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Evidence of Combined Site Effects and Foundatıon-Soil-Structure Interaction Effects on Seismic Response of Rc Buildings

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Abstract: The seismic excitation experienced by structures is a function of earthquake source effects, travel path effects, local site effects, and soil-structure interaction (SSI) effects. SSI effects related to variation of the structural behavior recently became a common practice in structural seismic design. Building seismic codes usually consider site effects through site factors, which reflect amplification of seismic waves due to the change in the geological contrast. For seismic structural analysis purposes, however, they consider the assumption of a fixed base, where, the input motion at the base of the structure is taken as equal to the free field ground motion. This paper investigates, in a rational way, the influence of kinematic and inertial SSI effects combined to local soil conditions effects on RC multistory buildings, resting on different design sites, through a global explicit transfer function for lateral component of the response. It comes from the combination of the transfer functions of structure, foundation and soil. It was found that the approach allows capturing the realistic physical fluctuations of the rock input motion before it excites the superstructure.

Keywords: Soil-structure interaction, Site effects, Transfer function, RC buildings

Introduction

Most civil engineering structures involve direct contact with the ground. When subjected to earthquake ground motions, structures responses and ground displacements are dependent of each other. The seismic waves excite the structure, which in turn, modifies the input (free field) ground motion. This difference in ground motion is due to interaction between the foundation, geological backgrounds underlying and surrounding the foundation and the superstructure.

The seismic excitation experienced by structures is a function of earthquake source effects, propagating path effects, local site effects, and soil-structure interaction (SSI) effects. The latter result due to the presence of the foundation and its flexible supports. In seismic structural design, it is usually needed to provide engineers by effective input motion which refer to rock acceleration records. However, because of its extremely high stiffness, firm-to-rock soils underlying the ground surface constrain the rock motion to be very close to the free field motion. Structures founded on soils of such a nature are considered as having a fixed base, conversely, in the case of soft soil deposits, the foundation motion will usually deviate from the free field motion. This deviation is governed by the transfer function (TF) of the soil deposits and foundation system.

SSI effects produce kinematic interaction effects related to the inability of foundation to follow ground motion due to its greater stiffness, and inertial interaction effects caused by the existence of structural and foundation masses. Almost, all proposed SSI modeling approaches deal separately with kinematic and inertial interaction. Wu (1992) analysed distinctly the effects of kinematic and inertial interaction effects for simple structures supported by rigid rectangular foundations and excited by representative earthquake ground motions.

Zania and Tsompanakis (2009) studied the effects of soil conditions and inertial SSI on dynamic response and stability of earth structures. Recently, Sayyadpour and Behnamfar (2016) investigated the inertial SSI effects on non-linear response of steel buildings built on different soil conditions. Several other studies (Lin and Miranda, 2008; Karapetrou *et al*., 2015) dealing with SSI effects adopted the same approach, which is unable to consider the combined effect of both phenomena, as it happens in real cases.

In this study, the problem of site effects combined to both kinematic and inertial SSI effects and their influence on reinforced concrete (RC) buildings is addressed through a global TF. The TF is a mathematical mean governing the input/output relationship of a physical system in the frequency domain. The global TF results from a simple multiplication in the frequency domain of site, foundation and structure TFs. The expected roof-level structural response could, therefore be captured through the combination of the rock motion with the global TF. The study will conducted on typical multistory buildings founded on sites classified according to the Algerian Seismic Resisting Rules (RPA99, ver 2003, simply referred below by RPA99). Appropriate selection of building types relative to their weight and stiffness properties may well highlight combined kinematic and inertial SSI effects.

RPA99 SSI Effects and Site Effects Consideration

The northern part of Algeria is a moderate to strong seismic region, as evidenced by recent seismic risk studies (Benouar 1994, Bouhadad and Laouami 2002), where, many sites show geotechnical, topographic and geological conditions leading to the appearance of local effects (Laouami et al., 2006, Laouami and Slimani, 2013). In RPA99, the amplification phenomenon is indirectly considered through normalized response spectra corresponding to four soil categories (Table 1). For site and SSI effects consideration, RPA99 simply recommend specific and additional investigations. Beneldjouzi and Laouami (2015) proposed a novel method for modelling site effects based on a mean TF for each RPA99 site class. The proposed TFs can be used to make an appropriate site classification and reasonable estimation of site amplification potential (fig. 1).

Study purpose

For seismic structural design purposes, most building seismic codes assume the hypothesis of a fixed base corresponding to a rock site. They also provide mean site factors associated with average design response spectra. Site factors (Beneldjouzi and Laouami, 2015; Beneldjouzi et al., 2017) reflect the amplification of seismic waves due to the change in the geological contrast between the bedrock and sedimentary material deposits. In the case of loose soil deposits, this amplification is partially reduced by the SSI effects. Indeed, because of presence of the foundation rigid bodies, retransmission of a part of the seismic energy from the structure to the ground is produced due to radiative damping at the soil-foundation interface. The nature of soil deposits will affect the dynamic properties of the soil-foundation-structure system because of additional flexibility.

Contemporary seismic codes (IBC 2012, ASCE 7-16, Eurocode8...) propose formulas for period and damping ratio lengthening in the case of a flexible base, but the latter do not allow capturing the effective properties of the seismic motion at the base of the structure. A good assessment of soil motion should implicate understanding all fluctuations to a suitable level of detail, in order to identify the expected structural response and the associated seismic damage.

The objective of this study is to highlight the combined site effects and SSI effects on the response of typical RC buildings founded on regulatory sites. Algerian regulatory considerations about site conditions are mainly pointed in this study. To this purpose, the methodology proposed by Beneldjouzi and Laouami (2015) is considered. Following this methodology, an average transfer function performed over a wide sample of 1-D soil profiles has been proposed for each soil type, based on a stochastic simulation approach. A probabilistic model using the random field theory allowed generating the bounded SW velocity values in each layer of any profile, in agreement with RPA99 requirements. The same 1-D profile simulation results are used in this study, with the only difference that they deal with the corresponding equivalent one layer soil profiles, obtained through the average SW velocity from the multi-layer profiles over a depth of 30 m. Only equivalent linear TFs are used herein to emphasize seismic behavior of the considered RC buildings.

Building Types and modeling

To ensure an adequate lateral load carrying capacity, resisting moment frames associated with bidirectional RC shear wall systems are an effective solution for multi-story RC buildings introduced within the revised RPA99. Currently, that is the most common construction system in Algeria, recognized economically viable and technically easy. The studied buildings are within that construction system and are of substantially symmetrical geometry. To meet requirements of RPA99, the buildings are of mixed structural system (shear wall associated with moment frames), with RC stairs and fillings of hollow brick masonry (fig. 2). They stay on raft foundation and have one basement floor, ground floor plus three floors (R+3) and seven floors (R+7), respectively. Floors and roof are of two-way solid RC flat slab. The basement floor's and floor's highs are of 3m and 3.06 m, respectively. This choice reflects the wish to target a specific natural frequency values characterizing buildings ranging from rigid to flexible. The dimensions of the structural elements in both directions are given in Table 3. It is well established that SSI effects are particularly strong for a rigid building based on a flexible support, whereas they are less obvious when the soil loses flexibility and becomes stiffer. Several authors, (Stewart et al., 1999, among others), consider that structures of multi-story buildings having predominant fundamental mode can be studied as a 1 degree of freedom (D.O.F) systems with the properties (mass, stiffness, frequency and eigen mode) of the first mode (fig. 5). A fixed base modal analysis allowed extracting the properties of the fundamental mode for the studied buildings (Table 4), to be used in flexible base buildings analysis.

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Table 1. RPA99 site categories

Site type	Geotechnical description	Mean value of V_s (m/s)
S1	Rock site:	
	Rock or other similar geological formation	$V_s \geq 800$
S2	Stiff site:	
	Deposits of dense sand, gravel and/or over consolidated clay with 10 to 20 m thickness	$V_s \geq 400$ From 10 m depth
S3	Soft site:	
	Deep deposits of medium dense sand, gravel or medium raid clay	$V_s \geq 200$ From deep of 10 m
S4	Very soft site:	
	Deposits of releases sand with/without presence of soft clay layers	$V_s \geq 200$ In the firsts 20 m

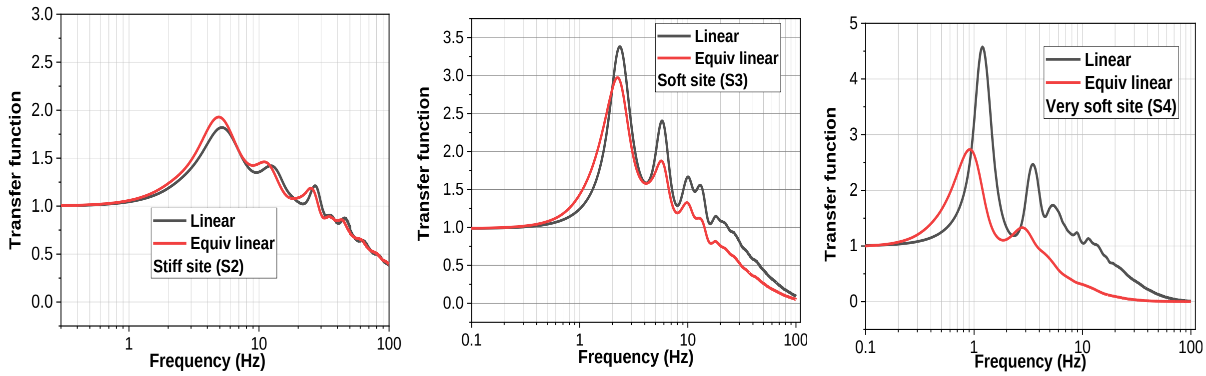


Figure 1. Mean transfer functions for RPA99 seismic site classes from Beneldjouzi and Laouami (2015). Mean transfer functions were performed for linear and equivalent linear cases. In this study, we deal with equivalent linear transfer functions to emphasize seismic behavior of RC buildings.

Methodology

The simulated multilayer soil profile are all representative of RPA99 site classes in terms of average V_s values and thicknesses of the different soil layers. Except for the S1 site representing the rock site (Table 1), the deterministic TF is calculated for the equivalent one layer profile in the linear case. To agree with requirements of the seismic design, soil nonlinearity should be considered, since it is commonly accepted that soil deposits behave non-linearly under strong seismic motions near the soil surface. The mechanical properties associated with dynamic loading are the SW velocity, V_s (or the shear modulus, G), the damping ratio, β and the Poisson's coefficient, ν. The variation of dynamic properties (mainly G and β) is governed by intermediate to high deformation levels (10^{-2} ~ 5%), which generally originate as a result of medium to high seismic stresses. In this study, the dissipative character is considered as an approximation of the soil nonlinear response.

Figure 2. 3D FE models of the studied buildings made with CSi SAP2000 ver 15

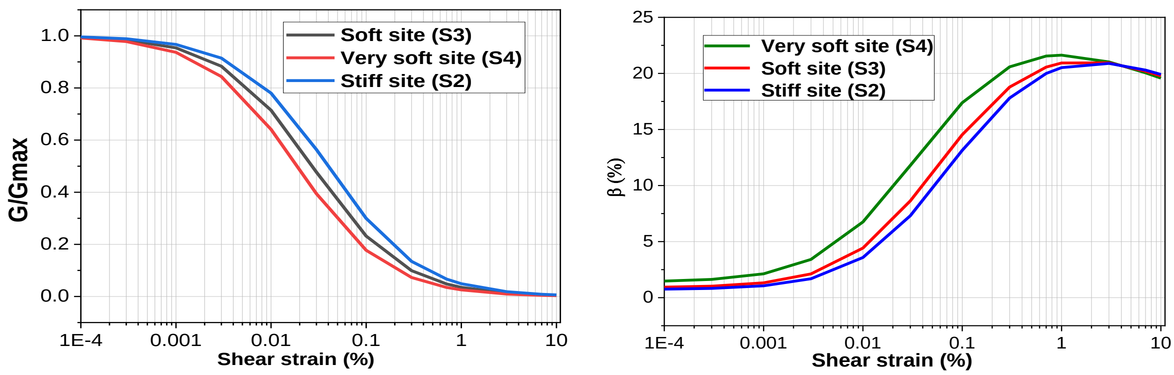


Figure 3. Small strain shear modulus reduction curve and damping ratio increasing curve of sites considered in this study performed according to Seed and Idriss (1970)

1-D equivalent linear analysis conducted by a developed computer program led to modified G and β values, based on decreased G and increased β reduction curves selected to this end (fig. 3). G and β reduction curves (Fig. 3) were made following the Seed and Idriss (1970) variation curves, as no data on G and β variations are available for the regulatory sites. These reduction curves were taken from the literature (Seed and Sun, 1989) and were selected according to the dissipation level which varies following the soil mechanical properties of the considered sites.

Following the Allison et al., (1994) methodology (eqts. 3-9), the equivalent linear TF of each soil profile is combined first to the structure's TF, then, the resulting one is combined to inertial effect TF and, finally, to inertial and appropriate kinematic TF to obtain global TF including site effects and both kinematic and inertial SSI effects. In all cases, a mean TF for lateral response is obtained by averaging combined TF of the simulated soil profiles over the whole considered frequency range.

Foundation stiffness and damping

Impedance functions represent the frequency-dependent stiffness and damping characteristics of soil-foundation system. Solutions for the complex impedance function proposed by Pais and Kausel (1988) are used:

$$K_j^d = K_{j/e}^s (k + i a_0 c) \tag{1}$$

$$K_{j/e}^s = K_j^0 \alpha_j \eta_j \tag{2}$$

where, K_j^d, is the dynamic impedance function for *j* mode; $K_{j/e}^s$, is the static impedance along *j* direction for a circular foundation of *R* radius and with *e* embedment, resting on an homogenous soil layer of h_f depth. $K_{j/e}^s$ is a function of the static stiffness K_j^0, for a rigid foundation on a semi finite medium. k, is a term of static stiffness depending on the dimensionless frequency: $a_0=\omega R/V_s$; with ω, the circular frequency; V_s, the SW velocity in the soil layer and *R*, the foundation radius. *c*, is the damping factor. α_j and η_j are the stiffness modifiers referring, respectively, to dynamic effect and embedment foundation. Elsabee and Morray (1977) and Kausel (1974) proposed solutions for static stiffness modifiers as given in the table 3, where, *G* is the complex shear modulus: $G=G_0(1+2i\beta)$, where, G_0 stands for the reduced small strain shear modulus with increasing shear strain. *e* is the foundation embedment depth and *ν*, the soil Poisson's ratio.

Table 2. Dimensions in Cm of building's structural element

		R+3	R+7	
Element		stories 1-4	stories 1-4	stories 5-8
	C1 (*axb*)	40x40		40x40
Column	C2 (*axb*)		50x50	
	C3 (*axb*)			
Beam	b (*bxh*)	30x40	30x40	30x40
Slab	D (*e*)	16	16	
Wall	W (a_w)	20	20	
E(MPA)	32000			
ν	0.3			
ρ_c(t/m^3)	2.5			

Seismic Response of Multistory RC Buildings Considering Soil-Foundation-Structure Interaction

Unlike buildings on fixed base, flexible base has an obvious effect on the buildings seismic behavior and offers a prominent reduction in the internal forces produced within the superstructure. The equations of the dynamic equilibrium of the above 1DOF representative system are written as follows:

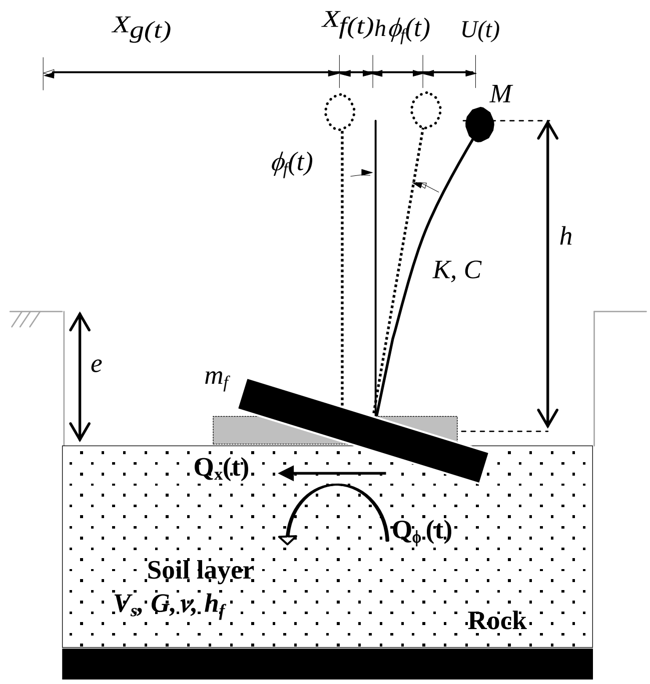


Figure 4. Simplified modelling of coupled dynamic soil foundation–structure system for horizontal and rocking motions with characteristics *K, C, M* and *h* of the first mode. V_s, *G*, *ν* and h_f stand, respectively, for SW velocity, shear modulus, Poisson's ratio and thickness of the soil layer. Q_x and Q_ϕ are, respectively, the shear force and the overturning moment at foundation-soil interface. *e*, is the foundation embedment.

Table 3. Static stiffness formulas with the corresponding dynamic modifiers from Kausel (1974) and Elsabee and Morray

Degree of freedom	Static stiffness	Soil stiffness modifire	Embedment stiffness modifire	Radiation damping
Translation along x axis	$K_x^0 = \frac{8GR}{(2-\nu)}$	$\alpha_x = (1 + \frac{1}{2}\frac{R}{h_f})$	$\eta_x = (1 + \frac{2}{3}\frac{e}{R})(1 + \frac{5}{4}\frac{e}{h_f})$	$c_x = \begin{cases} \frac{0.65\beta_s\xi}{1-(1-2\beta_s)\xi^2} \; if \; \xi = \frac{a_0}{a_{01}} \leq 1 \\ c_x' \; if \; a_0 > a_{01} = \left(\frac{\pi}{2}\right)\left(\frac{R}{h_f}\right) \end{cases}$ $c'_x = \frac{\pi\left(1+(1+\alpha)\frac{e}{R}\right)}{K^s_{x/e}/GR}$ $\alpha = \frac{V_P}{V_S} = \sqrt{\frac{2(1-\nu)}{1-2\nu}}$; k_x=1
Rocking about y axis	$K_\phi^0 = \frac{8GR^3}{3(1-\nu)}$	$\alpha_\phi = (1 + \frac{1}{6}\frac{R}{h_f})$	$\eta_\phi = (1 + 2\frac{e}{R})(1 + 0.7\frac{e}{h_f})$	$c_\phi = \begin{cases} \frac{0.5\beta_s\xi}{1-(1-2\beta_s)\xi^2} \; if \; \xi = \frac{a_0}{a_{01}} \leq 1 \\ c_\phi' \; if \; a_0 > a_{02} = a_{01}\frac{V_P}{V_S} \end{cases}$ $c'_\phi = \frac{\pi\left(\frac{\alpha}{4} + \frac{e}{R} + \frac{(1+\alpha)}{3}\left(\frac{e}{R}\right)^3\right)\frac{a_0^2}{b+a_0^2} + 0.84(1+\alpha)\left(\frac{e}{R}\right)^{2.5}\frac{b}{b+a_0^2}}{K^s_{\phi/e}/GR^3}$ $k_\phi = 1 - \frac{0.35a_0^2}{1+a_0^2}$ $b = \frac{2}{1+e/R}$

$$\ddot{U} + 2\xi\omega_0\dot{U} + \omega_0^2 U = -(\ddot{X}_f + h\ddot{\phi}_f) \quad (3)$$

$$m_f\ddot{X}_f + M(\ddot{X}_f + h\ddot{\phi}_f + \ddot{U}) + Q_x(t) = 0 \quad (4)$$

$$I_f\ddot{\phi} + Mh(\ddot{X}_f + h\ddot{\phi}_f + \ddot{U}) + Q_\phi(t) = 0 \quad (5)$$

where, M and m_f are the masses of the superstructure and the foundation, respectively, I_f, is the moment of inertia of the foundation with respect to its horizontal axis, $Q_x(t)$ and $Q_\phi(t)$ are the Shear force and the overturning moment at the soil-foundation interface. $\omega_0 = \sqrt{K/M}$, is the fundamental circular frequency of the structure, $\xi = C/2M\omega_0$, is the damping ratio of the structure. Assuming that the excitation and the responses induced by the sol-foundation-structure system are harmonic, the dynamic equilibrium of the system can be rewritten as (Prasad, 1989):

$$\begin{bmatrix} M(TR)_x + m_f & Mh(TR)_x \\ Mh(TR)_x & I_f + Mh^2(TR)_x \end{bmatrix}\begin{Bmatrix} \ddot{X}_f \\ \ddot{\phi}_f \end{Bmatrix} - \frac{1}{\omega^2}[K_f]\begin{Bmatrix} \ddot{X}_f \\ \ddot{\phi}_f \end{Bmatrix} = \frac{1}{\omega^2}[K_f]\begin{Bmatrix} \ddot{X}_g \\ \ddot{\phi}_g \end{Bmatrix} \quad (6)$$

where $[K_f]$ is the impedance matrix of the foundation. $(TR)_x = 1 - \omega^2 H(\omega)$, in which, $H(\omega)$, is the transfer function of the 1DOF oscillator:

$$H(\omega) = -\frac{1}{(\omega_0^2 - \omega^2) + i2\xi\omega_0\omega} \quad (7)$$

Assuming that the absolute rotation of the soil is insignificant, $(\ddot{\phi}_g = 0)$, the solution of this system is given in the following form:

$$U = H_u T_u \ddot{X}_g \quad (8)$$

and

$$\ddot{U} = -\omega^2 H_u T_u \ddot{X}_g \quad (9)$$

where, *U*, is the response of the system, H_u , is the TF of the oscillator, T_u, is a dimensionless factor evaluating the effect of inertial interaction:

$$T_u = \frac{B_3}{B_1 a_0^4 - B_2 a_0^2 + B_3} ; \quad B_1 = (\varepsilon_i + \varepsilon_m)(\mathrm{TR})_x + \varepsilon_i \varepsilon_m \quad ; B_2 = (k_x + k_\phi)(\mathrm{TR})_x + \varepsilon_m k_\phi \ ; B_3 = k_x(k_\phi + \varepsilon_i a_0^2)$$

$\varepsilon_i = I_f/Mh^2$, $\varepsilon_m = m_f/M$, $k_x = K_x R^2/(MV_s^2)$, $k_\phi = K_\phi R^2/(Mh^2 V_s^2)$

and

$\ddot{X}_g = -\omega^2 X_g$. *R*,

is the equivalent radius of the foundation. The response accounting for the soil-structure interaction and site effects may be obtained by the equation below:

$$\ddot{U}(\omega) = -\omega^2 H_u T_u TF_S \ddot{X}_g(\omega) \tag{10}$$

where, TF_s, is the soil's TF.

Table 4. Data required for the soil-structure interaction analysis related to the superstructures and foundations of the studied buildings

		R+3	R+7	Designation
h (m)		19.5	23.3	Superstructure high related to the first mode
b (m)		15.3	15.3	Fondation's width
L (m)		29	29	Fondation's length
e (m)		3	3	Foundation embedment depth
h_f (m)		30	30	Soil layer high
e_f (m)		0.8	0.8	Fondation's thickness
ξ_0 (%)		5	5	Modal structural damping
M (t)		1428.5	3297.2	Modal structural mass
m_f (t)		768	768	Foundation's mass
f (Hz)		4.3	1.22	Building's fundamental frequency
	S2	0.3		
v_s	S3	0.35		Poisson's ratio
	S4	0.4		

Results and discussion

R+3 building

Figure 5a shows the TF of the structure with fixed base on S2 site which reveals a well noticeable amplification peak, compared to that corresponding to structure with fixed and rigid base. The latter reflects the dominance of site effects, in accordance with the rigid nature of the structure having a natural frequency lying around the soil dominant frequency. The TF of combined site and SSI effects prevails at the same level of amplification and remains overhead of that corresponding to a fixed base and rigid foundation. This explains the site effects control the response of the superstructure rather than SSI effects. The inertial interaction did not have a dominant effect and remembers presence of rigid structure on firm soil.

For the S3 site (fig. 5b), the amplification peak caused by the site effects due to change in the stiffness contrast near the surface is slightly reduced to a level up to that corresponding to rigid foundation. The inertial interaction effects are generated by an increase in the flexibility of the system and leads to a somewhat more damped response of the superstructure. The two amplification peaks appear at a frequency corresponding to the structure's fundamental frequency, but which is in shift with the ground's dominant frequency, located upstream of the latter. Once again, it is well showed that site effects have a dominant control of the structural response because of the weak additional flexibility inherent in soft site, leading to moderately damped superstructure seismic response.

For that reason, the very soft nature of the S4 site led to an amplification markedly lower than that corresponding to a rigid foundation (fig. 5c). SSI effects are very well evidenced, due to the important additional flexibility, brought by the weak stiffness of S4 site. Both site and SSI effects had a downward trend around the natural frequency of the structure and led to a considerably more damped response of the superstructure, dominated jointly by the two effects. A slight bump also appears around the soil's dominant frequency, but remains without influence on the overall trend of amplification.

R+7 building

The TFs of figure 6a show amplification peaks having close amplitudes, with a slight dominance of the case of fixed base on S2 site. The response of the superstructure is governed rather by the site effects, in the same way as the R+3 building. It is easily seen that inertial effects are not influent with a value approaching the unity around the dominant structural frequency and one can speak of absence of SSI effects. Nevertheless, two other peaks dominated by site effects appear at, respectively, the soil's natural frequency and at around 10 Hz, although they remain at relatively lower level. On the other hand, the figure 6b points out that for the S3 site, the response is dominated by inertial interaction effects whose TF has a slightly lower peak than one corresponding to a fixed base on S3 site. The two TFs have a remarkably high level of amplification due to a large amplification, occurring at the natural frequency of the structure.

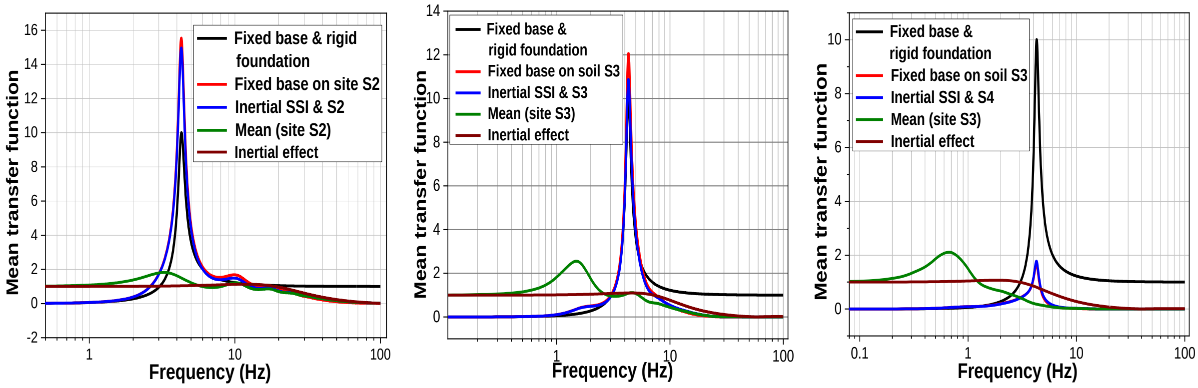


Figure 5. Mean transfer functions of the R+3 building's structure with a fixed base combined to that of site S2, S3 and S4. The transfer functions of the sites and inertial effects are also separately represented, in addition to transfer functions of that combined effects. Site transfer functions designate herein the mean transfer functions calculated over the whole sample of the simulated soil profiles.

The response of the superstructure is then dominated by the effect of inertial interaction, which is significant compared to the case of fixed base and rigid foundation. Because of passage to very loose medium from rigid formation in the case of S4 site leading to important damping effect (fig. 6c), the TF of the structure exhibits a significant amplification peak, compared to the case of fixed-base structure on rigid foundation.

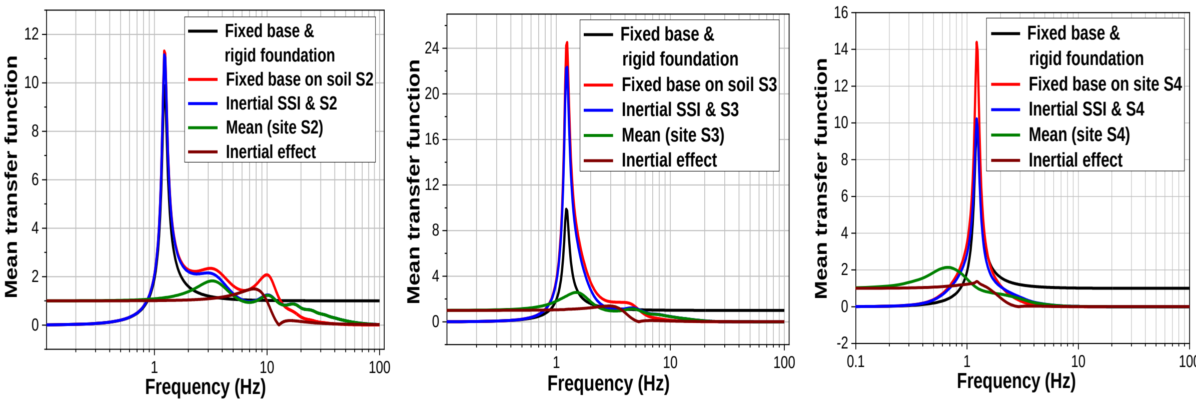


Figure 6. Transfer functions of the R+7 building's structure with a fixed base combined to that of site S2, S3 and S4. The transfer functions of the sites and inertial effects are also separately represented, in addition to transfer functions of that combined effects. Site transfer functions designate herein the mean transfer functions calculated over the whole sample of the simulated soil profiles

In fact, site effects pushed the amplification at a level clearly highest than those of fixed base and rigid foundation around the structure’s fundamental frequency, even though the soil's natural frequency places upstream of the structure's fundamental peak. The response of the structure remains dominated by the inertial interaction, which allowed reducing the amplification exhorted by the nature of the site. The very soft nature of the S4 site enables the advent of SSI effects when dealing with a stiff structure, which is in agreement with what occurs in real cases.

Effect of Kinematic Interaction

Kinematic interaction effects are caused by the inability of foundation to follow ground motion due to the greater foundation stiffness compared to the ground. The presence of foundation rigid bodies gives rise to a base slab averaging effect when the foundation dimensions are in the same order of magnitude as the wavelength (Clough & Penzien, 1993) and, a wave scattering effects at the corners of the foundation will result. The mathematical transformation from the free field motion to the foundation input motion could be performed by a specific frequency dependent TF. It represents the ratio of the foundation motion to the free field motion:

$$H_k = \frac{u_F}{u_g} \tag{10}$$

where, u_F, is the foundation motion and u_g, is the ground motion. For embedded shallow foundation, seismic motion at the foundation level is further reduced because of reduction of ground motion with depth. The model used in this study is the Kausel *et al*., (1978) model’s, adapted for rectangular shaped foundations from embedded rigid cylinder solution subjected to vertically propagating shear waves, for translational and rocking modes (Table 5).

Table 5. Kinematic transfer functions used in this study from Kausel et al., 1978

Degree of freedom	Kinematic transfer function
Translation along *x* axis	$H_{kx} = \cos\left(\frac{D\omega}{V_s}\right) \quad for \ \frac{D\omega}{V_s} < 1.1$
Rocking about *y* axis	$H_{k\phi} = 0.26\left[1-\cos\left(\frac{D\omega}{V_s}\right)\right] \quad for \ \frac{D\omega}{V_s} < \frac{\pi}{2}$

D, is the embedment depth (*e*), ω, is the circular frequency and V_s, is the SW velocity value of the soil layer. The solution considers the response of the foundation embedded in the actual soil and subjected to the seismic environment defined in the free field at the soil structure interface before the soil has been excavated. The investigation of figures 7a to 8c shows that, except for the case of the R+3 building on S4 site (fig. 7c), the kinematic interaction has no effect on the structural response compared to that of the inertial interaction effects.

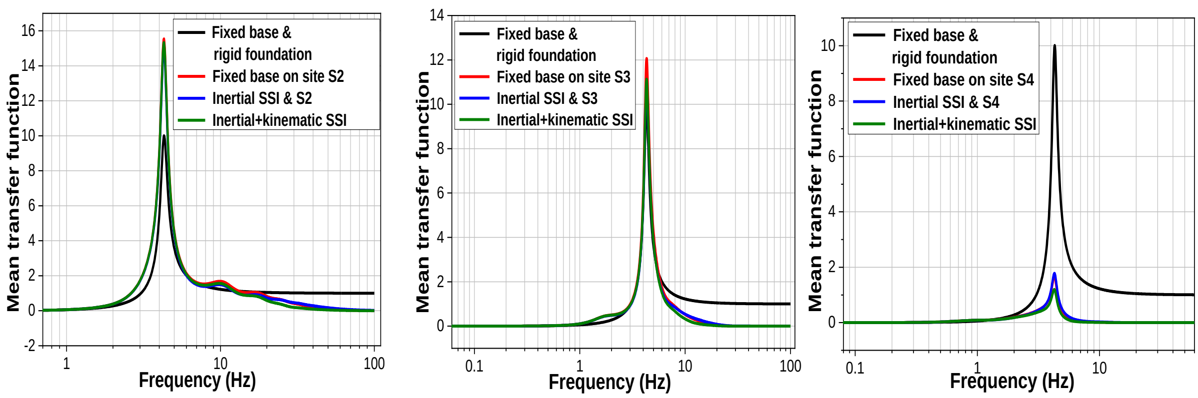
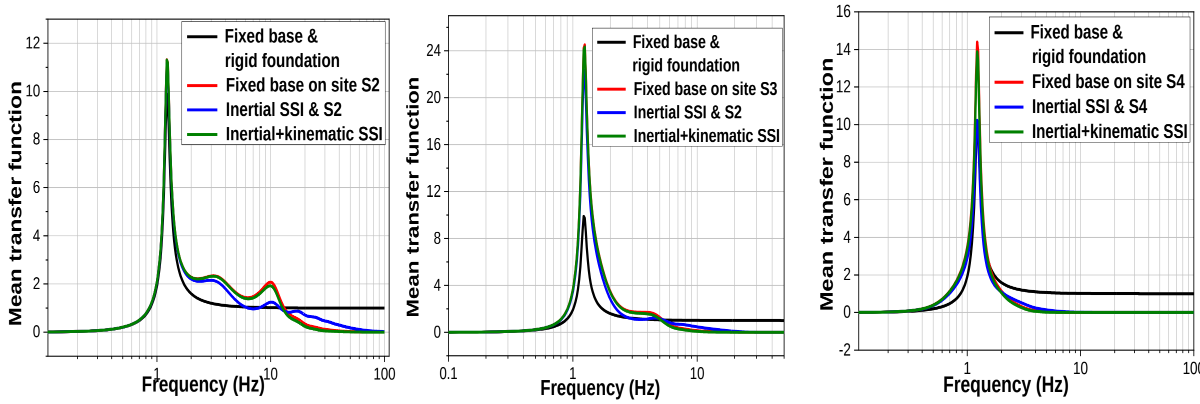


Figure 7. Transfer functions of the R+3 building’s structure with a fixed and with a fixed base combined to that of site soils. The figure also shows transfer functions of inertial SSI effects combined to site effects in addition to inertial and kinematic interaction effects combined to soil effects

This could be due to the kinematic TF, which does not have a frequency preference in reducing structural response over the whole frequency considered range. Kinematic interaction, on the other hand, is influent compared to the case of a fixed base and rigid foundation, and follows fluctuations of the site effects. Except for the R+3 building on S4 site, TF of combined kinematic, inertial and soil effects clearly has a overall trend to follow site effects TF in all other cases (figs. 7a, 7b and 8a to 8c). In the case of the R+3 building on S4 site, the response of the superstructure is widely influenced by the effects of kinematic interaction, which has allowed reducing the amplification level caused by soil and inertial interaction effects. In the other cases, the response of the superstructure remains slightly dominated by the combined soil and inertial interaction effects, compared to soil effects alone and absence of kinematic interaction effects is due likewise to weakness of dimensions ratio of the foundation and embedment encountered in these common buildings.



(a) (b) (c)

Figure 8. Transfer functions of the R+7 building's structure with a fixed and with a fixed base combined to that of site soils. The figure also shows transfer functions of inertial SSI effects combined to site effects in addition to inertial and kinematic interaction effects combined to soil effects

Conclusion

The influence of kinematic and inertial SSI effects combined to local site effects on typical RC multistory buildings was analyzed in this study, based on a global explicit TF modeling the soil-foundation-structure system. It comes from a simple combination, in the frequency domain, of the TFs of structure, foundation and soil. Site effects are modeled by TFs made following the Beneldjouzi and Laouami methodology according to RPA99 requirements.

For the R+3 building, the TF of the fixed-base structure on S2 site reveals a noticeable amplification peak, appeared around the fundamental structural frequency. In that case, inertial interaction effects has no influence on the structural response since it has not made any change to soil effects. As well, a clear trend to follow soil effects is observed for S3 site, where, combined soil and inertial effects lightly control the response of the superstructure.

Because of important change in stiffness contrast near the soil surface, the amplification peak related to the S4 site reduced to a level widely below that corresponding to rigid foundation, and allows the appearance of broad inertial interaction effects, generated by an increase in the flexibility of the system, and leads to a more damped response of the superstructure. The very soft nature of the S4 site led to an amplification markedly lower than that corresponding to a rigid foundation.

For the R+7 building on, respectively, S2 and S3 sites, the TFs show amplification peaks having similar amplitudes. The structure has not broadly reacted to the soil-structure interaction due to the nature of the R+7 building and the foundation supports, due to their comparable flexibilities. Soil effects lightly govern the response of the superstructure and one can speak of absence of soil-structure interaction effects. In the case of S4 site, inertial interaction effects whose TF has a widely lower peak than one corresponding to soil-structure TF dominate the structural response.

In all cases, however, it is clearly showed that, except for the case of the R+3 building on S4 site, the kinematic interaction has no effect on the structural response compared to that of the inertial interaction effects, and has an overall trend to follow soil effects.

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