NUMERICAL SIMULATION OF IMPEDANCE FUNCTIONS AND THEIR EFFECT ON THE DYNAMIC BEHAVIOUR OF TOWERS

Abir Jendoubi[1] , Frédéric Legeron[2] and Mourad Karray[2]

[1] PhD student, Faculté de génie, Université de Sherbrooke, Québec, Canada, J1K 2R1
[2] Prof., Faculté de génie, Université de Sherbrooke, Québec, Canada, J1K 2R1
[3] Prof., Faculté de génie, Université de Sherbrooke, Québec, Canada, J1K 2R1
Email: abir.jendoubi@usherbrooke.ca

ABSTARCT

Almost any type of structural system may be subjected to one form or another of dynamic loading during its lifetime. In particular, transmission towers are subjected to important dynamic loads such as wind. To account for wind load, a rigorous study tacking into account soil structure interaction can be performed. A key step of this study consists of estimating the dynamic response of the foundations by calculating their complex impedance functions (i.e. dynamic stiffness K and damping C) or the displacement functions (inverse of impedance functions).

The purpose of this work is to evaluate the displacement functions of strip footings on the surface of some homogeneous soil in which the shear velocity increases as a function of the effective overburden stress. Three typical cases are considered. For each case, the adopted mechanical characteristics correspond to a type of soil.

In order to study their effect, the obtained impedances are applied to a simplified model of transmission tower under harmonic and transient wind loading. Finally, a real transmission tower modeled with the finite element software ADINA is studied. Two situations are considered (i) the tower supports are rigid or (ii) the foundation flexibility is modeled with impedances. Results indicate that support reactions can be affected by tacking into account soil-structure interaction.

Key words: Impedance function, dynamic soil-structure interaction, shear wave velocity, transmission towers, oscillating frequency, FLAC, ADINA.

1.INTRODUCTION

Interaction between structures, their foundations and the soil medium below alter the behaviour of the structure considerably compared to the result obtained when the structure is considered on rigid foundations. A model for the soil-foundation-structure interaction system is needed to improve the design of important structures under dynamic loads. A critical study of state of the art of modeling soil-structure interaction is presented by Roy et al.(2002). Using analogy of single oscillator, SSI have been extensively studied. For surface foundations resting on a half space, Jennings and Bielak(1973) and veletsos and Meek (1974) propose analytical solutions based on numerical results.

The study of the wave propagation in a continuum and the use of computer codes make it possible to take into account dynamic soil-structure interaction by calculating the impedance or displacement functions representing flexibility and damping effect of foundation. Calculations of impedances are carried out using several methods (Sieffert and Cevear 1991, Shekar and Rana 2002, Gazetas 1991, Stewart and Fenves 1999, Wolf 1985, Veletsos and Vebric1973 and Novak and El Sharnouby 1983) such as: analytical solutions, semi-analytical and boundary formulations, dynamic finite-element methods and hybrid methods combining analytical and finite element approaches (Jacquart and al 2005). In this work, the finite difference method and the quiet boundary method suggested by Lysmer and Kuhlemeyer (1969) are used.. Calculations are performed with the software FLAC (Itasca 2002) in order to evaluate the real and imaginary parts of displacement functions for a soil with a variable shear wave velocity as it is typical of real soils.

Impedances obtained with FLAC are applied to a simplified tower subjected to a harmonically varying load of sine_wave in the first case and under a transient wind loading in the second case. Finally, a typical lattice tower is considered. Transmission towers were modeled with the software ADINA.

Results indicate that the response of transmission towers is greatly affected by soil structure interaction. The influence is more important when the impedances used correspond to a cohesive soil than when the soil is granular. Moreover, damping is a very important parameter in the study of the influence of the dynamic impedances on transmission tower's response.

2. EVALUATION OF IMPEDANCE FUNCTIONS

The most complex and time-consuming task in the determination of the tower reactions is the computing of the soil impedances functions. Assuming the medium homogenous and the soil linearly elastic, model consists of a grid with square elements (0.5m$\times$0.5m). The foundation, vibrating under the action of a harmonic exciting force, was modeled with structural beam elements.

To solve the problem of reflection at the model boundaries, the method of quiet boundaries suggested by Lysmer and Kuhlemeyer (1969) was used in this study. Boundaries located at the bottom, right and left side of the mesh involve dashpots attached independently to the boundary in the vertical and horizontal directions (figure 1). A proportional Rayleigh damping is used to simulate the mechanical damping. A value of 5 % that is typically used for soil-structure interaction problems is adopted. Numerical simulations are performed for three cases: (i) granular sandy media; (ii) cohesive soil; (iii) granular gravely soil. A 20m width and 15m height model is used. The half width of the strip footing foundation *B*, subjected to horizontal sinusoidal loading, is 2m

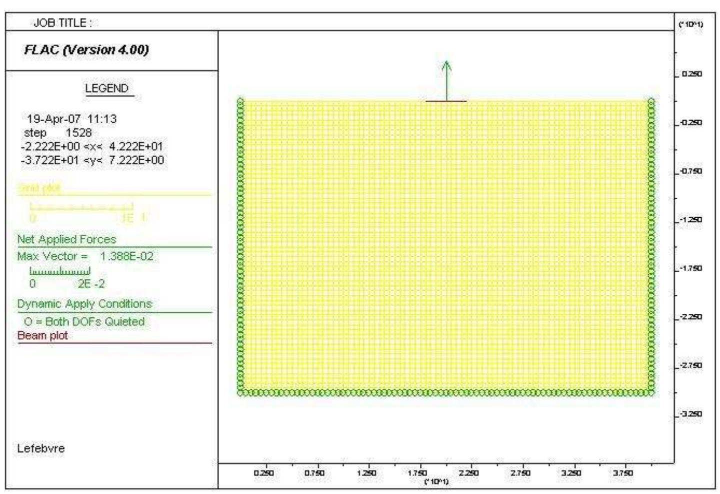


Figure 1 Model for numerical simulations (FLAC)
of soil–structure interaction problem

The usual assumption of homogenous layer or half space with constant shear modulus *G* may not be realistic as the shear wave velocity increases with depth even for homogenous soils. The shear wave velocity increases as a function of the effective overburden stress (σ') and the velocity normalized by a stress of 100 kPa (V_{s1}) according to the following equation (Hardin and Drnevich 1972).

$$V_s = V_{s1}\left(\frac{\sigma'}{100}\right)^{1/4} \qquad (2.1)$$

When V_s is varying with depth, each soil is divided into five layers with a height of 3m for each layer. V_s is constant for each one of these layers. Its value corresponds to the average value in the medium of the layer. Simulations were performed over a range of frequency ratios:

$$a_0 = \frac{\omega B}{V_s} \qquad 0.05 < a_0 < 3.5 \qquad (2.2)$$

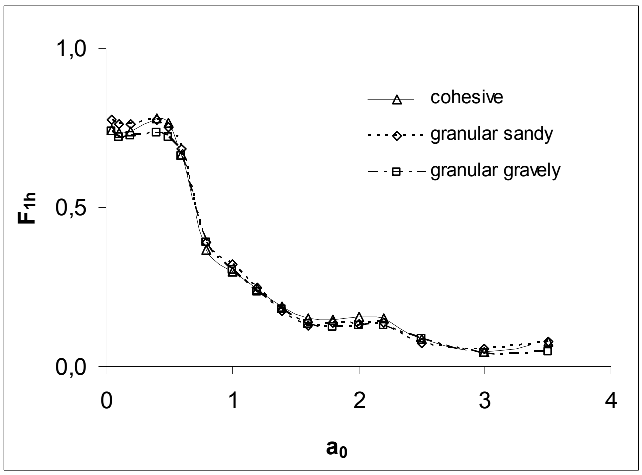


Figure 2 Real parts of displacement functions

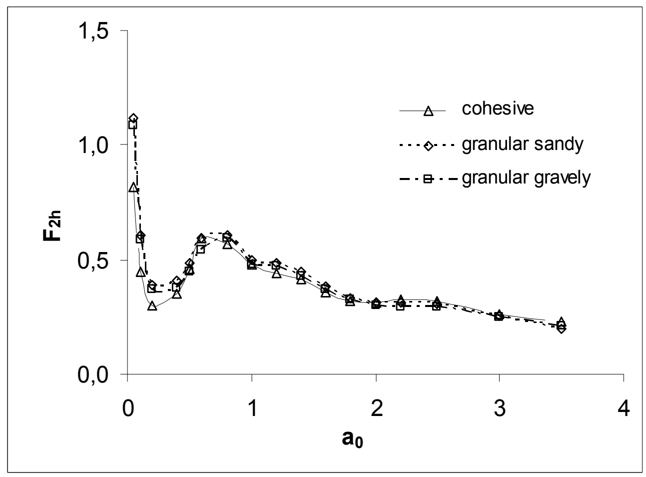


Figure 3 Imaginary parts of displacement functions

Due to space limitation, only the real (F_{1h}) and imaginary (F_{2h}) parts of displacement functions associated with a horizontal vibration are presented in this paper. The results associated with the vertical loading are given in Jendoubi (2007). In the systems with single degree of freedom, impedances are related to the displacement functions according to the following equations:

$$K = \frac{f_1}{f_1^2 + f_2^2} \qquad \omega C = \frac{f_2}{f_1^2 + f_2^2} \qquad (2.3)$$

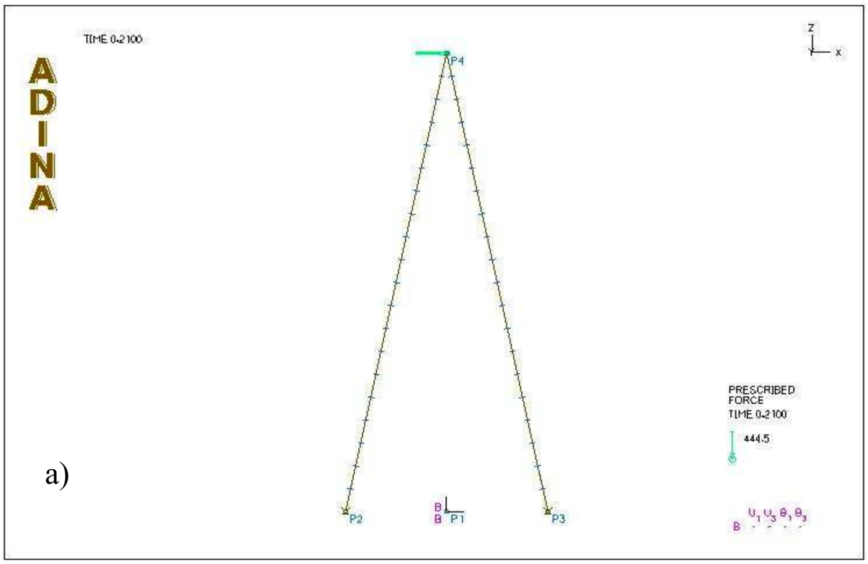
The displacement functions F and the impedance K can be written:

$$\mathrm{F} = f_1 + if_2 \qquad \mathrm{K} = K + \mathrm{i}\omega\mathrm{C} \qquad (2.4)$$

3. SIMPLIFIED TOWER UNDER HARMONICALLY VARYING LOAD

To check the adequacy of the numerical integration methods and the use of impedances, a simplified model of lattice tower with the consideration of soil–structure interaction (SSI) is proposed to investigate its dynamic behavior. The tower response is calculated in the time domain using a finite element package ADINA. A transient-dynamic analysis was performed. The method used here is Newmark average acceleration method with Full Newton iterative procedure for energy convergence. Parametric study by varying the frequency magnitude was pursued.
The structure is 10m height and is modeled using 2-node 2D beam elements. the elastic steel tower is discretized into 40 elements. The simplified tower is shown in figure 4-a.

The system is subjected to a harmonically varying load of sinosoidal wave having an amplitude 1 and circular frequency ω applied at the top of the model in the X-direction as shown in the figure 4-a. Structural damping is not considered for this analysis. The soil is replaced with accurate impedance functions that are calculated with FLAC and applied in the translational directions. Usually, it is recommended that the time step used is approximately 1/10 of the lowest global period that was considered important (could be based on modal participation factor calculation).



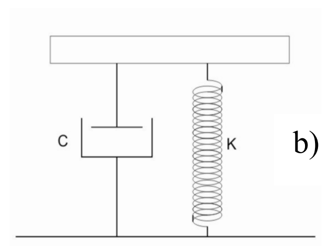


Figure 4 a) model of simplified tower b) model of vertical impedance

As a result of the soil flexibility of under dynamic excitation, soil structure interaction produces several effects on the tower response. It can be seen on the figure 5 that the amplitude increases as damping decreases and frequency approaches resonance frequency. When damping is small, the resonance frequency is approximately equal to the natural frequency of the system.

The fundamental frequencies of the tower depend on the impedances. With rigid supports, the fundamental frequency is about 10Hz. For K=300 n/m, *f* is equal to 0,15 Hz as seen in the figure 5.

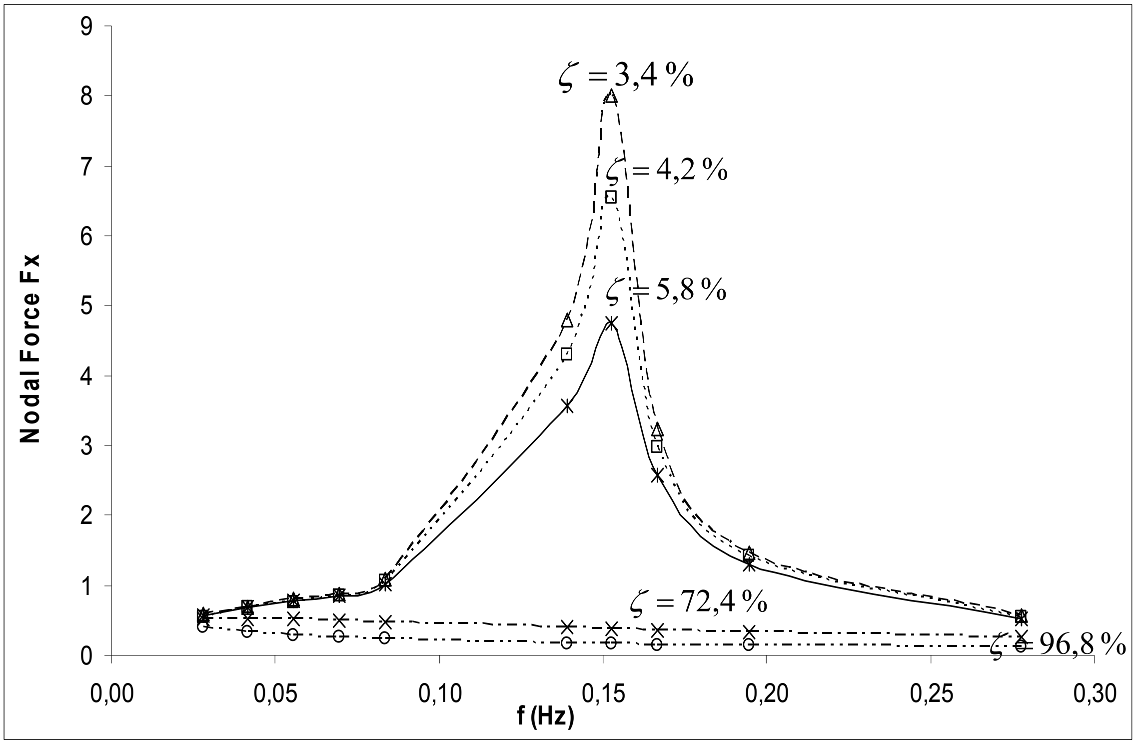


Figure 5 Influence of damping ratio on nodal forces Fx

4. SIMPLIFIED TOWER UNDER WIND LOADING

For transmission lines structural design, wind loading is one of the important parameters. It is divided into two parts, the mean part (1025.39 N) and the fluctuating part which is time dependent (82.03U (t)). The time function U (t) is presented in the figure 6 and is typical of wind speed fluctuation. .

The average speed of wind is 25 m/s. It is applied as concentrated loading to facilitate calculation of the wind forces. An in-house program [12] was used to generate the wind loading. This included the task of creating a program called WindGen that generated simulated wind speed using Shinozuka method based on the specified spectra.

After preparing the wind data as well as the finite element model presented in figure 4-a, the transient dynamic analysis of random wind loading is ready to be pursued. To do this, the WindGen result must be integrated in the ADINA input file that contains the model.

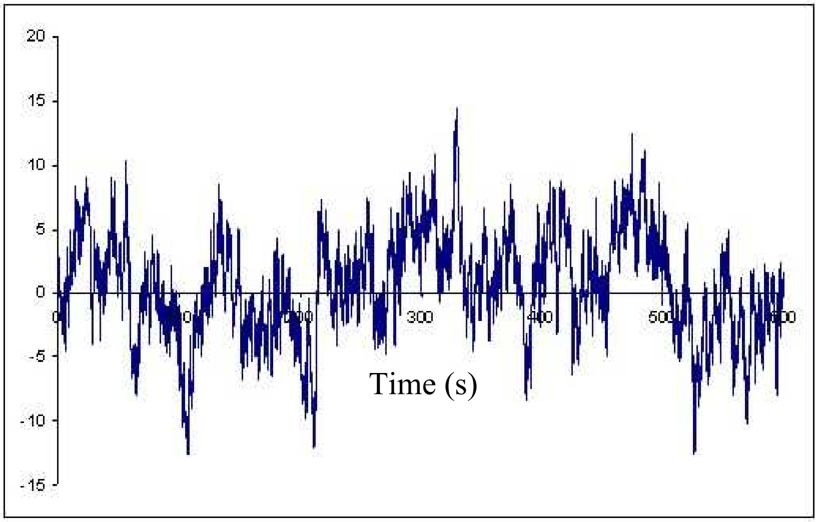


Figure 6 Time history of fluctuating part of wind speed

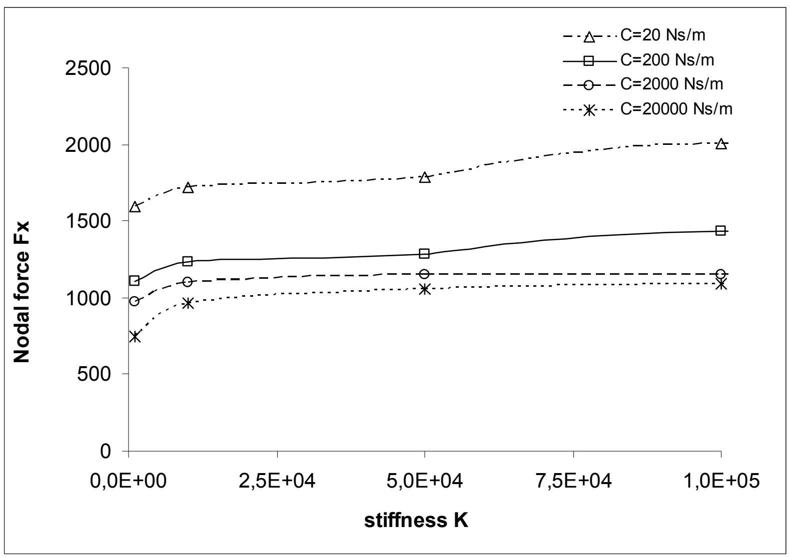


Figure 7 Influence of impedances under transient wind

Figure 7 shows the variation of nodal force F_x as a function of stiffness. Each curve corresponds to a value of damping C. The augmentation of K induces an increase in nodal force. The augmentation is more important for lower values of K (below 1000 N/m). The values of nodal force increase as damping decreases.

5. INFLUENCE OF SOIL STRUCTURE INTERACTION ON DYNAMIC BEHAVIOUR OF A STEEL TOWER:

A typical latticed transmission tower, shown in the figure 7-a 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 surface foundations. The distance between two supports at the base of tower is equal to 4m.The conductors are 35mm in diameter and span 150m. Each foundation is modeled with a spring and a dashpot in the three directions of translations. The tower is subjected to a transient wind loading during a period of 10min (figure 6). Two situations are considered (i) the tower supports are rigid; or (ii) foundations flexibility modeled with impedances.

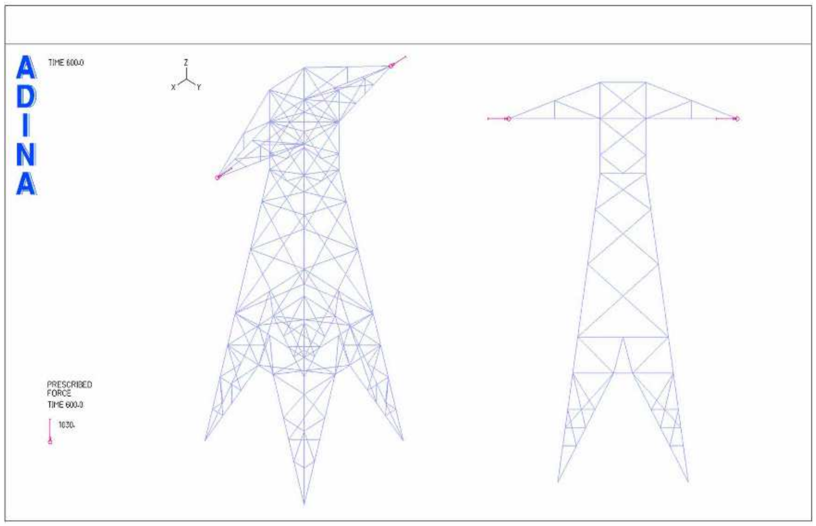


Figure 8 Model of lattice transmission tower

In order to evaluate the difference between considering a tower with a rigid foundation and a tower with flexible and damped foundations, two different soils sites are considered. The first site corresponds to a granular sandy media with various shear wave velocity V_{s1}=200m/s, ν=0.33 and ρ=1800 kg/m^3. The second site concerns a cohesive soil with V_{s1}=100 m/s, ν=0.45 and ρ=1600 kg/m^3. The supports reactions in each case are compared to those obtained with rigid supports on the base of the tower. The results corresponding to two supports are summarized in the Table 1.

Table.1. Supports reactions in the different cases

		R_z(N)	R_y(N)	R_x(N)
Rigid supports	support 1	14220	2940	3033
	support 2	20731	4311	4245
Sandy soil (V_{s1}=200 m/s)	support 1	12619	2713	2704
	support 2	18346	3943	3962
comparison	support 1	-11.26%	-7.72%	-10.84%
	support 2	-11.51%	-8.10%	-7.09%
Cohesive soil (V_{s1}=100 m/s)	support 1	12537	2340	2332
	support 2	18811	3508	3536
comparison	support 1	-11.84%	-20.41%	-23.11%
	support 2	-9.26%	-18.64%	-16.69%

Compared to results obtained with impedances, the values of reactions are larger if we suppose that the tower is resting on a rigid foundation.

The difference is greater when the soil is less rigid and consequently more deformable. Damping may also have a major importance, but overall, the influence of the impedances is higher for a cohesive soil than for a granular soil. Finally, according to the values obtained. It is noted that the use of the impedances instead of the rigid supports influence the reactions in a significant way. Thus, soil structure interaction affect the dynamic tower's response to wind. Nevertheless, more thorough calculations are necessary to qualify and generalize the impact of impedances specifically to evaluate the effect of damping and flexibility separately and to check influence for other types of dynamic loadings.

6. CONCLUSION

The present study has showed that combining finite difference method and quiet boundaries solves the problem of wave reflection and allows the consideration of the soil as a half-space medium. When the variation of the shear modulus with the depth is taken into account, it reflects better the reality of a homogeneous soil in which shear wave velocity increases as of function of overburden stress. Calculations with variable shear wave velocity could also provide displacement functions for foundations in the case of inhomogeneous soils.
The simplified tower indicates the accuracy and versatility of finite element models used in this paper.
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 makes it possible to predict the effect of soil-structure interaction on the behaviour of any 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 transmission tower examined in this paper shows the importance of this approach.

REFERENCES

Gazetas G. (1991). Formulas and charts for displacements of surface and embedded foundations. *Journal of Geotechnical Engineering*, **117 : 9,** 1363-1381.
Hang S., Gani F. and Légeron F. (2005), Générateur de vent appliqué au génie civil, Université de Sherbrooke.
ADINA R&D Inc. (2004), Automatic Dynamic Incremental Nonlinear Analysis (ADINA), ADINA R&D Inc.
Jendoubi A. (2007). Étude de l'influence des impédances de fondation sur le comportement dynamique des lignes de transport d'énergie électrique. *Mémoire de maîtrise*, Université de Sherbrooke, Faculté de génie.
Lysmer J. and Kuhlemeyer R.L. (1969). Finite dynamic mode for infinite media. *Journal of the engineering mechanics division ASCE*, **95**.
Novak M. et El Sharnouby B. (1983). Stiffness constants of single piles. *Journal of Geotechnical Engineering*, **109: 7**, 961-974.
Itasca consulting group, Inc. (2002) . FLAC User's Guide. *Minneapollis, Minnesota USA.*
Roy R., Dutta SC. and Moitra D. (2002). Soil-structure interaction in buildings with isolated and grid foundations: a critical study on the state of the art with recommendations. *The bridge and structural engineers*, **31:4**, 15-36.
Veletsos A.S. and Vebric B. (1973). Vibration of viscoelastic foundations. *Earthquake engineering and structural dynamics*, **2**, 87-102.
Wolf, J.P. (1985). Dynamic soil-structure interaction, prentice Hall, London. 466p.
Veletsos A.S. and Meek J.W. (1974). Dynamic behaviour of building-foundations system. *Earthquake engrg. and struct. Dyn.,* **3**, 121-138.
Jennings P.C. and Bielak J. (1973). Dynamics of building-soil interaction. *Bull. seismologicalSoc. Of Am.* **63:1**, 9-48.
Sekhar C.D et Rana R. (2002). A critical review on idealization and modeling for interaction among soil foundation structure system. *Computers and Structures*, **80 :20**, 1579-1594.
Sieffert J.G. and Franck C. (1991). Manuel des fonctions d'impédance - Fondations superficielles. France presses académiques ed. 175p.
Rosset, J. M.. (1980). A review of soil-structure interaction: the status of current analysis methods and research. *Ed. J. J. ed. Johnson, Report. Nos. NUREG/CR-1780 and UCRL-53011, US Nuclear Regulatory Commission and Lawrence Livermore laboratory.*
Pecker A. (2005). Dynamique des ouvrages et Dynamique des Structures. Doc pédagogique, École Nationale des Ponts et Chaussées, France.