A case study of Soil-Foundation-Structure-Interaction for aseismic design of wind turbines

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ABSTRACT

Wind farms in New Zealand have a combined capacity of about 690 MW and supply around 6% of New Zealand's annual electricity generation. This is about the amount of electricity 300,000 kiwi homes use in a year. Wind farms don't emit greenhouse gases as they generate electricity and are one way we can reduce emissions. There is currently approximately 2,500 MW of wind generation consented in New Zealand and developers are exploring sites throughout New Zealand for new wind farms.

One of the challenges with building wind farms in New Zealand is the high seismic hazard. Seismic demands on the foundations and tower can be significant and affect the capital costs of wind farm developments. Considering Soil-Foundation-Structure-Interaction (SFSI) effects during earthquakes and equivalent linear dynamic analysis of the structure-foundation-ground system has proven to be beneficial in optimizing tower and foundation designs in areas with moderate or high seismic hazard.

This paper presents a case study comparison between elastic response spectra analysis and equivalent linear response history analysis of a wind turbine tower on shallow foundation. The tower is located on a shallow soil site in an area of high seismicity in New Zealand. The foundation has been modelled in three different ways: as a fixed base, using a soil-spring bed and considering the soils as a continuum. The results of the dynamic analysis, including the soils modelled as a continuum, show significant reductions in seismic demands on the tower and supports when compared to the results of more traditional response spectra analysis.

1 INTRODUCTION

Wind farms in New Zealand have a combined capacity of about 690 MW and supply around 6% of New Zealand's annual electricity generation, as of 2017. This is about the amount of electricity 300,000 kiwi homes use in a year. Wind farms produce clean green energy and thus reduces emission of greenhouse gases. There is currently approximately 2,500 MW of wind generation consented in New Zealand and developers are exploring sites throughout New Zealand for new wind farms.

One of the challenges with building wind farms in New Zealand is the high seismic hazard in some areas. Seismic demands on the foundations and towers can be significant and affect the capital costs of wind farm developments. It has been noted that consideration of Soil-Foundation-Structure-Interaction (SFSI) could be beneficial in optimizing the design of towers and foundations in areas of moderate or high seismic hazard.

This paper presents a case study comparison between commonly used elastic response spectrum analysis and equivalent linear response history analysis of a wind turbine tower on a shallow foundation. This tower is on a shallow soil site in an area of high seismicity in New Zealand. A parametric study has been completed to understand the impacts of various foundation modelling assumptions on the predicted response. Three different options for modelling the shallow foundation have been considered, namely, as a fixed base, using a beam on nonlinear Winkler springs and considering the soils as a continuum.

Following sections describe the adopted methodology, selection criteria and scaling of ground motion records to match the target spectrum, one dimensional (1D) Ground Response Analysis (GRA) to estimate surface ground shaking demands, equivalent linear parameters to model nonlinear soil (equivalent linear stiffness and associated damping) and structural analysis with selective results. The paper concludes a significant reduction in seismic demands can be achieved when SFSI is considered.

2 METHODOLOGY

A nonlinear analysis model considering fully coupled soil-fluid interaction of soil elements, structural members including material inelasticity and geometric nonlinearity and a large number of ground motion records are expected to provide the most accurate response of the tower and foundation, at the expense of a disproportional computational and engineering effort. Therefore, a simple yet accurate enough approach, as described below, is adopted to assess the effects of SFSI on the seismic demands at the tower base, through the following steps.

- Perform a 1D equivalent linear ground response analysis using rock outcropping ground motion records selected and scaled to match the design spectrum for Site Class A (rock) in accordance with NZS 1170.5. This is to derive the equivalent linear soil parameters, namely secant stiffness to (average) peak shear strain and associated equivalent viscous damping ratios. These parameters are used to model the foundation surrounding soils as a continuum. The resulting surface response spectrum (average of 5 records) is then compared with the NZS 1170.5 design spectrum for Site Class C, the code spectrum for this shallow soil site.
- Develop three structural analysis models with various degrees of complexity to understand the effect of SFSI on the seismic demands at the turbine tower's base.
- Carry out two seismic analyses for each model. The first analysis is a response spectrum analysis using Site Class C spectrum at 5% of critical damping. The second analysis is a dynamic analysis using the selected set of ground motion records.

3 SELECTION AND SCALING OF GROUND MOTION RECORDS

An ensemble of 5 single component ground motion records is selected and scaled to match the design spectrum for Site Class A in accordance with Section 5.5 of NZS 1170.5. All records are selected from actual records that have a similar seismological signature, i.e., magnitude, source characteristics including fault mechanism, and source-to-site distance, as tabulated in Table 1, as the signature of the events that significantly contributed to the target design spectrum of the site over the period range of interest. Since the site is in a proximity to two major faults, records with near fault effects, such as presence of a velocity pulse, are included in the selected set. The records are selected from rock sites only, as the records are to be applied at the bedrock level.

Table 1 Ground motion records selection criteria

Parameter	Value	Comment
Earthquake magnitude	7.0 – 9.0 M_w	Site is in close proximity of Wellington and Northern Ohariu faults, prescribed as major faults in Table 3.6 of NZS 1170.5
Source to site distancer	< 20 km	
Records with velocity pulse	Yes	
Period range of interest	1.2 – 4.1 s	Fundamental period is ~3.1 s ($0.4T_1 – 1.3T_1$)
V_{s30} range	750 – 1400 m/s	Average Vs30 ~ 950 m/s
Faulting mechanism	Strike-slip	
Pulse period	3.0 ~ 5.2 s	Fundamental structural period ~ 3.1 s
Scale factor	0.5 – 2.0	

Figure 1 presents a comparison of selected ground motion record spectrum and the target bedrock design spectrum.

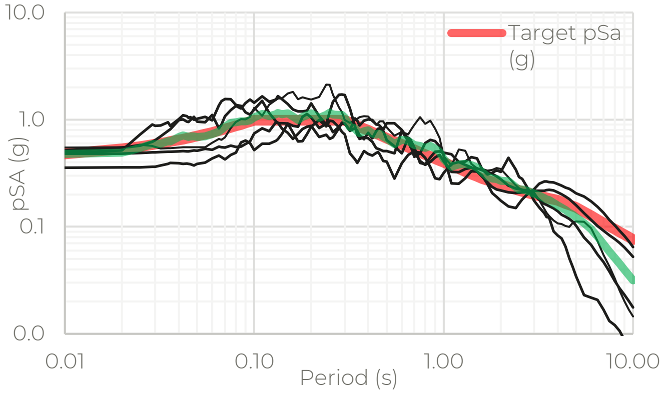

Figure 1 Comparison of target spectrum and ground motion record spectrum

In the absence of a site specific probabilistic seismic hazard assessment study, the target spectrum for earthquake selection and scaling is derived from NZS 1170.5 for Site Class A using the following parameters.

- Design seismic event – 500years return period.
- Seismic zone factor – 0.42

- Shortest distance to a major fault – 2 km
- Structural performance factor Sp – 1.0

Note that for response spectrum analysis, design spectrum for Site Class C is used, since the applied seismic loading is at the base of foundation.

4 1D GROUND RESPONSE ANALYSIS

A total stress equivalent linear 1D ground response analysis was completed to derive the surface ground motions, equivalent linear soil stiffness and associated equivalent viscus damping values. These parameters are then used to model the soil continuum using a simplified 2D linear elastic plane strain element.

Figure 2 shows an idealised shear wave velocity profile derived from five measurement logs, in relation to the founding level, ground level and bed rock level.

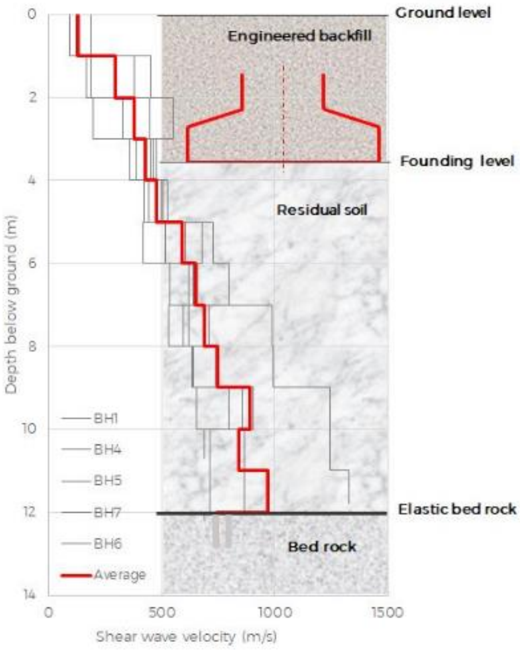

Figure 2 Shear velocity profile and relevant levels

The backbone curve describing the nonlinear stress-strain behaviour of a soil element is derived based on the empirical relationships proposed by Darendeli (2001) and as recommended in the Geotechnical Design Manual of Washington DoT (2019). The initial shear modulus is estimated from the average shear wave velocity profile as shown in Figure 2.

Previous research (Stewart et al 2014) recommended that elastic bed rock to be used in conjunction with rock outcropping motions. Accordingly, the underlying bed rock is considered as elastic with a shear wave velocity of 1200 m/s and elastic damping of 2% of critical damping.

Figure 3 compares the surface response spectrum due to 1D ground response analysis (GRA) and design spectrum for site classes A and C. An amplification in the response spectrum is noted at the site period of 0.12s and periods below, and practically no amplification is noted for period beyond 0.20s. The peak shear strain is about 0.6%, with an average strain of 0.3% in the top ~2.0m only. Therefore, equivalent modulii (~15% of initial stiffness) and damping ratios (~19.50% of critical damping ratio) are used to model the top 2m of soil, and initial modulii and damping ratios are used for the remaining depth of soil.

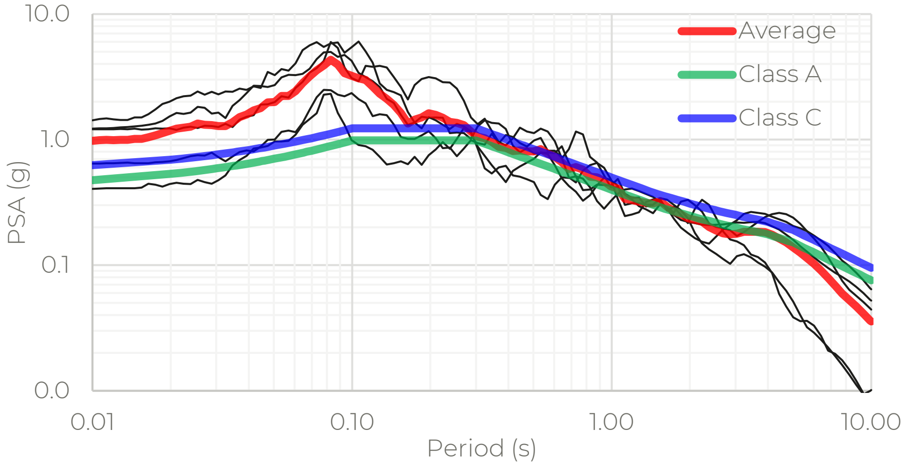

Figure 3 Comparison of surface spectra from 1D GRA and design spectra for Site Classes A and C.

5 STRUCTURAL ANALYSIS

A number of structural analyses with various degrees of complexity has been completed. This is to understand the structural response of the wind turbine tower and how various modelling assumptions related to foundation flexibility and damping influence it. Each model was analysed for three primary load cases, namely, self-weight, response spectrum analysis and analysis using an ensemble of five ground motion records.

5.1 Structural analysis models

The first model is a stick model of the wind turbine generator tower with fixed base. This is considered as the base model. The stick model comprises 3D linear elastic frame elements with nodes at the structural joint locations (transverse weld locations). Each frame element has assigned to average section properties for the parts of the tower it represents.

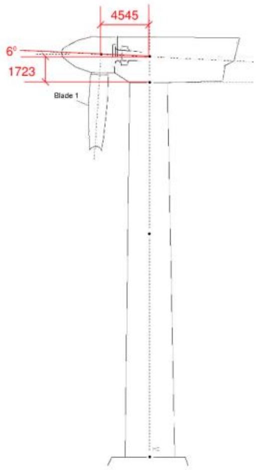

Figure 4 Location of nacelle and blade assembly and the tower

The self-weight of tower is estimated to be 1300 kN, and the weight of nacelle, rotor and blades is about 1860 kN. The total weight of the tower assembly excluding foundation amounts to 3160 kN. The weight of nacelle and rotor assembly is lumped eccentrically at the tower top, whilst the weight of tower is lumped at each joint location.

The second model extends the stick model by introducing a series of vertical compression-only bi-linear springs. This is to include the interaction of foundation raft and the soil underneath. The soil spring parameters are estimated in accordance with ASCE 41 based on the average shear wave velocity of the surface layer.

The third model includes the foundation raft and surrounding soils using 2D plane strain quadrilateral elements. The interface between foundation raft and soil is modelled with a series of compression-only springs to allow uplifting of raft. A very high elastic stiffness is assigned to these compression springs so that compressive force is transferred to the ground with negligible relative displacement. The soil mesh is sized to include shear waves with max frequency of up to 30 Hz. The soil mesh size is refined further near the foundation to smooth out any unrealistic stress concentration. A translationally fixed boundary was assumed at the base, whilst a periodic boundary condition is assigned to the sides of the soil boundary. The periodic lateral boundary is set by constraining translational degrees of freedom of each node on the left boundary to the corresponding node at the same elevation on the right boundary.

A summary of all analysis models is tabulated in Table 2 and are presented in Figure 5.

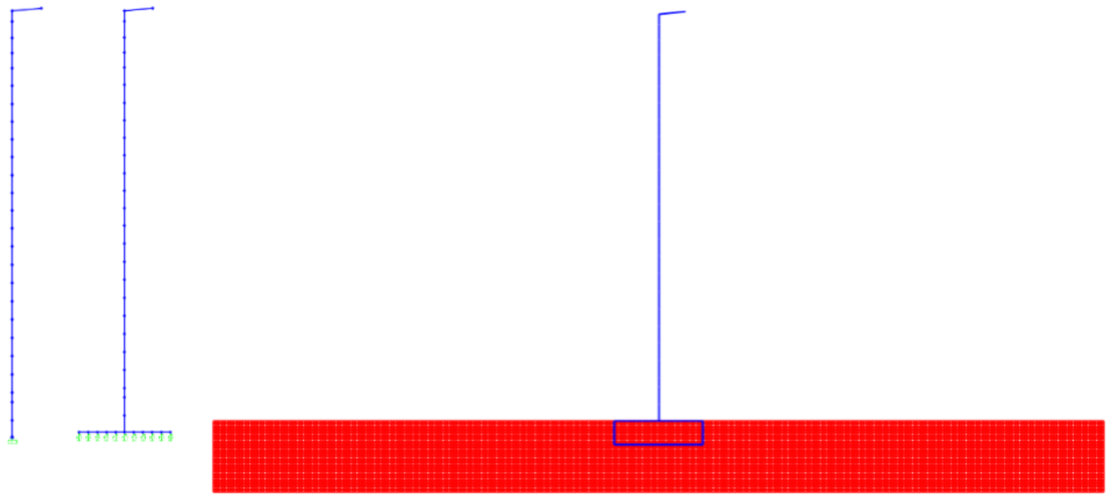

Figure 5 Summary of analysis models, fixed base (left), spring bed (centre) and soil continuum (right)

Table 2 Summary of analysis models

Parameter	**Fixed base**	**Spring bed**	**Soil continuum**
Inertial effect	Yes	Yes	Yes
Kinematic effect	No	No	Yes
Hysteretic damping	No	Approximately	Yes
Radiation damping	No	No	Yes

5.2 Analyses

The dead load analysis is completed for all three models as the basic load case. This is to confirm that the models are behaving as expected.

A response spectrum analysis is completed and first 12 modes of vibration contributing more than 95% of the modal mass are combined using the Complete Quadratic Combination (CQC) rule. Table 3 presents a comparison of fundamental time period and 1st mode mass participation factor for all three models.

Table 3 Summary of modal response parameters

Parameter	Fixed base	Spring bed	Soil continuum
Fundamental period (s)	3.07 s	3.24 s	3.31 s
1st mode participation factor	74.82%	75.48%	55.43%

The fundamental mode participation factor for the soil continuum model is substantially smaller than the other two models, because the former (soil continuum) model includes the mass of the surrounding soil. This increases total mass of the system and thus reduces the mass participation factor.

The response history analysis is carried out for all three models. The first two models are analysed using surface records from the 1D GRA whilst the third model utilised the bed rock motions. All records are applied at the base of the analysis model. A mass and stiffness proportional Rayleigh damping is used along with Newmark's integration scheme to carry out the response history analysis.

A summary of moments at the tower base from all analyses undertaken in this study is tabulated in Table 4. The bracketed values are the moments normalised with respect to the soil continuum model moments.

Table 4 Summary of moments (kNm) at the tower base

Load cases	Fixed base	Spring bed	Soil continuum
Dead load	8960 (0.99)	9015 (1.0)	9050 (1.0)
RSA (Class C)	37950 (1.27)	36200 (1.21)	29925 (1.0)
RHA (average)	28800 (1.20)	24500 (1.02)	24000 (1.0)
RHA (std dev)	7500 (2.34)	2000 (0.63)	3200 (1.0)

Results from dead load analysis confirm that all analysis models are similar. A considerable amount of reduction in the base moment can be achieved using a response history analysis when SFSI is considered.

5.3 Sensitivity study

Parametric studies have been undertaken to assess the influence of soil parameters and domain size on the analysis results. All sensitivity analyses are completed for one record only.

Previous analysis was carried out using average soil parameters. A sensitivity study was undertaken for the third analysis model, where the shear modulus of soil taken as 50% and 200% of the average value. Table 5 show the influence of variation of soil parameters on the tower base moment. It is found not sensitive to the soil stiffness variation.

Table 5 Sensitivity of soil stiffness on the base moment (kNm) of tower (continuum model only)

Load case	50% of G	100% of G	200% of G
Dead load	9100 (1.01)	9050 (1.00)	9030 (0.99)
RSA (Site Class C)	29400 (0.98)	29925 (1.00)	30200 (1.01)
RHA (one record)	24700 (0.98)	25200 (1.00)	25400 (1.01)

The vertical sites of the soil domain in the third model are constrained by a periodic lateral boundary condition. This assumes that the effect of the structure on the soil vibration diminishes with distance and reflections of seismic waves at the vertical model boundaries. Therefore, as distances sufficiently afar, the effect of the structure is negligible. To understand the effect of domain size, three models are developed where the widths are 10, 15 and 20 times the foundation raft width. Note that the 15 times the foundation width is considered in the third model.

Table 6 presents the influence of variation of domain size on the tower base moment. It is also found not sensitive to the adopted domain size.

Table 6 Sensitivity of soil domain size on the base moment (kNm) of tower

Load case	**10 B**	**15 B**	**20 B**
Dead load	9050 (1.01)	9040 (1.00)	9020 (1.00)
RSA (Site Class C)	29925 (1.00)	30000 (1.00)	30200 (1.01)
RHA (one record)	25170 (0.99)	25300 (1.00)	25390 (1.00)

6 CONCLUSIONS

Summarised herein are the outcomes of a seismic SFSI study of a wind turbine located in an area of high seismic hazard in New Zealand. A set of 5 ground motion records was selected and scaled to match the design spectrum for Site Class B in the period range of interest. A 1D ground response analysis was carried out using the selected ground motion records to determine the equivalent linear soil stiffness and associated damping values, which were used to develop the soil continuum model. Three structural analysis models with varying degrees of soil flexibility and damping consideration were developed. All three analysis models were analysed for two seismic cases, a response spectrum analysis and a response history analysis.

Following observations can be made from results of the analysis of all three models.

- The fixed base model without any consideration of soil flexibility and additional damping results the most conservative results, irrespective of the analysis method considered.
- The spring bed model includes soil flexibility but excludes the radiation damping effects. This model produces results similar to the soil continuum model.
- When the effect of soil-foundation-structure interaction is included in the analysis model (the soil continuum model), seismic response reduced significantly from that estimated using a fixed base model, irrespective of the analysis method considered. This is partly due to the longer first mode period of vibration due to soil flexibility, but more due to the effects of radiation and hysteretic damping related to soil continuum.

In conclusion, an optimum tower base and foundation raft can be designed using an equivalent linear response history analysis considering soil-foundation-structure interaction.

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