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Modeling and mitigation of excessive dynamic responses of wind turbines founded in warm permafrost

Mingyan Zheng [a,b], Zhaohui (Joey) Yang [c], Shihao Yang [a,b,*], Benjamin Still [c]

[a] China University of Geosciences, Wuhan 430074, China
[b] University of Alaska Anchorage, Anchorage, AK 99508, USA[1]
[c] Civil Engineering Department, University of Alaska, 3211 Providence Dr, Anchorage, AK 99508, USA

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ABSTRACT

Field monitoring data provide evidence of excessive vibration on the wind turbines founded in warm permafrost (referring to soils frozen for more than two consecutive years with a temperature close to its melting point), which was attributed to resonance between the rotor and the tower-foundation system. This study presents a finite element (FE) model of the turbine-tower-foundation-soil system for analyzing causes of resonance and assessing effectiveness of mitigation measures. This model decouples the aerodynamic effects of the rotor from the turbine system. Aerodynamic simulation of the rotor was performed to provide wind thrust time series on the tower top. The lateral interaction between pile foundation and warm permafrost was modeled by distributed p-y springs and details on how to evaluate the permafrost p-y curves were provided. The FE model was used to investigate the sensitivity of wind turbine structural fundamental frequency to the permafrost temperature. It is found that, in addition to 9% seasonal change, the turbine-tower-foundation-soil fundamental frequency can decrease by 7% when the permafrost temperature increases from −2 °C to 0 °C. Analyses by using this model show that resonance can occur when the rotor speed is in the vicinity of the structural fundamental frequency, and increase the fatigue load on both the tower and foundation. The resonance is likely caused by the seasonal and long-term change in fundamental frequency of the turbine-tower-foundation-soil system and the inability of the controller to adjust its control parameters with time. Results show one tuned-mass-damper of 3% mass ratio is capable of reducing the tower peak acceleration and displacement during resonance by 50%, and reducing the peak shear and bending moment in the foundation by 40%. Adopting a controller with parameter updating capability together with using passive structural control techniques such as tuned-mass-dampers may be an effective control design strategy for wind turbines founded in warm permafrost.

1. Introduction

Continuous winds across the barren tundra in Western Alaska, USA, are ideal for wind energy development. Over the last decade wind turbines have been constructed in many villages. Many of these wind turbines were founded in warm perennially frozen soil, or permafrost, which requires extra precaution in foundation design. Reinforced concrete mat foundation was experimented but proven not appropriate due to high material and construction costs [1] and thermal impact to the underlying permafrost. Current practice favors a deep foundation consisting of a steel pipe pile group and a pre-cast concrete mat acting as a pile group cap, along with a mechanism to keep the ground cool. The dynamics of wind turbines are important, and often are a controlling aspect in foundation design. Resonance between the soil-foundation-structure system and the rotor should be avoided.

There have been many investigations of the impact of soil-structure interaction on wind turbine structural dynamic responses. Friedmann [2] presented a comprehensive review on aeroelastic and structural dynamic aspects of horizontal-axis wind turbines, and discussed isolated blade aeroelastic problem and the coupled rotor-tower system. Bhattacharya and Adhikari [3] investigated the soil-foundation impact on the natural frequencies and damping factors of the turbine tower founded on a monopile, developed an analytical model considering the rotational and translational flexibility of the foundation, and presented experimental methods to assess these flexibility parameters. Harte et al. [4] developed a Multi-Degree-of-Freedom model of an onshore horizontal-axis wind turbine supported on a shallow

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* Corresponding author at: China University of Geosciences, Wuhan 430074, China.

E-mail address: yangsh0105jh@gmail.com (S. Yang).

[1] Formerly Visiting Professor.

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foundation, and concluded soil-structure interaction affects the wind turbine response. Ong et al. [5] reported on dynamic analysis of an offshore wind turbine supported on a monopile including the effects of wind-wave and soils; pile-soil interaction was modeled by axial load transfer (*t-z*) curve, tip load–displacement (*Q-z*) curve and lateral load-deflection (*p-y*) curve. Lombardi et al. [6] studied the long-term behavior of a model wind turbine supported on a monopole in clay, and investigated the change of natural frequency and damping with cyclic horizontal loading. Feyzollahzadeh et al. [7] presented dynamic response analyses of offshore wind turbine towers with a fixed monopile platform by an analytical method and the foundation was modeled by coupled springs, distributed springs or apparent fixity length models. Aasen et al. [8] and Jung et al. [9] investigated the effects of different foundation modeling approaches on the structural response of offshore wind turbine towers, demonstrated that both stiffness and damping used in foundation models have a noticeable effect on the fatigue damage.

However, studies of wind turbines supported by a deep foundation in warm permafrost are scarce. Satari and Hussain [1] developed a finite element (FE) wind turbine model including tower, foundation and frozen soils, and found the tower frequency nearly resonated with the operational frequencies of the wind turbine for certain soil conditions, and concluded that proper separation of these frequencies is often controlled by design. Dilley and Thornley [10] investigated several foundation designs for wind turbines in Alaska, and concluded that a standard foundation was not cost-effective for all turbines, as soil conditions vary greatly from warm permafrost to bedrock.

The existence of a thick active layer on top of the warm permafrost, that freezes in winter and thaws in summer, adds to the complexity of the dynamic soil-foundation-structure interaction problem in cold regions. The stiffness of soils changes by roughly two orders of magnitude in the freeze-thaw process [11]; these changes can certainly impact the dynamic properties of the soil-foundation-tower system. For bridges with short piers founded on deep foundations, a 300% change in the fundamental frequency has been observed between summer and winter seasons [12]. A sufficient separation between the natural and operational frequencies is required to avoid resonance. Ideally a 15–25% safety margin should be met between the fundamental natural frequency and the rotor operational frequency (also called 1P) and blade passing frequencies such as 3P and 6P [13,14] for three-bladed turbines. The safety factor reserved for the recommended rotor revolutions per minute (rpm) is quite small considering the possible variation in wind turbine fundamental frequency due to existence of an active layer, seasonal fluctuation in ambient temperature, and change of temperature in warm permafrost. No field measurement of wind turbine tower vibration response is available to assess the actual dynamic performance of the wind turbine and its foundation in cold regions.

This study focuses on the analysis and mitigation of excessive dynamic responses observed on wind turbines supported by a pile group in warm permafrost. It first provides a brief description of the site condition, foundation and wind turbine, and a summary of wind turbine dynamic properties identified from vibration data, existing control strategy and resonance issues. A model of the turbine-tower-foundation-soil system is proposed with the warm permafrost modeled by a Winkler type foundation for investigation of tower fundamental frequency sensitivity to permafrost temperature change. Aerodynamic effects on the rotor were modeled to provide wind thrust time series for simulation of dynamic responses of the tower and foundation. Effectiveness of passive structural control techniques such as tuned mass dampers (TMD) for mitigating excessive vibration was assessed. In the end, control strategies for such wind turbines are discussed.

2. Brief description of the site, foundation and wind turbine

Quinhagak, located on the eastern shore of Kuskokwim Bay in western Alaska, is underlain by warm permafrost between −0.4 °C and −0.1 °C [15]. Fig. 1 presents temperature, moisture content and soil profile from two bore holes that were less than 35 m apart. The site is populated by gently sloping hummocks on a fairly flat terrain with less than 1.5 m vertical relief. Permafrost was found to the depth of boring at 12 m and consisted of an organic mat of about 0.5 m thick at the surface followed by organic silts between 0.5 and 1.5 m, low plasticity silts from 1.5 to 3 m, and well-graded gravelly sand to 9 m deep. Below 9 m in depth is silt. Moisture content decreases from 30% in the organic silt and silt layers to about 15% at the gravelly sand layer. During construction, the top layer organic materials was replaced with approximately 0.6 m gravelly sand underlain by insulation boards.

No long-term meteorological data is available from this study site. Instead, the data from a met tower site of similar terrain in Bethel, AK, about 115 km north of Quinhagak, was used [16]. The long-term annual average wind speed is 6.7 m/s at a height of 30 m and 7.3 m/s at a height of 50 m above ground level with northeast prevailing wind direction. The average wind shear exponent as calculated between the 50-m and the 30-m anemometer data is 0.19. The turbulence intensity from all directions and for all months ranges from 0.06 to 0.14, which is low and unlikely to contribute to excessive wear of wind turbines. The average wind power density is about 345 W/m^2 at 30 m height, indicating Class 4 or a rating of “good” for wind power development according to the seven level classification system [17].

Three Northern Power 100 Arctic upwind turbines were installed at this study site. Fig. 2 illustrates the configuration of the wind turbine and foundation system, and the location of the accelerometers for vibration monitoring. The foundation consists of six 40.6 cm diameter steel pipe piles with 0.95 cm wall thickness embedded 9 m into the permafrost, as shown in Fig. 2. The piles are equally spaced at the corners of a hexagonal pile group cap made of reinforced concrete ($f'c$ = 34 MPa (5 ksi) and a water/cement ratio of 0.45). As the mechanical properties of warm permafrost such as stiffness and compressive strength decreases quickly as its temperature approaches the freezing temperature of water, it was determined that temperatures below −0.6 °C are required to ensure stability of the foundation throughout the life of the structure. As the in situ temperature is warmer than the required permafrost temperature, a passive cooling system consisting of six two-phase liquid-to-vapor thermal syphons [18] was installed along the six-pile foundation with one placed vertically next to each pile for the total length of the embedment. As a passive cooling system, it only works when the air temperature is colder than temperature of the soil surrounding the thermal syphons.

The direct-drive, three-bladed, variable-speed, and stall-controlled turbine has a rotor of 21 m diameter and a rigid hub. It is supported on a hollow tapered tubular steel tower with a hub height of 37 m, a diameter of 2 m and a wall thickness of 1 cm at base, and a diameter of 1.2 m and a wall thickness of 0.8 cm at top. The rated electrical power of the wind turbine is 100 kW, the rated wind speed is 14.5 m/s, and the rotation speed is between 40 and 59 rpm, or 0.667 Hz to 0.983 Hz. The cut-in wind speed at which the turbine starts to generate electrical power, is 3.5 m/s and the cut-out wind speed at which the turbine will be brought to rest is 25 m/s according to the turbine specification. The mass of the rotor and a standard nacelle is 7200 kg and that of the tower is 13,800 kg.

A total of six accelerometers were installed on the inside surface of the wind turbine tower for vibration monitoring (Fig. 2). Three accelerometer pairs oriented to East-West or North-South