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Effect of soil-foundation-structure interaction on the seismic response of wind turbines

Sam Austin *, Sukhvarsh Jerath

Department of Civil Engineering, University of North Dakota, 234 Centennial Drive Stop 8115, Grand Forks, ND 58202-8115, USA

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A B S T R A C T

Soil-foundation-structure interaction can affect the seismic response of wind turbines. This paper studies the effects of soil-foundation-structure interaction on the seismic response of 65 kW, 1 MW, and 2 MW horizontal-axis wind turbines with truncated cone steel towers. Four types of foundations with frequency-based design were analyzed, including spread foundation, mono pile, pile group with cap, and anchored spread foundation. Soil is modeled both implicitly (subgrade reaction modulus) and explicitly. The finite element model developed using the ANSYS program was first validated using experimental data. Numerical models are then analyzed in both frequency and time domains using the Block Lanczos and generalized HHT-α formulations. Recommendations were given to simplify the soil-foundation-structure interaction analysis of wind turbines subjected to seismic loading.

1. Introduction

Wind turbines are the world's fastest-growing source of renewable energy across America and around the globe. In 2015, the US wind industry installed a total of 8598 Megawatts (MW) of new power capacity, a 77% increase over 2014 [1]. Decreasing number of prime sites with high wind availability and good access, coupled with increasing demand for higher power output has increased the need to use taller towers with longer blades especially in less windy sites [2]. In seismic regions, taller wind turbines develop large seismic forces that are sometimes bigger than the wind forces [3]. In such cases, an inaccurate estimate of the seismic force can result in either structural failure or uneconomic design. An important factor in estimating the seismic forces on wind turbines is the soil-foundation-structure interaction, which is affected by different parameters including turbine size, foundation type, and soil properties.

This paper analyzes the soil-foundation-structure interaction effects on the seismic response of wind turbines. Three wind turbine capacities are selected for the study, namely, 65-kW (similar to the experimental model), and 1-MW and 5-MW (representing the current lower and upper threshold of utility scale sizes). In this study, horizontal-axis turbines with truncated cone steel towers were used. Foundation types are spread foundation, mono pile, pile group with cap, and anchored spread foundation. Soil effects are included using modulus of subgrade reaction and also explicit model. The finite element model developed using the ANSYS program was first validated using experimental data. Natural frequencies of numerical models are then examined using the Block Lanczos method with ANSYS program. Next, time history analysis is performed using the records from the 1992 Landers Earthquake and the generalized HHT-α formulation. Recommendations are provided to simplify the soil-foundation-structure interaction analysis of wind turbines subjected to seismic loading.

2. Literature review

Prowell et al. [4] analyzed a full soil-structure system with a 5-MW wind turbine with a hub height of 90 m and a rotor diameter of 126-m. A detailed finite element model of the turbine was created, including a full three-dimensional (3-D) soil mesh to study the influence of soil-structure interaction (SSI) on the dynamic properties and response. The turbine was modeled on 3- to 15-m (9.8- to 49-ft) thick soil profiles with varying stiffness and subjected to a 1994 Northridge Earthquake record. Their investigation found that for these conditions the SSI influence on the first and second longitudinal bending modal parameters was relatively

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* Corresponding author.
E-mail addresses: sam.austin.jb@ceamerica.com (S. Austin), sukhvarsh.jerath@engr.und.edu (S. Jerath).

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minor, while the SSI influence on the maximum moment and shear demand distributions along the tower height was more significant. Prowell et al. recommended the selection of a range of carefully chosen ground motions to match the anticipated shaking for the proposed site in SSI analyses.

Hongwang [5] analyzed the seismic response of two 1.65-MW and 3-MW wind turbine models, including the SSI and P-Δ effects under horizontal and vertical components of six historical earthquake time histories. The SSI was modeled by connecting the turbine base to a rigid support mounted on translational and rotational springs and dampers. The results showed that the SSI caused a 7% decrease in the first natural frequency, 10% decrease in the horizontal acceleration at the top of the tower, 10–12% decrease in the tower base moment, and 5–6% decrease in the tower base shear force. The SSI had no significant effect on the vertical acceleration and axial force of the towers, but the P-Δ effect increased the tower base moment slightly.

Kourkoulis et al. [6] performed a parametric seismic analysis on two wind turbines with 2 MW and 3.5 MW capacities supported on suction caisson foundations under static cyclic and earthquake loads. The analysis included non-linear SSI caused by sliding between the caisson skirt and the soil and gap formation. The model included 3-D soil elements with shell elements representing the interface, beam elements for tower, and a concentrated mass representing the rotor blades and nacelle. The results showed that interface failure could reduce the capacity of suction caisson foundations especially in foundations with deep caissons. It was also shown that foundation rotation caused by interface problems could cause irrecoverable displacement on the nacelle level. Increasing the caisson diameter was found to be a better solution compared to increasing the depth of embedment.

Kjørlaug et al. [7] studied the dynamic response of a wind turbine supported on mono pile foundations under horizontal and vertical earthquake excitations. A non-homogeneous, deep-soil stratum was considered. Their analyses showed an acceleration amplification factor of 2 from the ground surface to the top of the tower. Vertical earthquake excitations were found to be critical in low-to-moderate seismic areas.

Cheng and Lien et al. [8] evaluated the load bearing characteristics of the jacket foundation pile for offshore wind turbines on the west coast of Taiwan. Effective stress analysis, with consideration of pore pressure generation and soil/liquid coupled analysis, was conducted. A numerical procedure to evaluate the design of offshore wind turbine foundation piles in the sand and clay interlayered soil was developed.

Loubser et al. [9] analyzed a 3D finite element model of wind turbine and foundation with fully non-linear material and discreet reinforcement using DIANA 3-D software. It was found that a 30% material saving can be achieved using PLAXIS model.

Katsanos et al. [10] presented a comparative survey of the published research relevant to the seismic analysis, design and assessment of wind turbines. The use of full FE models, including the nacelle and the rotor blades, the supporting tower as well as the soil-foundation system, along with time domain analysis was recommended. It was also shown that due consideration should be paid to the SSI phenomena, since the soil compliance and the earthquake-induced inertial interaction between the superstructure and the soil foundation system may significantly modify the dynamic characteristics of a wind turbine and its seismic response. It was also found that current foundations systems of wind turbines with gradually increasing size in areas of high seismicity may be vulnerable. It was suggested that advanced techniques of modeling and analysis should be adopted to scrutinize the demanding foundation structures and the soil underneath.

3. Methodology

A parametric study is performed in both time and frequency domains. A series of wind turbines with different sizes and capacities with different foundation types and two types of soil model are analyzed using the Block Lanczos method for modal analysis and generalized HHT-α method for transient analysis. Block Lanczos is a frequency domain method used by the ANSYS program. In this method, eigenvalue solver uses the Lanczos algorithm where the Lanczos recursion is performed with a block of vectors. Block Lanczos uses the sparse matrix solver and is especially powerful when searching for eigenfrequencies in the eigenvalue spectrum of a given system. The convergence rate of the eigenfrequencies, when extracting modes in the mid-range and higher end of the spectrum, will be about the same as when extracting the lowest modes. This method is recommended to find many modes of large models and it can handle poorly shaped solid and shell elements [11]. The generalized HHT-α method is an implicit time scheme similar to the Newmark method in which the structural stiffness matrix is factorized to solve for $\{u_{n+1}\}$ at time t_{n+1}. Systems are assumed to have frequency based design.

3.1. Frequency-based design

In the analysis and design of wind turbines, tower design is usually controlled by its frequency limits to prevent interference with turbine operational frequencies [12]. Fig. 1 shows the allowable frequency range in a typical frequency design problem. Natural frequencies (f_{n1}, f_{n2}, etc.) should be separated from operational frequencies (f_{op1}, f_{op2}, etc.) with a safety margin. Considering that the operational frequencies of utility scale wind turbines typically range from 0.1 Hz for larger turbines to 0.5 Hz for smaller ones, the natural frequency of these turbines should be above this range to prevent resonance. In other words, the ratio of natural to operational frequency must be greater than 1, preferably with a 10% safety margin. The recommended values for this factor of safety are between 1.1 and 2. If the safety margin is not big enough, the effect of soil-foundation-structure interaction can shift the natural frequencies of the structure too close to operational frequencies and dynamic amplification can occur. Therefore, assuming a fixed tower base in the design may not be conservative; and it may be necessary to analyze the soil-foundation-structure interaction. In other words, unlike other structures, the design of wind turbine foundations may not be governed by soil bearing capacity alone and can be significantly affected by the dynamic properties of the wind turbine.

3.2. Seismic load

Selected seismic load should have frequencies close to the frequency of the turbine so that they can excite the natural modes of the turbine. The East-West and vertical components of the Landers Earthquake (June 28th, 1992) record have Peak Ground

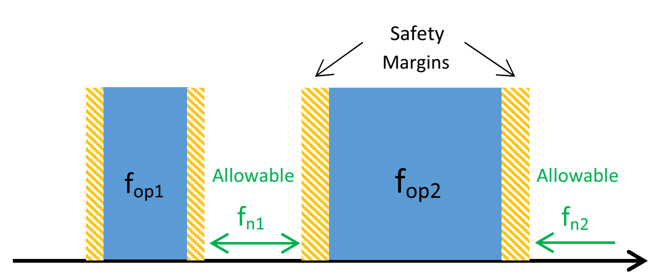

Fig. 1. Allowable frequency range in frequency-based design.

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