DESIGN CONSIDERATIONS AND SEISMIC PERFORMANCE OF WIND TURBINE TOWERS CONSIDERING SOIL-STRUCTURE INTERACTION

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ABSTRACT

Wind turbine design has advanced significantly in terms of its size and type in recent years. However, the design of the towers is generally based on a fixed based structural model, and the dynamic soil-structure interaction is ignored even for soft soils. In structural engineering practice, dynamic soil-structure interaction is considered as a favorable effect to reduce the seismic response of the structure. Soil-structure interaction consists of two parts, namely, inertial and kinematic interactions in substructuring technique. In this study, the seismic response of a wind turbine tower is investigated with/without soil-structure interaction. Three strong ground motion data recorded at bedrock are modified according to the Soil Type C and are used in the dynamic analyses. The substructure methods is applied in two steps. In the first step, a kinematic interaction model is constructed. The kinematic interaction model allows to obtain the effective input motions and the equivalent soil dynamic rigidity matrices at the foundation level for the inertial interaction model, which is the second step of substructure method. The linear dynamic analyses are carried out for earthquake ground motions (EQGMs). The results are presented in terms of maximum displacement, base shear and stress. The results show that SSI alters the seismic response to a certain degree, but does not always have reducing effect of the seismic response of wind turbine towers, mainly due to its flexible structure.

KEY WORDS: Wind Turbine Tower, Soil-Structure Interaction, Inertial Interaction, Kinematic Interaction

1. INTRODUCTION

Wind turbine design has become popular in recent decades due to the increasing demand on renewable and clean energy sources. It is considered as a renewable and sustainable energy source in Turkey in recent years and major companies are investing significant amount of money to build wind turbines all across the country. The cost of the transportation of wind turbine tower components is considered to be a major portion of the overall turbine cost (approximately 10-15% of the overall cost). The net loads on the tower of the wind turbine come from the tower head assembly. These loads are transmitted to the foundation via the tower. The axial load on the rotor composes the main load on the tower. Dynamic loading is generated by wind turbulence blade-tower interaction. The tower-blade interaction generated at the blade passing frequency (BP) (equal to the rotational frequency (P) multiplied by the number of blades (B)) causes the rotor load to diminish slightly when the blade passes in front of the tower for the case of an upwind rotor. Another excitation frequency occurs at 1P due to the unavoidable mass imbalance in the rotating parts. Basic design philosophy is to avoid the resonance phenomena between the frequencies of the wind turbine tower components and the tower and the frequencies of the dynamic loading. Thus, the first step in the design of the tower should be based on its first bending resonant frequencies, or rather the discrete spectrum of all of the natural tower frequencies. The major dynamic excitation frequencies due to dynamic loading should be avoided in the tower resonant frequency spectrum.

Structural and ground displacements are dependent on each other when an earthquake hits the structure, i.e. they are coupled. This phenomenon is called soil-structure interaction (SSI). However, SSI is often neglected in design codes, because it is believed that it has a beneficial effect on the seismic response of the structure. The reason for this is that considering SSI elongates the structure's fundamental period reducing the seismic demand on the structure. In many of the cases, SSI causes the accelerations de-amplify at the foundation level compared with the accelerations considering no SSI.

The seismic response of a wind turbine tower considering SSI is investigated in this study. The steel wind turbine tower in this study has a steel square tubular cross section. Three earthquake ground motions (EQGM) recorded at bedrock are selected for the linear dynamic analyses. The selected EQGMs are first scaled for the existing soil conditions for the fixed base model. Then, to consider SSI, the selected EQGMs are input to the soil medium at the engineering rock level and the effective input motions (EIMs) at the foundation level are obtained from the kinematic interaction model. The EIMs are then applied to the inertial interaction model and the seismic response of the tower is obtained.

2. DESIGN REQUIREMENTS FOR WIND TURBINE TOWERS

Wind turbine tower design should include the following loading and requirements (Hau, 2005):

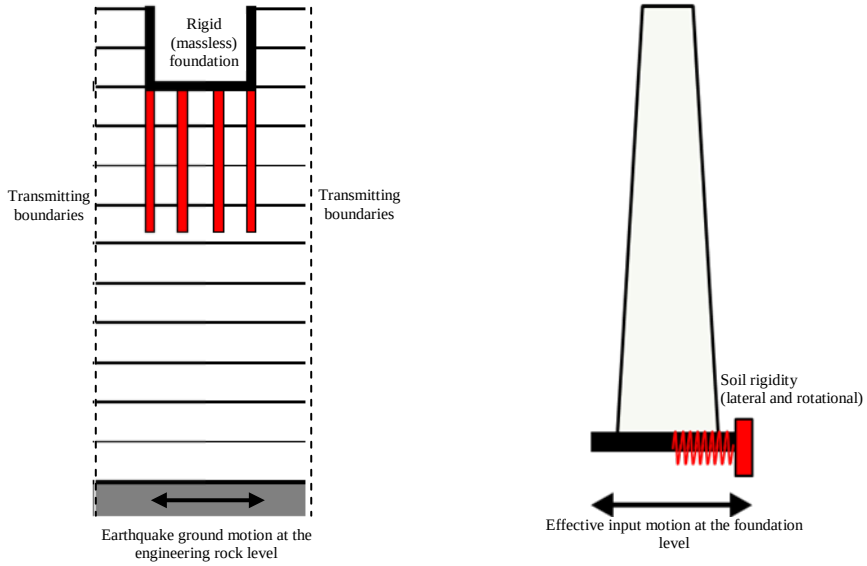
a. Dynamic loadings (sever earthquakes, extreme winds, aerodynamic rotor thrust),
b. Static loads (called breaking strength) (tower-head weight, tower's own weight),
c. Fatigue loading (dynamic loading caused by the rotor thrust, vibrational behavior in cases of resonance) (this is an additional load),
d. Stiffness requirement (first and second natural bending frequencies are the most important one, natural torsion frequency should also be checked),
e. Buckling strength (resistance to local buckling of the steel tube wall should be checked).

The most common design code for wind turbine towers in the world is IEC 61400-1 (2005) that suggests the following approach for load combinations be used to verify the structural integrity of the wind turbine tower:

a. Normal design situations and appropriate normal and extreme external conditions,
b. Fault design situations and appropriate external conditions,
c. Transportation, installation and maintenance design situations and appropriate external conditions.

3. SOIL-STRUCTURE INTERACTION (SSI)

In general, SSI can be taken into account with two approaches: a) direct method, b) sub-structure method (Aydınoğlu, 1993 and 2011). In direct method, a single model is constructed considering both the structure and the underlying soil medium. The effect of the surrounding unbounded soil medium is considered by imposing transmitting boundaries to the along the far-field interface. As different from the direct method, substructure method treats the soil medium and the superstructure as a single substructure. With this approach, soil-structure interaction is divided into two parts, namely, kinematic interaction and inertial interaction. In today's world, direct method is not used very often because of the modeling complexities and the lack of softwares. However, the substructure method is commonly used for soil-structure interaction problems. Figure 1 shows a common model for the kinematic and inertial interaction in substructure method. The results obtained from kinematic and inertial interaction analyses should be combined in an appropriate way (Aydınoğlu, 2011).



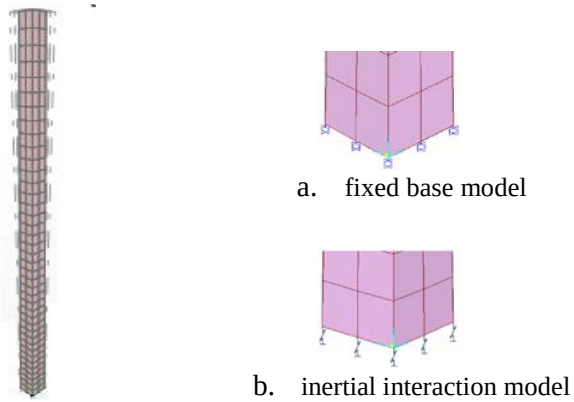
a. Kinematic interaction model b. Inertial interaction model

Figure 1. Modeling for substructure method

4. STRUCTURAL ANALYSIS

4.1. Structural modeling

SAP2000 (CSI, 2011) structural analysis program is used for the structural modeling and dynamic analyses of the wind turbine tower. The wind turbine tower has a 3.76 m × 3.76 m base cross-section, 2.69 m × 2.69 m top cross-section and is 80 m in height. The wall thickness of the tower is taken as 2.54 cm (1 inch). The overhead mass is assumed to be 75 t. The steel grade is classified as A992F$_y$50 with a unit weight of 8500 kg/m^3 including the weight of painting, bolts, stiffeners and welts instead of steel weight of 7850 kg/m^3. Figure 2a shows the fixed base structural model of the wind turbine tower, whereas Figure 2b shows the inertial interaction model constructed adding linear lateral and horizontal coupled springs.



a. fixed base model

b. inertial interaction model

Figure 2. Structural model of the wind turbine tower

4.2. Design loads and load cases

Three EQGMs scaled for two different earthquake levels, D2 and D3 are used for the linear dynamic time history analyses. D2 and D3 earthquake levels refer to the ground motions that have moderate and rare

probability of occurrences during the structure's service life, respectively (the probability of exceedence in 50 years is 10% and 2% and the return period is 475 years and 2475 for D2 and D3, respectively). The time histories and characteristics of the selected EQGMs are given in Figure 3a and Table 1, respectively. The selected EQGMs are input to the kinematic interaction model (Figure 1a) and the corresponding effective input motions (EIMs) are obtained at the foundation level (Figure 3b). The engineering rock level is assumed to be 80m below the surface and the piles are assumed to be 52m below the foundation level. The soil medium is assumed to be hard clay between the foundation level and the engineering rock level. For the fixed base model, the selected EQGMs are scaled for Soil Type C (Figure 3c). Uniform hazard spectrum as defined by İYBDY (2008) is used in constructing the response spectra corresponding to the D2 and D3 earthquake levels. The response spectra of the selected EQGMs corresponding to the engineering rock level, EIMs at the foundation level and scaled for Soil Type C are given in Figure 4.

Unit forces in both orthogonal directions are applied to the kinematic interaction model (Figure 1) to obtain the equivalent soil dynamic rigidity matrices for the D2 and D3 earthquake levels (Table 2) (Siyahi *et. al.*, 2011). The effective input motions at the foundation level (Figure 3b) are applied to the inertial interaction model (Figure 1b). Both components of the effective input motions are applied at the same time to the inertial interaction model. Table 3 shows the first three periods of the fixed base model and inertial interaction model for D2 and D3 earthquake levels. The tower's first two periods corresponding to the fixed base model increased approximately 6.9% and 7.7% when SSI is considered (Table 3). It should be pointed out that the periods for the D2 and D3 earthquake levels in inertial interaction models remained almost the same mainly because of the equivalent soil dynamic rigidity matrices are very close to each other (Table 2).

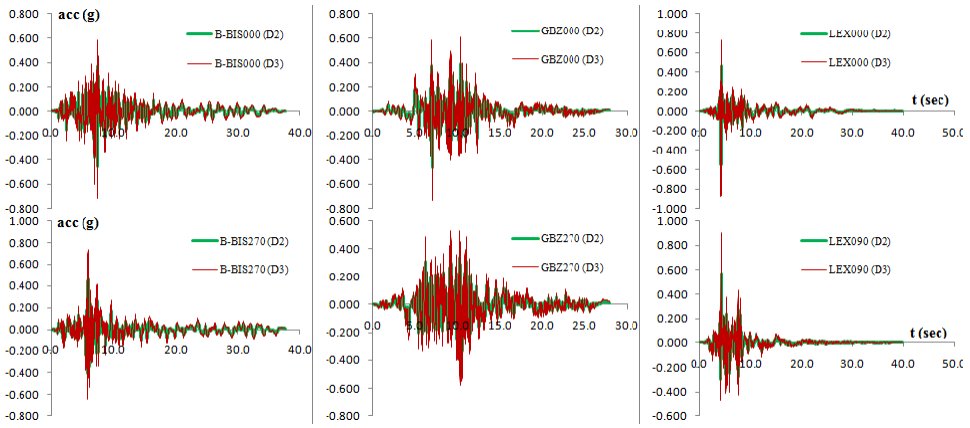
Top displacements and base shear forces corresponding to the fixed base and inertial interaction models are given in Table 4. Top displacements decrease under D2 and D3 levels EQGMs when inertial interaction is considered except the D3 level Loma Prieta EIM. The total base shear did not show a general trend of decreasing, it increased in some cases (Table 4). Figure 5 shows the normal stress distribution for the fixed base inertial interaction models. The inertial interaction models caused, in general, less normal stress on the tower compared with the fixed base model (Figure 6).

Table 1. Characteristics of the selected EQGMs

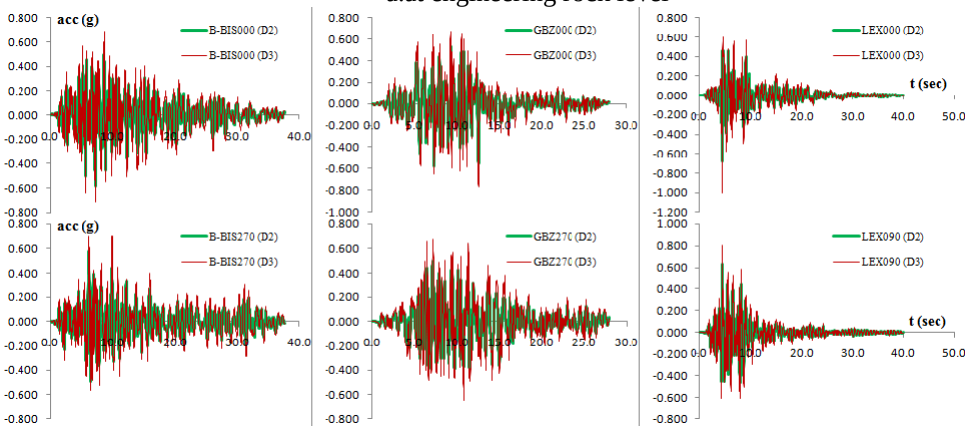
EQ	Moment Magnitude	Fault Mechanism	Station	Component (H1)	Component (H2)	Epicentral Distance (km)	Shortest Distance (km)	Soil Type (NEHRP)
Irpinia, Italy-02 23.11.1980	6.20	Normal	Bisaccia	B-BIS000	B-BIS270	18.89	14.74	B
Kocaeli, Turkey 17.08.1999	7.51	Strike-Slip	Gebze	GBZ000	GBZ270	47.03	10.92	B
Loma Prieta 18.01.1989	6.93	Reverse-Oblique	Los Gatos-Lexington Dam	LEX000	LEX090	20.35	5.02	B

Table 2. Equivalent soil dynamic rigidity matrices

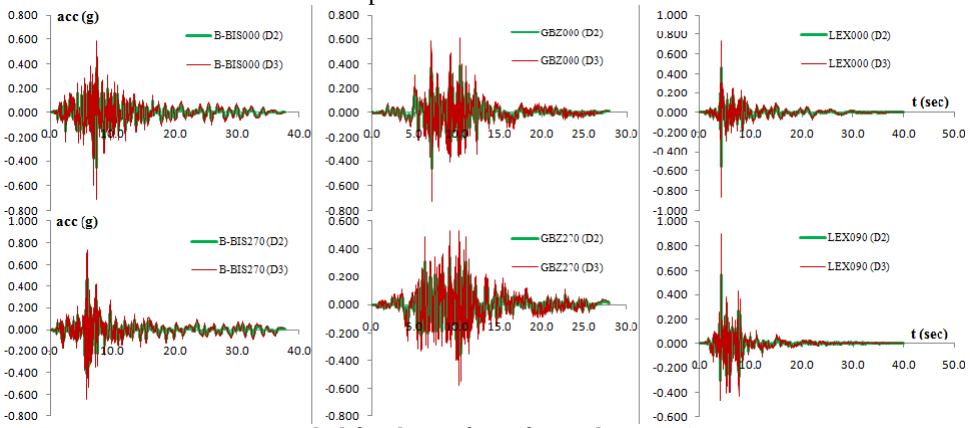
Earthquake Level	Equivalent soil dynamic rigidity matrix (kN/m)
D2	$S_{00}^{g}=\begin{bmatrix}S_{xx} & S_{xy}\\ S_{yx} & S_{yy}\end{bmatrix}=\begin{bmatrix}1.4672E+07 & -1.4962E+05\\ -1.4962E+05 & 1.4501E+07\end{bmatrix}$
D3	$S_{00}^{g}=\begin{bmatrix}S_{xx} & S_{xy}\\ S_{yx} & S_{yy}\end{bmatrix}=\begin{bmatrix}1.3897E+07 & -1.3441E+05\\ -1.3441E+05 & 1.3742E+07\end{bmatrix}$



a.at engineering rock level



b.effective input motion at the foundation level



c.scaled for the surface (for Soil Type C)

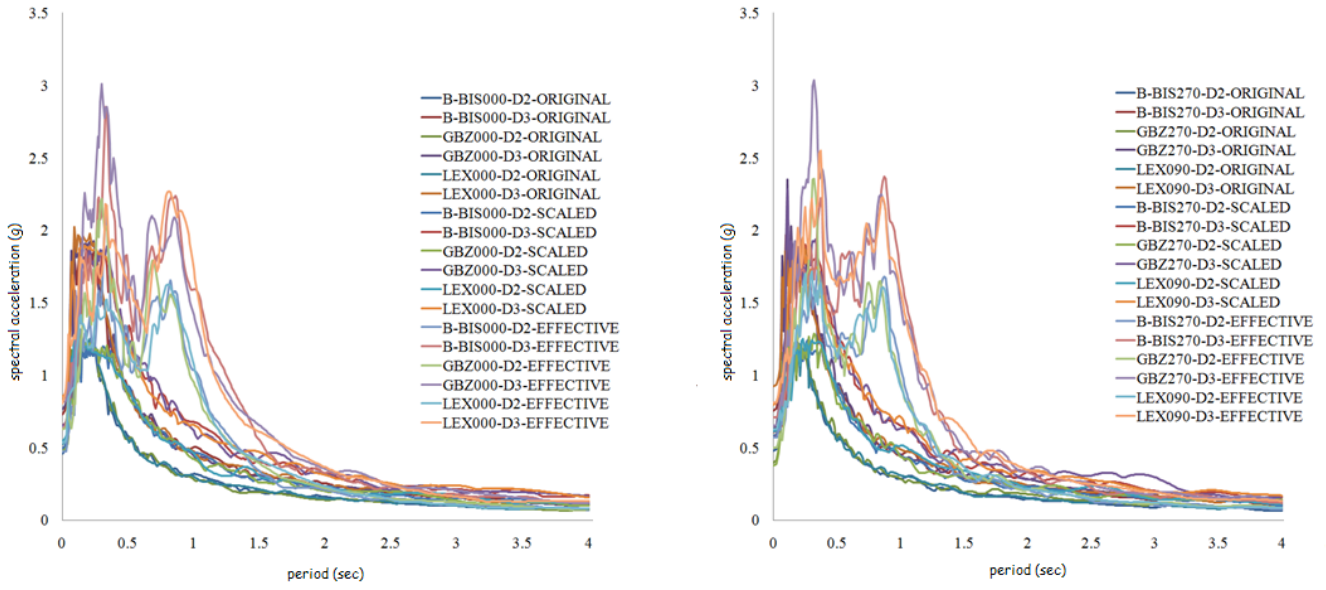
Figure 3. Time histories of the selected EQGMs

Table 3. First three periods of the wind turbine tower

Mode	T (sec)		
	Fixed base	Soil-structure interaction	
		D2	D3
1	2.47	2.64	2.65
2	0.39	0.42	0.42
3	0.24	0.24	0.24

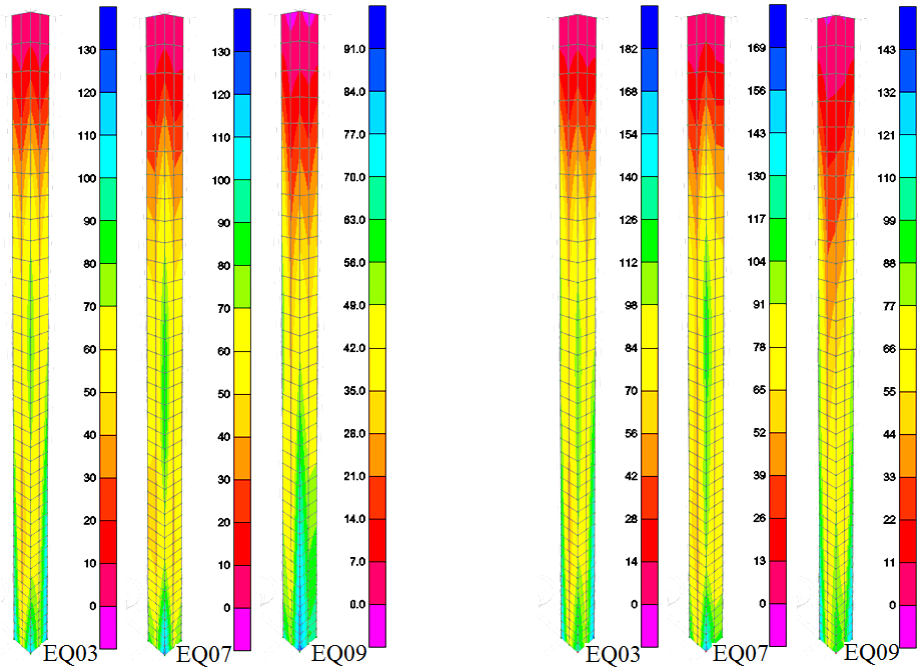
Table 4. Maximum displacement and base shear forces of the wind turbine tower

Model	Earthquake	D2 Level			D3 Level		
		Irpinia	Kocaeli	Loma Prieta	Irpinia	Kocaeli	Loma Prieta
Fixed base	Displacement (m)	0.60	0.42	0.55	0.80	0.64	0.56
	Base Shear (kN)	1266.93	1232.81	986.61	1808.09	2182.36	1429.00
SSI	Displacement (m)	0.36	0.34	0.40	0.57	0.59	0.64
	Base Shear (kN)	1010.11	1457.14	1174.22	1485.82	2032.56	1637.45



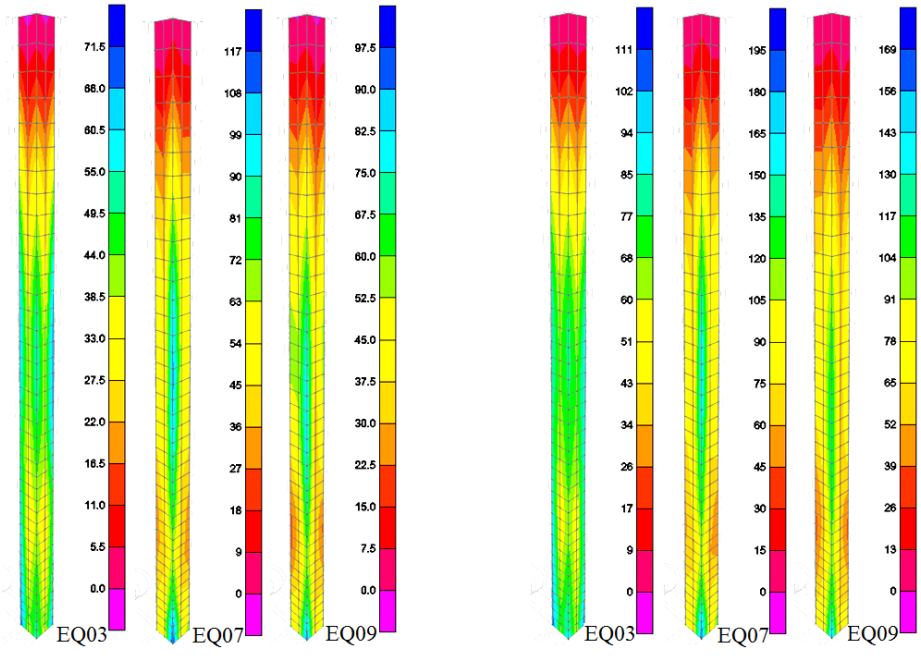
a.H1 component b.H2 component

Figure 4. Response spectra of the selected EQGMs corresponding to the engineering rock level, effective input motions at the foundation level and scaled for Soil Type C



a.D2 earthquake level b.D3 earthquake level

Figure 5. Normal stress distribution for the fixed base model (Dead + Earthquake) (N/mm^2)



a.D2 earthquake level b.D3 earthquake level

Figure 6. Normal stress distribution for the inertial interaction model (Dead + Earthquake) (N/mm^2)

5. RESULTS AND COMMENTS

In design of wind turbine towers, the SSI effect is generally neglected as it is often the case in the design of structures. More and more wind turbine towers are being built due to the increasing demand of clean and renewable energy sources. Since the basic design philosophy in design is to avoid the resonance phenomena between the frequencies of the wind turbine tower components and the tower and the frequencies of the dynamic loading, more sophisticated models are needed incorporating SSI effect. This study investigated the SSI effect on the seismic response of a wind turbine tower by adapting the substructure method. The substructure method is applied in two steps. In the first step, a kinematic interaction model is constructed. The kinematic interaction model allows to obtain the effective input motions and the equivalent soil dynamic rigidity matrices at the foundation level for the inertial interaction model, which is the second step of substructure method. The linear dynamic analyses are carried out for three EQGMs. The basic results obtained from this study is summarized below:

1) Considering SSI effect in design of wind turbine towers is not always increasing or decreasing the base shear. This is pretty consistent with the fact that the wind turbine tower studied in this paper has around 2.5 sec period with/without SSI. The difference would be mainly from the small variation in response spectra.
2) SSI elongates the fundamental period of the wind turbine tower, which might be beneficial in design satisfying the stiffness requirement.
3) Substructure technique can easily be applied to consider SSI effect on the seismic response of wind turbine towers.

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