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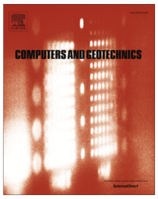

Research Paper

Wind-induced dynamic amplification effects on the shallow foundation of a horizontal-axis wind turbine

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ABSTRACT

Wind loads are random variables, which induce significantly greater responses in structures than do static loads. We develop a finite-infinite element model of a 2 MW wind turbine using ABAQUS and then verify it with in situ data. The adopted dynamic constitutive model of the soil is based on the Davidenkov skeleton curve. The results demonstrate that the dynamic amplification factors (DAFs) strongly depend on wind speed and spatial position. Considerable values of the DAFs, ground acceleration, and ground velocity are observed, suggesting that the responses of the shallow foundation of a wind turbine are affected by dynamic wind loads.

1. Introduction

Wind energy, because of its clean, safe and sustainable nature, is now playing an important role as a source of power [1]. Recently, new wind farms are increasingly being installed in mountainous and hilly regions in many countries as a strategy for narrowing the regional energy disparity. Unlike building structures, a wind turbine must withstand great horizontal wind forces and moments, which account for a large proportion of its total load [2]. Wind loads are highly random variables that can be transmitted to the foundation and the subsoil, producing considerable vibrations and increased stresses, strains and deformations therein. Thus, the shallow foundations that are often preferred for onshore wind turbine must show satisfactory performance in resisting dynamic loads. In many codes [3,4], the pseudo-static approach is used to address structural dynamics problems related to wind loads. This method considers only the ultimate state and neglects the variation in soil properties (i.e., soil stiffness, shear strength, bearing capacity, etc.) under dynamic loading. Good knowledge of the dynamic amplification level and the zone of influence can help to determine if it is necessary to consider the dynamic characteristics of the soil. As a result, the need to evaluate dynamic amplification effects may arise in properly assessing the safety and stability of a shallow foundation for a wind turbine resting on heterogeneous residual soil.

Research on the dynamic responses of shallow foundations has undergone considerable development during the past decades, with most attention being focused on seismic analyses [5–7]. However, the response of a shallow foundation subjected to vibrations from the superstructure is different because the stress waves propagate in the opposite direction with respect to seismic waves and the inertial mass of the soil becomes less important. To date, various methods have been applied to analyze the vibration responses of shallow foundations. Al-Homoud and Al-Maaitah [8] conducted a series of forced vertical vibration tests on shallow foundations resting on sand. Their results showed that an increase in natural frequency and a reduction in amplitude occur with increasing embedment depth, degree of saturation and footing base area. They also found that a circular foundation results in lower dynamic response values compared with other types of foundations. Pasten et al. [9] proposed a numerical scheme for analyzing dynamic responses under repetitive vertical loads. They reported that the vertical settlement, horizontal displacement, footing rotation, and stress redistribution within the soil mass evolve as the number of load cycles increases. Displacements and rotation become more

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pronounced as the cyclic load amplitude increases. Chen et al. [10] performed dimensionless parametric analyses to investigate the dynamic responses of soil-foundation systems subjected to harmonic horizontal forces and rocking moments.

Nevertheless, only a few related works have been reported in the field of wind turbines. Harte et al. [11] and Taddei et al. [12] studied the effects of soil-structure interaction on the dynamic behavior of shallow foundations for wind turbines, and they both reported that the soil-structure interaction affects the wind turbine response. The latter further noted that for wind turbine footings, the mass and the geometry do not noticeably affect the dynamic response, whereas the relative stiffness of the structure and soil plays an important role. Based on field tests, Currie et al. [13] examined the dynamic behaviors of the embedded ring of a concrete foundation for a wind turbine under various working conditions. More recently, Madaschi et al. [14] conducted experimental tests on the dynamic behavior of the shallow square foundation of a full-scale 11 kW wind turbine under the rocking motion of the tower. They observed that the vibration of the wind turbine tower induces a sort of forced, damped harmonic excitation in the shallow foundation. However, most of these studies on shallow foundations for wind turbines and the corresponding subsoil went no further than the analysis of the dynamic responses and gave little attention to wind-induced dynamic amplification effects, which are of primary interest to engineers.

The purpose of the present research is to examine the magnitude of the dynamic impact of random wind loads on the shallow foundation and subsoil of a mountain wind turbine and the size of the influence zone. To that end, a series of numerical calculations is conducted using the finite element code ABAQUS. A dynamic constitutive model based on the Davidenkov skeleton curve is employed to characterize the dynamic behaviors of the soil. After the validation of the adopted numerical model against in situ test results, the contact-pressure-based dynamic amplification factor (DAF), the soil-stress-based DAF and the foundation-settlement-based DAF are evaluated under different wind speed conditions. The accelerations and velocities at the ground surface that are induced by dynamic wind loads are also analyzed.

2. Modeling of a wind turbine with a shallow foundation

2.1. Numerical model

A typical 2 MW horizontal-axis wind turbine, of the type that is commonly installed in the central and southern mountainous areas of China, is studied in this paper. Its key parameters are summarized in Table 1. Since a wind turbine can be considered to be symmetric, only a half model is simulated using the finite element software ABAQUS, as shown in Fig. 1. The three-dimensional model essentially consists of four parts: the tower, the foundation ring, the foundation, and the subsoil. The nacelle and rotor are modeled as point masses (i.e., m_1 and m_2) to consider their inertial effects.

Table 1
Key parameters of a 2 MW horizontal-axis wind turbine.

Parameter	Value
Rotor diameter, D_{rotor}	93.4 m
Hub height, H_{hub}	80 m
Cut-in wind speed, v_{in}	3 m/s
Rated wind speed, v_{r}	11 m/s
Cut-out wind speed, v_{out}	25 m/s
Rated rotor speed, ω_{r}	12.3 r/min
Nacelle mass, m_1	80.0 t
Rotor mass, m_2	48.5 t
Number of blades, N	3
Blade mass, m_3	9.0 t

Infinite elements based on the previous work by Lysmer and Kuhlemeyer [15] are used for the bottom and the surrounding boundaries to represent the boundary conditions at infinity; refer to Fu and Zheng [16]. The nodes at the bottom boundary of the finite element model are fully fixed in both the vertical and horizontal directions, and the nodes at the surrounding boundary of the finite element model are fixed in the horizontal direction. Coulomb's friction law with a friction coefficient of 0.35 is applied to simulate the tangential behavior between the foundation and the subsoil. The contact in the normal direction at the interface between them is considered to be a hard contact [17]. The mesh tie constraint provided in ABAQUS is adopted to connect the foundation to the foundation ring and the foundation ring to the tower.

The reinforced concrete is modeled as an isotropic elastic material with a mass density of 2500 kg/m^3, an elastic modulus of 40 GPa, and a Poisson's ratio of 0.25. The steel is regarded as elastic-perfectly plastic. Its mass density is 7850 kg/m^3, its elastic modulus is 205 GPa, its Poisson's ratio is 0.3, and its yield stress is 235 MPa. The model adopted to describe the dynamic behavior of the soil will be presented in detail in the next section.

2.2. Dynamic constitutive model of the soil

A nonlinear visco-elastic constitutive model, which was developed based on the Davidenkov skeleton curve, is utilized to characterize the behavior of soil subjected to dynamic loads. Here, this model and the parameters employed are briefly summarized. Further details about the model can be found elsewhere [18–22].

The Davidenkov skeleton curve is expressed as follows:

$$\tau(\gamma) = G\gamma = G_{\max}\gamma[1 - H(\gamma)], \tag{1}$$

with

$$H(\gamma) = \left[\frac{(\gamma/\gamma_0)^{2b}}{1 + (\gamma/\gamma_0)^{2b}}\right]^{a}, \tag{2}$$

where $G_{\max}$ is the maximum shear modulus, γ is the shear strain, and a, b and γ_0 are the parameters related to the dynamic behavior of the soil.

According to Mashing's law, the hysteresis loop in terms of the octahedral stress τ_{oct} and the octahedral strain γ_{oct} based on the Davidenkov skeleton curve can be written as follows:

$$\tau_{\mathrm{oct}} = \tau_{\mathrm{oct,c}} + G_{\max}(\gamma_{\mathrm{oct}} - \gamma_{\mathrm{oct,c}})\left[1 - H\left(\left|\frac{\gamma_{\mathrm{oct}} - \gamma_{\mathrm{oct,c}}}{2}\right|\right)\right], \tag{3}$$

where $\tau_{\mathrm{oct,c}}$ and $\gamma_{\mathrm{oct,c}}$ are the shear stress amplitude and the shear strain amplitude, respectively, corresponding to the turning points for unloading and reloading in the hysteresis loop of the octahedral stress τ_{oct} and the octahedral strain γ_{oct} (see Fig. 2).

Rewriting Eq. (3) in incremental form yields the following:

$$\tau_{\mathrm{oct}}^{t+\Delta t} = \tau_{\mathrm{oct}}^{t} + G^{t+\Delta t}(\gamma_{\mathrm{oct}}^{t+\Delta t} - \gamma_{\mathrm{oct}}^{t}), \tag{4}$$

where for the initial loading stage,

$$G^{t+\Delta t} = \left.\frac{\partial\tau}{\partial\gamma}\right|_{t+\Delta t} = G_{\max}\left[1 - \left(1 + \frac{2ab}{1 + |\gamma_{\mathrm{oct}}/\gamma_0|^{2b}}\right)H(|\gamma_{\mathrm{oct}}|)\right], \tag{5}$$

and for the unloading and reloading stages,

$$\begin{aligned} G^{t+\Delta t} &= \left.\frac{\partial\tau}{\partial\gamma}\right|_{t+\Delta t} \\ &= G_{\max}\left[1 - \left(1 + \frac{2ab}{1 + |(\gamma_{\mathrm{oct}} - \gamma_{\mathrm{oct,c}})/2|^{2b}}\right)H\left(\left|\frac{\gamma_{\mathrm{oct}} - \gamma_{\mathrm{oct,c}}}{2}\right|\right)\right], \end{aligned} \tag{6}$$