Effect of Radiation Damping on The Seismic Response of Bridge

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ABSTRACT

The importance of soil damping properties on the seismic response of bridge structure to earthquake ground motion is presented. The dynamic response of the structure dependents on damping characteristics, geometry and the state of stress of soil layers and their boundaries. For a homogeneous half space, simplified expression for radiation damping based on wave propagation can be used. For a soil layer bounded by a rock medium, the radiation damping will be different from that of a homogeneous half space case. Numerical results for two cases of soil profile underlying the bridge shallow foundation are presented, the first case is a homogeneous half space and the second case is a soil layer bounded by a rigid medium. The results of both cases are compared to show the effect of radiation damping on the dynamic response of the bridge.

Keywords: radiation damping, seismic, soil-structure interaction.

INTRODUCTION

During earthquake ground motion, soil conditions influence the dynamic response of structures. If the foundation of the bridge is resting on a homogeneous half space, the vibration coming from the structure will be radiated away into the soil mass through radiation damping as well as dissipated through hysteretic material damping. The radiation of these waves away from the structure foundation depends on the dynamic characteristics and the material type of the soil medium. If the medium is composed of soil layers underlain by rock medium, the geometry of the profile will be different from that of a homogeneous half space due to the presence of boundaries between layers. This latter case will result in reflection and refraction, at the boundaries between different soil layers. of outgoing waves from the vibrating structure. The reflected waves back to the medium affects the response of the bridge structure since the radiation damping will have different value from that of homogeneous half space.

In the past decades, several research works have developed formulations of radiation damping for different situations [6-7]. The simplified formulation of spring-dashpot model is based on impedance functions obtained from a rigid massless foundation resting on a foundation soil and subjected to harmonic motion [6], [15-17].

The introduction of flexibility to the soil-foundation system will result in the lengthening of the fundamental period of the system. Simplified procedures for SSI in nonlinear inelastic seismic analyses formally presented in [6] [13].

Many other approaches for assessing the response in SSI were developed, namely the substructure approach [15] where the response of the soil-structure system is obtained by superposition. Since the response using the substructure technique is based on the superposition of the responses, it is restricted to linear systems only. Another approach that can be used for nonlinear systems is the direct method which considers the soil and the structure together in one model [15].

The dynamic response of the structural system including SSI to seismic ground motion can be obtained in two different ways, namely direct or indirect methods [16]. In the direct method, the complete model includes soil-foundation and superstructure and the analysis is performed for the whole system. In the indirect method, the system is solved in two phases considering kinematic and inertia interactions [9].

It is important to point that in SSI there are two effects, namely inertia and kinematic effect. The first effect, inertia, is related to the base shear and moments transmitted to the foundation interface by the vibrating structure. These effects cause displacements and rotations of the foundation element relative to the free-field. The energy dissipation of the waves coming from the vibrating structure are transmitted to the soil via the hysteretic soil damping and the radiation damping. In fact, if the medium is a homogeneous half space, the outgoing waves will be transmitted away from the structure foundation by the radiation damping and the energy of these waves will be dissipated. In the presence of a rigid layer or boundary, the effect of radiation damping will be different from the case of half space since part of the energy of the outgoing waves will be reflected at the boundary. The second effect. Kinematic, is related to the difference between the free-field motions and the foundation motions due to the presence of a stiff foundation on the surface of soil or embedded in soil.

In this paper, the bridge dynamic response is examined for two types of foundation soil. The first is a structure resting on a homogeneous half space and the second is a structure resting on a layer underlain by rock medium. The objective of this study is to show the importance of the radiation damping and its effect in calculating the dynamic response to earthquake ground motion of a bridge pier with shallow foundation including soil-structure interaction (SSI).

RESPONSE OF BRIDGE STRUCTURE INCLUDING SOIL-STRUCTURE INTERACTION

The response of the bridge including soil-structure interaction (SSI) depends on the dynamic properties of the soil layers. Since seismic waves propagate through soil media in a complex fashion, a simplification can be made assuming a shear wave propagating vertically towards the free surface. The wave motion can be modified by the geometry of the geological soil profile as it travels through the layers. If the layers are not susceptible to be liquefied during the ground motion only site effect can be considered, and the analysis combines the inertia and the kinematic effects depending on the relative stiffness between the foundation and the soil. The seismic waves can be amplified or de-amplified depending on the relative stiffness of adjacent soil layers. As amplification of seismic waves occurs, the period of the soil-structure system lengthens and therefore it may lead to significant yielding of the bridge pier.

The inertia loads and the bending moment resulting from the response of the superstructure depend greatly on the condition of soil layers since the peak of the spectral acceleration curve will be in the long period range.

For the analysis, the model of SSI shall include the properties of the structure and the foundation soil.

The formulation of stiffness and damping given by [4-5] and [7] are used. Similar formulas for static stiffness are given by [2]. The formulas given by the CHBDC standard are for a shallow foundation embedded in a homogeneous and uniform soil extending below the foundation of the structure. These expressions correspond to static stiffnesses that need to be corrected to get dynamic stiffness values. The multipliers for dynamic stiffness as well as for damping coefficient are given by [4-5] and [7]. The stiffness and damping of foundation are described in terms of an impedance function that accommodates translational and rotational deformations relative to the free-field [13]. The impedance functions are dependant on the soil properties, the geometry of the foundation element and the soil layer of the soil profile. Usually when using a computer three-dimensional SSI model, they are represented by a 6 by 6 matrix linked to the base of the footing. For the response spectrum analysis, the stiffness formulas given by the CHBDC can be applied by ignoring the radiation damping, however, the response spectrum curves should be calibrated to account for the overall damping factor of the SSI system. For time history analysis including SSI, ignoring the effect of the radiation damping will not describe adequately the system. In this latter case, the formulas given by the CHBDC cannot be applied to a structural system by ignoring the effect of radiation damping when performing a time history analysis.

Reflection and refraction of seismic waves

Seismic waves generated at a source can be of different nature namely compression P-wave and shear SV-wave. The waves can propagate in a soil medium towards the surface in a vertical or an inclined manner.

When the medium is a homogeneous half space, the incoming incident waves at the free surface are reflected to the soil medium. When the incident wave is propagating vertically it will be reflected at the free surface into one single wave of the same nature (Figure 1).

Figure 1. vertically incident waves a) P-wave b) SV-wave.

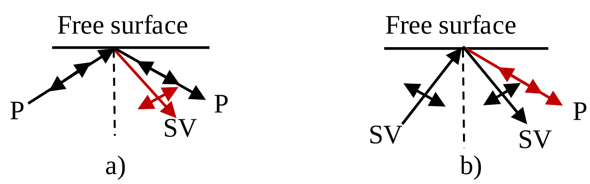


Figure 2. inclined incident waves a) P-wave b) SV-wave.

When the incident wave is propagating in an inclined angle with respect to the horizontal it will be reflected into two types of waves namely shear wave and compression wave (Figure 2). In this case the outgoing waves are transmitted away from the free surface and never come back. This way of transmission is caused by the radiation damping.

When the medium is a not homogeneous and there is a boundary that separates the layers, the incoming incident waves at the free surface or at the foundation element are reflected to the soil medium in the manner shown in Figure 2. In this situation, the outgoing waves, when arriving at the interface between two layers they, are either transmitted through the boundary or reflected to the medium with some energy. The part of the outgoing waves reflected to the medium correspond to the loss of their energy that is different from the case of homogeneous half space. In this case, the effect of radiation damping is not fully present because of the presence of the boundary between the two media which dictates the relative stiffness between them. Since for the case of a homogeneous half space the outgoing waves never come back, the amount of radiation damping will not change. For the case of a two-layer soil profile with the presence of a rigid boundary, the radiation damping will be reduced by the radiation coefficient to include the wave reflection effect at the rigid boundary.

The amount of the wave transmission depends on the relative stiffness between the two layers. Expression of the radiation damping factor that depends on the characteristics of adjacent media has been developed [14]. If the wave crossing the boundary between two layers is a shear wave, then the coefficient is function of the shear wave velocities of both layers. Eq. (1) gives the radiation damping coefficient [14] as

$$r = \frac{\rho S}{\rho_1 S_1} \tag{1}$$

Where ρ_1 and S_1 referring to the semi-infinite medium as medium 1 with suffix 1 and the region inside the medium, the soil layer, without any suffix.

This represents the amount of energy radiated away through the boundary. For the case of a homogeneous half space this coefficient is equal to one because we assume the properties are the same everywhere. Since we are assuming that the input wave is in the form of a shear wave, then only this coefficient is used. Therefore, the reduction of the radiation damping is considered for the case of a layer with rigid boundary only by applying it to the radiation damping expressions.

Description of the bridge structure

The bridge considered is a two-span deck plate girder supported on one pier and two abutments. The pier is composed of cap-beam and four concrete columns of diameter 1.5 m. The total length of the bridge is 60 m and the total width of the deck is 14 m. The deck is composed of five precast prestressed beams of NEBT type with height of 1.4 m that support a reinforced concrete slab of thickness 200 mm and a wearing surface of 65 mm thick. The slab deck is designed to meet the minimum thickness requirement according to the CHBDC standards. The deck beams are supported on elastomeric bearings. At the abutments, the deck is free to move in the longitudinal direction and restrained in the transverse direction. The beams are continuous and are fixed to the central pier cap through anchorages system designed to remains elastic during earthquake ground motion so that inertia forces are transmitted directly from the deck to the pier cap. The pier-columns height is 5.8 m. All the columns are supported on a shallow foundation of dimensions 6m wide and 12m long and 1.5m thick embedded 2m below the ground surface and resting on the soil.

The specified compressive strength of concrete f'c = 35 MPa, the yield strength of reinforcing steel fy = 400 MPa and the concrete density γc = 24 kN/m^3. The Modulus of elasticity of concrete is calculated according to clause 8.4.1.7 of the (CHBDC) code and that of steel is Es = 200,000 MPa. The material properties of the shallow foundation are the same as for the pier columns. The weight of the bridge structure is input as a mass concentrated on the top of the pier.

Description of the soil properties

The properties of the two soil profiles, homogeneous half space and the soil layer underlain by rock, are shown in Table 1.

Table 1. Shear wave velocity on a homogeneous half space.

Type of soil	Shear wave velocity, Vs (m/s)	Mass density, ρ (kg/m3)	Radiation damping coefficient*	Shear modulus, G =ρVs2 (MPa)
A	2000	2200		8800
D	360	1800	0.147	233
	270		0.11	131
	180		0.074	58

*Determined using properties of medium Type D divided by properties of medium Type A

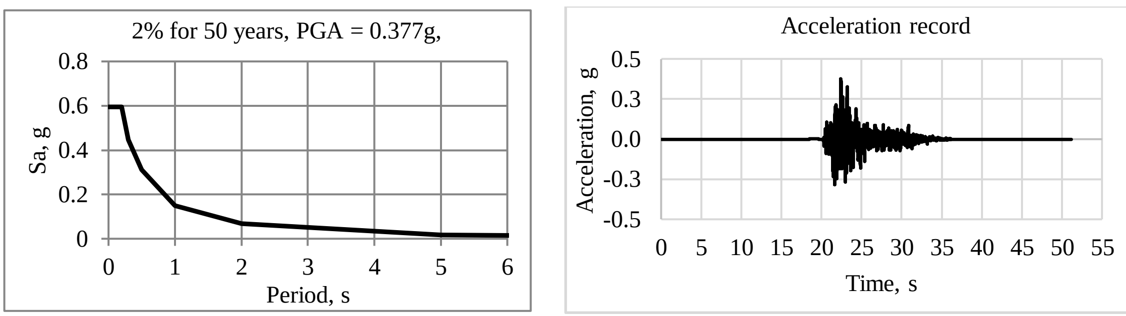
Description of the SSI system

The present study is mainly concerned with the investigation of the effect of radiating damping on the response calculations. The bridge structure is modelled using a simplified model consisting in an equivalent column with a mass on top of it and supported on a shallow foundation. The foundation soil is represented by translational and rotational springs and dashpots. The soil physical characteristics, springs and dashpots, are assumed as lumped parameters at the foundation level and are represented by the stiffness and damping coefficients respectively. Thus, a set of translational and rotation springs are placed beneath the foundation of the structure to model the soil medium. The damping of the system is a partition of structural or inherent damping and that associated with SSI which includes hysteretic and radiation damping of soil [7] [16].

Two models of the bridge structure are considered for the free vibration analysis namely fixed base and flexible base conditions. The purpose of the analysis of the two models is to conduct free vibration analysis and to compare their fundamental periods.

GROUND MOTION AND ACCELERATION SPECTRUM

The classification of soils for site effects is based on the average shear wave velocity in 30 m of soil (Vs30). The data considered for the analysis are obtained from CHBDC standards as the peak ground acceleration PGA = 0.377g and the spectrum for soil type C and the acceleration record [1] used are presented in figure 3.



a) b)

Figure 3. a) Acceleration spectrum for soil type C, b) Acceleration time history for soil type C.

RESULTS AND DISCUSSION

The stiffness and damping expressions considered for the translational and rocking modes of vibration are given by [7] and [10]. The coefficients of the footing correspond to y-translation parallel to the width B (longitudinal direction of the bridge) and rocking bout x, x-translation parallel to the length L. the foundation has a width B = 6m and a length L = 12m. The cases for the shear wave velocity considered are as shown in Table 1.

According to [10] if bedrock is present at a shallow depth beneath a footing, the static stiffness of vibration increases particularly the vertical mode. The rocking stiffness remains essentially unaffected.

Free vibration

For fixed-base condition, the structure has a stiffness k and mass m, the undamped natural circular frequency is $\omega = \sqrt{k/m}$, and an assumed damping ratio of 5% of critical damping. For the case of flexible base condition, the structural foundation is assumed to be a rigid rectangular footing of length L and width B, embedded at depth D into the ground. The fundamental periods of vibration of the bridge structure for both models with fixed base and flexible base conditions are shown in Table 2.

The effective properties of the columns' cross sections for the fixed base condition are assumed as uncracked. These results show that resonant condition is avoided for both conditions, fixed and flexible base, after comparing the fundamental period of the structure for both models with that of the soil profiles as given by Table 1.

The lengthening of the period the fundamental period of the flexible-base model compared to the fixed-base model is characterized with the period lengthening ratio as given by [7], [13] which is related to dimensionless parameters [3].

Table 2. Fundamental period of SSI system.

Shear wave velocity, Vs (m/s)	Bridge structure with fixed base Period T (s)	Bridge structure with flexible base Period T (s)
	0.93	
2000		0.93
360		1.13
270		1.31
180		1.91

Time history analysis

In this section, the dynamic response of the bridge structure subjected to earthquake ground motion including SSI for soil type D is obtained. During strong motion earthquake, the bridge-foundation system will undergo cyclic motions which intensity depends on the fault rupture, the soil properties, soil profile geometry and site response. The seismic demand applied at foundation level is a horizontal acceleration record given by Figure 3b. The response is obtained using Newmark-integration scheme applied to a system composed of a concentrated mass at the top of the pier and a mass of the foundation concentrated at the base of the pier. The supports are represented by horizontal and rotational springs and dashpots that represent the stiffnesses and the radiation damping of the foundation soil respectively.

The soil types and the maximum displacements corresponding to the response of a bridge pier resting on a homogeneous medium of type D subjected to earthquake acceleration are shown in Table 3.

Table 3. soil types and maximum displacement response of mass.

Type of soil	Shear wave velocity, Vs (m/s)	Radiation damping coefficient Equ 1	Maximum displacement of mass on homogeneous medium (mm)	Maximum displacement of mass on layer surrounded by a rigid medium (mm)
A	2000		30	30
	360	0.147	52	60
D	270	0.11	70	78
	180	0.074	90	97

The effect of soil type on the response of the bridge pier indicates the elongation of the fundamental period of vibration as given by Table 2 and the increase in displacement as shown in table 3. The codes give a range of values for the average shear wave velocity Vs for soil type D that vary from 180 m/s to 360 m/s. This interval of variation clearly shows that the values of the shear wave velocity Vs are well different since the period of the structure including SSI depends on this parameter taking an average value will not suffice since the displacement amplitudes are so much different. In case of very slender pier the displacement amplitudes will have larger value and may influence the non-linear response of the pier. Another case is that the case of an isolated bridge including SSI will have larger values of displacement response due to the presence of isolators placed on the top of the pier to reduce the effect of the shear force. This type of structure will be affected if soil-structure interaction is included.

For the case of a layer of soil type D surrounded with a rigid medium, the response is different then that of the homogeneous semi-infinite medium. The response of the SSI pier system will increase by an amount dictated by the wave reflection, at the rigid boundary separating this soil and the exterior rigid medium, back to the soil type D containing the structure. The amount of wave transmission away from the structure depends on the geometry and the characteristics of the layers. Equation 1 gives the radiation coefficient and its computed values, shown in table 3, corresponding to different values of the shear velocity Vs for interior medium type D and exterior medium type A.

The response spectrum of the mass is obtained for each type of soil A and D as well as for each value of the shear velocity Vs of soil type D corresponding to the case of a pier on a homogeneous semi-infinite medium. Figure 4 gives the spectral accelerations computed for the mass. Moreover, as shown in table 3, the increase in displacement amplitudes for the case of a layer surrounded of a stiff boundary is mainly attributed to the wave reflection back to the interior medium which affects greatly the dynamic response of the structure.

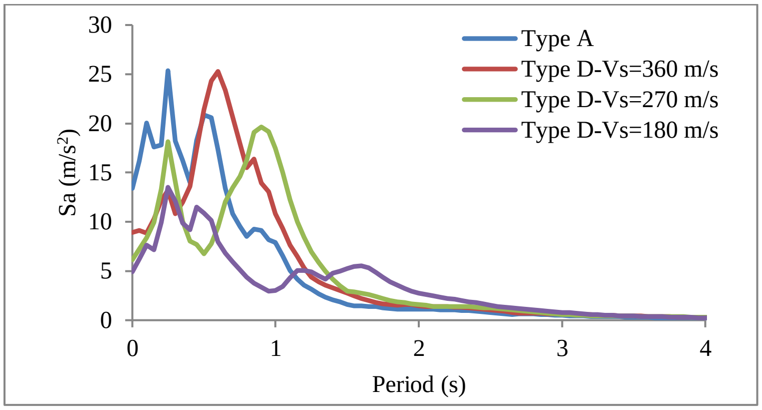


Figure 4. Spectral acceleration for different values of the shear wave velocity Vs.

The spectrum curves show amplification of the spectral acceleration as the values of the shear wave velocities decrease compared to the fixed base condition represented by soil type A. The significance reduction in spectral acceleration is at the short period range whereas for the medium and long period ranges the spectral acceleration increases compared to the fixed base condition. This is attributed to the reduction in the stiffness of the soil medium that affects the response of the SSI system. The ground motion is also affected by the changes in the shear wave velocity which results in a change of the free-field at the foundation support. The SSI affects the input ground motion that is different from the free-field one, this effect is noticed from the THA and is not shown in Figure 5. The difference between the motion in the free-field, far from the structure, and the motion at the foundation assumed rigid is related to kinematic interaction [8].

When the medium is of type D and surrounded with rigid boundaries representing a stiffer medium, the waves reflected at the rigid boundary to the interior medium result in an increase of the spectral acceleration Sa for all the ranges of Vs. The increase in Sa is found by determining the percentage of waves transmission from the interior to the exterior region depending on the relative stiffness between the two media. The increase of the spectral accelerations is quantified by using the radiation coefficient given by Equation 1.

The amplification can be important as shown for the case of a dam structure resting on a soil type D bounded by rock medium and subjected to harmonic incident ground motion at 30 degrees to the horizontal (Figure 5) [12]. For this case, the amplitude of the reflected wave at the boundary has almost the same intensity as the input at the base of the structure and the corresponding radiation coefficient is equal to 0.46.

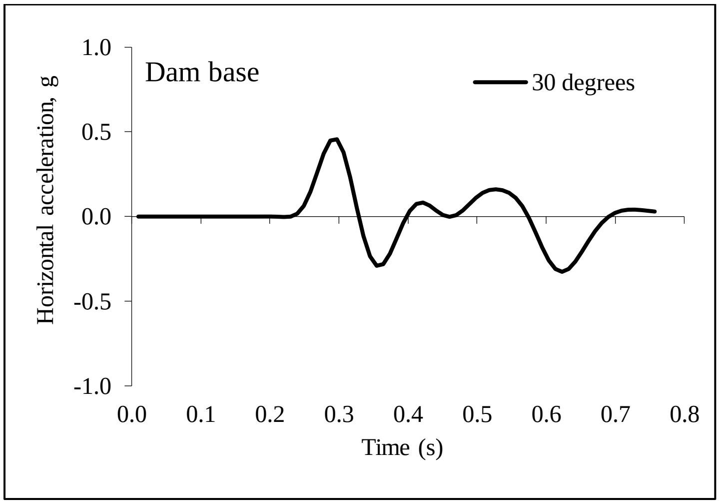


Figure 5. Response of base of dam to inclined SV *wave for soil type D bounded by rock.*

CONCLUSIONS

In this study, the seismic response of bridge pier supported on a shallow foundation for two types of soil profile is presented. The free vibration and the linear time histories are performed considering fixed base and flexible base conditions. The fundamental periods of the bridge pier structure for both fixed and flexible base conditions are compared and the response spectrum curves are obtained for the different type of shear wave velocities.

The results show that:

- For the same type of soil, the fundamental period of vibration increases using the range of values given by the codes for soil classification. This also influences the maximum displacement amplitude which increases accordingly;
- For the case of the medium of type D and surrounded with rigid boundaries, the waves reflected at the rigid boundary to the interior medium result in an increase of the spectral acceleration;
- The response spectrum curves show maximum values increase in the medium period range as well as the long period range. This lengthening may affect more slender structures and isolated bridge structures. These two cases are of importance and need to be addressed in future research.
- This interval of variation of the shear wave velocity Vs for the same class of soil “D” leads to different periods of the structure when including SSI since they depends on this parameter.
- Taking an average value for the shear wave velocity Vs will not suffice since the displacement amplitudes are so much different. In case of very slender pier the displacement amplitudes will have larger value and may influence the non-linear response of the pier.
- The increase in displacement amplitudes for the case of a layer surrounded of a stiff boundary is mainly attributed to the wave reflection back to the medium.

The study was limited to linear response of the bridge pier including SSI. Also, the study considers one ground motion only, the effect of ground motion characteristics was not considered.

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REFERENCES

[1] Atkinson, G. M. “Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum”, Can. J. Civ. Eng. 36, 991-1000.

[2] CSA. (2014). Canadian Highway Bridge Design Code (CHBDC), CAN/CSA S6-14. Canadian Standard.

[3] Bielak, J. (1975). “Dynamic behavior of structures with embedded foundations”, *Journal of Earthquake Engineering and Structural Dynamics*, 3(3), 259-274.

[4] Dobry, R. & Gazetas, G. (1985)., “Dynamic stiffness and damping of foundations by simple Methods”, *Proc. ASCE Symp. on Vibrational Problems in Geotechnical Engineering*, Detroit, Michigan, 75-107.

[5] Dobry, B. R., Gazetas, G. and Stokoe, K., II. (1986). « Dynamic Response of Arbitrary Shaped Foundations ». Journal of Geotechnical Engineering. 112(2), 109-135.

[6] Federal Emergency Management Agency, FEMA-440. (2005). “Improvement of Nonlinear Static Seismic Analysis Procedures”.

[7] Gazetas G. (1991). “Formulas and charts for impedances of surface and embedded foundations”. J Geotech Eng ASCE, 117(9), 1363–1381

[8] Kausel, E. (2010). “Early history of soil–structure interaction» Soil Dynamics and Earthquake Engineering”. 30(9), 822-832.

[9] Mylonakis, G. and Gazetas G. (1997). “soil pile bridge seismic interaction and inertial effects. part i: soft soil”. Earthquake Engineering and Structural Dynamics, 26(3), 337‑359.

[10] Mylonakis, G., Nikolaou, S. and Gazetas G. (2006). “Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations”. Soil Dynamics and Earthquake Engineering. 26, 824–853.

[11] Naimi, M., Sarma, S.K. and Séridi, A. (2001). “New inclined boundary conditions in seismic soil structure interaction problems”. Engineering Structures. Elsevier Science Ltd., 23(8), 966-978.

[12] Naimi, M. (2015). “Dynamic response of a Dam Structure to Incident Seismic Waves”, 11CCEE Canadian Conference on Earthquake Engineering, Vancouver, BC, July 24-25th.

[13] Stewart, J. P., Comartin, C. and Moehle, J. P. (2004). “Implementation of soil-structure interaction models in performance-based design procedures”. 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6.

[14] Veletsos, A. S. (1977). "Dynamics of structure-foundation systems", *Structural and Geotechnical Mechanics,* Prentice-Hall, Inc., Englewood Cliffs. NJ. 333-361.
[15] Wolf, J. P. (1997). "Spring-dashpot-mass models for foundation vibrations". Earthquake Engineering and Structural Dynamics, 26(9), 931–949.
[16] Wolf, J. P. (1985). "*Dynamic Soil-Structure Interaction*", Prentice-Hall. Englewood Cliffs, NJ. 466p.
[17] Wolf, J. P., Deeks, A. J. (2004). "Foundation Vibration Analysis: a strength-of-material approa7ch". Oxford: Elsevier.