DYNAMIC SOIL-STRUCTURE INTERACTIONOF MODERN WIND TURBINES

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ABSTRACT

This paper assesses the way soil-structure interaction phenomena affect the seismic response of modern wind turbines. To this end, a novel element for three-dimensional finite element analysis of rigid rectangular foundations is proposed and implemented using the computational platform OpenSees. It is worthy of note that the proposed model is capable of capturing the effect of soil nonlinearity. Afterward, using the NREL 1.5-MW baseline turbine, some interaction models are introduced and the effects of three types of cohesionless soils, including soft, medium and stiff soils are investigated. Modal analyses show a decrease in natural frequencies when SSI is considered; and higher modes especially undergo bigger changes. The effect of viscous damping on the predicted turbine response is evaluated as well. Finally, several nonlinear dynamic time-history analyses are performed using three earthquakes with different peak ground accelerations to evaluate the effect of SSI on the maximum internal forces of the tower. Results reveal that SSI influence on the value and distribution of the maximum moment and shear demand will be significant. The alterations in the response of the tower are likely to require redesign of the turbine to account for SSI.

INTRODUCTION

Over the past decade wind energy and wind turbines have been becoming more important around the globe as a source for clean and renewable power. Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production. This would require wind turbines to be installed over large areas. Earthquakes always pose a threat to these structures and their survival through earthquake events will mitigate financial loss due to disruption and theneed for replacement.

Existing studies include using simplified models with point masses for the nacelle and rotor at the top of the tower as a way to remove the complexity of modeling.The more precise and complicated models with more details of a real wind turbine have also been used.Haenler et al. (2006)investigated a turbine with an 80-m rotor diameter and 60-m hub height under both wind and seismic loadings and found that higher modes of the tower were more important for earthquake loadings than typical wind loadings.Zhao et al.(2007)presented a hybrid multi-body system for modeling turbine dynamics and concluded that a minor earthquake had a negligible impact on the tower's base shear and bending moment. Ishihara and Sarwar(2008) evaluated seismic demands for two different sizes of wind turbines and realized that higher mode responses were much more important. A shell model was constructed and validated against experimental results by Nuta(2010). It showed good agreement in lower frequency response.

The effect of soil-structure interaction on the seismic behavior of a 5-MW baseline wind turbine was studied by Prowell (2011). In this study, a finite element model for a wind turbine was developed and verified by the published properties of the baseline turbine. Using a three-dimensional soil mesh, the model was extended and modified to simulate a 15-meter layer of a soil under the 1994 Northridge earthquake. The soil-structure interaction was recognized as an effective factor in shear and moment demand of the tower.Taddei and Meskouris(2014)investigated the seismic response of a soil-turbine system, which involved a 1.5-MW wind turbine grounded on a layered half space. The soil was simply idealized as a generalized spring, according to the majority of standard codes. They discovered that varying the thickness of the layer in soil modeling had little effect on the first frequency.

TOWER MODELING

The wind turbine tower is modeled using nonlinear beam-column elements with fiber sections and a distributed mass for the tower and point masses on top for the nacelle and rotor, which are located in their real place. Steel01 material in OpenSeesis used for modeling the tower, whose hysteretic behavior is shown in Figure 1.

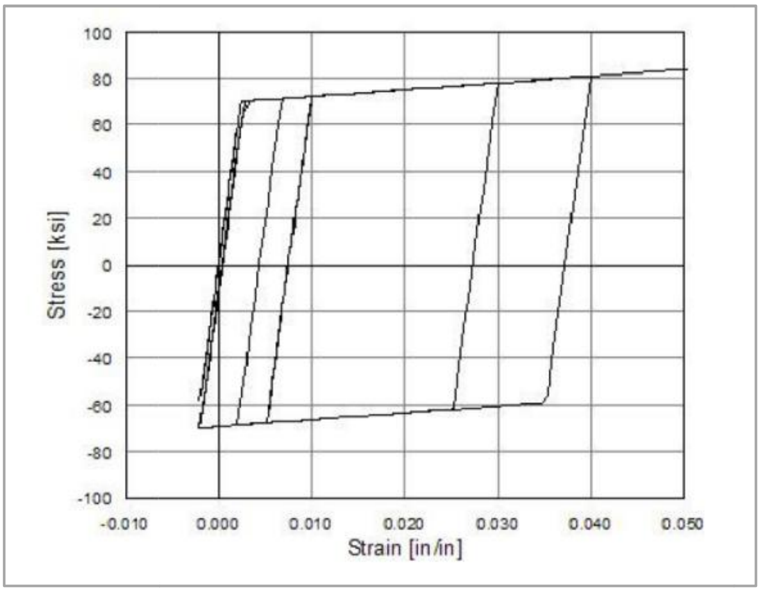


Figure 1. Hysteretic behavior of Steel01 material(Mazzoni et al., 2007)

FOUNDATION MODELING

A novel element for three-dimensional finite element analysis of rigid rectangular foundations is deployed(Esmaeili, 2014). The main assumption of the method is rigidity of these foundations, which seems to be a valid assumption due to the common ratio between their sizes in different dimentions. The model comprises four sidefaces and one bottom face which remain plane and show no relative deformations.Each of the bottom face and four side faces of the foundation is assumed to be in contact with three sets of distributed translational springs in three mutually perpendicular directions so as to take account of soil properties in the stiffness matrix. It is worthy of note that the proposed model is capable of capturing the effect of soil nonlinearity. The element has only six degrees of freedom, which are attributed to the central node of the foundation (

Figure **2**). The factor that distinguishes the proposed model from the previous ones is its ability to decrease the number of degrees of freedom and the analysis time.

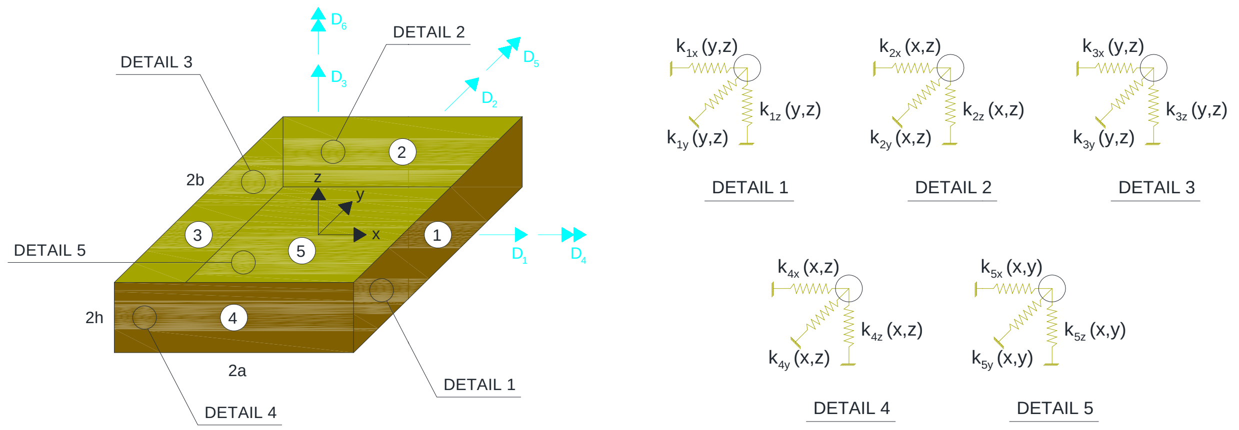


Figure 2.The proposed element for three-dimensional finite element analysis of rigid rectangular foundations

The stiffness matrix of the element has been formulated (Esmaeili, 2014) and one of its components is as follows:

$$[S]=\begin{bmatrix} S_{11} & & & & & \\ 0 & S_{22} & & & SYM & \\ 0 & 0 & S_{33} & & & \\ 0 & S_{42} & S_{43} & S_{44} & & \\ S_{51} & 0 & S_{53} & S_{54} & S_{55} & \\ S_{61} & S_{62} & 0 & S_{64} & S_{65} & S_{66} \end{bmatrix} \qquad (1)$$

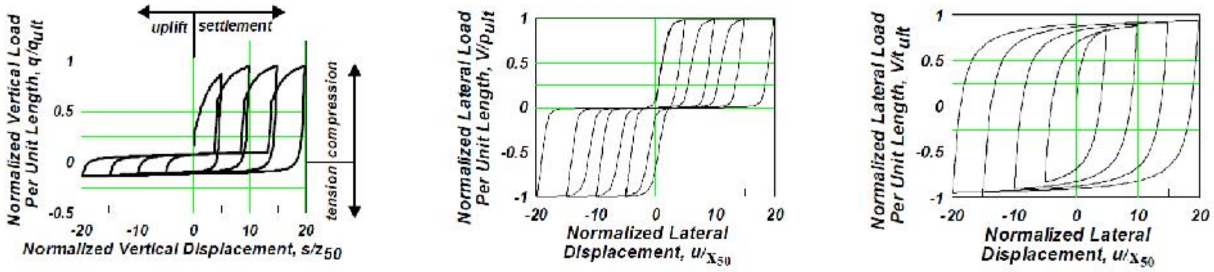
$$S_{11}=\int_{-h}^{h}\int_{-b}^{b}(k_{1x}+k_{3x})dydz+\int_{-h}^{h}\int_{-a}^{a}(k_{2x}+k_{4x})dxdz+\int_{-b}^{b}\int_{-a}^{a}k_{5x}dxdy \qquad (2)$$

where k_{ab} represents the stiffness for face (a) in the direction of (b).To determine the displacement of an arbitrary point of the foundation such as A(x,y,z) and calculate the forces of springs, matrix [R] is defined as:

$$[R]=\begin{bmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & x \\ 0 & 0 & 1 & y & -x & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

SOIL MODELING

In this research, the modified versions (Raychowdhury, 2008) of QzSimple1, PySimple1 and TzSimple1 materials are utilized to model the soil around the foundation. The aforementioned models, which were first introducedand used for soil-pile modeling (Boulanger, 2000), are employed here for simulating vertical load-displacement behavior, horizontal passive load-displacement behavior against the side of the foundation and shear-sliding behavior at the base and side faces. The backbone curves of the models are shown in Figure 3.



a. QzSimple1 b. PySimple1 c. TzSimple1

Figure 3. The backbone curves of soil models (Boulanger, 2000)

INTERACTION MODELS

In order to assess the effect of soil-structure interaction on the tower's response, the NREL 1.5-MW baseline turbine is utilized. The properties of this wind turbine are presented in Table 1.Afterward, four different models are developed. The base of the first model is encastre, whereas the rest are supported on pad foundation systems with three types of cohesionless soils, including soft, medium and stiff soils (Table 2).Figure 4 shows the dimensions related to the designed foundation for interaction models.

Table 1. The properties of the 1.5-MW wind turbine

Property	Value
Tower height	82.39 m
Diameter (bottom section)	5.6 m
Wall thickness (bottom section)	17 mm
Diameter (top section)	2.8 m
Wall thickness (top section)	8 mm
Rotor hub height	84.29 m
Rotor mass (with hub)	26.15 ton
Nacelle mass	51.17 ton
Tower mass	123 ton

Table 2. Interaction models and soil properties

Model No.	Support	$\gamma\ (\frac{kN}{m^3})$	ϕ°
1	Encastre	-	-
2	Soft Soil	17	30
3	Medium Soil	19	35
4	Stiff Soil	21	40

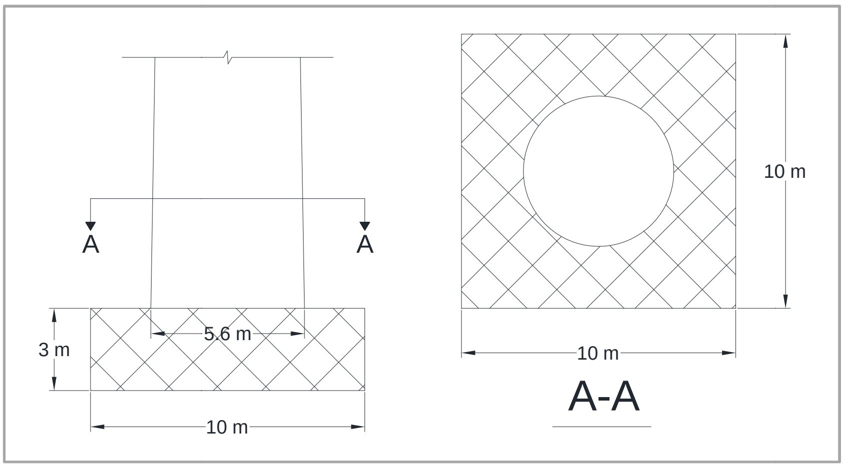


Figure 4. The dimensions related to the designed foundation for interaction models

FINITE ELEMENT MODEL PROPERTIES

The results of the modal analysis of theinteraction models indicate that considering the soil-structure interaction in modeling wind turbines means lowernatural frequencies and the natural frequencies of the tower are lower for softer soils. It is also observed that higher modes undergo bigger changes. Changes in natural frequencies of the interaction models are presented in

Table **3**.It is noteworthy that, for structures similar to the turbine tower, eliminating the effect of higher modes in analysis would be unrealistic. This might be confirmed by calculating the effective masses of higher modes (Figure 5).

Table 3. Changes in natural frequencies

Model No.	Change	
	1st bending mode	2nd bending mode
1 (Encastre)	0 %	0 %
2 (Soft)	-1.5 %	-3.2 %
3 (Medium)	-0.7 %	-1.4 %
4 (Stiff)	-0.2 %	-0.7 %

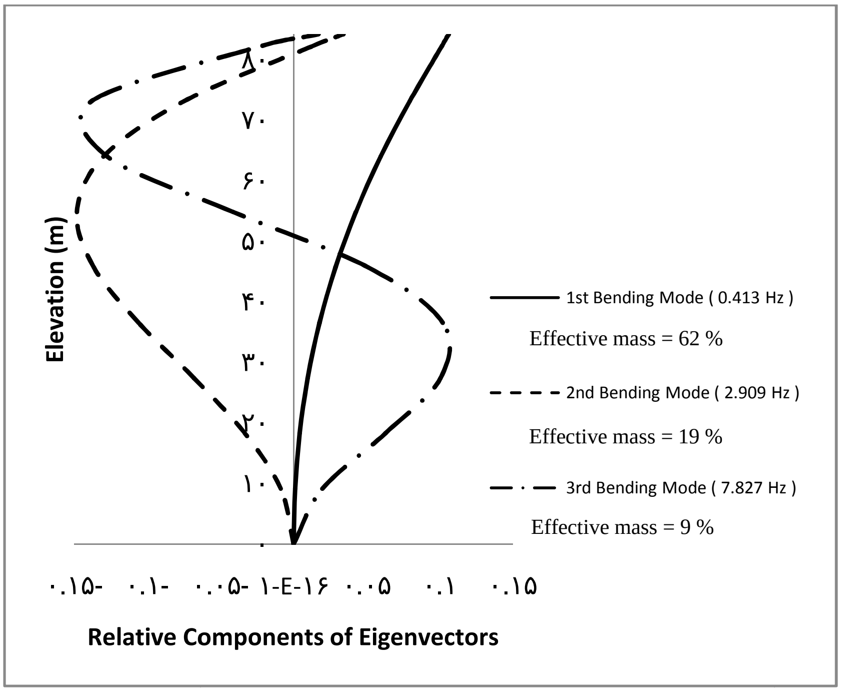


Figure 5. Modal properties of model 1

DAMPING

In order to measure the effect of damping ratio on the dynamic response of wind turbines, model 1 is selected. Given the effective masses in the first three modes of the tower (Figure 5), the first and second bending modes are employed in calculating Rayleigh damping. Damping ratiosof 1%(IEC, 2005)and 5% (IBC, 2006) are considered for the first bending mode, whereas the damping ratio of the second mode would be a constant value of 2%. Afterward,the model is horizontally excited by three earthquakes: 2003 Bam earthquake, 1978 Tabas earthquake, and 1940 El Centro earthquake. The peak ground accelerations of the said earthquakes are respectively 0.81g, 0.84g, and 0.32g.Figures 6, 7 and **Error! Unknown switch argument.**show that the variations in damping do not considerably affect the maximum acceleration of the top of the tower.

With respect to the following nonlinear dynamic analyses, the damping ratio of the first and second modes will be kept constant at2% so as to calculate Rayleigh damping matrix, in which the damping ratio for the third mode of the tower will be equal to 4.8% (Figure 9).

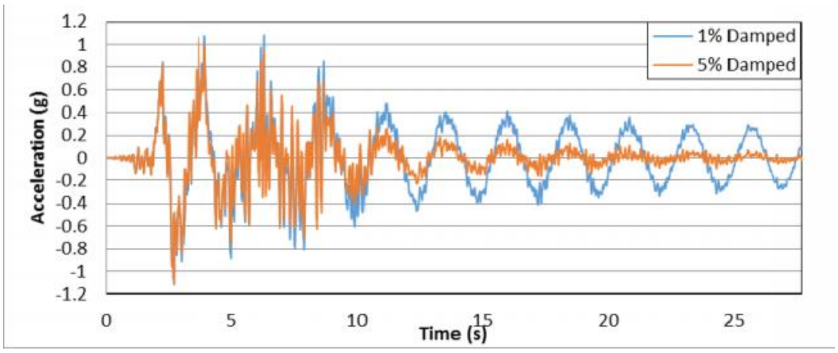


Figure 6. The acceleration at the top of the tower for the 2003 Bam earthquake

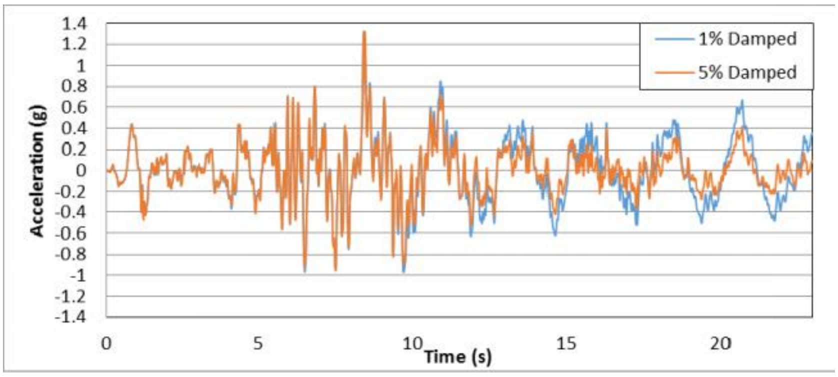


Figure 7. The acceleration at the top of the tower for the 1978Tabas earthquake

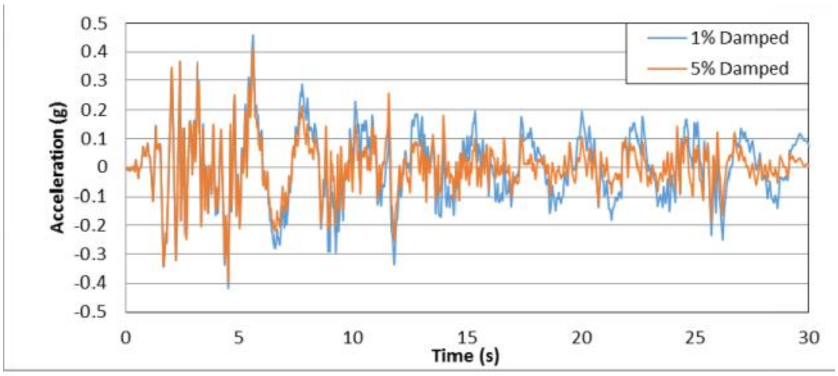


Figure 8. The acceleration at the top of the tower for the 1940 El Centro earthquake

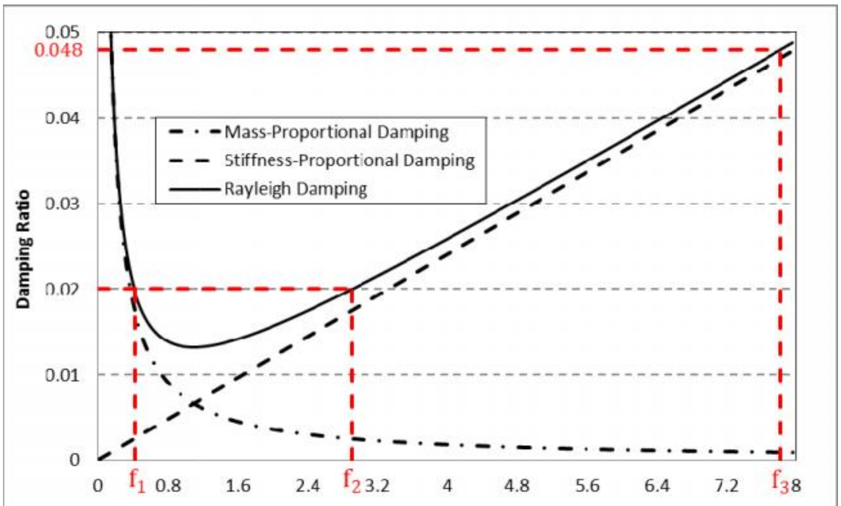


Figure 9. Modal damping ratios for calculation of Rayleigh damping matrix

EFFECTS OF SSI ON THE TOWER'S SEISMIC RESPONSE

Finally, several nonlinear dynamic time-history analyses are conducted using the horizontal components of three earthquakes (Bam, Tabas and El Centro) with different peak ground accelerations (0.2 g, 0.4 g and 0.6 g) in order to assess the effect of SSI on the maximum internal forces of the tower.

Table 4 summarizes the relative changes (with respect to the fixed base model) in average response of the tower as a member of a soil-foundation-structure system. It is observed that considering SSI always results in a greater maximum base shear and the softer the soil, the bigger the increase (up to even 31 %). With respect to the maximum base moment, taking SSI into account makes the response either increase or decrease. For the earthquakes with large PGAs, the maximum base moment decreases up to 12 %, whereas it increases up to 7 % for the earthquakes with small PGAs.

Table 4.Relative changes(with respect to the fixed base model) in average response of the tower as a member ofa soil-foundation-structure system

Response	Base shear			Base moment		
Model No.	Relative change					
	0.2 g	0.4 g	0.6 g	0.2 g	0.4 g	0.6 g
1 (Encastre)	0 %	0 %	0 %	0 %	0 %	0 %
2 (Soft)	27 %	31 %	18 %	7 %	5 %	-12 %
3 (Medium)	8 %	8 %	4 %	2 %	2 %	-4 %
4 (Stiff)	3 %	3 %	1 %	1 %	1 %	-1 %

Table 5 shows the relative changes (with respect to the PGA of 0.2 g) in average response of the tower as a member of an interaction system.The tower of model 1always behaves in a linear elastic manner. Hence, an increase of n % in PGA results in an increase of n % in inertial forces and, as a result, maximum baseshear of the tower. According to the obtained results, the aformentioned proportionality seems not to be true for the base moment. The reason lies in the fact that the eccentric gravity loads, due tothe rotor and nacelle, also play a role in the process of calculating the maximum base moment. It should be noted that these gravity loads are independent from the changes in PGA. Furthermore, a more precise look at the results reveals that as the PGA increases, the rate of increase in the tower's response decreases.

Table 5. Relative changes (with respect to the PGA of 0.2 g) in average response of the tower as a member of an interaction system

Response	Base shear			Base moment		
Model No.	Relative change					
	0.2 g	0.4 g	0.6 g	0.2 g	0.4 g	0.6 g
1 (Encastre)	0 %	100 %	200 %	0 %	94 %	188 %
2 (Soft)	0 %	106 %	179 %	0 %	89 %	137 %
3 (Medium)	0 %	100 %	188 %	0 %	94 %	169 %
4 (Stiff)	0 %	100 %	196 %	0 %	94 %	181 %

CONCLUSION

The main results of this paper could be summarized as follows

- A novel element for 3D finite element analysis of rigid rectangular foundations, which is capable of capturing the effect of soil nonlinearity, was introduced.
- Modal analyses showed a decrease in natural frequencies when SSI was taken into account; and higher modes especially underwent bigger changes.
- The natural frequencies of the tower were lower for softer soils.
- The research suggests that damping is of relatively little influence on the peak acceleration at the top of the tower.
- Results revealed that SSI influence on the value and distribution of the maximum moment and shear demand would be significant.
- Considering SSI always meant a greater maximum base shear and the softer the soil, the bigger the increase (up to even 31 %).

- The maximum base moment decreased up to 12 % for the earthquakes with large PGAs, as a result of soil-structure interaction.
- The maximum base moment increased up to 7 % for the earthquakes with small PGAs,as a result of soil-structure interaction.
- The tower of the fixed base modelalways behaved in a linear elastic manner. In other words, an increase of n % in PGA meantan increase of n % in inertial forces.
- As the PGA increased, the rate of increase in the tower's response decreased.

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