

Effect of the Dynamic Soil -Structure Interaction on Rigid Transmission Line Towers Subjected to Wind and Impulse Loads

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ABSTRACT

Transmission lines (TL) towers are traditionally analyzed assuming fixed base. However, this assumption is questionable as foundation is not rigid in most cases. In other fields, such as seismic engineering, it has been reported in the past that the foundation stiffness and damping affects the structural behavior while in interaction with the structure specifically under dynamic loads. In this paper, the soil-structure interaction (SSI) effect on transmission line (TL) behavior is studied. The soil is replaced by foundation impedance, a set of frequency dependent spring and dashpot. For this purpose, a parametric study on a simplified case is presented for two types of dynamic loads: wind load and impulse load supposed to represent the effect of the shock wake following the breakage of a conductor of ground wire. To complement this parametric study, a real case is used in the analysis. The behaviour of the foundation is determined with software FLAC with its foundation impedance. Two types of soil are used in the analysis: (i) cohesive soil; (ii) granular soil. The paper confirms that foundations can modify structural behaviour significantly.

Introduction

Transmission line (TL) structures are typically modeled with the assumption of fixed base, disregarding the flexibility of foundations. This assumption is questionable as soil-structure interaction (SSI) is important in other fields of structural engineering (Roesset 1980) such as seismic engineering (Gazetas and Mylonakis 1998) and generally in case of dynamic loadings. As TL structures are designed to sustain dynamic loads such as wind load (Ronaldo et al. 2003) and loads resulting from a conductor that breaks (McClure and Lapointe 2003). Both loads are dynamic in nature. Nevertheless, structural design of TL is typically performed with static loads calculated and calibrated to be equivalent to the actual dynamic load. In the analysis, TL towers are supposed fixed on infinitely stiff foundations. However, many practitioners have questioned this assumption (Warburton 1978) as soil-structure interaction (SSI) has a significant

importance in other structural engineering fields (Roy et al. 2002) such as seismic engineering (Mylonakis and Gazetas 2000). The objective of this paper is to quantify the effect of SSI with a parametric study on a simplified structure by varying idealistic soil conditions and on the case of a low voltage TL lattice tower with two type of soil foundation. To evaluate this effect, full dynamic transient analysis needs to be performed. In order to evaluate the effect of SSI, a tower is simplified and foundation stiffness and damping are varied. The structure and foundations are then subjected to wind loadings and impulse load. The results are evaluated to investigate the effect of modeling foundation in the analysis. In this parametric study, foundation impedance is varied over a wide range to obtain a sensitivity of the parameter studied. To reinforce the results of this parametric study, a real tower with granular and coherent soil foundation is studied.

Presentation of the Parametric Study

The simplified structure modeled with the software ADINA (ADINA 2004) and shown in Figure 1a is used in the parametric study. The two members of the structure are connected at the top and all loads are applied at the top. The two members are therefore subjected mainly to axial forces as it would be in a real tower. The axial cross section of the members is 0.001m^2 . The structure is 10m height modeled using 2-node beam elements. The beams are weightless. The modulus of elasticity of the material used is 200000 MPa. The main members are divided into 20 beams. At the top a structure, a concentrated mass of 395 Kg is added so as the structure has a frequency of 10 Hz with rigid base. This value is typical of latticed towers. The structure is supported by two footings of 2m width. The distance between the bases is equal to 4m. To model the foundation, vertical and horizontal impedances are added at the two bases of the structure (see Fig 1b). The soil stiffness is varied from 500 kN/m to $5 \cdot 10^5$ kN/m corresponding to system frequency from 0.5 to 9.85 Hz. Three values of soil damping C were considered ($C=100, 500$ and 1000 kNs/m).

Applied Loadings

The loadings used are wind and impulse load. For the wind loading, time series of wind speed at the top of the structure are generated by the software Windgen (Hang et al. 2005). The wind time series are compliant with the power spectral density proposed by Simiu and Scanlan (2003) for three intensities of turbulence, 10, 15 and 18%. As well, two average wind speeds $\overline{U}(z)$, 25 and 40 m/s, are used. Due to the random nature of wind, for each wind condition (average wind speed and intensity of turbulence), three time series are generated. Figure 2 presents such time series and power spectral density. The time series $u(z,t)$ are converted into wind force with the following equation:

$$F(z,t) = \frac{1}{2} \rho C_d A \bar{U}(z)^2 + \frac{1}{2} \rho C_d A \bar{U}(z) u(z,t)$$

Assuming a unit mass of air 1.25 kg/m^3 , a drag coefficient C_d of 1.0 and an exposed area A of 1.0 m^2 . This force is applied at the top of the structure in the ADINA model. The wind series are 4096s long. Only 3600s are kept in the analysis to avoid the consideration of the initial transient response.

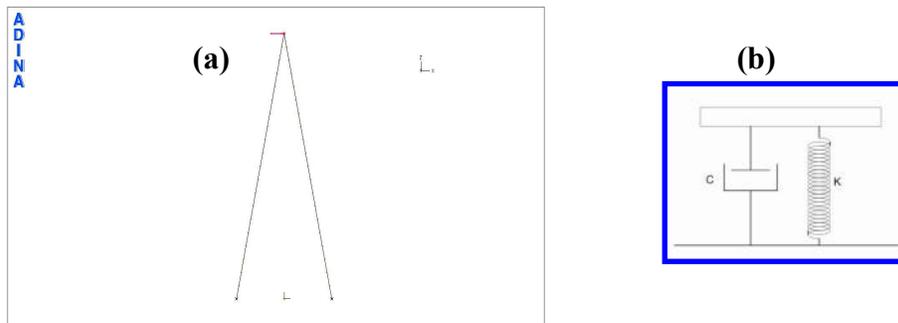


Figure 1. (a) model of simplified tower; (b) model of vertical impedance

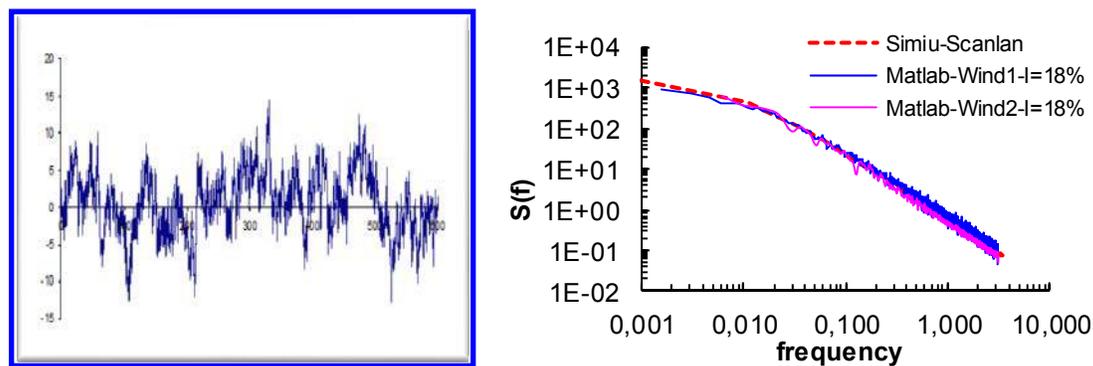


Figure 2. (a) Wind time series (turbulent part only); (b) power spectral density

The impulse load is taken to represent the effect of a shock wave resulting from a breakage of conductor or ground wire. When a conductor or a ground wire breaks, a series of dynamic tensile shock wave in the conductor is moving along the cable and reflects partially at boundary conditions. This dynamic load transmitted to the tower is generally a series of impulse loads with variable amplitudes, damping with times. Each impulse load has a duration comprised between 0.1s and 0.5s and it is a half sinus. In this work, due to space limitation, only two impulse loads are used with duration t_d of 0.1 and 0.25s (Figure 3). Calculations are run for $10t_d$.

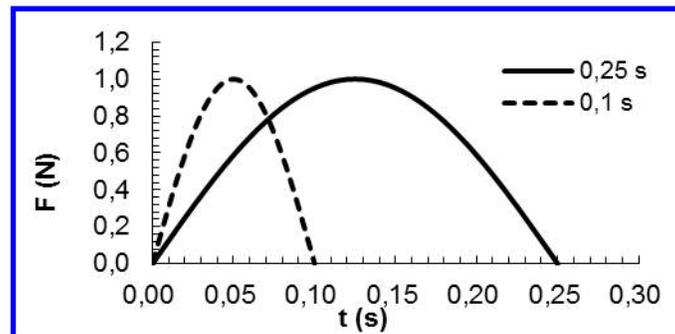


Figure 3. Impulse load applied at the top of the structure

Simplified Structure under Wind Loading

Variation of Maximum Response with Soil Impedances

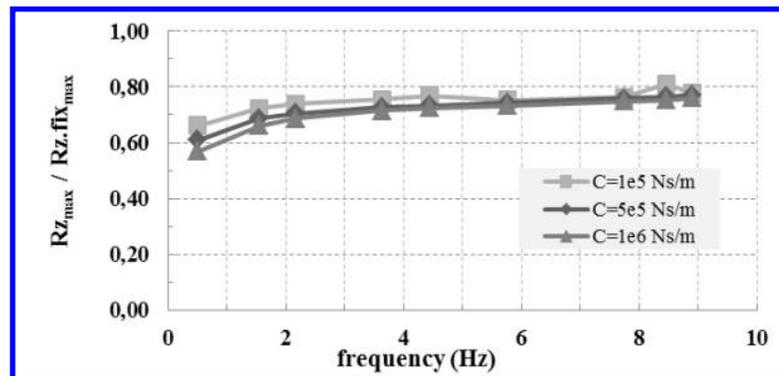


Figure 4. Variation of maximum horizontal response to wind ($I=10\%$)

Results are presented in terms of ratio between the reactions with impedances on the structure supports and the reactions with fixed base. Due to space limitation, only an example of support's reactions is presented on Figure 4 as function of the soil-structure system frequency obtained from numerical calculations and varying between 0.5 and 9.85 Hz. It can be observed that the reactions on the base of the structure increase when the natural frequency increases. The augmentation is more important for lower frequencies (between 0.5 and 4 Hz). The amplitude of response decays with increasing soil damping. Responses remain to be constant in the range of frequency varying from 6 to 9 Hz. Then the soil damping doesn't affect the response near the natural frequency of the system with fixed base. The influence of soil damping is more significant for lower frequencies (about 0.5 to 4Hz).

Comparison to the Simplified Structure with Fixed Base

In this section, the response of the structure on a rigid base is compared to the response of the structure with flexible supports. Two typical soils were considered on

Table 1. Impedances on the base of the simplified structure under wind loading

Cohesive soil (6.8 Hz)				Granular soil (8.7 Hz)			
K_z	C_z	K_x	C_x	K_z	C_z	K_x	C_x
1750.10^4	6650.10^2	1490.10^4	3750.10^2	6300.10^4	1380.10^3	6100.10^4	8050.10^2

the base of the simplified tower. A granular soil with a shear wave velocity equal to 200 m/s and $\rho = 1800 \text{ Kg/m}^3$ and a cohesive soil with shear wave velocity 100m/s and $\rho = 1600 \text{ Kg/m}^3$. In the numerical model, the soil is replaced by impedance functions (soil stiffness and soil damping). Based on the solution developed by Gazetas (1991) impedances used in this work are obtained from numerical simulations with the software FLAC (Jendoubi et al. 2011). The calculated impedances were introduced in the software ADINA as linear springs and dashpots.

In order to produce the maximum effect on the structure response, an iterative calculation was made by applying impedance and checking each time the value of the frequency of the system until obtaining a system frequency equal to the frequency calculation of impedances. For example, In the case of granular soil the final frequency is 8.7 Hz while it is equal to 6.8 Hz for the cohesive soil. Soil stiffness ($K_{x,y}$ at KN/m) and damping ($C_{x,y}$ at KNs/m) corresponding to those frequencies are illustrated on the Table 1. Using those impedances, the maximum values of reactions obtained with three wind intensities are illustrated in Table 2. It can be observed that, compared to the results obtained with fixed base, the difference is between 27% and 36% for both sandy and cohesive soils as shown in the Table 2.

Simplified Structure under Impulse Loads

The impulse loads shown on the figure 3 are applied on the top of the simplified tower model. The values of soil stiffness and damping applied on the model supports are related to the impulse load frequency. For example, when the impulsion duration is 0.1s, the frequency is equal to 5Hz and the impedances are determined at this frequency as shown on Table 3.

Table 2. Reactions (KN) on the base of the simplified structure under wind loading

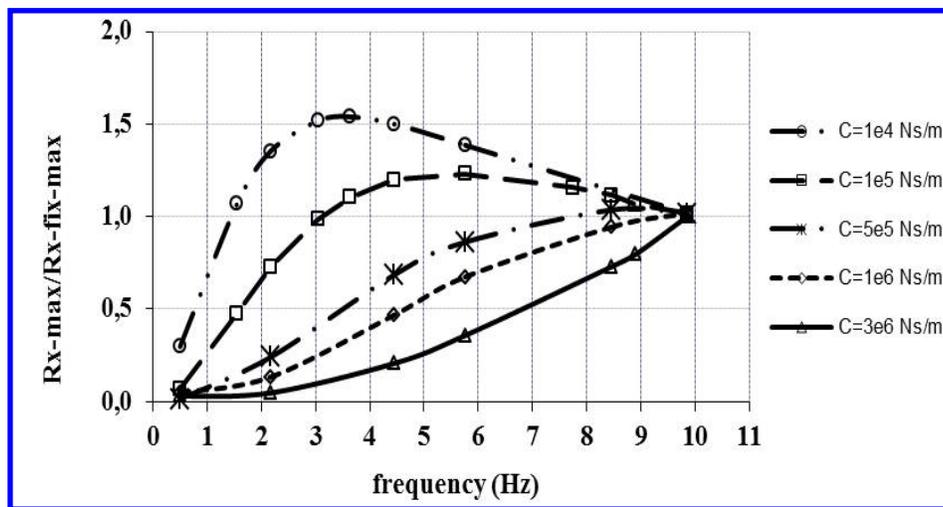
Wind	10% (v=40m/s)		15% (v=40m/s)		18% (v=25m/s)	
	Rx	Rz	Rx	Rz	Rx	Rz
fixed base	3.294	16.470	4.094	20.469	1.792	8.959
Cohesive soil	2.256	11.189	2.961	14.715	1.152	5.756
	31.5%	32.1%	27.7%	28.1%	35.7%	35.8%
Sandy soil	2.239	11.195	2.998	14.918	1.153	5.759
	32.0%	32.0%	26.8%	27.1%	35.7%	35.7%

Table3. Impedances on the base of the simplified tower under impulse load

f (Hz)	Cohesive soil				Granular soil			
	K_z	C_z	K_x	C_x	K_z	C_z	K_x	C_x
2.0	1620.10^4	1060.10^3	1509.10^4	7000.10^2	5000.10^4	3220.10^3	3770.10^4	3390.10^3
5.0	1650.10^4	7050.10^2	1420.10^2	3550.10^2	5900.10^4	1630.10^3	6100.10^4	1310.10^3

Variation of Maximum Response with Soil Impedances

Results are presented on Figures 5 and 6 in terms of ratio between the values of reactions with impedances on the structure supports and the values of reactions with fixed supports. The dimensionless reactions are function of soil-structure system frequency. We conclude that the response amplitude increases with soil stiffness except if there is a dynamic amplification. For higher frequencies, near the fundamental frequency of the structure with fixed base, the reactions amplitude tends approximately to the same value. As one can see for shock duration equal to 0.25s (Figure 5), there is a dynamic amplification for low values of soil damping ($C \leq 10^4$ N.s.m⁻¹). This phenomenon is not observed for td equal to 0.1s (Figure 6) because the duration is short so that damping hasn't significant effect on support reaction. The influence of soil damping is more important at lower frequencies.

**Figure 5. Horizontal reactions due to impulsive loading 0.25s**

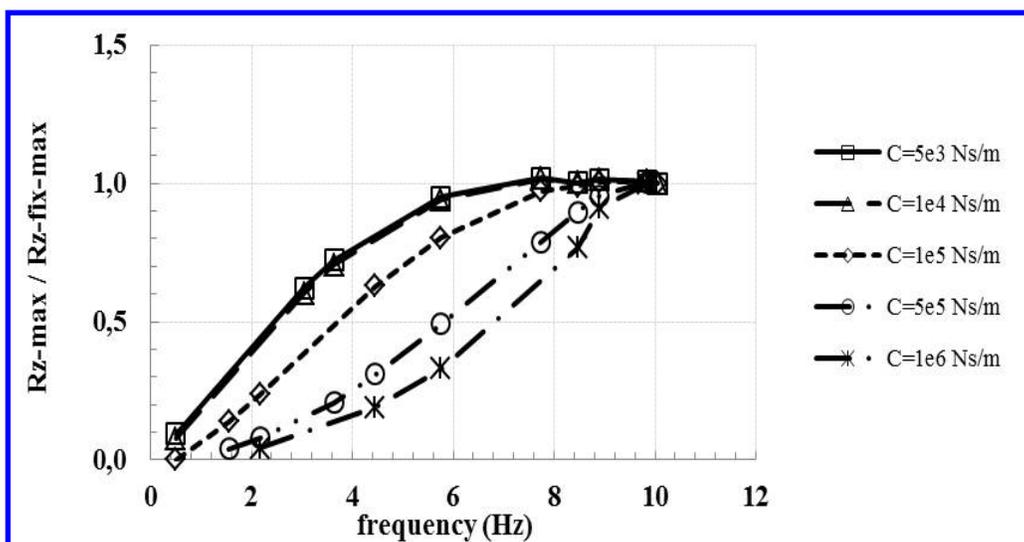


Figure 6. Vertical reactions due to impulse loading 0.1s

Comparison to the Structure with Fixed Base

As shown on Table 2 (frequency excitation 2 and 5 Hz), inversely to soil stiffness, soil damping is proportional to impulsion duration. The impedances of cohesive soil are lower than those of granular soil. Nevertheless, the support's reactions of cohesive soil are more important (Table 4). It shows the influence of soil damping on the response. In the cases of shock duration equal to 0.25, soil damping has a great influence on the dynamic response. However, when shock duration is 0.1s, soil damping hasn't the same importance. The damping forces haven't sufficient time to absorb much energy from the structure. In the case of shorter duration, the influence of soil stiffness is more significant. Then the reactions values are greater when the soil is a sandy media. Compared to the results with fixed base, taking into account SSI reduces the values of reactions from 27% to 45% (Table 4) in the both cases of sandy and cohesive soils.

Table 4. Reactions on the base of the simplified structure under shock loads

	Impulsion 0.1s		Impulsion 0.25s	
	Rx	Rz	Rx	Rz
fix	0.85	4.23	0.54	2.72
Cohesive soil	0.58	2.32	0.46	2.11
	32%	45%	15%	22%
Sandy soil	0.64	2.95	0.38	2.13
	25%	30%	29%	22%

Real Case: Lattice Transmission Line Tower

Tower Modeling

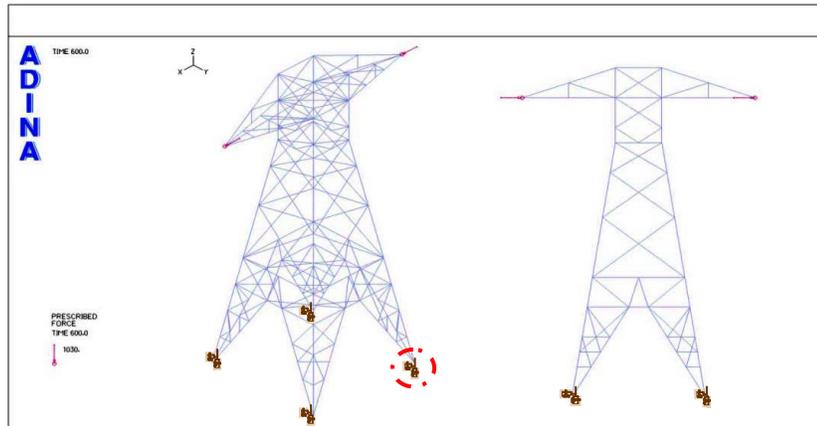


Figure 7. Model of the real steel transmission line tower

A typical steel transmission tower with real foundations (Legeron et al. 2010) shown in the Figure 7 is considered to illustrate the effect of the soil structure interaction. The tower modeled with the finite element software ADINA is 10m height. It consists of 144 beam elements and 130 truss elements and it is supported by four footings with 2m width. The mass of the tower is 3531 Kg and the fundamental frequency with rigid base is 10 Hz. The distance between two supports at the base of tower is equal to 4m. The tower is subjected to a transient wind loading and impulse loads.

Soil Impedances Applied on the Bases of the Real Tower

Foundations on the base of the tower are modeled with springs and dashpots applied in the three directions of translations. The values of impedances used in ADINA model are obtained from FLAC simulations (Jendoubi et al. 2011) In the case of wind loading, to produce the maximum effect on the structure response; an iterative calculation was made by applying impedance and checking each time the value of the frequency of the soil-structure system until obtaining a system frequency equal to the frequency of calculation of impedances. The values of applied soil stiffness and damping are presented on the Table 5. In the case of granular soil the final system frequency is 6.5 Hz while it is equal to 3.9 Hz for the cohesive soil. When the tower is subjected to impulse loads, the soil impedances used in this section depend on the impulsion

Table 5. Impedances on the base of the real tower under wind loading

Cohesive soil (6.5 Hz)				Granular soil (3.9 Hz)			
K_z	C_z	K_x	C_x	K_z	C_z	K_x	C_x
1700.10^4	7700.10^2	1540.10^4	3670.10^2	6000.10^4	1500.10^3	6200.10^4	1050.10^3

frequency and they are the half of the impedances illustrated in Table 3 and corresponding to the frequencies of 2 and 5 Hz.

Real Tower under Wind Loading

The real tower is subjected to the same wind loadings used for the simplified structure. The soil structure interaction was performed taking into account typical cohesive and granular soils with the properties presented previously. Table 5 summarizes and compares the results obtained for the two typical soils in the case of wind loading with turbulence intensity equal to 15 %. Compared to the results obtained with fixed base, the difference is between 32% and 36% for both sandy and cohesive soils. The values of impedances corresponding to a sandy soil are greater than those of the cohesive soil. Also, the reactions with granular soil are slightly more important than those with cohesive media.

Real tower under impulse loads

The half sine impulse loads described previously in the parametric study of the simplified structure are applied to the real tower model as shown on the Figure 7. The values of reactions on the base of the structure are summarized in the Table 7. Compared to the results with fixed base, taking into account SSI reduces the values of reactions from 5% to 54% in the both cases of granular and cohesive soils. The role of SSI is always beneficial except when the soil damping is low so that the dynamic response is amplified. For example, in the case of shock with a frequency of 2 Hz (duration 0.25s), the maximum vertical reaction of the structure supports with impedances is 18% greater

Table 6. Reactions on the base of the transmission tower under wind loading

Wind intensity	15% (V=40m/s)	
	R _x	R _z
fixed base	2323	10925
Cohesive soil	1497	7426
	35.5%	32.0%
Sandy soil	1502	7462
	35.4%	31.7%

Table 7. Reactions on the base of the transmission tower under impulse loads

	Impulsion 0.1s			Impulsion 0.25s		
	Rx	Ry	Rz	Rx	Ry	Rz
fix	0,46	0,45	2,20	0,28	0,28	1,37
Cohesive soil	0,27	0,22	1,00	0,27	0,24	1,61
	41%	51%	55%	4%	14%	-18%
Sandy soil	0,33	0,31	1,45	0,20	0,19	1,08
	28%	31%	34%	29%	32%	21%

than the reactions with fixed base. In this case, the SSI becomes detrimental for the structure.

Simplified method to evaluate the effect of SSI

In this section, a simplified method is given to evaluate the effect of SSI. In Figure 8, the damping ratio of the soil-structure system is shown as function of the system frequency with impedance divided by the system frequency with fixed base. Considering now a real structure with frequency f and a frequency f_{fix} of the structure with fixed base, the damping ratio of the structure can be determined with the logarithmic decrement method. Using Figure 8, it is easy to know approximately the soil damping. The Figure 9 contains Figures 5 and 6 at the same time. Knowing the values of f/f_{fix} and the value of soil damping deduced from Figure 8, it is possible to determine the ratio between the reaction with flexible base and the reaction with fixed base and

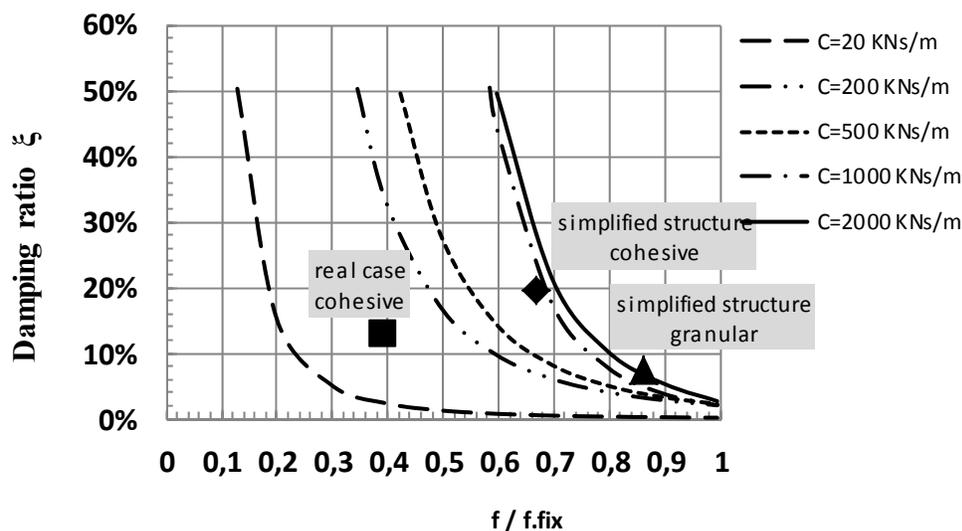


Figure 8. The damping ratio of the soil-structure system

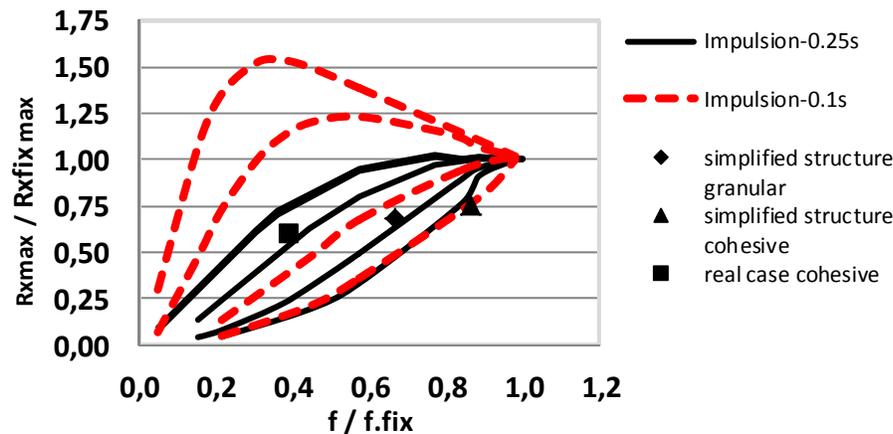


Figure 9. Parametric study of the simplified structure under impulse loads

then the effect of SSI. This method was checked for several models of structures with different proprieties. Three examples are presented on Figures 8 and 9: The simplified structure with two types of soils and the real case with cohesive soil on the base.

CONCLUSION

The effect of soil structure interaction on rigid TL tower has been examined in this paper using a parametric study by variation of soil stiffness and soil damping. Based on the substructure method, two softwares were used for soil simulation (FLAC) and the structure modeling (ADINA). The main conclusions of this paper can be summarized as follows:

- Taking in the account the SSI is very important for the TL structures which are very exposed to dynamic loads such as wind and impulse loads.
- Damping has much less importance in controlling the maximum response of a structure to impulsive loads than for periodic or harmonic loads because the maximum response to a particular impulsive load will be reached in a very short time, before the damping forces can absorb much energy from the structure.
- In most cases, the beneficial role of SSI is confirmed in this paper. However, in the case of low soil damping, the response considering the SSI is greater than the response with rigid base. This may lead to unsafe design of the structure.
- Depending on the tower configuration and the dynamic loading, the effect of soil-structure interaction could have a large influence in the overall response of the tower.
- The use of dimensionless impedance and the parametric study of the simplified structure make it possible to predict the effect of soil-structure interaction on the behaviour of any type of structure. This can be performed by replacing foundation by a set of dashpot and springs representing impedance in a finite element model. The example of the real transmission tower examined in this paper shows the importance of this approach.

- All analyses performed in this paper assume linear elastic materials. This is an unrealistic assumption.

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