Seismic analysis for wind turbines including soil-structure interaction combining vertical and horizontal earthquake

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SUMMARY:
This paper presents a seismic response model including SSI and P-Δ effecting under both horizontal and vertical earthquake actions. The SSI was addressed by connecting the turbine based to a rigid support with translational and rotational springs and dampers whose properties were derived based on assumed soil properties. The proposed model was applied to 1.65MW and 3 MW wind turbines. The two wind turbines was analyzed under six historical earthquake records both horizontal and vertical motions. The analysis of the results revealed that the SSI was to show a 7% decrease in the first natural frequency, and approximately 10% decrease at the tower top horizontal acceleration,10%-12% decrease at the tower base horizontal moments, 5%-6% decrease at the tower base horizontal shear load for two wind turbines. The SSI analysis was to show almost no effect to vertical acceleration and axial load of tower. The P-Δ effecting analysis shows a slight effect to tower base moment. Based on the considered seismic hazard level, it appears to be important to considered earthquake loads for moment demand in the tower for Multi-megawatt wind turbines.

Keywords: Multi-megawatt wind turbines; soil structure interaction; horizontal and vertical earthquake action; time domain simulation

1. INTRODUCTION

Wind turbine structures have the most common tall and slender geometric forms, and have a heavy turbine on the top of tower. The structural characteristics determined their seismic response should be influenced by wind turbine operational state, soil-structure interaction, P-Δ effecting, horizontal earthquake and vertical earthquake coupling effect[DNV-OS-J101]. There are several current important standards have simple procedures for estimating seismic loading based on one degree of freedom and site design acceleration response spectra[IEC, GL,DNV]. Because ignoring high models, the soil-structure interaction, P-Δ effecting, and vertical earthquake are not included in these simple procedures, which may lead the seismic load calculated following the current standards is not accurate.

Several different models for determining seismic loads on wind turbines have been published in recent years. Prowell and Verrs(2009) presented a comprehensive review of the literature regarding various simplified and full-system wind turbine models used for seismic analysis of turbine loads. Bazeos et al. (2002) presented a finite element model of a prototype 450kW turbine with a 38 meter tall steel tower designed for installation in Greece. The main research results of SSI analysis was to show a significant decrease in the frequencies at which the second and third tower bending modes. Witcher (2005) used an alternative approach to calculate seismic response of 2 MW wind turbine by using the GH Blade. The author found that the base moment demand obtained by using analytic techniques in the time domain are in agreement with in the frequency domain. Zhao et al.(2006) presented a multi-body model of wind turbine towers with consideration of soil-structure interaction to investigate their seismic in time domain. The SSI is represented by a frequency-independent discrete parameter model. The results showed that the peak tower displacement is dominated by wind forces. The inclusion of SSI resulted reduced fundamental frequencies of wind turbines, it was concluded that SSI has a large influence on the dynamic characteristics of the wind turbine tower. T.Ishihara et al.(2008) presented a simplified formula for the seismic load evaluation of wind turbine towers based on response spectrum analysis. A modified damping correction factor for the design response spectrum for wind turbine structures with low damping ratio is proposed to incorporate uncertainty in seismic loads. The seismic load calculated by proposed simplified formula is evaluated through comparison of results with time history analysis for wind turbines of capacities from 400kW to 2MW, the results showed good agreement with time history analysis results. Otoniel Díaz-Nevárez(2010) presented the development of a new analytical model for the seismic response of a wind turbine. This model involves a multi-body system with 16 degrees of freedom. The analysis of results revealed that the blade roots are safe and the stresses induced in the tower by the extreme wind loads were in general larger than those produced by the earthquake loads in combination with the steady average wind loads. These results were based on the analysis of a particular wind turbine subjected to specific earthquakes, cannot be general applicability to other wind turbines. I. Prowell. et al.(2010) estimated the seismic load for a NREL 5MW offshore wind turbine using Fast code. It presented a comparison of three earthquake loading scenarios of the 5-MW baseline wind turbine: idling; continued operation through an earthquake; and an emergency shutdown initiated by an earthquake. The results revealed that it is important to consider earthquake loads for moment demand in the tower of the NREL 5-MW wind turbine based on the considered seismic hazard level.

Among the above-mentioned studies, there are few researches about seismic load of wind turbine considering SSI, P-Δ effecting under both horizontal and vertical earthquake. For this reason, this paper presents a new seismic response model including SSI and P-Δ effect under both horizontal and vertical earthquake action for Megawatt-Scale wind turbines. The purposes of this paper are comprehensive studying earthquake response mechanism and investigate the effects of SSI, P-Δ effect on the seismic response of wind turbine structures.

2. WIND TURBINE STRUCTURAL SYSTEM

A wind turbine structure system, shown in Fig.1(a),consists of blade, turbine, tower and a shallow foundation of radius r_0 and thickness of e embedded in the surface of a homogeneous elastic half-space soil medium under horizontal and vertical ground motion. In this study, the wind turbine structure system is modeled as multi-degree of freedom system [Ray W.]. Rotor, nacelle and blades are modeled as a lumped mass m_i and moment of inertia I_1 situated at hub height, the foundation is modeled as a rigid thickness plate with radius r_0, moment of inertia I_0 and mass m_0. The rigid foundation-soil interaction is modeled by the spring-damper-mass model. The horizontal, rocking and vertical spring stiffness $k_{h,0}$, k_φ and $k_{v,0}$, dampers with coefficient $c_{h,0}$, c_φ and $c_{v,0}$ are shown in Fig1(b). The values of these coefficients in an earthquake response analysis are listed in Table 1.

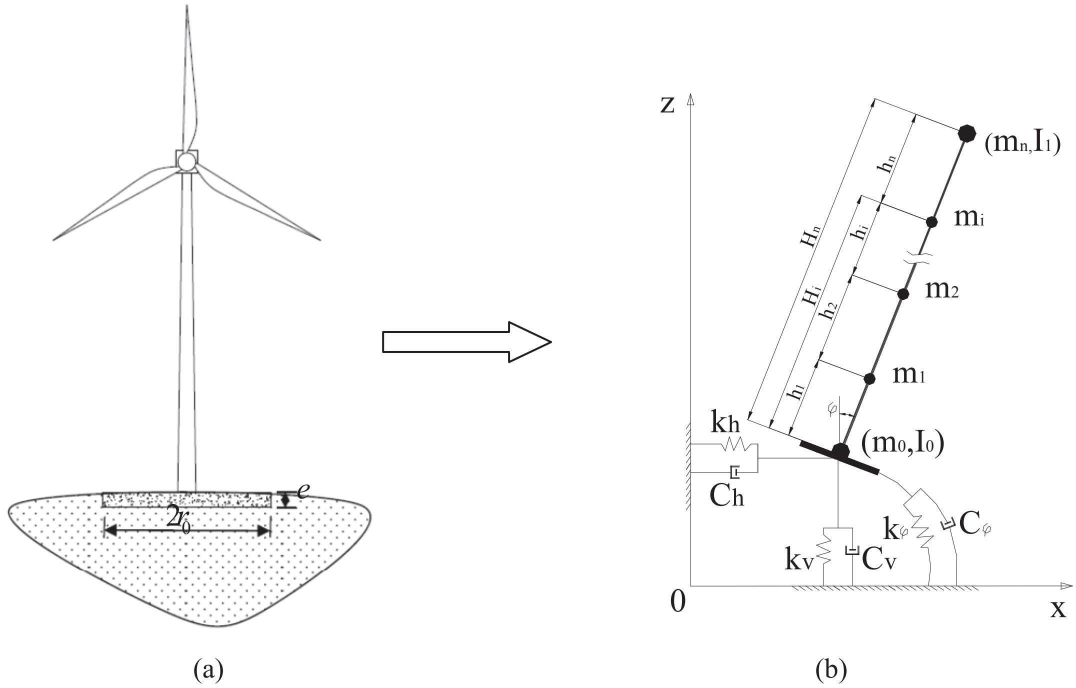

Figure 1. Analysis model of wind turbine

Table 1. Values of coefficients about spring-damper-mass model

Degree of freedom	Spring stiffness	Vicious damper	Mass
Horizontal	$k_{h,0}=\dfrac{8Gr_0}{2-v}(1+\dfrac{e}{r_0})$	$c_{h,0}=\dfrac{(0.68+0.57\sqrt{\dfrac{e}{r_0}})r_0k_{h,0}}{c_s}$	0
Vertical	$k_{v,0}=\dfrac{4Gr_0}{1-v}(1+0.54\dfrac{e}{r_0})$	$c_{v,0}=\dfrac{(0.80+0.35)\sqrt{\dfrac{e}{r_0}})r_0k_{v,0}}{c_s}$	$0.38\dfrac{r_0^2}{c_s^2}k_{v,0}$
rocking	$k_{\varphi,0}=\dfrac{8Gr_0^3}{3(1-v)}\eta_1$	$c_{\varphi,0}=\dfrac{0.16r_0}{c_s}k_{\varphi,0}$	$(0.33+0.1\dfrac{e^2}{r_0^2})\dfrac{r_0^2}{c_s^2}k_{\varphi,0}$

$\eta_1=1+2.3\dfrac{e}{r_0}+0.58(\dfrac{e}{r_0})^3$; r_0 =radius of foundation; G =shear modulus of the soil; ρ =mass density; v =Poisson's ratio; $c_s=\sqrt{G/\rho}$, e =embedded depth of foundation.

3. EQUATIONS OF MOTION

The equations of motion of the wind turbine structure model are derived from the dynamic equilibrium for each degree-of-freedom. z -direction:

$$\left[M_v\right]\{\ddot{z}\}+\left[C_v\right]\{\dot{z}\}+\left[K_v\right]\{z\}=-\left[M_v\right]\{1\}\,\ddot{z}_g(t) \tag{1}$$

Where $\left[M_v\right]$, $\left[C_v\right]$, $\left[K_v\right]$ are the vertical mass, vertical damping, vertical stiffness matrices, respectively; $\{z\}$ is the vertical displacement vector, can be expressed as:

$$\{z\}=\{z_n, z_{n-1}, \ldots z_2, z_1, z_{v,0}\} \tag{2}$$

x -direction: For considering geometric nonlinearity ($P-\Delta$ effecting) of wind turbine system, the motion due to horizontal excitation and vertical excitation is assumed to be coupled. The additional horizontal load at each mass i can be estimated as:

$$L_{hi}=N_i\left(\frac{x_i-x_{i-1}}{h_i}\right)-N_{i+1}\left(\frac{x_{i+1}-x_i}{h_{i+1}}\right)+N_i\varphi \tag{3}$$

$$N_i=\frac{EA_i}{h_i}(z_i-z_{i-1})-m_{v,i}g \tag{4}$$

Where L_{hi} is the additional horizontal load of ith mass point, x_i is the lateral displacement of ith mass point, N_i is the axial load of ith floor, φ is the rotate angel of the foundation.

$$\left[M_h\right]\{\ddot{x}\}+\left[C_h\right]\{\dot{x}\}+(\left[K_h\right]+\left[K_N\right])\{x\}=-\left[M_h\right]\{1\}\,\ddot{x}_g(t) \tag{5}$$

Where $\left[M_h\right]$, $\left[C_h\right]$, $\left[K_h\right]$, $\left[K_N\right]$, $\ddot{x}_g(t)$ are the mass, horizontal damping, horizontal stiffness, horizontal stiffness by $P-\Delta$ effecting, horizontal ground motion matrices, respectively.

$$\left[M_h\right]=\begin{bmatrix} m_{h,n} & & & & & & m_{h,n}H_n \\ & m_{h,n-1} & & & & & m_{h,n-1}H_{n-1} \\ & & \ddots & & & & \vdots \\ & & & m_{h,2} & & & m_{h,2}H_2 \\ & & & & m_{h,1} & & m_{h,1}H_1 \\ & & & & & m_{h,0} & \sum_{i=0}^{1} m_{h,i}H_i \\ m_{h,n}H_n & m_{h,n-1}H_{n-1} & \cdots & m_{h,2}H_2 & m_{h,1}H_1 & 0 & (I_0+I_1+\sum_{i=1}^{n} m_{h,i}H_i^2) \end{bmatrix}$$

$$\left[C_h\right]=\begin{bmatrix} c_h & -c_h & & & & & \\ -c_h & 2c_{h,} & -c_h & & & & \\ & & \ddots & & & & \\ & & -c_h & 2c_h & -c_h & & \\ & & & -c_h & 2c_h & -c_h & \\ & & & & & -c_{h,0} & \\ & & & & & & -(\frac{1}{3}c_{v,0}r_0^2+c_\varphi) \end{bmatrix}$$

$$K_N=\begin{bmatrix} \frac{N_n}{h_n} & -\frac{N_n}{h_n} & & & & 0 & N_n \\ -\frac{N_n}{h_n} & \frac{N_n}{h_n}+\frac{N_{n-1}}{h_{n-1}} & \frac{N_{n-1}}{h_{n-1}} & & & 0 & N_{n-1} \\ & & \ddots & & & 0 & \vdots \\ & & -\frac{N_3}{h_3} & \frac{N_3}{h_3}+\frac{N_2}{h_2} & -\frac{N_2}{h_2} & 0 & N_2 \\ & & & -\frac{N_2}{h_2} & \frac{N_2}{h_2}+\frac{N_1}{h_1} & -\frac{N_1}{h_1} & N_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ N_n & N_{n-1} & \cdots & N_2 & N_1 & 0 & \sum_{i=1}^{n} N_i h_i \end{bmatrix}$$

$$K_h = \begin{bmatrix} k_{h,n} & -k_{h,n} & & & & & \\ -k_{h,n} & k_{h,n}+k_{h,n-1} & -k_{h,n-1} & & & & \\ & & \ddots & & & & \\ & & -k_{h,3} & k_{h,2}+k_{h,1} & -k_{h,2} & & \\ & & -k_{h,2} & k_{h,2}+k_{h,1} & -k_{h,1} & & \\ & & & & & \sum_{i=1}^{n} m_i - k_{h,0} & \\ m_n(\ddot{z}_g+\ddot{z}_{v,0}) & m_{n-1}(\ddot{z}_g+\ddot{z}_{v,0}) & \cdots & m_2(\ddot{z}_g+\ddot{z}_{v,0}) & m_1(\ddot{z}_g+\ddot{z}_{v,0}) & 0 & \begin{matrix} -\frac{1}{3}(k_{v,0}r_0^2+k_{\varphi,0}) \\ +\sum_{i=1}^{n} m_i(\ddot{z}_g+\ddot{z}_{v,0}) \end{matrix} \end{bmatrix}$$

Where $M_{h,i}$ is the horizontal mass of ith mass point, H_i is the height of ith mass point relative to foundation, c_h is the horizontal damping coefficient of mass points, r_0 is the radius of the foundation, $k_{h,i}$ is the lateral stiffness of ith floor, $\ddot{x}_g(t)$ is the horizontal ground motion of acceleration.

Summary: the response of wind turbine structures under both horizontal and vertical earthquake ground motion can be calculated by the following procedures:

1. Selecting horizontal and vertical ground acceleration $\ddot{x}_g(t)$, $\ddot{z}_t(t)$ according seismic site class;

2. Define the wind turbine structures and foundation properties;

3. Solve the equilibrium equation of Eq. 1 to determine the vertical seismic response $z(t)$;

4. Substituting $z(t)$ into Eq. 4 to determine the N_i;

5. Substituting N_i into stiffness matrix $\left[K_N\right]$;

6. Solve the equilibrium equation of Eq. 5 to determine horizontal seismic response $x(t)$.

4. ANALYSIS OF SMALL WIND TURBINE TESTED AT UCSD

A full-scale shake table test of a 65 kW wind turbine was carried out at the University of California, San Diego. The turbine was 22.6m tall and consisted of three sections of constant Cross-section connected by conical joints. A Summary of the turbine properties is presented in (Ian Prowell 2009). Based on the engineering properties, and Young's Modulus for steel=200GPa. Using the paper method, the fundamental frequency and the second frequency are 1.732Hz and 11.63Hz, respectively, which showed good agreement with experimentally observed results 1.7Hz and11.7Hz-12.3Hz. The Model was used to conduct dynamic base excitation simulations. Based on the East-West component of June 28th, 1992 strike-slip Landers Earthquake recorded, and damping was set to 1% for the first mode. Fig. 2 shows the horizontal acceleration response of top of tower (100% and 200%) for the calibrated model. This good agreement between computed response and experimentally observed.

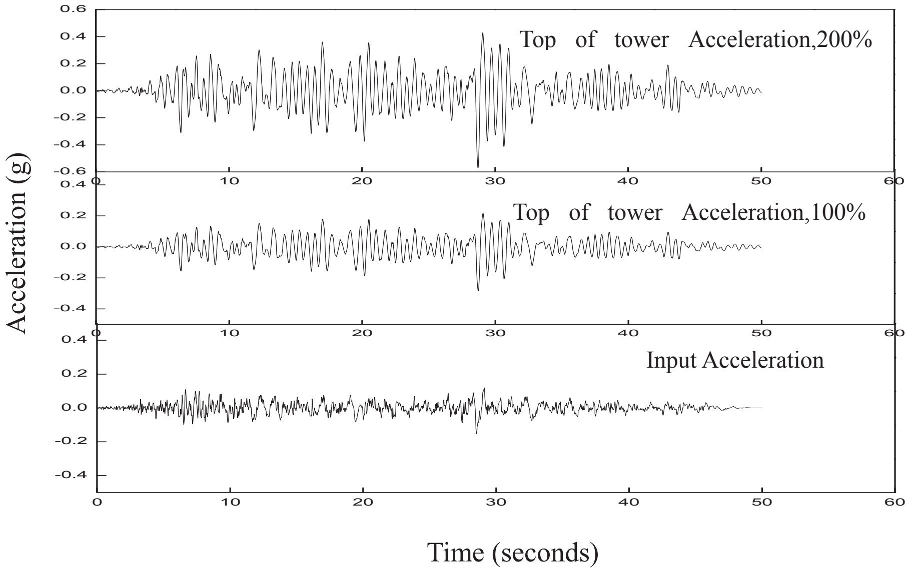

Figure 2. Acceleration top of tower for Landers 100%, 200%level simulation by the model

5. WIND TURBINE MODELS

In this study, two wind turbines with rated power of 1.65MW and 3MW are selected as typical examples for investigation. Details of basic parameters of wind turbines are summarized in Table 3. Assuming wind turbines are located the site which is classed as Code for Seismic Design of buildings of China. The shear wave velocity is 140m/s-250m/s for the site. The reference average design wind velocity is 12m/s for the two wind turbines in this site. The wind turbine foundations are designed in accordance with Design Regulations on Subgrade and foundation for WTGS of Wind Power Station. The soil properties and estimation diameter of foundation of the site are summarized in table 4.

Table 3. Main parameters of wind turbines

Property	Values	
Power rating	1.65MW	3MW
Rated wind speed(m/s)	14.4	15
Rotor diameter(m)	82	90
Lower section length and diameter (m)	25.33(3.98)	25.0(4.5)
Middle section length and diameter(m)	25.33(3.42)	27.5(4.0)
Top section length and diameter(m)	25.33(2.3)	27.5(3.0)
Tower wall sickness(mm)	25;16.6;11	34;23;15
Rotor hub height(m)	77	81.6
Tower mass(kg)	115000	160000
Nacelle mass(kg)	52000	70000
Rotor mass(with hub, blades)(kg)	68800	61100
Moment of inertia(kg.m^2)	3.56×10^6	3.18×10^6

Table 4. Soil properties and foundation diameters

Site	Shear modulus	Characteristic value of soil	Poisson's ratio
	3(MPa)	150(kPa)	0.3
Foundation radius and Embedded depth (m)	1.65MW	$r_0 = 11, e = 2.0$	
	3.0MW	$r_0 = 15, e = 2.5$	

6. EARTHQUAKE HISTORIES

For the horizontal and vertical acceleration time histories a set of 6 earthquake records were used for the site. These earthquake records are available from sources the PEER Ground Motion Database. The target response spectrum is the design earthquake spectrum as formulated in the Codes for Seismic Design of Buildings of China (GB 5011-2010). Fig.3 shows the results of response spectrums of selected earthquake records against the target response spectrum of the site. The spectral response acceleration is 0.5g and damping ratio is 5%.

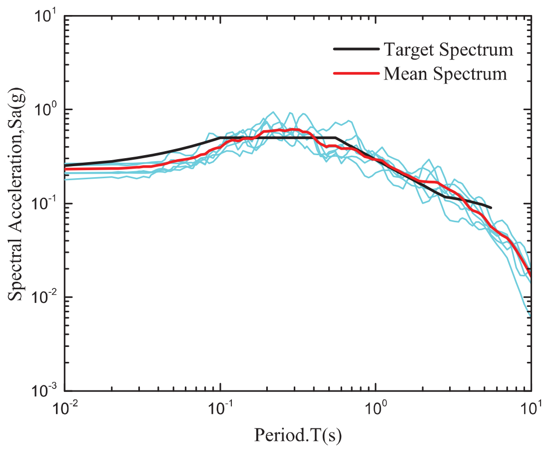

Figure.3. Target response spectra and Mean response spectra

7. ANALYSIS RESULTS

7.1 Eigen value analysis

Eigen value analysis was carried out both fixed base and considering SSI for two wind turbines, the natural periods of first three tower modes are presented in Table 5. The analysis of the results revealed that the SSI was to show a approximately 7% decrease in the first natural frequency for both wind turbines, about 10% decrease in the second and third frequency. It is worth noting the significant influence of SSI on the first natural frequency, it is necessary to considering SSI for calculating the natural frequency for Multi-megawatt wind turbines.

Table 5. The first three natural frequencies of 1.65MW and 3MW wind turbines

Modes	1.65MW			3MW		
	Fixed	SSI	Ratio(%)	Fixed	SSI	Ratio(%)
1	0.294	0.274	6.8	0.382	0.359	7.5
2	1.923	1.759	8.5	2.917	2.382	10.1
3	4.001	3.605	9.8	7.943	5.310	10.2

7.2Acceleration responses

Fig. 4 shows the horizontal and vertical acceleration response at the top of the tower for the Holtville Post office earthquake record. Damping was set to 5% for the first mode. SSI was to show a decrease in the horizontal acceleration at the top of the tower, and has less influence to the vertical acceleration of the top of the tower. The mean and the max acceleration response at the top of tower are presented in Table 6. The analysis results shows the SSI was to show 8.5% decrease in horizontal acceleration response for 1.65MW wind turbine, and 8.9% decrease in the horizontal acceleration for 3MW wind turbine. The vertical acceleration responses are almost equal for 1.65MW and 3MW wind turbines, and SSI has less influence on the vertical acceleration.

Table 6. The Max. and Mean of accelerations response of top of tower (m/s^2)

Wind Turbines	Horizontal Acceleration					Vertical Acceleration				
	Fixed-based		SSI			Fixed-based		SSI		
	Mean (1)	Max.	Mean (2)	Max.	$\frac{(1)-(2)}{(1)}\%$	Mean (1)	Max.	Mean (2)	Max.	$\frac{(1)-(2)}{(1)}\%$
1.65MW	0.695	1.17	0.636	1.14	8.5	1.886	2.18	1.879	2.18	0.3
3.0MW	1.193	1.504	1.087	1.245	8.9	1.940	2.22	1.941	2.22	0.05

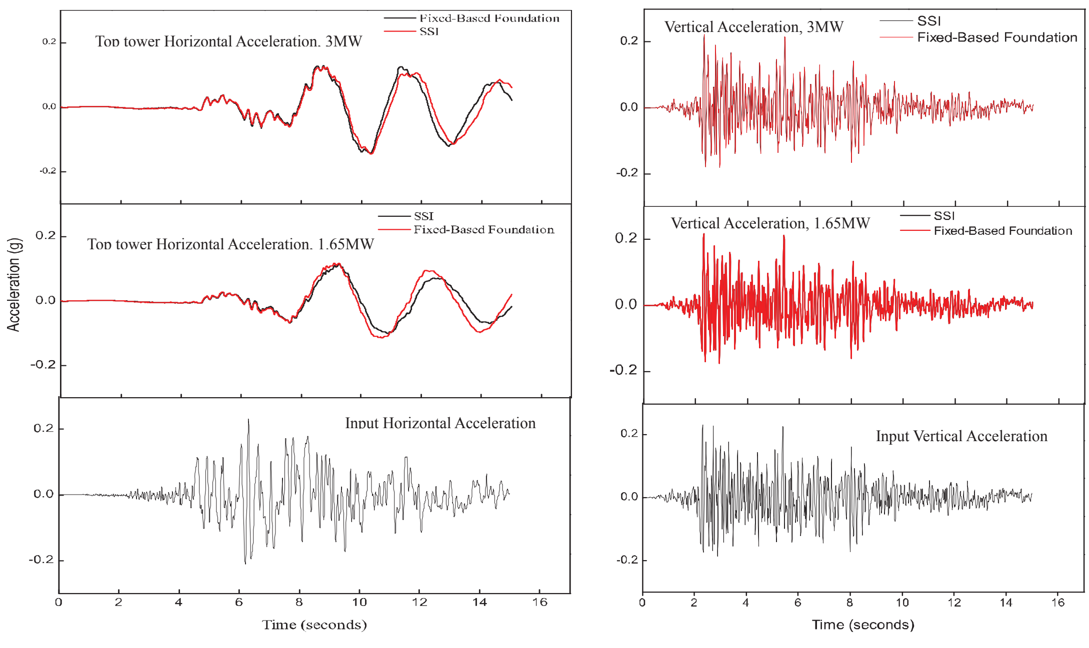

Figure.4. Acceleration response at the top of the tower for Imperial Valley-06 Holtville record

7.3 Tower base moment and tower base shear load

Table 7 and Table 8 are presented the tower base moment and the tower base shear load, respectively. Damping was set to 5% for the first mode. The average wind velocity is 12m/s. The analysis of the results showed that the SSI was to show an approximately 12.2% decrease in the tower base moment and 5.0% decrease in the tower base shear load. The SSI was to show 9.7% decrease in the tower base moment and 6.2% decrease in the tower base shear load. Based on the considered seismic hazard level and damping level, Table 7 showed the tower base moment deduced by earthquake are 21% and 33% of the moment deduced by wind load for 1.65MW and 3MW wind turbines, respectively. Table 8 shows the tower base shear load deduced by the earthquakes are 41% and 56% of the base shear load deduced by wind load. It appears to be important to consider earthquake loads for moment demand and shear demand in the tower for the Multi-megawatt wind turbine.

Table 7. Tower base moment of two wind turbines(kN.m)

Wind Turbine	Earthquake $\times 10^3$					Wind $\times 10^3$	
	Fixed-based		SSI		$\frac{(1)-(2)}{(1)}\%$	Wind Load moment(3)	$\frac{(2)}{(3)}\%$
	Mean (1)	Max.	Mean (2)	Max.			
1.65MW	7.76	8.63	6.81	7.65	12.2	32.5	20.9
3.0MW	15.29	20.8	13.8	19.6	9.7	41.5	33.2

Table 8. Tower base shear load (kN)

Wind Turbine	Earthquake $\times 10^3$					Wind $\times 10^3$	
	Fixed-based		SSI		$\frac{(1)-(2)}{(1)}\%$	Wind Load (3)	$\frac{(2)}{(3)}\%$
	Mean (1)	Max.	Mean (2)	Max.			
1.65MW	180.6	246.5	171.6	226.7	5.0	422	40.7
3.0MW	302.5	361.3	283.9	332.2	6.2	508.7	55.9

7.4 Axial load

The mean of the maximum axial load is presented at table 9. It's showed that SSI is no influence on the tower base axial load. The earthquake deduced approximately 17% increase in the self-gravity of wind turbine structures. It appears to be necessary to consider earthquake loads for axial demand in the tower for avoiding tower buckling.

Table 9. Tower base axial load (kN)

Wind turbines	The Max. of mean Fixed-base	The Max of mean SSI(1)	Gravity (2)	$\frac{(1)-(2)}{(2)}\%$
1.65MW	2792.08	2792.09	2394.3	16.6
3.0MW	3582.4	3582.38	3061.3	17.0

8. CONCLUSION

This paper presents a seismic response model including SSI and P-Δ effecting under both horizontal and vertical earthquake actions. Based on the considered seismic hazard level and site condition, the research results revealed that the SSI has significant influences on the natural frequency, horizontal acceleration at top of tower and tower base moment of 1.65MW and 3MW wind turbines. The SSI has less influence on the vertical seismic response of wind turbines. P-Δ effecting has slightly influence on the base tower moment. The study shows that it is important to considered earthquake loads for moment demand and vertical load in the tower of the 1.65MW and 3.0MW reference turbines in selected seismic zone.

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