Assessment of the Dynamic Response of the Soil to Strong Ground Motion at a Wind Farm

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SUMMARY:
An assessment of the dynamic response of the soil to strong ground motion at a wind farm was undertaken. The assessment was carried out in accordance with the international guidance for the design and safety requirements of wind turbines. The objective of the site response analyses is to capture the effect of the soil layers on the ground motions recorded on the surface. The effect of site response is studied using the equivalent linear one-dimensional wave propagation analysis. Typical soil profiles within the wind farm have been considered for this study. Time history at the surface was obtained for each input ground motion. The effects of input motion uncertainty and uncertainty in soil properties are discussed and quantified. The amplification factor for typical soil profile was estimated using the transfer function method. The implication of the soil amplification factor for the wind turbine structures was also discussed.

Keywords: site effect, strong ground motion, wind farm

1. INTRODUCTION

An assessment of the dynamic response of the soil to strong ground motion at a wind farm was undertaken. Local site conditions play an important role in earthquake-resistant design. A significant part of damage observed in destructive earthquakes around the world is associated with seismic wave amplification due to local site effects. The local site conditions could be very different due to variations in thickness and properties of soil layers and could have significant effects on the characteristics of earthquake ground motions on the ground surface. The soil amplification factors are directly related to the shear-wave velocity profiles, modulus degradation and damping ratio of the soil. Site response analysis is therefore a fundamental part of assessing the seismic hazard.

A local site effect analysis should be conducted to evaluate the response of local soil conditions that is caused by the motion of the bedrock immediately beneath it. If the geotechnical characteristics of a site are known then, the site effects should be estimated using numerical analysis. The one dimension response is the main method used in practice. For one dimensional response analysis the soil and bedrock surface are assumed to be extending horizontally. The method uses the geotechnical parameters of the soil to estimate the ground response for a specific input motion.

2. REGULATORY FRAMEWORK FOR DESIGN WIND TURBINES

Earthquake-resistant design of a new structure requires an analysis of its response to earthquake shaking. Ground motion can be specified in many different ways, i.e. peak ground acceleration, shapes of response spectra and time history.

Several standards for the design and safety requirements of wind turbines exist. The most significant one is from the International Electrotechnical Commission (IEC, 2005), which is the leading organization that compiles international standards for electrical technologies. The IEC documents act as a basis for national standardization and also as a reference for international contracts. Part one of IEC 61400-1, Wind turbines – Part 1: "Design requirements" (IEC, 2005) specifies minimum design requirements to assure the engineering integrity of wind turbines. The IEC guidelines provide recommendations regarding the methods to use for the evaluation of the overall stability of the structure. The assessment of earthquake conditions is outlined in Clause 11.6 (Assessment of earthquake conditions) and Annex C (Assessment of earthquake loading).

Germanischer Lloyd (GL, 2010) is an internationally operating certification body for wind turbines. Certification of small, medium and large wind turbines is carried out on the basis of the GL's Guideline for the Certification of Wind Turbines (GL, 2010). The GL's guidelines for the earthquake requirements are very similar to those of IEC.

IEC (2005) specifies the following: (1) the ground acceleration shall be evaluated for a 475-year recurrence period; (2) The seismic load evaluation may be carried out through frequency domain methods, in which case, the operational loads are added directly to the seismic load. The seismic load evaluation may be carried out through time-domain methods, in which case, sufficient simulations shall be undertaken that the operational load is representative of the time averaged values. For analysis carried out in the time-domain, a minimum number of six simulations per load case must be performed (GL, 2010).

According to IEC, 2005, the procedure for assessment of earthquake loading includes the following steps, which were followed in this investigation: (1) evaluate or estimate the site and soil conditions required by the relevant local standard (2) use the normalized design response spectrum and the seismic hazard-zoning factor to establish the acceleration at the first tower bending eigen-frequency assuming a damping of 1% of critical damping.

Wind turbines are not directly addressed in building code provisions, interpretations and implementations (Eurocode, EC, 2004). Building code procedures assume certain dynamic characteristics that are not always applicable to wind turbines. It is recognized that the dynamic behavior of wind turbines is distinct of other building structures (Prowell *et al*. 2008). In some cases this can be shown to be both overly conservative and un-conservative with dependence on whether frequency or time domain methods are employed in the evaluation of seismic loading (Ntambakwa and Rogers , 2009 and Prowell and Veers, 2009). IEC Guidelines suggest the use of a damping ratio of 1%, however, the assumed levels of damping embedded in the design response spectrum of building codes are typically 5%.

3. SITE RESPONSE METHODOLOGY AND SOIL MODEL

The most widely used analytical method is the multiple reflection models for the propagation of S-waves in a one-dimensional column. Site effect is modeled by the one-dimensional site response program, Shake, (Idriss and Sun, 1992). The Shake software calculates the seismic site response based on the solution of vertical propagation of shear waves through a one-dimensional column of soil. The S-waves propagates from bedrock outcrop through a column of visco-elastic layers. Nonlinearity of the shear modulus and damping is accounted for by the use of equivalent linear soil properties using an iterative procedure to obtain values of modulus and damping, which are compatible with the effective strains in each layer. The Shake 2000 program needs specific geotechnical inputs (Ordonez, 2010). The input parameters are as follows: soil type, thickness of the layers and unit weight of the material, shear modulus value of the material or shear wave velocity, dynamic soil properties and earthquake acceleration time history. The input time series could be assigned to the rock or other sub layers that the soil profile have. The output acceleration is computed at the specified sub-layer.

The non-linear behavior of soils is well known and can be determined in a laboratory environment. In the case of local shear modulus reduction curves and damping curves being unavailable, well established published stiffness reduction curves (generic curves) should be used. At the wind farm site the shear modulus degradation curves and damping ratio curves were selected using generic data. Typically, modulus reduction curves and damping curves are selected on the basis of published relationships for similar soils (e.g., Seed and Idriss, 1970; Seed et al., 1986; Sun et al., 1988; Vucetic and Dobry,1991; Electric Power Research Institute, EPRI, 1993; Kramer, 1996).

The generic curves developed by EPRI (1993) are most suitable to model pressure-dependent cohesionless soils, with gravels, sands, and low PI clays and were, therefore, used to model soil at the site. EPRI (1993) develops a set of dynamic curves to represent six different ranges of depths, down to a depth of 305 m.

Unit weight and shear wave velocity are estimated using available borehole data and the surface wave survey. According to borehole data the bedrock occurs at depth of about 32 m. At the proposed location of the wind farm shear wave velocity models were created for typical soil profile at the site. The shear wave velocity model for typical soil profile is based on an average shear velocity to the depth of 32 m obtained from the shear wave survey. The shear wave velocity below bedrock is assumed and has the value of 750m/s.

Table 1 shows values of shear velocity profiles used in the Shake analysis. These tables display an average velocity, standard deviation and a minimum and maximum value at each depth. The variability of velocities will be used to estimate the uncertainty in the site effect.

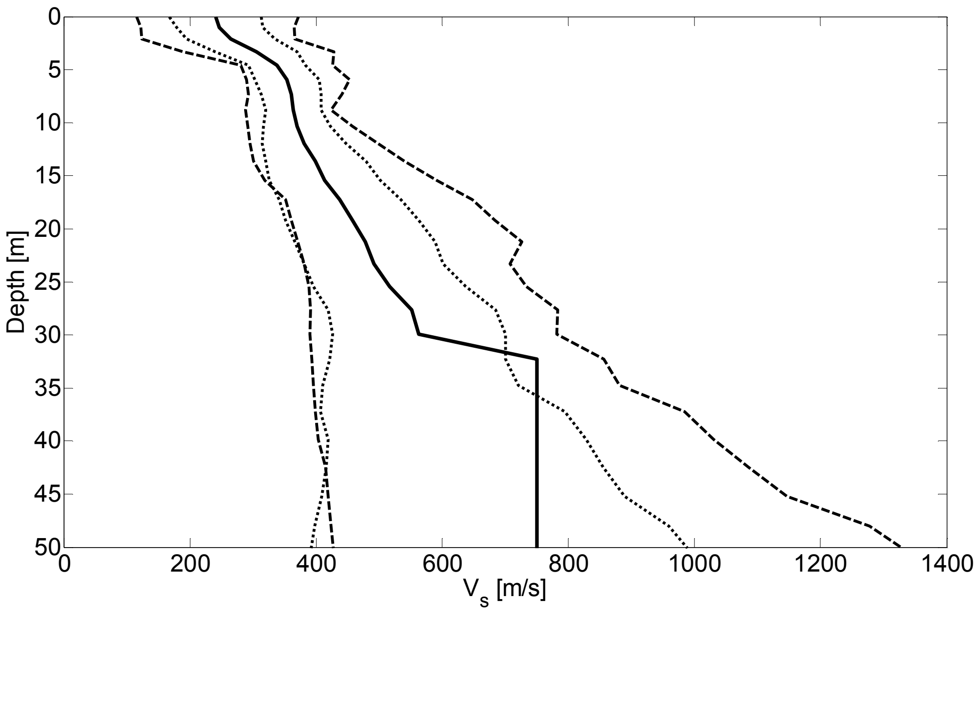

Figure 1. Shear velocity profiler (solid line), minimal and maximal range of velocity observations (dashed lines); and average shear velocity profile plus/minus standard error (dotted lines)

Table 1. Shear wave profile used to estimate site effect.

No	h [m]	Vs [m/s]	std [m/s]	Vs-min [m/s]	Vs-max [m/s]
1	0.0	241	73	116	372
2	1.0	247	68	122	365.0
3	2.0	265	70	124	367
4	3.3	305	65	189	428
5	4.6	339	45	281	427
6	5.9	354	51	289	453
7	7.3	361	47	293	441
8	8.8	364	44	289	424
9	10.3	370	53	291	458
10	12	381	66	295	498
11	13.7	400	70	301	540
12	15.4	314	88	319	591
13	17.3	438	96	352	648
14	19.2	458	105	361	683
15	21.2	478	111	371	726
16	23.3	491	111	381	708
17	25	516	121	389	733
18	28	552	133	392	783
19	32.0	750			

4. ESTIMATION OF AMPLIFICATION FACTOR AT SITE

The transfer function is defined as the ratio of the Fourier amplitude spectrum of surface motions to the Fourier amplitude spectrum of the corresponding motions on a rock outcrop. Site response transfer function is the amplification factor for the specified frequency range. To carry out the Shake analysis a 1D geologic model of the soil column was created.

The acceleration time histories were used as input motions at the bottom of soil column for a typical soil profile. The variability of input ground motion and its effect on the amplification factor was included in the analysis. As recommended by the GL (2010) guidance, six earthquakes were selected. A suite of acceleration time histories were obtained from an online strong ground motion database, Pacific Earthquake Engineering Research, PEER, (2010). The selecting of strong ground motion records requires consideration of the controlling earthquake magnitude, distance and site conditions. The suite of ground motion has magnitudes ranging between 6.5 and 6.7 and site to source distance ranging between 10 km and 30 km. Acceleration time histories, in order to be suitable for analysis, should have spectral characteristics compatible to the uniform hazard spectra (UHS). The amplitude of a recorded time history was therefore adjusted to match the UHS between 0.05 s and 4.5 s period.

The shape of the amplification factor function is presented in Figure 2 and Table 2. The maximum amplification of 2.5 at 0.25 sec is observed. The most outstanding feature of the amplification factor is the amplitude peaks at 0.055sec, 0.06 sec, 0.09 sec and 0.25 sec. The peak values of amplification vary from 1.65 to 2.5. The small values of standard deviations indicate that all time histories of the six earthquakes have almost the same transfer function.

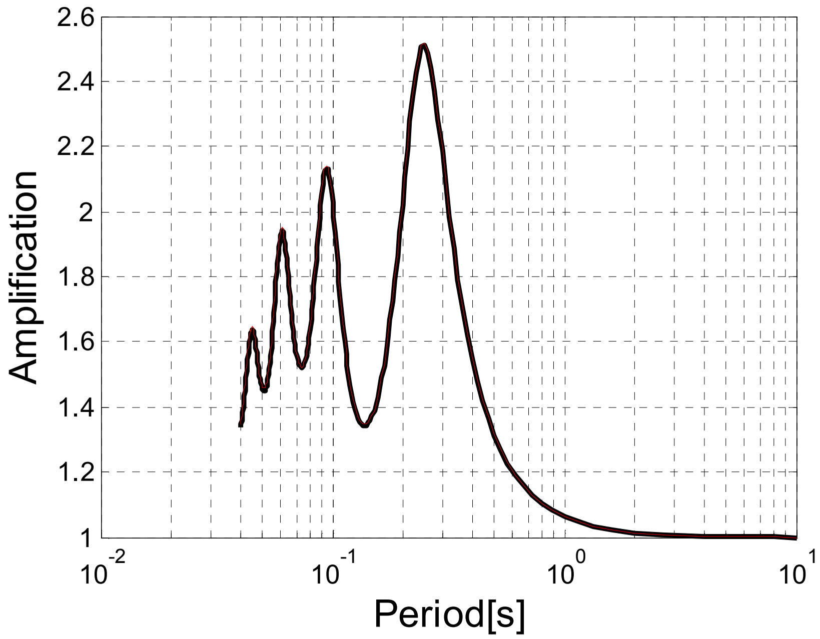

Figure 2. Average transfer function. Maximal amplification is 2.5 at period 0.25sec

Table 2. Average amplification and standard deviation for site.

Period [sec]	Amplification	std
0.05	1.45	0.006
0.06	1.93	0.014
0.07	1.56	0.005
0.08	1.64	0.012
0.09	2.06	0.017
0.10	2.03	0.008
0.20	2.02	0.009
0.30	2.15	0.010
0.40	1.55	0.005
0.50	1.31	0.003
0.60	1.20	0.002
0.70	1.14	0.001
0.80	1.11	0.001
0.90	1.08	0.001
1.00	1.06	0.001
2.00	1.01	0.000
3.00	1.00	0.000
4.00	1.00	0.000
5.00	1.00	0.000

The input parameters of both soil properties and input ground motions are subject to variability. The typical soil profile (Figure 1) shows significant shear wave profile variability. The sensitivity analysis was performed to investigate the effects of the variability of shear wave velocity on the amplification factor at soil profile. This was done by randomizing the shear velocity profiles. Those profiles were created by using the random generated shear wave velocity from intervals between the lower and upper bounds of the shear velocity. The result of the sensitivity analysis is shown on Figure 3. Figure 3 should be investigated in comparison with Figure 2, which shows the amplification factor for an average velocity profile. Both analyses reveal dominant soil amplification around 0.3 sec. However, the amplitudes of amplifications are different. The average profile (Figure 1) has an average amplification factor of 2.5 and the randomized analyses profile (Figure 3) has an average amplification factor of 2.2. The standard deviation in analysis with the average velocity profile is very small in comparison with the randomized analysis.

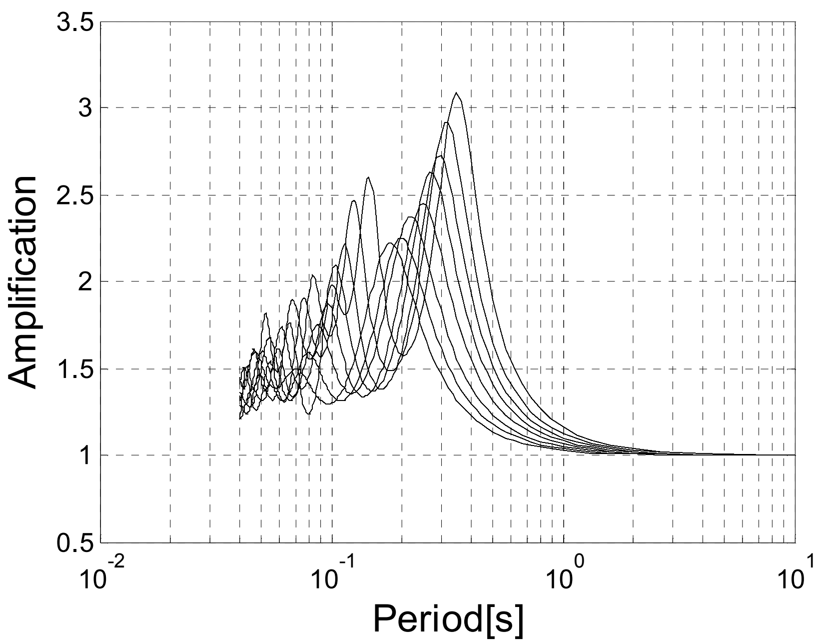

Figure 3. Amplification factor for randomized analysis of typical soil profile

5. DISCUSSION

The natural frequency of the considered turbine is 3 sec. According to the building regulation codes, a band of periods from 0.6 to 6 sec (EC, 2004) or from 0.6 to 4.5 sec (ASCE, 2007) should be analyzed for the structure with the natural period of 3 sec. The lowest period that should be considered is 0.6 sec. Figures 2 and 3 show maximum amplifications in periods relevant to the turbine. The amplification of 1.2 is at 0.6 sec. However, sensitivity analysis shows amplification of 1.5 at 0.6sec (see Figure 3).

Soil columns do not amplify the response spectra between 2.0 sec to 4.5 sec; therefore, the fundamental mode of the turbine will not be affected by soil conditions. The maximum amplifications are much lower than the natural frequency of the turbine. It means that the fundamental mode of the turbine will be not affected by maximal amplification of soil resonance.

6. CONCLUSION

An assessment of the dynamic response of the soil to strong ground motion at the planned wind farm was undertaken. The assessment was carried out in accordance with the IEC (2005) and GL (2010) standards for the design and safety requirements of wind turbines. The objective of the site response analyses was to capture the effect of the soil layers on the ground motions recorded on the surface. The effect of site response was studied using the equivalent linear one-dimensional wave propagation analysis. The site characterization is based on average soil's shear wave velocity in the upper 32 meters. The amplification factor for soil profile was estimated using the transfer function method. Maximal amplification of 2.5 is observed at 0.25 sec. The maximum amplifications are much lower than the natural frequency of the turbine. It means that the fundamental mode of the turbine with natural frequency 3 sec will be not affected by maximal amplification of soil resonance.

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