博士論文（要約）

Numerical study of dynamic loading on wind turbine supporting structures considering nonlinear soil-structure interaction

（地盤と構造物の非線形相互作用を考慮した風力発電設備支持構造動的荷重の数値予測）

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Wind energy has aroused great attention and numerous wind farms have been installed in terms of onshore and offshore in the past decades. However, wind turbines suffer from many challenges and mature technologies are still required to support the design of wind turbines. The soil-structure interaction is a key factor that affects enormously the dynamics of the fixed-bottom wind turbines in terms of fatigue limit states (FLS), serviceability limit states (SLS), ultimate limit states (ULS) as well as accidental limit states (ALS). As for the FLS and SLS analyses, the initial or equivalent spring stiffness and dashpot damping are used to represent the stiffness and damping of the foundation-soil system as the boundary condition in the analyses of wind turbine supporting structures. However, the ways to determine the initial or equivalent stiffness and damping and their contributions to the modal damping ratios of wind turbine supporting structures are unclear. Regarding to the ULS and ALS analyses, the ultimate capacity of soil matters. The nonlinear spring with the backbone curve calibrated by static or slow cyclic tests is unsuitable for the dynamic analysis since the soil properties are amplitude-dependent and frequency-dependent. In terms of the ALS analysis, the foundation uplift usually occurs, however, the equivalent linear soil-structure interaction model is adopted in current design practice, which does not consider the foundation uplift.

In this study, the linear soil-structure models are first built to accurately predict the modal damping ratios and the effects of soil properties and foundation types on modal damping ratios are then investigated by a systematic research. After that, a new dynamic Winkler model is proposed to capture the soil nonlinearity and geometrical nonlinearity in the dynamic analysis of gravity foundation and finally the effect of foundation uplift on the seismic loading of wind turbine supporting structures is investigated quantitatively and systematically.

In Chapter 1, the general background of this study including development and challenge of wind energy, wind turbine foundations, earthquakes induced damages of wind turbine as well as the sway-rocking model in JSCE guideline are presented.

In Chapter 2, the problems relevant to modal damping study, the nonlinear Winkler model for the dynamic analysis of gravity foundation as well as the seismic loading study on wind turbine supporting structures are defined and outline of this thesis is clarified.

In Chapter 3, modal damping of wind turbine supporting structures is studied. The modal damping ratio for each mode is crucial to characterize the dynamic behavior of offshore wind turbines and widely used by simulation software in wind turbine engineering, such as Bladed and FAST. In this study, modal damping ratios of offshore wind turbines are systematically studied for different soil properties and foundation types. Firstly, the modal damping ratios and modal frequencies for the first and second modes of a gravity foundation supported offshore wind turbine are studied. An offshore wind turbine supported by a monopole foundation is then investigated to clarify the characteristics of modal damping ratios and modal frequencies for the monopole foundation. The soil parameters are identified by means of genetic algorithm (GA). Predicted modal damping ratios and modal frequencies as well as modal shapes show good agreement with the field measurements for both foundations. Finally, a sensitivity analysis study is carried out to investigate the effects of soil properties and foundation types on modal damping ratios. For the gravity foundation supported offshore wind turbine, soil properties affect the modal damping ratio of second mode largely, but affect that of first mode little, while for the monopile supported offshore wind turbine, soil properties affect the modal damping ratios of the first and second modes significantly. Predicted natural periods and modal damping ratios of first mode for both foundations by a pair of simple models agree well with those by numerical models.

In Chapter 4, a dynamic Winkler model for the gravity foundation supported structure is proposed. The Winkler model is proposed by first applying PySimple3 model to capture the soil nonlinearity and then assembling with gap model to capture the geometrical nonlinearity for the dynamic analysis of the gravity foundation. After that, the proposed model is validated by a series of shaking table tests of a bridge pier under various seismic intensities and compared with the previous QzSimple2 model. Results show that the proposed model captures the experimental q-z backbone curve well while the QzSimple2 model significantly overestimates that in terms of linear region and ultimate capacity. The predictions by the proposed Winkler model show reasonable agreement with experiments for both superstructure and foundation responses whereas those by the previous model substantially underestimates the foundation settlement but overestimates the superstructure acceleration.

In Chapter 5, the mechanism of wind turbine supporting structures under the strong earthquake is investigated. A comparison study is first performed to investigate the effect of foundation uplift on the seismic loading of wind turbine tower and gravity foundation by using the soil-structure interaction models with and without considering the foundation uplift, which is followed by a series of sensitivity analysis studies with variable soil stiffnesses and earthquakes intensities. Foundation uplift significantly increases the seismic loading of gravity foundation and without considering the foundation uplift, the seismic loading on gravity foundation is significantly underestimated. Effect of foundation stiffness on the seismic loading are then investigated in the same way by using the weak foundation compared to the rigid foundation. Weak foundation can reduce the seismic loading of wind turbine tower substantially while the seismic loading on wind turbine tower is substantially overestimated by rigid foundation assumption. After that, a fractional strategy is defined to reveal the mechanism of wind turbine supporting structures under strong earthquake. Foundation uplift will occur under a severe earthquake but is not always beneficial since it may cause the crack of weak foundation, which, however, protects the wind turbine tower.

In Chapter 6, the conclusions are summarized, and the future work is discussed.

The contents in Chapter 3, 4, 5 and 6 are scheduled to be published as a journal within 5 years.