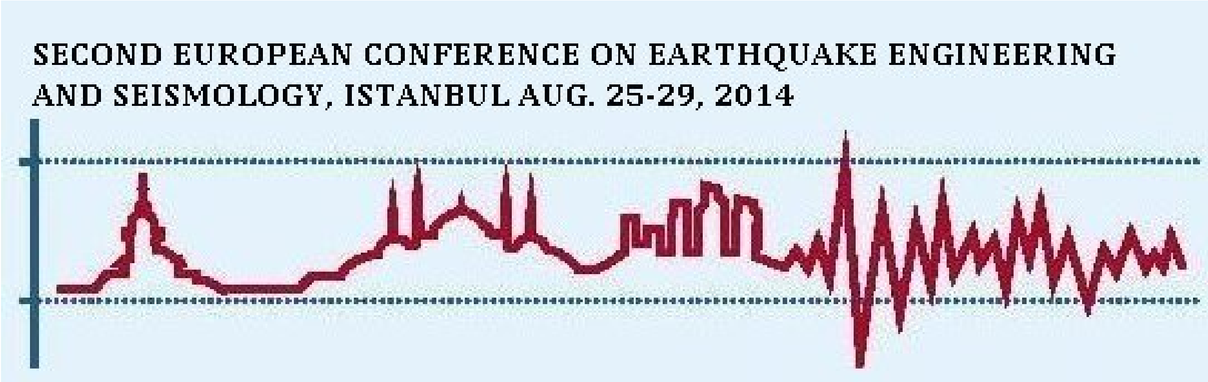

AXISYMMETRIC FINITE ELEMENT METHOD CONSIDERING DYNAMIC INTERACTION OF WIND TURBINE, PILE FOUNDATION AND SOIL AND TIME HISTORY RESPONSE ANALYSIS METHOD COMPARISON

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ABSTRACT

Comparison between the results of earthquake response on a representative 2MW 80 meters tall wind turbine tower with reinforced concrete pile foundation using Time History Response Analysis Method with SR model and Finite Element Method has been done in order to understand the differences between this two models for future application of FEM model in cases where structure-pile-soil interaction is complex to represent with SR model. With Axisymmetric Finite Element Method, by modelling axisymmetric elements it is possible to model in 2D with the accuracy of a 3D model and with the use of lateral and base viscous boundary conditions, smaller calculation time is needed. This comparison between the two models has been done considering hard soil, standard soil and soft soil for a level 2 earthquake. Results comparison between the models showed that respect SR model results, FEM model wind turbine tower displacement increased by a maximum of 20% (at tower top) while bending moment decreased by 18% (at tower bottom) due to the change in the natural period of the tower depending on the analysis model. On the other hand, major differences in the results were shown for acceleration and shear force between the two models for standard and hard soil, while for soft soil the response was similar. This could be explain because in FEM model, radiation damping, which affects mainly higher modes of vibration that highly affects acceleration and shear force, is considered when evaluating the wind turbine tower response.

INTRODUCTION

In Japan, at the end of 2012, the number of installed wind turbines was 1,913 while the total installed capacity was 2.64 million kW (NEDO, 2013), having a prospect around 20 million kW for onshore farms in 2030. In order to get the approval from the Industrial Safety and Inspection Department (dependent of the Ministry of Economy, Trade and Industry) to install a wind turbine in Japan it is mandatory to present a document where tower design must be explained in detail. To verify the wind turbine tower safety, long term wind loads, short term snow loads, typhoon wind loads, in-service

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loads and earthquake loads for level 1 (medium earthquakes) and level 2 (approximately a 500-year return period earthquake) ground motions must be calculated. Although for standard 80m tower with 1st mode natural period around three seconds, typhoon wind loads or in-service wind loads are usually higher than earthquake loads, in case of soft soils where ground motions are amplified ,earthquake response can be extremely high leading to a high bending moments at the bottom of the tower. To obtain earthquake loads, wind turbine tower response for three recorded ground motions and for three design earthquakes must be calculated. The more common method to calculate earthquake loads is the Time History Response Analysis Method which uses sway-rocking spring (hereinafter referred as SR model) to represent the soil-pile-building interaction (JSCE, 2010). However there is some cases were wind turbine would be installed few meters offshore and the foundation is sustained by piles up to the water level. In that case structure-soil interaction might be difficult to represent with the conventional SR model. So even if FEM models are not common in practical design, in cases like the mentioned above FEM model is more efficient to do the complex dynamic response analysis. We propose the Axisymmetric Finite Element Method to reproduce, and solve, that complex conditions with accuracy and, comparing to other FEM methods, with small calculation time. As a first step on this research we focused on the comparison of the wind turbine tower response against seismic ground motions for the SR model and the mentioned FEM model. Since soil conditions has important influence on the results the study has been done for different types of soils.

The study is conducted for a representative 2MW 80m tall wind turbine tower with an approximate nacelle weight of 1400 kN and a tower cylinder diameter from 4300 mm at the bottom to 3000 mm at the top of the tower. The tower cylinder thickness varies from approximately 55 mm at the bottom to 16 mm at the top. The foundation has an octagonal form and is 15 m long and 3 m tall. There is a total of 8 reinforced concrete piles and their diameter is 1500 mm.

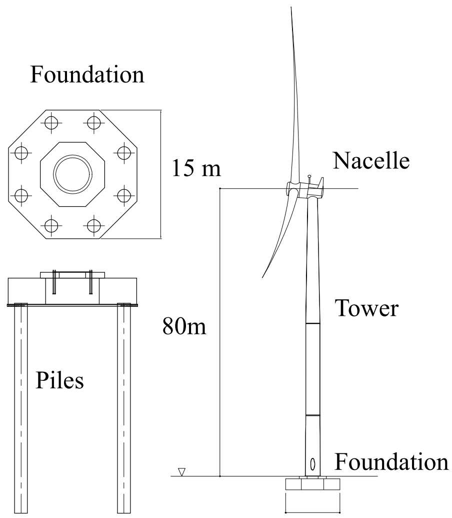


Figure 1. Tower and Foundation section

SOIL CHARACTERISTICS

The amplification of the bedrock ground motion depends on the soil profile, which is usually estimated by geotechnical data. In this study a soil composed by alluvial sand (As) and alluvial gravel (Ag) at the top 16 m, and diluvial clay (Dc) and diluvial sand (Ds) for the remaining 28 meters has been considered. In order to understand how soil characteristics may influence in both analysis models, comparison analysis has been carried out for three different types of soils defined as hard soil (natural period of 0.34 seconds), standard soil (natural period of 0.44 seconds) and soft soil (natural period of 0.75 seconds). Those three soils shear wave velocity Vs for each layer is shown in Table 1. For hard soil shear wave velocities between 300 m/s and 500 m/s are considered while for soft soils those velocities are mainly between 100m/s and 300 m/s. The mean curves, which are determined to represent the nonlinear relationship of G-γ and h-γ for sand and clay under the condition of shear strain are shown in Fig.2. Those curves were obtained from the mean values of maximum damping factor and initial reference shear strain for different soil samples in Japan (AIJ, 2016).

Table 1. Soil shear wave velocity Vs (m/s)

Layer	Thickness(m)	Hard soil	Standard soil	Soft Soil
As1	7.13	360	230	120
As2	7.45	480	290	160
Ag	1.45	320	400	200
Dc1	2.90	350	300	220
Ds1	14.60	390	360	240
Ds1	10.75	450	450	450
Bedrock		500	500	500

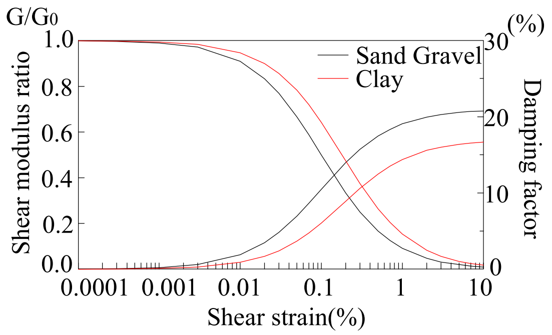


Figure 2. Relationship of G-γ and h-γ and shear stain for sand and clay

TIME HISTORY RESPONSE ANALYSIS

Time History Response Analysis is usually done using observed earthquake records at ground level and three or more artificially created ground motions. Those artificial ground motions are created using observed earthquakes phase characteristics, usually near-field earthquake, far-field earthquake and random wave, and the design spectrum defined by the MLIT (Ministry of Land, Infrastructure, Transport and Tourism). With artificial ground motion at bedrock level and the soil model, ground motion at tower foundation bottom is calculated.

A. Design ground motion

The basic design earthquake acceleration response spectrum, defined as S_o, of the seismic ground motion at the engineering bedrock level is given in Eq.(1). The engineering bedrock level is assumed to be a soil layer whose shear wave velocity is equal or more than 400 m/s.

$$S_0\,(\mathrm{m/s^2}) = \begin{cases} 3.2 + 30T & T < 0.16 \\ 8.0 & 0.16 < T < 0.64 \\ 5.12/T & 0.64 < T \end{cases} \tag{1}$$

The phase of the 1968 Tokachi-oki earthquake (Hachinohe NS1) and the 1995 Great Hanshin Earthquake (JMA Kobe NS2) has been used along with the design spectrum mentioned above to create the artificial ground motions used in this study. Despite Japanese Building code has a two-stage design philosophy, in this study only level 2 (life-safety limit state) has been considered. The equivalent linear analysis for the non-linear soil to obtain the ground motion at foundation bottom level was carried out by SHAKE. Ground motions at bedrock level are shown in Fig.3 and the values for the acceleration and velocity at the bedrock and at the surface are shown in Table 2.

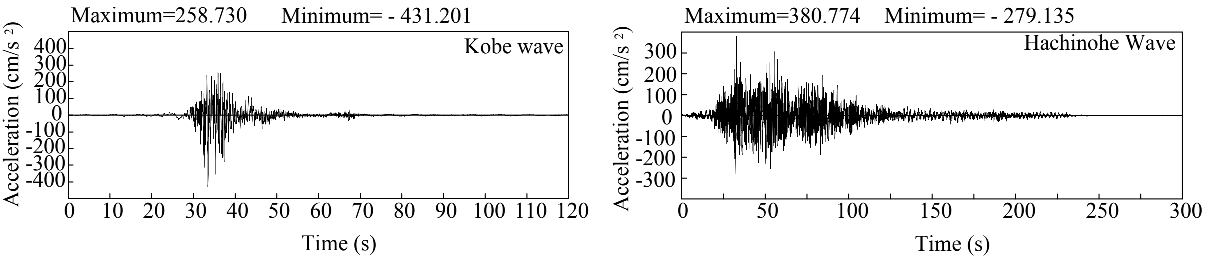


Figure 3. Kobe and Hachinohe wave at bedrock level

Table 2. Input ground motion

Ground motion	Soil type	Acceleration at bedrock (m/s^2)	Velocity at bedrock (m/s)	Acceleration at surface (m/s^2)	Velocity at surface (m/s)
Kobe phase	Hard soil	4.31	0.49	4.64	0.52
	Standard soil			5.27	0.60
	Soft soil			4.42	0.71
Hachinohe phase	Hard soil	3.81	0.62	3.78	0.69
	Standard soil			4.52	0.74
	Soft soil			3.94	0.76

The design ground motion spectral acceleration, velocity and displacement for the three different types of soils at the surface and at the engineering bedrock are shown in the tripartite response spectrum (Fig.4). Tripartite response spectrum is calculated for a 5% damping and as can be observed in the spectrum, for soft soil the response for higher periods increases while for standard and hard soils higher response is obtained for lower periods. Since wind turbine tower natural frequency is close to three seconds, we can expect higher response for soft soil than for hard and standard soil.

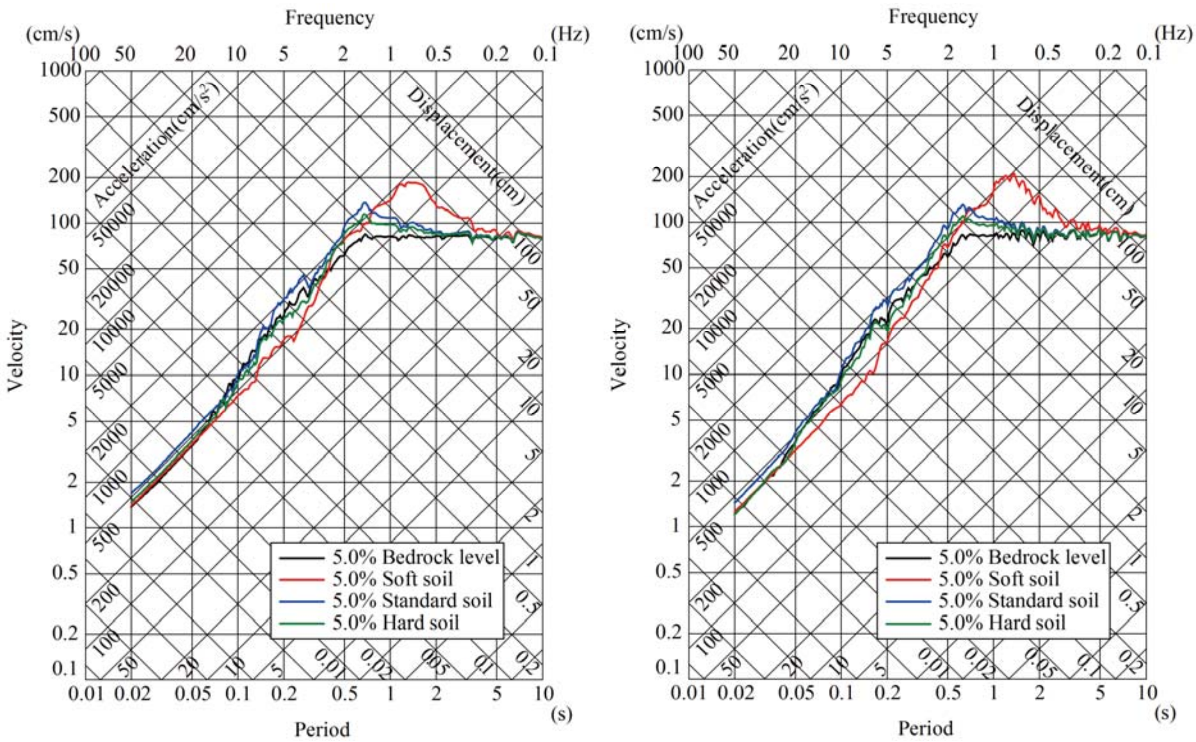


Figure 4. Tripartite response spectrum at the Engineering Bedrock

B. Analysis model

The analysis model is shown in Fig.5. The wind turbine tower has been divided in 30 stories, one for each section of the tower and one for the nacelle. The nacelle, rotor and blades weights are all in the top mass point of the lumped model. The interaction between the soil-pile-tower is represented by sway-rocking parameters Kr, Cr, Ks and Cs. The numerical evaluation of the dynamic response is done using the Newmark-beta method (Beta=1/4) with an integration interval of 0.001 sec. The restoring force for the tower is considered linear and the analysis is carried out with flexural-shear model. The Rayleigh damping of the structure is 0.5% for the first and the second mode of vibration.

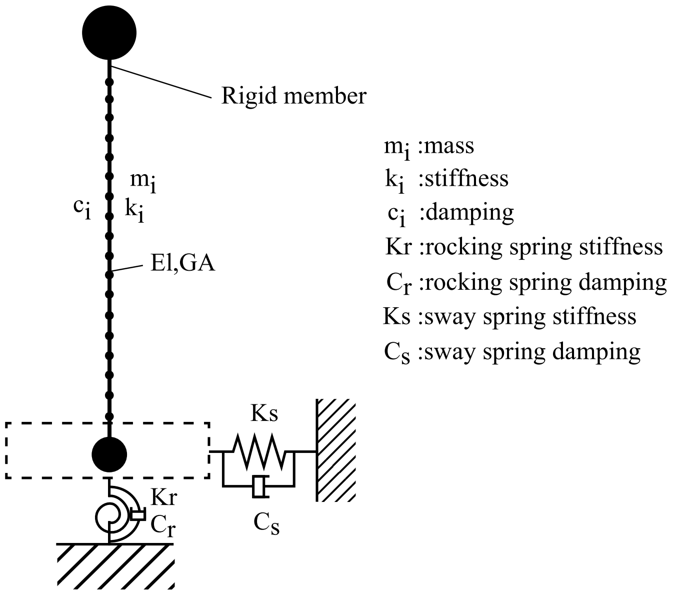
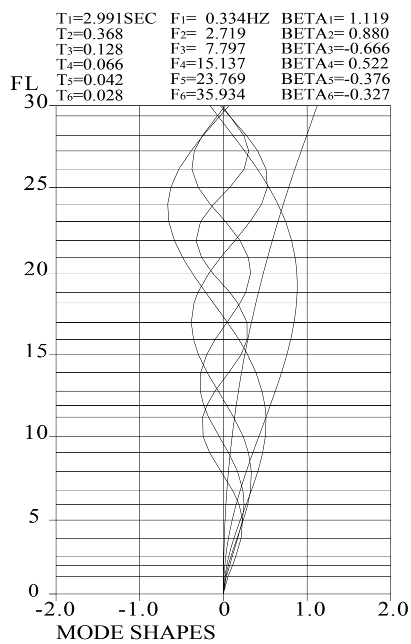


Figure 5. SRmodel

In Fig.6 eigenvalue analysis results for fixed model and SR model for each type of soil are shown. The first mode of vibration period increases from 2.99 seconds for the fixed model to 3.02 seconds for the SR model soft soil. In the SR model, the sway natural period can be observed; at the 4th mode of vibration for hard soils and in the 2nd mode of vibration for the soft soil. Also can be observed that participation factors for hard and standard soil are high at 3rd and 4th vibration mode while 1st and 2nd modes are higher in soft soils.

Fixed model		
Mode	Period (s)	Participation factor
1st	2.991	1.119
2nd	0.368	0.880
3rd	0.128	0.666
4th	0.066	0.522
5th	0.042	0.376



Hard model		
Mode	Period (s)	Participation factor
1st	3.005	1.121
2nd	0.371	0.931
3rd	0.131	1.146
4th	0.086	1.391
5th	0.066	0.753

Standard model		
Mode	Period (s)	Participation factor
1st	3.008	1.221
2nd	0.373	0.995
3rd	0.137	2.696
4th	0.120	2.398
5th	0.067	0.199

Soft model		
Mode	Period (s)	Participation factor
1st	3.015	1.127
2nd	0.377	1.354
3rd	0.225	1.096
4th	0.129	0.319
5th	0.068	0.049

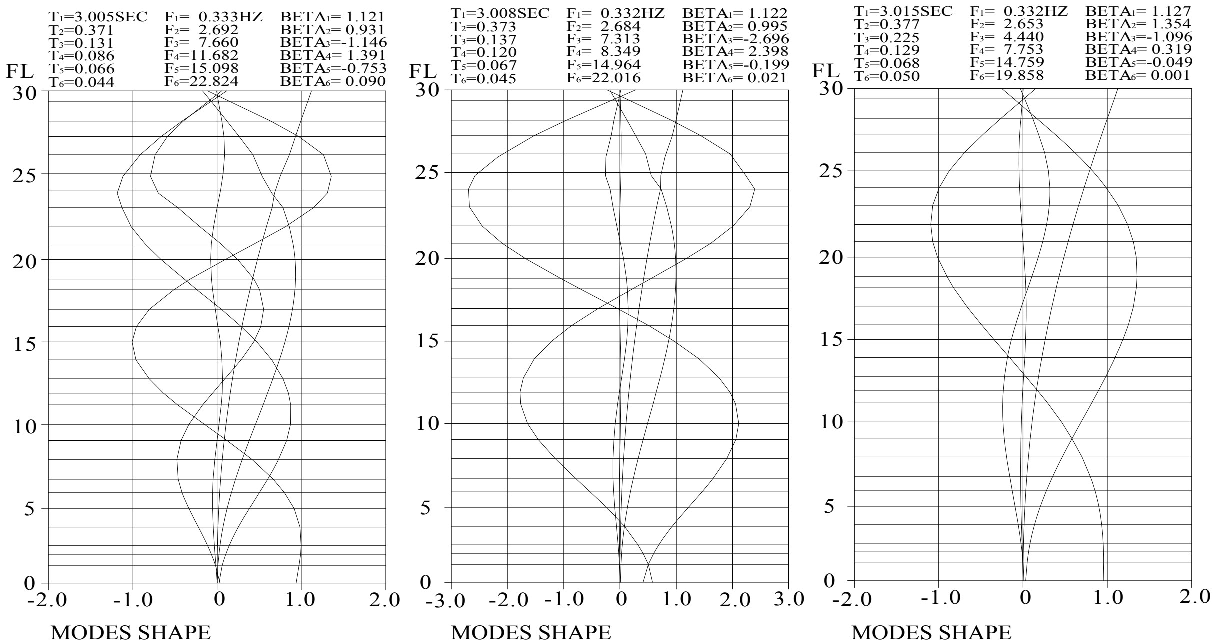


Figure 6. Natural period of wind turbine tower for fixed and SR mode

AXISYMMETRIC FEM ANALYSIS

A. Analysis model

In the Axisymmetric FEM model, wind tower, piles and the soil are modelled together. By using this method, ground motions considering structure-soil interaction as well as the structure response considering this structure-soil interaction can be calculated. This analysis is done considering lateral viscous boundaries which allows to calculate without losing resolution in the results even with decreasing the mesh resolution. Also base viscous boundary condition is considered, treating bedrock as elastic halfspace and removing the waves produced by reflection on the bedrock. When solving this type of axisymmetric problem, by modelling using axisymmetric elements, the modelled zone is expressed in a bi-dimensional model per unit of circumferential length and it is possible to model in 2D with a precision in the results close to the 3D model. The non-linear soil is simulated with the equivalent linear analysis method. Also in order to reduce the calculation time, frequency response analysis was used in the calculations. In Fig.7 the analysis model is shown. The wind turbine tower is modelled as a beam element with the same multi-degree-of-freedom model as the SR model while the foundation and the soil as a solid element. The piles are modelled as ring piles along the circumferential direction.

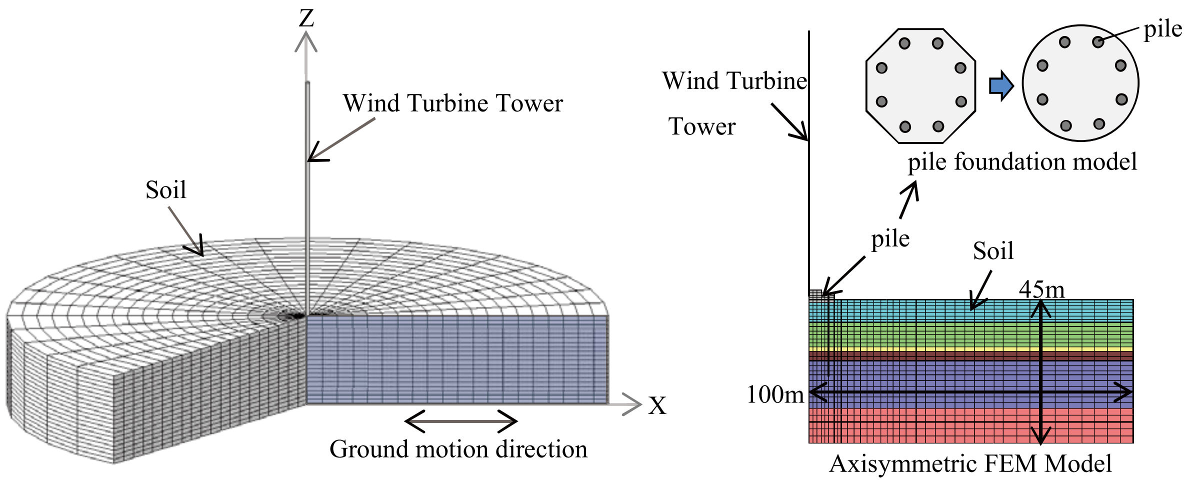


Figure 7. FEM model

MODELS RESULT COMPARISON

Fig.8, Fig.9, Fig.10 and Fig.11 shows maximum response displacement, bending moment, acceleration and shear force values for SR model and FEM model for each type of soil and for the two ground motions. Also, in Table 3, wind turbine tower mode of vibration period is shown for both models. As can be observed in the table, FEM model 1st natural period is around 3.2 seconds while SR model is around 3.0 seconds. This can be due to the fact than in FEM model, foundation rocking and vertical spring is considered in the analysis.

Table 3. Tower natural period (seconds)

Model	Mode	Hard soil	Standard soil	Soft Soil
FEM	1st	3.215	3.215	3.247
	2nd	0.416	0.417	0.422
	3rd	0.143	0.143	0.142
	4th	0.071	0.071	0.071
SR	1st	3.005	3.008	3.015
	2nd	0.371	0.373	0.377
	3rd	0.131	0.137	0.225
	4th	0.086	0.120	0.129

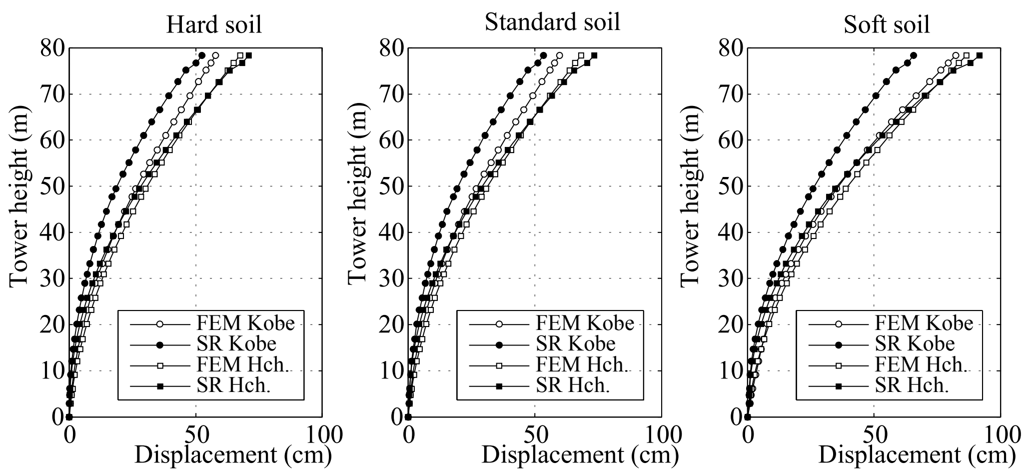


Figure 8. Maximum response displacement

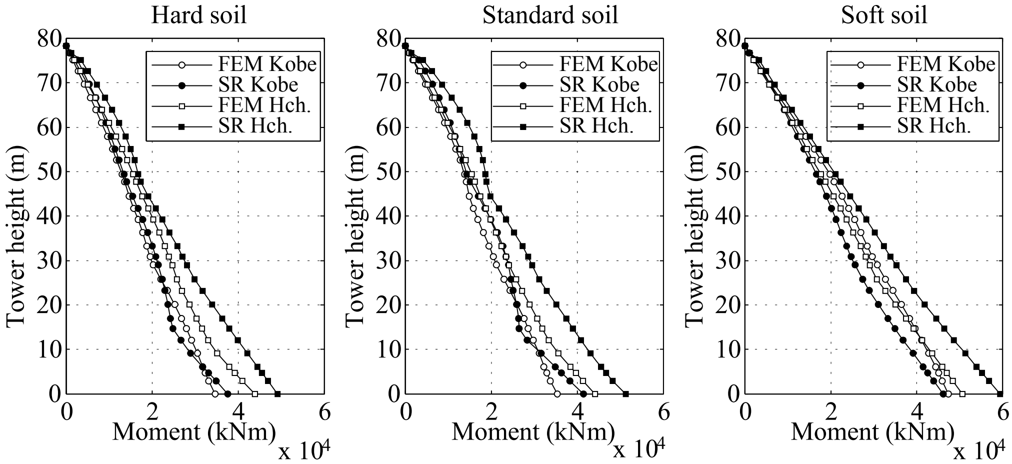


Figure 9. Maximum response bending moment

The difference between the two models results R is defined as the ratio between SR model results and FEM model results and is shown in Table 4. This difference was calculated with the values at the tower top for the displacement and at the tower bottom for the bending moment, where values are maximum. As can be seen, independently of the soil type, displacement results difference depends on ground motion while for bending moment in the most of cases SR model results are higher. This is due to the fact that bending moment is highly dependent on the 1st mode of vibration period and FEM model has larger period than the SR model.

Table 4. Displacement and bending moment R (SR model results/FEM model results)

Ground motion	Soil type	Displacement	Bending moment
Kobe phase	Hard soil	0.91	1.07
	Standard soil	0.89	1.18
	Soft soil	0.80	0.98
Hachinohe phase	Hard soil	1.05	1.12
	Standard soil	1.07	1.16
	Soft soil	1.06	1.17

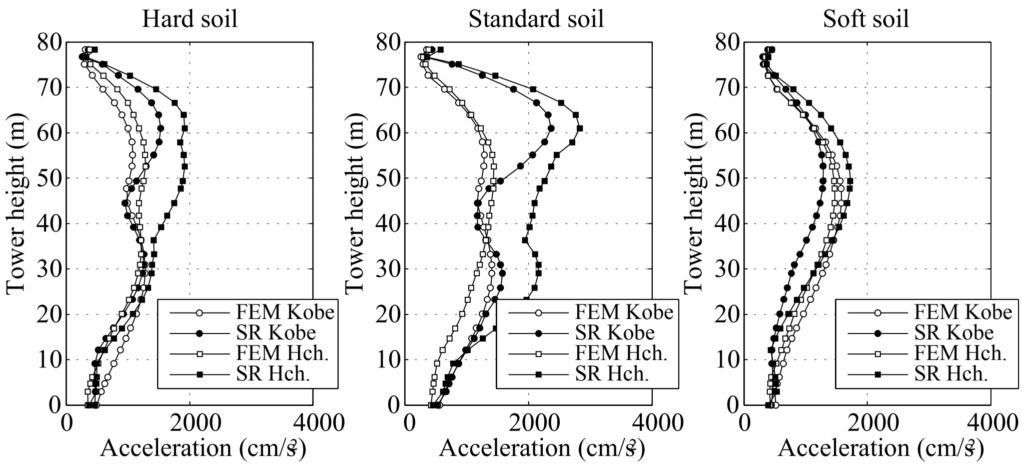


Figure 10. Maximum response acceleration

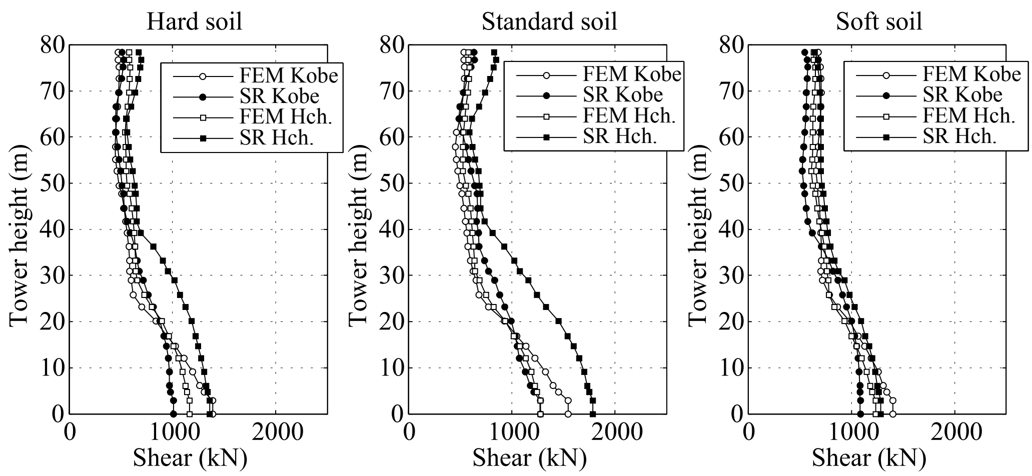


Figure 11. Maximum response shear force

As can be observed in Table 5, the results difference between models for acceleration and shear force varies depending on the soil type. Since acceleration and shear force are highly dependent on higher modes of vibration and in order to understand the difference between the two models, response spectrum at the tower bottom for both models was calculated. In Fig.12 and Fig.13 can be observed that response amplification for lower periods due to the soil-pile-structure interaction is higher for SR model than for FEM model. This could be explained because in SR model, soil radiation damping, which affects mainly higher modes of vibration, is ignored (see Fig.14) when structure natural frequency is smaller than soil dominant frequency, while FEM model considers it. Also, it was found that small response difference for soft soil was because higher modes of vibration periods does not correspond to higher response values produced by soil response amplification.

Table 5. Acceleration and shear force R (SR model results/FEM model results)

Ground motion	Soil type	Acceleration	Shear force
Kobe phase	Hard soil	1.59	1.21
	Standard soil	3.34	1.30
	Soft soil	1.27	1.26
Hachinohe phase	Hard soil	1.49	1.52
	Standard soil	3.05	1.69
	Soft soil	1.47	1.26

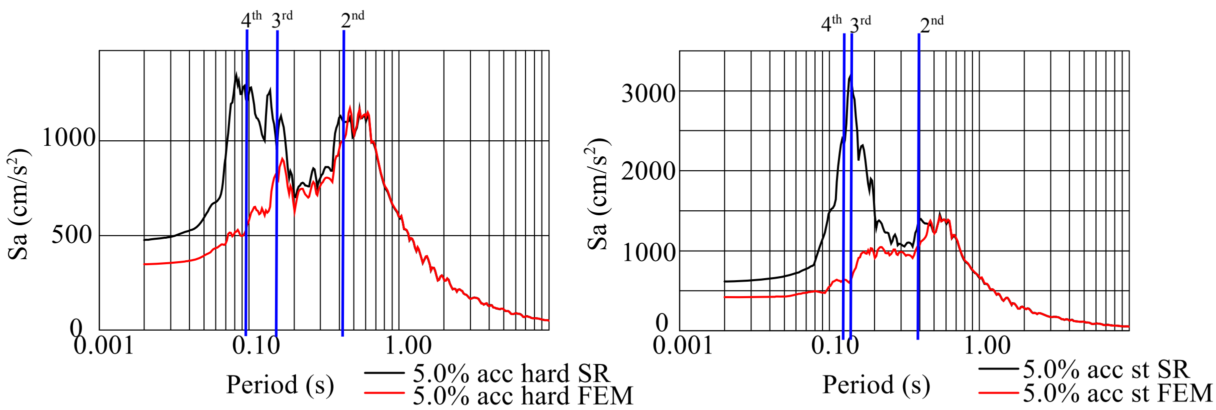


Figure 12. Response spectrum for hard (left) and standard (right) soil

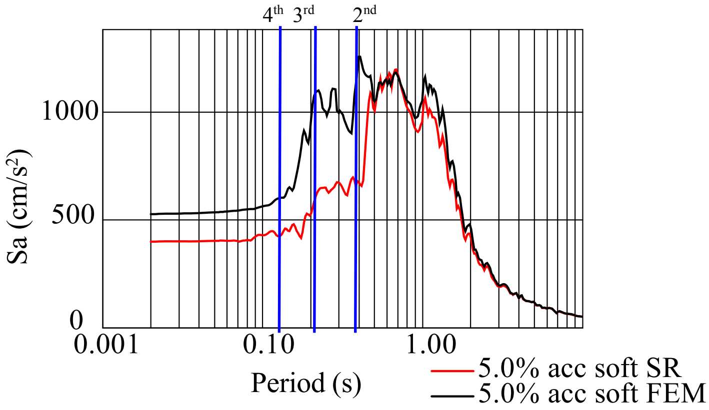


Figure 13. Response spectrum for soft soil

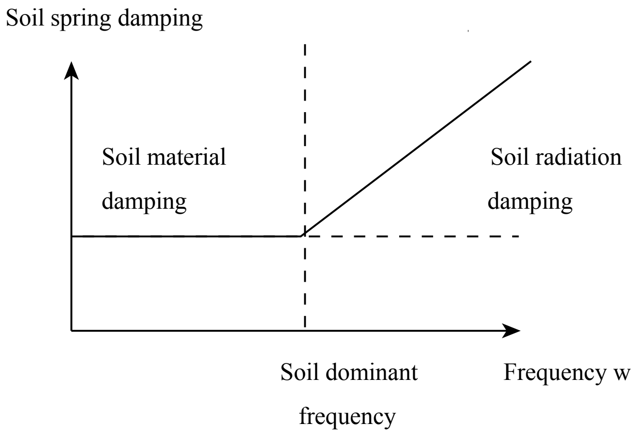


Figure 14. SR model soil spring damping

CONCLUSIONS

Comparison between SR model and FEM model has been carried out for three type of soils. Results of simulations showed that displacement and bending moment divergence between analysis models do not depend on the soil while divergence for acceleration and shear force are high dependent on the soil conditions. Also was observed that natural period of the structure is larger for FEM model than for the SR model. Finally, since soil radiation damping is considered only in FEM model, this model had smaller response for higher modes of vibration. In this paper we focused mainly on the wind turbine tower response so the next step in this study is to focus on the soil and the pile response.

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