BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 63 (67), Numărul 3, 2017
Secția
CONSTRUCȚII. ARHITECTURĂ

SEISMIC SAFETY EVALUATION OF WIND TURBINE BEHAVIOR DURING OPERATIONAL LIFETIME CYCLE

BY

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Received: July 28, 2017
Accepted for publication: August 31, 2017

Abstract. The fast increasing of wind turbine construction came with some particular design rules and construction technological problems, especially in seismic areas. Thus, seismic action must be considered apart from wind actions when it comes to wind turbine design and construction in the prone seismic area. Also, the foundation soil conditions have to be taken into account for wind turbines design for avoiding resonance, as they directly affect the dynamic characteristics of the tower. The present paper aims to assess the effects of soils structure interaction upon a wind turbine tower, located in Iasi region, considering recorded accelerogram in situ of recent earthquakes from 1986, 1990 and 2000. The wind turbine of 70 meters height having 4 different types of soil support was subjected to Time History Analyses, as to have a better understanding of future behavior based on identification of possible maximum responses of this type of structures under the action of Vrancea's earthquakes.

Keywords: wind turbine; soil structure interaction; earthquake action; FE modeling; unconventional energy; soil conditions; time history analyses; wind turbine life cycle; resonance; foundation soil.

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1. Introduction

All over Europe an extensive exploitation of all un-conventional sources of energy is recorded. The accelerated development of technology all around the world developed new techniques of achieving energy. One of the main attractions for many researchers is the wind power technology.

The construction of wind turbines in Romania has increased during the last years. Building this class of energy structures came also with particular design rules and technological problems during in situ execution, especially in seismic areas. An extended caution should be taken when dealing with some particularities of wind turbines, especially in regions with high seismic hazard. Located at almost 200 km distance from Iasi city (Fig. 1), Vrancea epicenter from Romania is responsible for major tectonic earthquakes. In the past decades a series of earthquakes with magnitudes M, higher than 6 degrees on the Richter scale occurred in this region, namely: in 1977 with a magnitude of 7.4; in 1986 with a magnitude of 7.1, in 1990 with a magnitude of 6.7 and in 2000 with a magnitude of 6.0. All of these earthquakes were felt also in Iasi city in the North Eastern side of Romania. Also, according to researches performed in Romania for establishing the potential areas for placing wind turbines due to the speed velocities and hours per year of winds, Iasi region is located in a highly interested region (Fig. 2).

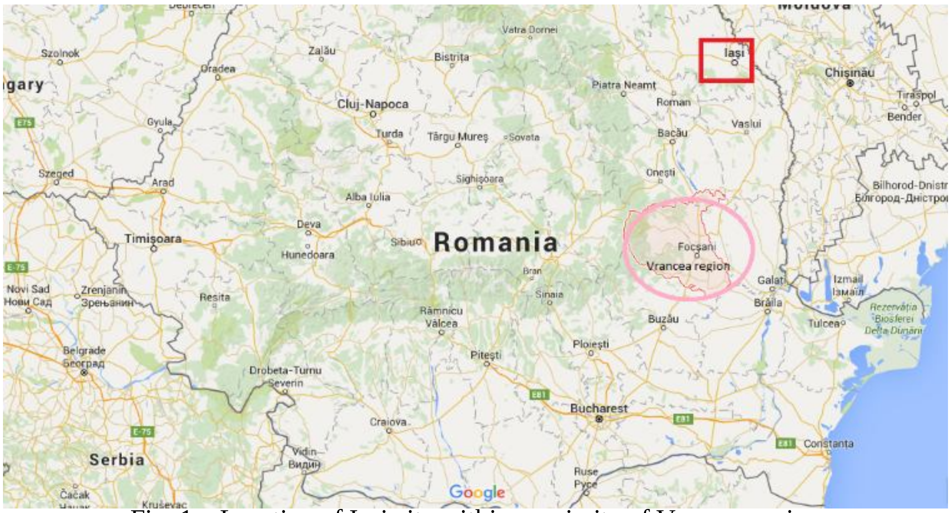


Fig. 1 – Location of Iasi city within proximity of Vrancea region (https://www.google.ro/maps/place/Vrancea+County/@46.1836777,25.6236664,7.19z/data=!4m2!3m1!1s0x40b42209fdcaefad:0xa8ba0287991a9703?hl=en)

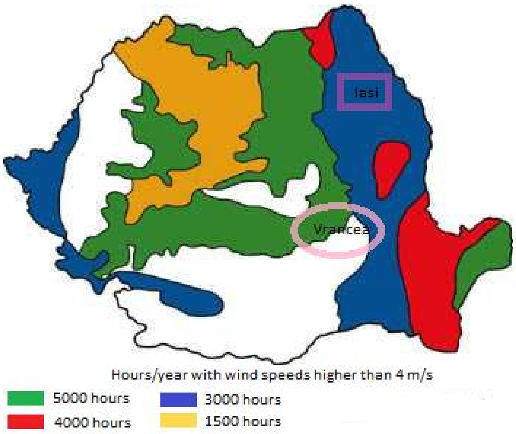


Fig. 2 – Location of Iasi city within the potential areas of wind turbines sites.

The innovations in construction techniques have led to a development of the modern times wind turbines with an increase of the distance on height from the earth, also being able to be moved from land to sea and built in seismic areas (Burton *et al*., 2001). The design of the tower should be treated with great attention in terms of avoiding failure and withstand accidental loading. Usually, the main focus of researchers is on the ability of the tower to resist the wind, but in earthquake regions a very important aspect is the seismic performance of the tower. Therefore, seismic actions must be investigated apart from wind actions when it comes to design and construction of wind turbine in the prone seismic area. Also, the main requirement in the international design codes is for wind turbines to be designed only for wind actions, but in countries with earthquakes it is necessary to consider also the seismic action (Hau, 2006).

Another aspect that should be considered when designing such structures is the foundation soil conditions as they directly affect the dynamic characteristics of the tower. This is due to avoiding resonance occurrence during the functioning of a wind turbine. In order to do this it is required to know and control the natural frequencies of vibrations of the tower that should not be in the range of operational frequencies of the turbine.

According to recent studies which consider soil conditions, smaller values of the natural frequencies are determined, compared to the cases when a fixed base of the tower was considered. Misleading results can outcome in the case of considering a fixed base for the tower’s structure, therefore soil - structure interaction should be considered for avoiding structural damage. (Olariu, 2013).

The knowledge of the natural characteristics of vibration of the structure can be used as an evaluation method for structural dynamic response. Also, the response spectrum can offer a better insight of the structural behavior.

Therefore, the Modal Analysis results of the structure, along with Time-History response considering the past recent earthquakes occurred in the construction site, is a relevant source of information in the attempt to evaluate the structural response during its life cycle. Based on these arguments, the present paper aims to assess the effects of soils structure interaction upon a wind turbine tower, located in Iasi region, an important hazardous region of Northeastern Romania, considering various earthquake actions typical for this situ.

This paper presents the results of a Time history analyses on a wind turbine having 70 m height, located in Iasi region considering 4 different types of supports conditions. For the Time History analyses some accelerogram of recent earthquakes recorded in Iasi situ from 1986, 1990 and 2000 have been applied. (INFP http://www.infp.ro/en/). The aim of this study is to have a better understanding of future behavior based on identification of possible maximum responses of wind turbines under Vrancea's earthquakes inputs. A comparison of the results from the FE analysis is performed in terms of maximum responses that may occur during the lifetime of a wind turbine located in Iasi region.

2. Theoretical Background of Wind Turbine Modeling

2.1. Design Particularities of Wind Turbine

The wind turbine's tower has to withstand operational vibrations on its entire life span. The frequencies produced by the operating rotor and blade-passing may increase the forces acting on the tower which can lead to insecure levels of structural safety. Apart from this, it is important to analyze the wind turbine tower for earthquake-induced accelerations, usually being enough to reduce the analysis in one horizontal direction, due to symmetry.

The usual support used for wind turbines are either slab or pile foundations. The soil conditions at the specific site is governing the choice. When the foundation soil has stiff properties a slab foundation is preferred, but when the foundation soil has softer qualities a pile supported foundation is used to transfer the loads to larger depths.

An important step for predicting the dynamic structural response to wind, wave and earthquake loading is computing of foundation stiffness, which is generally frequency dependent (Mohamed *et al.*, 2008).

Stiffness springs are common in modeling and analyzing soil structure interaction. As to represent the finite stiffness of the foundation soil a set of springs are used and they can be applied either in one or in several points of the structure. The types of foundation stiffness springs used in modelling are: k_z for vertical stiffness; k_x for horizontal stiffness; k_θ for rotational stiffness and k_t for torsional stiffness.

This article uses the following equations in order to compute the spring stiffness's considering: the bed coefficient of the foundation soil, c_x, c_θ and c_t; the aria of the foundation base, A_f; and the moment of inertia of the aria in relation with the horizontal rotational axis, I_f and the polar moment of inertia of the aria, I_z (Olariu *et al.*, 2014):

$$c_x = 0.7c_z; \quad c_\theta = 2c_z; \quad c_t = 1.5c_z; \tag{1}$$

$$k_z = c_z A_f; \quad k_\theta = c_\theta I_f; \quad k_x = c_x A_f; \quad k_t = c_t I_z. \tag{2}$$

2.2. Time History Analyses

Vrancea region in Romania, the main origin of earthquakes is governed by the intersection of three tectonic plates and hence the presence of seismic actions.

In this study, four accelerogram recorded in N-E Romania, respectively Iasi region were used. They are recorded for the following earthquakes: 1986 with 7.1 Magnitude; 30th of May 1990 – M = 6.7; 31st of May 1990 – M = 6.1 and 2000 – M = 6.0. The recoded accelerogram are on the NS longitudinal direction. Figs 3,…,7 are illustrating Time-History recorded accelerogram for the previous recorded earthquakes in Iaşi region.

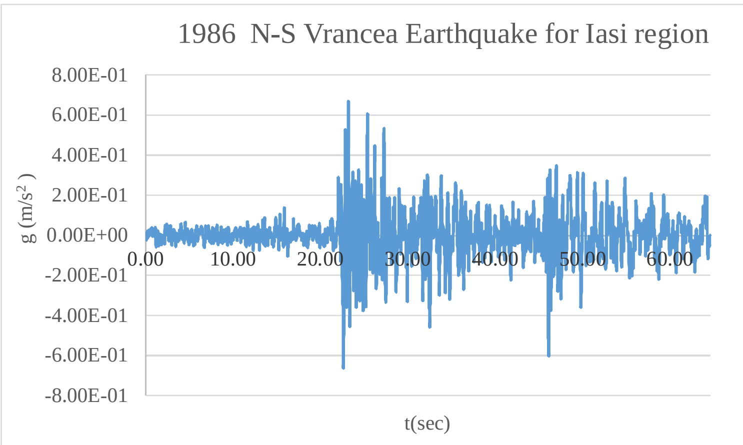


Fig. 3 – N-S 1986 Vrancea's earthquake, Iaşi region record.

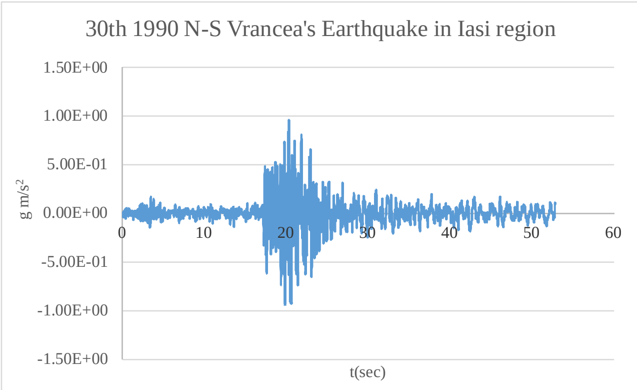


Fig. 4 – The N-S 30th of May 1990 Vrancea's earthquake, Iaşi region record.

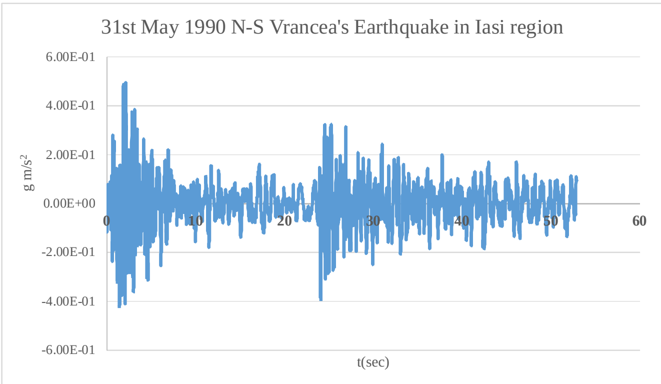


Fig. 5 – N-S 31st of May 1990 Vrancea's earthquake, Iaşi region record.

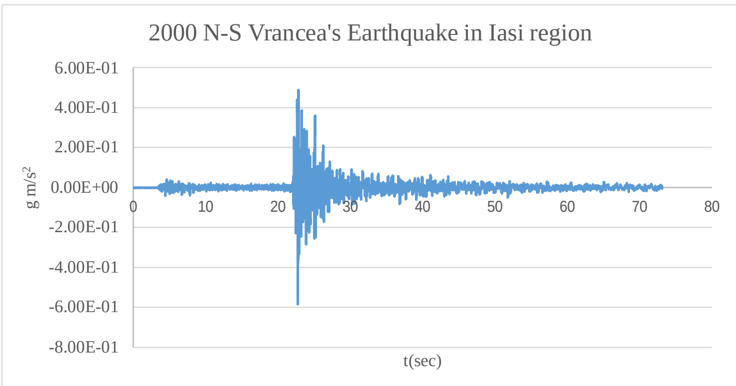


Fig. 6 – 2000 Vrancea's earthquake, Iaşi region record.

Due to the lack of knowledge of actual ground motion data inputs, Time History Analyses are not frequently applied although it provides a time dependent history of responses of the structure to that specific ground motion input (Fema 450, 2003). A detailed information about the stress and deformation state of the structure throughout the period of response is provided through this method (Doris Mehta *et al.*, 2008).

In this dynamic analysis method is possible by using finite element software environments to apply the earthquake motion directly at the base of the structure.

The seismic actions details of input data used in this study are presented in Table 1.

Table 1
Vrancea's Earthquakes Accelerogram (http://www.infp.ro)

Earthquake	Peak acceleration m/s^2	Total duration sec	No. of points	Spaced interval	Damping %
1986	6.69E-01	64.59	6460	0.01	5
30^{th} May 1990	9.58E-01	52.9	5290	0.01	5
31^{st} May 1990	4.96E-01	52.9	5290	0.01	5
2000	5.82E-01	73.1	7310	0.01	5

3. Finite Element Modeling of the Wind Turbine

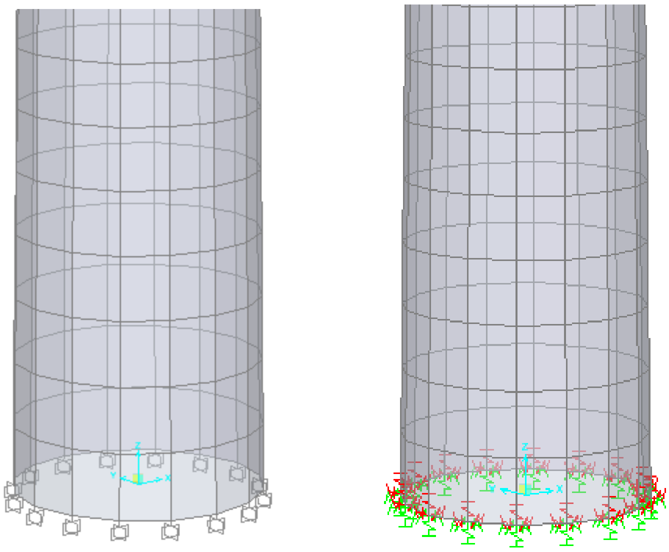
A particular case of a wind turbine, of 70 m height, located in Iasi region was chosen to highlight the importance of taking into account soil - structure interaction in a seismic analysis for these types of structures. FE simulations were carried out including seismic analysis within elastic linear domain using SAP 2000, vs.6 finite element computational environment (SAP 2000, 2010).

The tower model of the wind turbine has 1200 'shell' finite elements with different diameters and thickness on the height. The tower was made of steel with a tubular shape and the diameters are between 4.2 m at the base reaching 1.85m at the top. In table 2 the materials and masses of the model are presented.

Table 2
Material Properties and Masses used for the Model

Tower mass weight [tones]	Rotor and blades mass [tones]	Material type	Young modulus $[N/m^2]$
85.15	47	S355	2.1E+11

Fig. 7 is presenting details of the support of the wind turbine tower supports.



a b

Fig. 7 – Modeling details of the wind turbine tower, connection at foundation level: *a* – Rigid base; *b* – flexible base.

Four situations were considered for modelling the foundations soil stiffness, namely a fixed base and 3 flexible base modeled through springs. Table 3 is presenting the types of soils considered.

Table 3

Flexible Base Models Soil Characteristics

Soil type	Elastic compression coefficients, c_z N/m^3	Model name
Loose and clayey sands, clay and sandy clays	5E+06	FLEX1
Gravel, sand and clayey sand, clay and sandy clay	8.5E+06	FLEX2
Gravel, sand and clayey sand, clay and sandy clay plastic stiff	5E+07	FLEX3

The values of the spring stiffness's for translational displacement, (K_x, K_y, K_z), rotational displacement ($K_{\theta x}$, $K_{\theta y}$) and torsion (K_t) used for modeling the 3 elastic supports are presented in table 4. Because of the symmetry of the model the values of the stiffness's on the horizontal direction are equal on both X and Y axis, as well as for the rotational ones (Olariu *et al*., 2016).

Table 4
Characteristics of Elastic Springs in FLEX Models

Model	Stiffness			
	$K_{x,y}$ N/m	K_z N/m	$K_{\theta x,\theta y}$ Nm/rad	K_t Nm/rad
FLEX1	7.037E+08	10.053E+08	3.2 E+10	2.41E+10
FLEX2	1.203E+09	1.7187E+09	5.5E+10	4.12E+10
FLEX3	7.0371E+09	10.053E+10	32E+10	24.12E+10

For RIGID base model the support conditions were considered to be fixed as there are provided by the FE software.

Two computational analysis cases were considered, namely modal analyses to compute the dynamic characteristics and Time-History analyses using as inputs the recorded accelerogram presented in Figs. 5,…,9. All four cases were subjected to these analyses considering the soil structure interaction effects.

4. FE Analysis Results

For the Modal Analysis, 90 modes of vibrations have been analyzed, as to ensure a 91% mass participation factor on both horizontal axes. The results of the first four modes of vibrations are presented in Table 5.

Table 5
Periods of vibration of the wind turbine models

FE models	Period of vibration, [s]			
	1st Mode	2ndMode	3rd Mode	4th Mode
FLEX1	1.979664	1.979661	0.548694	0.325831
FLEX2	1.956103	1.9561	0.551888	0.317628
FLEX3	1.905554	1.905552	0.548641	0.306305
RIGID	1.8968	1.896794	0.548635	0.303809

From the results of the Modal Analysis is noticed an increase of flexibility for the models with elastic supports compared to the rigid case. For ensuring a proper stability and avoiding failure during operating, accurate modal analysis results are highly important. Therefore, for increased quality of results values the influence of soil flexibility needs to be considered.

The Time-History analyses considering the 4 earthquakes as inputs outputted displacements and accelerations responses, computed for all 4 models. Based on these results, some comparison graphs were plotted for the response in displacements recorded at the same joint at the top level of the tower for the 1986, 30th May 1990's, 31st May 1990's and 2000's Vrancea Earthquake Time- History analyses.

The first input for the models was the 1986's Vrancea earthquake accelerations.

Due to the symmetry of the structural model on *X* and *Y* directions, relevant for this case study was to analyze only the responses on the *OX* axis.

Processing the results of the first Time-History Analysis in case of 1986's Vrancea Earthquake accelerations recorded in Iasi region, the maximum values of displacements obtained at the joint on the top level of the tower were selected.

Table 6 presents the extreme responses in displacements at the top of the tower, for all four studied models in case of 1986 Vrancea earthquake input.

Table 6

Maximum and Minimum Displacements' Response, 1986's Vrancea Earthquake Input

FE models	Displacement m	Time step s	Displacement m	Time step s
	minimum		maximum	
Rigid	–0.04404	29.85	0.04381	27.02
FLEX1	–0.04895	35.87	0.05244	27.1
FLEX2	–0.04824	35.83	0.05018	27.06
FLEX3	–0.04411	29.85	0.04392	27.02

Based on these a comparison plot was created to better highlight the soil conditions upon the top level displacements. Fig. 8 is presenting the graphical representation of the maximum and minimum responses for each of the studied models.

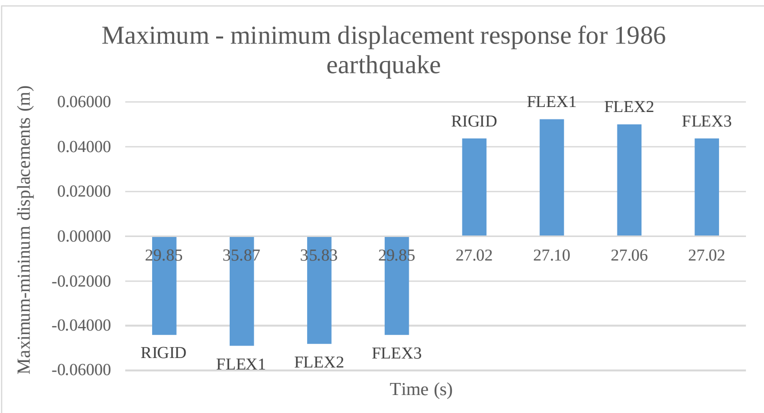


Fig. 8 – Comparison of maximum/minimum displacements' response at the tower's top level.

From the maximum-minimum responses plot, it can be noticed that the maximum displacements are produced in FLEX1 model and the minimum ones are for the RIGID model. Also, the times of recording the maximum/minimum values are identical for case model FLEX3 and RIGID model case, which highlights that there is a similarity of behaviour between a fixed support modeled through RIGID and FLEX3 model with consideration of the soil conditions. Also the maximum response has been obtained for the FLEX 2 model.

The Time-History Analysis has been using the accelerations recorded, in Iasi region during the 30th May 1990 Vrancea earthquake. The maximum values of displacements obtained at the top level of the tower, for the same joint as in previous analysis, were selected, being illustrated in Table 7.

Table 7

Maximum and Minimum Displacements' Response, 1990's Vrancea Earthquake Input

FE models	Displacement m	Time step s	Displacement m	Time step s
	minimum		maximum	
Rigid	–0.03389	33	0.03335	52.26
FLEX1	–0.03146	33.08	0.02757	32.27
FLEX2	–0.03268	33.06	0.02777	22.7
FLEX3	–0.03392	33	0.03327	52.26

Based on these responses for 30th May 1990' Vrancea earthquake input a plot was created for comparing the soil conditions influence upon the top level displacements. Fig. 9 is presenting the graphical representation of the maximum and minimum responses for each of the studied models.

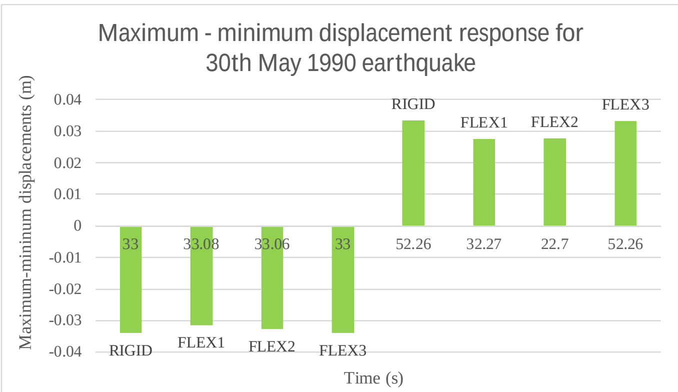


Fig. 9 – Comparison of maximum/minimum displacements response at the tower's top level.

Identifying the displacement responses, it can be noticed that the extreme responses for RIGID and FLEX3 cases occur at the same time which can be due to the soil properties used for modeling the FLEX3 supports which are similar to rigid base. According to SR EN 1998-1:2004 standard, FLEX3 soil conditions correspond to class A soil type. Also the maximum response was recorded for FLEX3 situation which is an exception as it should have behaved as a rigid foundation soil. A similarity in the responses for FLEX 2 and FLEX1.

The third Time-History Analysis was for 31st May 1990 Vrancea Earthquake accelerations recorded in Iasi region. The extreme values of displacements obtained at the top level of the tower for the same joint as in previous analysis were selected.

Table 8 is presenting the maximum and minimum response in displacements for all the studied models in case of 31st May 1990 Vrancea's earthquake input.

Table 8

Maximum and Minimum Displacements' Response, 31st May 1990's Vrancea Earthquake Input

FE models	Displacement m	Time step s	Displacement m	Time step s
	minimum		maximum	
Rigid	–0.033	47.62	0.033470	52.26
FLEX1	–0.03018	33.06	0.02749	46.85
FLEX2	–0.0305	33.04	0.02784	46.82
FLEX3	–0.03294	47.62	0.0334	52.26

A plot illustrating the comparison of these responses in case of 31st May 1990 earthquake input has been done and representing in Fig. 10 the maximum and minimum responses at the top level of the tower.

It can been identified that similar values, presented in Fig. 12 were recorded for the RIGID model as well as for the FLEX 3 model, which can lead to the conclusion that under this type of accelerations the fixed supports behaviour is optimum. Also the maximum/minimum response in displacements obtained for FLEX2 model and FLEX1 model are similar as it was observed in the other cases.

The fourth Time-History Analysis was executed using the accelerations recorded in Iasi region for 2000' Vrancea earthquake. The maximum values of displacements obtained at the top level of the tower for the same joint as in previous analysis were selected. Table 9 presents the maximum/minimum response in displacements for all the studied models in case of 1990 Vrancea's earthquake input.

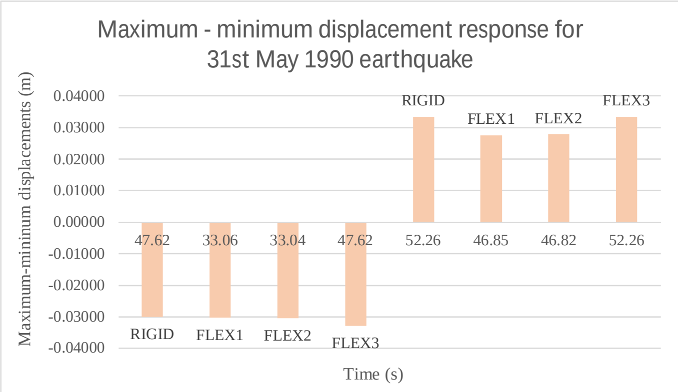


Fig. 10 – Comparison of maximum/minimum displacements response at tower's top level.

Table 8

Maximum and Minimum Displacements' Response, 2000's Vrancea Earthquake Input

FE models	Displacement m	Time step s	Displacement m	Time step s
	minimum		maximum	
Rigid	–0.0066	25.94	0.0062	26.79
FLEX1	–0.00633	25.99	0.00613	25.04
FLEX2	–0.00649	25.98	0.00600	25.04
FLEX3	–0.0066	25.94	0.00619	26.80

For this case, a comparison of the maximum versus minimum displacements responses was performed. Fig. 11 is presenting this comparison of the results recorded at the top level of the tower.

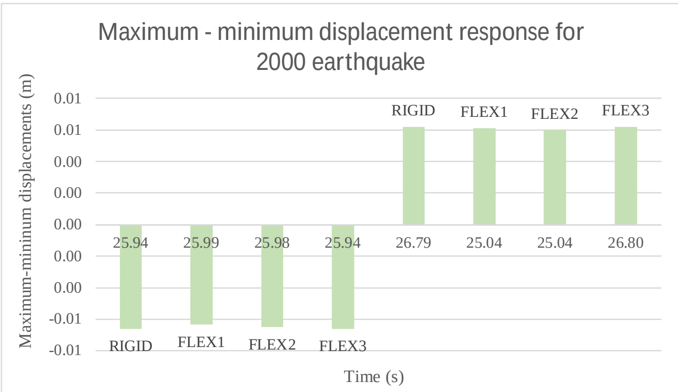


Fig. 11 – Comparison of maximum/minimum displacements response at the tower's top level.

The last comparison of the responses reveals a similarity of the displacement responses of RIGID and FLEX3 models and FLEX2 versus FLEX 1 model. The differences are less than 3% for each case.

For the 1986' earthquake input accelerations it is observed that the minimum displacements occur in case of the Rigid model and FLEX3 model, while the maximum displacements are recorded for FLEX1 and FLEX2 models which correspond to soil classes C and B, according to the SR EN 1998-1:2004 standard.

For the other cases, the situation is reversed, namely the FLEX2 and FLEX3 models have smaller displacements but the maximum percentage difference between the responses for all the cases varies from 2 to 18 %. Nevertheless, this emphasize that the seismic responses of a wind turbine are depending on foundation soil type especially and the input seismic action characteristics.

Accelerations were obtained in terms of response spectrum for all four case studies.

Figs. 12,…,15 presents a comparison of Response Spectra using the four models, exposed to all Vrancea's Earthquake inputs.

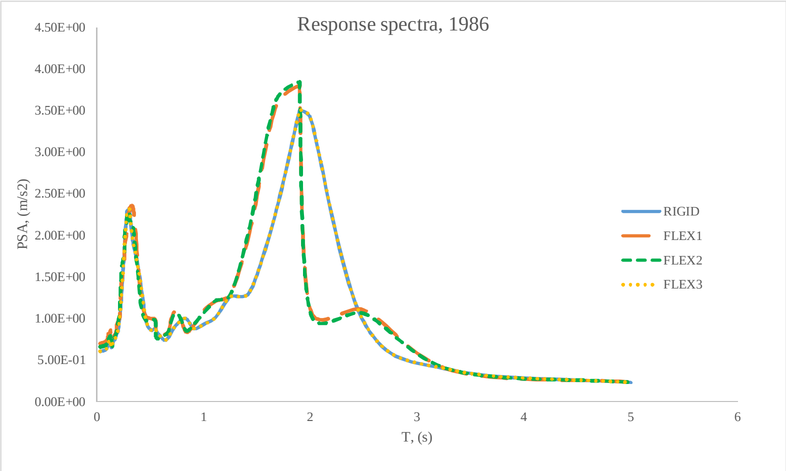


Fig. 12 – Comparison of models Response Spectra, 1986 Vrancea's input.

The response spectra comparison revealed that the maximum accelerations at the top of the tower are for in case of using RIGID and FLEX3 models. The minimum responses are encountered for the other two models. Also the similarities in responses in case of the RIGID and FLEX 3models have been identified also in terms of accelerations.

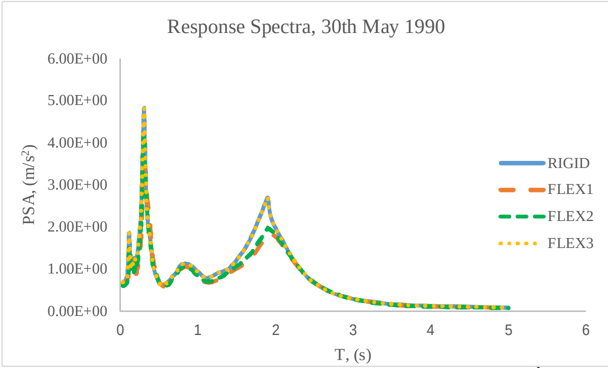


Fig. 13 – Comparison of models Response Spectra, 30th May 1990 Vrancea's input.

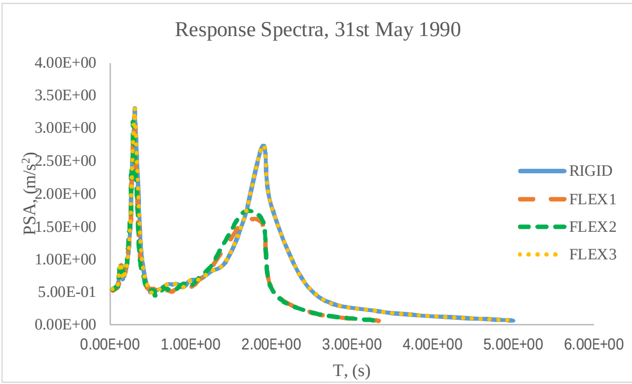


Fig. 14 – Comparison of models Response Spectra, 31st May 1990 Vrancea's input.

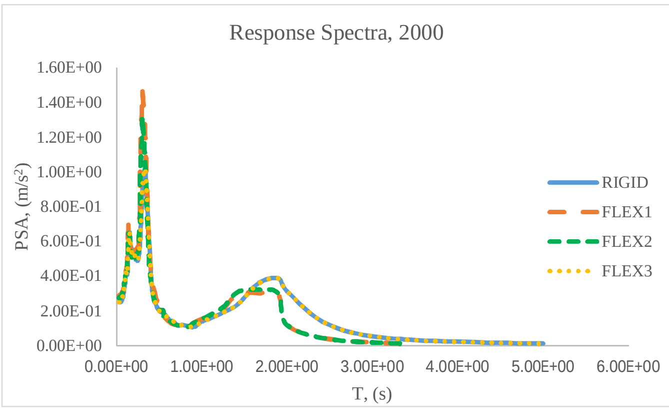


Fig. 15 – Comparison of models Response Spectra, 2000 Vrancea's earthquake input.

5. Conclusions

The seismic simulations of a wind turbine tower with different support models from flexible to rigid, have highlighted, once again, the importance of considering soil-structure interaction in the analysis of wind turbines, especially for particular high hazardous seismic sites.

The Modal Analyses results showed that the dynamic characteristics of the soil-foundation-wind turbine system have different values depending on the connections of the model to the soil, flexible versus rigid. By considering soil stiffness, larger periods of vibration are recorded than when a fixed base is modeled. Therefore, the overall stiffness is decreased by soil flexibility and the natural period of vibration increases for all modes of vibration.

The Time History Analyses results illustrated that the displacement and acceleration responses are influenced by soils flexibility. Usually, smaller displacements are recorded in case of a rigid base model compared to flexible ones which can lead unsafe situations. When considering a rigid support, the performance of the wind turbine during seismic actions can be significantly affected, having potential of high devastating effects. Therefore, soil structure interaction applied in analyzing a wind turbine plays an essential role in design and life-time cycle of structural functioning.

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EVALUAREA SIGURANȚEI SEISMICE A UNEIE TURBINE EOLIENE

(Rezumat)

Dezvoltarea accentuată a construcției turbinelor eoliene a ridicat probleme specifice de proiectare precum şi de execuție, in special in zonele active seismic. Astfel, în procesul de proiectare şi construcție a turbinelor eoliene in zonele active seismic trebuie considerat pe lângă acțiunea vântului şi influența acțiunii seismice. De asemenea, condițiile de fundare trebuie considerate pentru a evita intrarea în rezonanță. Acest articol evaluează efectele interacțiunii teren de fundare fundație structură în cazul unei turbine eoliene amplasată în Iaşi pe care sunt aplicate accelerograme ale cutremurelor din anii 1986, 1990 şi 2000. Înălțimea turbinei eoliene este de 70 de metri şi s-au folosit 4 tipuri de rezemare. Analize de tip Time History au fost realizate pentru a avea o vedere de ansamblu a comportării acestor tipuri de structuri la acțiuni seismice.