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TIME HISTORY ANALYSIS IN CASE OF A WIND TURBINE

BY

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Abstract. Due to the extended demands of the sustainability concept a new type of power source was needed at the entire world level. Therefore, in the past decade the wind turbine construction was highly extended. But this aspect came also with special design and building problems, especially in seismic areas. Romania is located in a seismic area having in Vrancea region the epicenter of major tectonic earthquakes relevant for the Eastern Europe. Therefore, in wind turbine design it is necessary to consider apart from the wind action as well as the seismic action when analysing the towers of wind turbines. The knowledge of the natural modes of vibration of the structure is an evaluation method of structural response under dynamic actions. Also, the response spectrum from a time history analysis can offer a better insight of the structural behavior. In order to consider the soil structure interaction the substructure method was used considering springs to model the soil structure interaction effects. This paper presents the results of a time history analysis on a 70 m tall wind turbine considering four different types of supports. The purpose of these analyses is to evaluate the maximum responses of this type of structures under the action of 1977 Vrancea's earthquake.

Key words: time history analysis; dynamic analysis; soil structure interaction; FE analysis; wind turbines.

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1. Introduction

The new tendency of sustainability requires that all unconventional sources of energy should be exploited. Therefore all around the world new techniques of achieving energy are developed. Wind power technology is a mature renewable energy technology, and it attracts many researchers' attention around the world. The construction of wind turbines is accelerating in the last decade all over Europe, as well as in Romania. This growth of wind turbines construction has revealed some design and building difficulties because care need to be taken when dealing with some particularities of these structures.

As the modern wind turbine generator's single-machine capacity becomes bigger and bigger, the distance from the earth becomes higher and higher, the working environment is moved from land to sea, from inactive areas to earthquake zones (Burton *et al*., 2001). In order to avoid failure and to stand up unexpected accidents, such as earthquake, waves, current, ice and snow, the design of the tower should be explored thoroughly. In the research process of the tower the main aspect studied is the tower's ability to resist the wind, but a very important subject is the seismic performance of the tower, mainly in seismic areas. The dynamic responses of a tower to seismic excitations and seismic loads must be investigated and considered in the structure design.

Studies have revealed that when soil stiffness is taken into account in analyses the natural frequencies of the structures differ (usually are smaller) from the case when a rigid base is considered (Olariu, 2012). Therefore in order to choose the best design solutions as to avoid structural damage it is necessary to consider soil - structure interaction.

This paper uses the finite element method to analyse the seismic time history of a 70 m wind turbine in order to determine the displacement curve over time and the stress state of the tower at each time.

2. Theoretical Background

Vrancea region from Romania is the main epicenter of the Eastern Europe. The seismic activity is governed by the three tectonic plates which are intersecting in the Vrancea area.

Depending of the nature of the terrestrial crust and of the depth, the Vrancea earthquakes influence the eastern half of Romania. In the last century, Romania has witnessed four earthquakes of magnitudes in the epicenter higher than 7 degrees on the Richter scale: in 1908 an earthquake with a magnitude of 7.1, in 1940 of 7.7, in 1977 of 7.5 and in 1986 of 7.2 on Richter scale. One of the most significant events for Romania from the effects point of view was the

1977 earthquake. Therefore, the 1977 Vrancea's earthquake accelerogram is used in most of the research studies (Fig. 1).

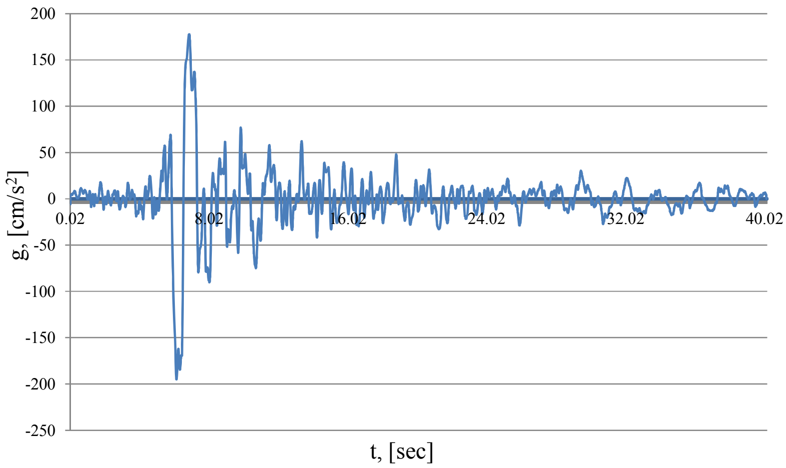

Fig. 1 – 1977 Vrancea earthquake accelerogram.

Linear response history analysis, known as time history analysis, is a numerical technique in which the response of a structural model to a specific earthquake ground motion accelerogram is determined through a process of a numerical integration of the eqs. of motion (Fema 450, 2003).

In comparison to the conventional methods, such as response spectrum or modal analysis method, time history analysis is not frequently used because of the lack of knowledge and availability of the actual ground motion data. The main advantages of the time history analysis is that it provides a time dependent history of the response of the structure to a specific ground motion. Based on the history response path dependent effects such as damping can be computed. On the other hand this method provides information about the stress and deformation state of the structure throughout the period of response (Mehta *et al*., 2008).

The analysis is carried out for each incremental time interval and at each stage structural response is evaluated. The method consists of a step by step direct integration in which time domain is discretized into a number of small increments, δt, and for each time interval the eqs. of motion are solved with the displacements and velocities of the previous step serving as initial values. Integration of this time acceleration history gives velocity history, integration of which in turn gives displacement history.

In this method of dynamic analysis, instead of going through a process of determining response spectrum for a given ground motion and then applying the results to a given structure, it is possible by using computers to apply the earthquake motion directly to the base of a given structure.

3. Case Study

3.1. Finite Element Modeling

The attention of this study is focused on evaluating the response of a wind turbine's tower considering the effects of soils in comparison to a fixed base assumption.

Four different types of supports were considered, namely: a rigid base and three soils modeled through springs. Based on previous research (Olariu, 2012) the three types of soils correspond to different classes of soil from the SR EN 1998-1:2004 standard (SR EN 1998-1:2004).

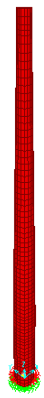

Fig. 2 – Wind turbine's tower model with stiffness springs at the base.

For analysis a 70 m tall steel wind turbine was considered having a circular foundation with a 16 m diameter and a 3 m depth. The steel tower was modeled through 'shell' finite elements having variable diameter and thickness along the height of the tower (Fig. 2). The rotor and the blades were modeled as a concentrated mass at the top of the tower.

The types of soils considered were characterized through elastic compression coefficients, denoted with c_z. The spring stiffness's were computed for translational displacement, namely k_x, k_y and k_z, and for rotational displacement on the x and y direction, $k_{\theta x}$ and $k_{\theta y}$ and, finally, for torsion, k_t. due to the symmetry some of the stiffness are equal.

Table 1 presents the values of the spring stiffness's used for modeling the three elastic supports.

Table 1
Spring Stiffness's Used for Elastic Base Modeling

Type of the support	k_x , k_y N/m	k_z N/m	$k_{\theta x}$, $k_{\theta y}$ N.m/rad	k_t N.m/rad
Support 1	70,371 × 10^4	100,530 × 10^4	3.2 × 10^{10}	2.412 × 10^{10}
Support 2	12,031 × 10^5	171,873 × 10^4	5.5 × 10^{10}	4.125 × 10^{10}
Support 3	70,371 × 10^5	100,531 × 10^6	32 × 10^{10}	2.412 × 10^{11}

3.2. Dynamic Simulations and FE Analysis

The methodology used for dynamic simulations considered two computational analysis cases. Modal analysis procedure was applied in order to evaluate the dynamic characteristics, the Eigen Frequencies and the Mode Shapes. The second method consisted of a Time History Analysis, applying as input data the recorded accelerations in Bucharest during the 1977 Vrancea Earthquake.

All the simulations have been conducted within the finite element software environment of SAP 2000, *vs*.14.2.3.

3.3. Processing of FEA Results

For the Modal Analysis procedure in free vibration, a number of over 90 modes of vibrations have been analysed, in order to ensure a mass participation factor of 91% upon both directions of axes. Table 2 presents only the results for the first four modes of vibrations, for which the mass participation factors exceeded the percentage of 70%.

Table 2
Periods of Vibration of the Wind Turbine Model

Mode of vibration	Period of vibration, [s]			
	Support 1	Support 2	Support 3	Rigid
1st Mode	1.979664	1.956103	1.905554	1.8968
2nd Mode	1.979661	1.9561	1.905552	1.896794
3rd Mode	0.548694	0.551888	0.548641	0.548635
4th Mode	0.325831	0.317628	0.306305	0.303809

The results of the modal analysis are showing an increase of flexibility for the models with elastic supports, due to the different types of soil conditions considered in comparison to the rigid situation. Accurate modal analysis results are highly important in designing wind turbine’s towers in order to ensure a proper stability and avoid failure during operation. Therefore, for precise results it is needed to consider the soil–structure interaction.

In order to understand the importance of the effect of soil structure interaction on the seismic response of a wind turbine’s tower a seismic analysis was performed considering the Time History Analysis procedure considering as input loading the 1977’ Vrancea earthquake acceleration record, presented in Fig. 3. The details of the input data of the seismic action are presented in Table 3.

Table 3
Input Data of the 1977's Vrancea Earthquake

Earthquake excitation	Peak acceleration cm/s^2	Total duration s	No. of points	Spaced interval	Damping %
March 4th 1977	194.927 cm/s^2 at 6.120 s	40.140	2008	0.02	5

Numerical simulations based on Time – History Analysis revealed also interesting results in terms of displacements and accelerations, computed for the four support cases. Based on the results, graphs were performed to compare the response in displacements at the top of the steel tower. The program Sap 2000 provides output data referring to displacements at any joint. Therefore it was chosen a joint at the top level of the tower. In Figs. 3,…,6 the displacements *versus* time plots on the X-direction for each of the studied cases are presented.

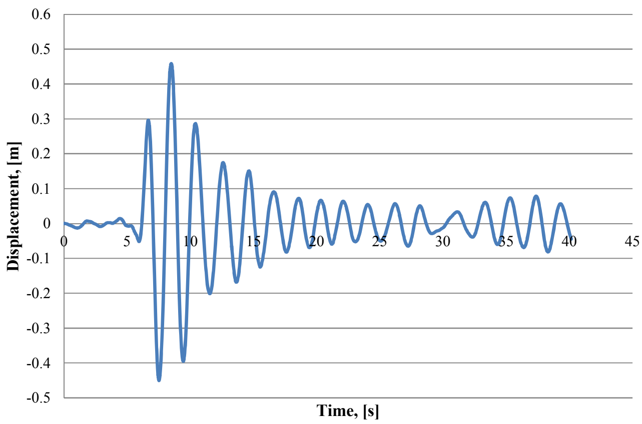

Fig. 3 – Displacement plot on the X-direction for Support 1.

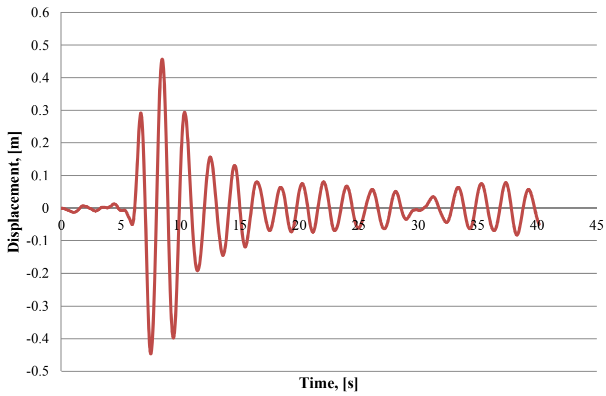

Fig. 4 – Displacement plot on the X-direction for Support 2.

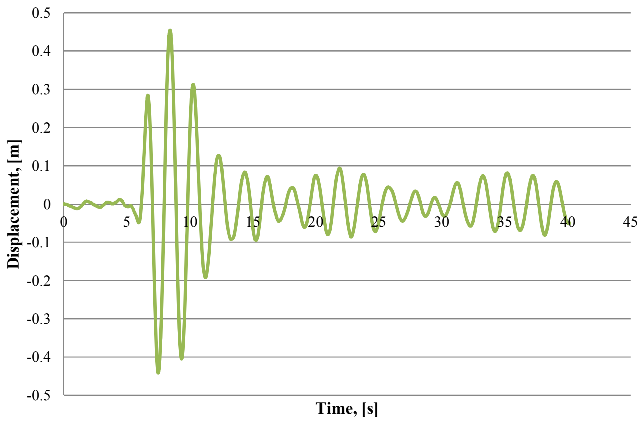

Fig. 5 – Displacement plot on the *X*-direction for Support 3.

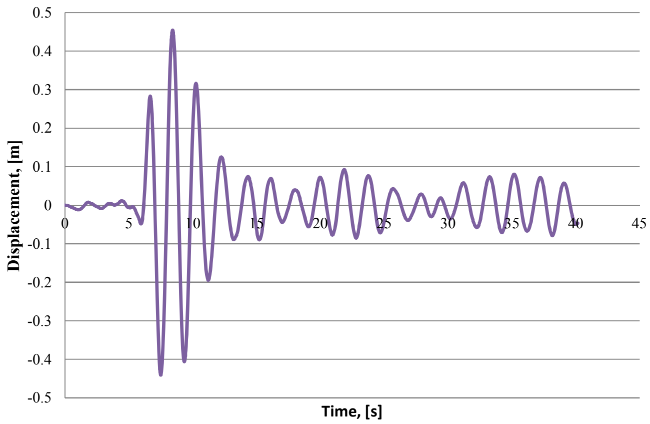

Fig. 6 – Displacement plot on the *X*-direction for Rigid Support.

Processing the results of Time – History Analysis for 1977 Vrancea Earthquake accelerations the maximum values of displacements obtained at top level of the tower were selected. In Table 4 the maximum and minimum response in displacements for all the studied cases are presented.

Table 4

Minimum-Maximum Displacement Responses at the Top of the Tower

Response	Time, [s]	Displacement, [m]			
		Support 1	Support 2	Support 3	Rigid Support
Minimum	7.5	–0.44841	–0.44593	–0.4418067	–0.44055
Maximum	8.42	0.45633	0.45988	0.454366	0.45396

From the displacement responses it can be observe that the minimum and the maximum responses for all the studied cases occur at the same time. Also a similarity between the Rigid Support and Support 3 is noticed, but this was expected due to the soil properties used for modeling the Support 3 which corresponds to a class A soil type according to the SR EN 1998-1:2004 standard. Furthermore from the displacement results it is noticed that the minimum displacements occur for the Rigid Support and Support 3, while the maximum displacements are recorded for Support 2 and Support 1 which correspond to soil classes B and C, according to the SR EN 1998-1:2004 standard. The maximum percentage difference between the responses for all the cases reaches 2%. Nevertheless this emphasize that the responses to a seismic input of a wind turbine are influenced by the type of foundation soil considered.

Besides displacements, also accelerations were obtained in terms of response spectrum. Fig. 7 presents a comparison between the response spectrums for all cases.

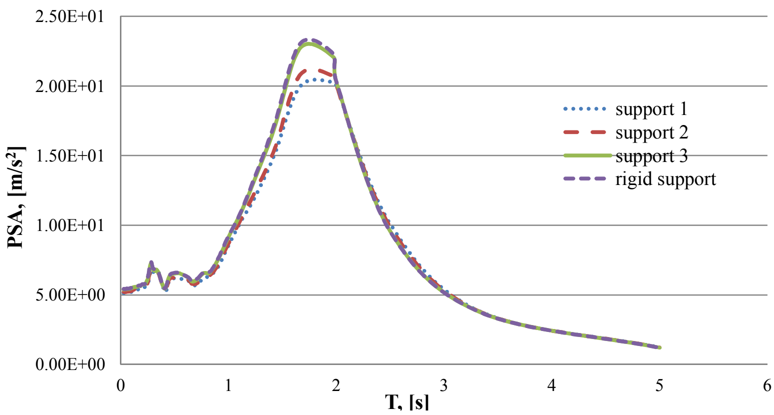

Fig.7 – Response spectrum comparison.

From the spectrum responses comparison it can be noticed that the maximum accelerations at the top of the tower are recorded for Rigid Support and Support 3 cases and the minimum accelerations for the other two cases. An inverse correspondence between the displacement and acceleration responses is identified; as the displacement is lower the acceleration is higher.

4. Conclusions

The dynamic simulations of a wind turbine's tower for different support cases from flexible to rigid base results have shown the importance of soils structure interaction. The modal analyses have revealed that the natural modes of vibration and the periods of vibration for the entire soil–foundation–wind turbine system are different for the flexible base cases than from the rigid support case. By considering soil stiffness the entire system has larger periods of vibration than considering the structure with a fixed base. Soil flexibility decreases stiffness and increases natural period of the tower for all modes of vibration. The Time History Analysis results showed that soils flexibility interferes with the displacement and acceleration responses. Smaller displacements are recorded for a rigid base situation than for flexible ones which can be misleading in terms of safety requirements. By considering a rigid support can significantly affect the performance of the wind turbine during earthquakes which can lead to devastating effects. Therefore considering soil–structure interaction in analysing a wind turbine plays an essential role in design and use of the wind turbine.

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ANALIZĂ „TIME HITORY" A UNEI TUBINE EOLIENE

(Rezumat)

Datorită cerinţelor de dezvoltare durabilă la nivel mondial a fost necesară exploatarea unor surse de energie neconvenţională. Astfel, construirea turbinelor eoliene a luat o amploare considerabilă în ultimul deceniu. Acest lucru a ridicat probleme de concepţie şi de execuţie, în special în zonele active din punct de vedere seismic. Romania este situată într-o zonă activă din punct de vedere seismic având regiunea Vrancea, epicentrul cutremurelor din Europa de Est. Astfel, este necesar în analiza turnurilor turbinelor eoliene, să se considere şi acţiunea seismică pe lângă acţiunea vântului. Cunoaşterea modurilor de vibraţie a structurii este o metodă de evaluare a răspunsului structural sub acţiuni dinamice. De asemenea, spectrele de răspuns obţinute în urma unei analize de tip „Time History" oferă o imagine clară asupra comportării structurale. Pentru luarea în considerarea a interacţiunii teren de fundare–fundaţie s-a

utilizat metoda substructurilor considerând resorturi de rigiditate. În această lucrare sunt prezentate rezultatele unei analize de tip „Time History” pe o turbină eoliană având aproximativ 70 m considerând patru tipuri de reazeme diferite. Scopul acestor analize constă în evaluarea răspunsului maxim ale acestor tipuri de structuri sub acţiunea cutremurului din 1977 din Vrancea.