considered as the response of concern. The outcome of the optimization is presented in graphical form as a Pareto front which can be used to select the best design for a given set of performance requirements and cost limitations. The design procedure presented in this study can also be directly applied to other structures which are supported by a piled-raft foundation and subjected to combined vertical, lateral, and bending moment loads.

2. Deterministic geotechnical design of piled-raft foundation

2.1. Deterministic loads and soil properties

The wind turbine foundation is subjected to vertical load due to the self-weight of the superstructure, horizontal

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