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FREQUENCY DEPENDENT PROXIES OF SOIL-STRUCTURE INTERACTION IMPACT FOR TYPICAL R/C BUILDINGS

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ABSTRACT

The scope of this study is to investigate the role of soil-foundation-structure-interaction in the dynamic response of typical reinforced concrete (RC) buildings, in order to identify the cases that the simplified assumption of support fixity underestimates seismic demand. For this purpose, two real RC buildings have been parametrically examined, namely, a regular in plan and elevation and an irregular one, both designed according to Eurocode 8 provisions. Ten equivalent single degree of freedom oscillators (SDOFs), which can be considered representative of real multi-degree of freedom structures has also been studied in a similar manner. Three different soil types are adopted with shear wave velocity V_s equal to 350, 250 & 150 m/s, respectively, while seismic response of the oscillators under multiple Ricker pulses of different amplitude and frequency is identified through non-linear response history analysis that takes into account material nonlinearities in both the soil and the superstructure. It is concluded that neglecting SFSI effects may lead to non-conservative estimates of specific Engineering Demand Parameters (particularly, inter-storey drift and ductility demand) under specific combination of ground motion frequency content and soil compliance, a fact which is illustrated in the series of dimensionless charts produced. These charts can be used as a quick reference for an approximate importance of soil-structure interaction prior to the design process.

Keywords: soil-foundation-structure interaction, inelastic response history analysis, ductility demand, RC buildings

INTRODUCTION

Over the past 40 and more years, considerable progress has been made in understanding Soil-Foundation-Structure-Interaction (SFSI) effects on dynamic characteristics and consequently seismic response of structures; readers may refer to Kausel (2010) for a detailed history of SFSI research. Despite extensive research in this subject, there is still controversy regarding the role of SFSI in the structural seismic performance (Mylonakis and Gazetas, 2000), since the SFSI phenomenon is an inherently complex and coupled dynamic problem.

The first studies quantifying the modification in the seismic demand of elastic single-degree-of-freedom (SDOF) structures were conducted by Jennings and Bielak (1973), Veletsos and Meek (1974), Veletsos and Nair (1975) and Veletsos (1977). They showed that the effects of inertial interaction on the structural response are mainly associated with an increase in the fundamental period of a replacement fixed-based SDOF system

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and a change in its relevant damping. Using the aforementioned concept, they also identified that considering SFSI can either decrease or increase the elastic seismic demand, depending on system parameters (i.e. structural aspect ratio, a dimensionless parameter expressing the relative stiffness of foundation and structure and a dimensionless parameter representing soil-to-structure mass) as well as the unique characteristics of the input ground motion itself. This replacement oscillator still forms the basis of the seismic design provisions currently in use to incorporate the effects of SFSI in design (i.e. EC8 (2004), NEHRP 2009 (FEMA 750)). Since a design spectrum consisting of a horizontal constant-acceleration branch from very low to medium periods and a descending branch at higher periods is used, the perception prevails that SFSI have a generally beneficial effect as per the seismic response as the structure, on account of the reduced design spectral acceleration.

While extensive work refers to date to linear SFSI, less attention has been given to SFSI effects on structures with nonlinear behavior. Amongst these studies, the response of an elastoplastic structure supported on an elastic half-space to a simple pulse has been examined by Veletsos and Verbic (1974) suggesting that structural yielding decreases the effects of SFSI due to increasing system flexibility. Ciampoli and Pinto (1995) came to a similar conclusion that ductility demand in terms of curvature remains essentially unaffected by SFSI, showing, however a tendency to decrease. In contrast to these findings, Bielak (1978), investigated the steady-state response of a bilinear hysteretic structure supported on an elastic half-space and found that, contrary to linear systems, SFSI can increase the ductility demand of the non-linear structure with respect to the case of a rigid foundation. The above later results (an increase in inelastic structural response) are also supported by more recent studies (Aviles and Pérez-Rocha (2003), Zhang and Tang (2009), Moghaddasi et al. (2011) and Jarernprasert et al. (2013)), highlighting the fact that SFSI detrimental effects for yielding systems are as important as for elastic systems. Furthermore, evidence from strong earthquakes has highlighted the possibility of critical impact on seismic response due to SFSI effects (Reséndiz and Roesset (1987); Mylonakis et al. (2006)).

The above controversy regarding the role of SFSI on the seismic demand of structures raises the fundamental question whether SFSI are effectively beneficial or detrimental (Mylonakis and Gazetas, 2000), an issue that is essentially the motivation of this study. More explicitly, it is aimed to investigate the role of soil-foundation-structure-interaction in the inelastic dynamic response of typical reinforced concrete (RC) buildings in order to identify, in a dimensionless and easy to interpret and use manner, the conditions under which the simplified assumption of support fixity underestimates seismic demand.

Along these lines, a parametrical non-linear response history analysis scheme is developed to study the response of two real reinforced concrete (RC) buildings along with ten SDOFs, representative of real multi-degree of freedom structures, resting on mat surface foundations on different soil conditions. The SFSI effects on specific Engineering Demand Parameters (such as inter-storey drift, ductility demand) are then evaluated and related directly to ground motion frequency content and soil compliance. Finally, the cases in which neglecting SFSI may lead to non-conservative estimates of EDPs are highlighted. It should be noted here that in the present study only the effects from inertial interaction were taken into account. Kinematic interaction effects were not considered assuming surface-supported foundations and vertically incident shear waves.

OVERVIEW OF THE CASES STUDIED

Real Reinforced Concrete Buildings

Two earthquake resistant RC buildings are examined (hereafter denoted as Building I and II), constructed in the cities of Thessaloniki and Lefkada, respectively in Greece (Figure 1). The first is designed according to EC8, with material properties (i.e., concrete class C20/25 and class B500c steel) (Sextos et al. 2015). The latter is an existing building constructed in the 80's according to the relevant national seismic code of 1959; however, it has been re-designed to EC8 with identical material properties for the purposes of comparison. Building I is a six-storey, regular in plan (9.5x11 m) and elevation (18 m) building with pilotis and basement designed for a peak ground acceleration of 0.16g (i.e., lowest seismic zone I in Greece). Building II is irregular both in plan (15x25 m) and in elevation (14.5 m). It consists of four storeys, basement and a loft at 2.5m in the ground floor, with a slab covering approximately 40% of the plan area. It was designed designed for a peak ground acceleration of 0.36g corresponding to Zone III of the highest seismicity in Greece.

Both buildings were modelled as three dimensional MDOF systems using the commercial software SAP2000 (CSI, 2014), while a point-hinge model was used for all RC members in the form of lumped plasticity at the ends of the beams, at the top and bottom of the columns and at the bottom of the walls at the ground level, for the purposes of the inelastic response history analysis.
It is pointed here that the basement was excluded from the finite element model, as it was considered for simplicity, that the superstructure rests on mat surface foundation. The fundamental periods of the two structural models assuming fixed base conditions were determined as follows: Building I: Tx = 0.506 s & Ty = 0.427 s and Building II: Tx = 0.499 s & Ty = 0.527 s.

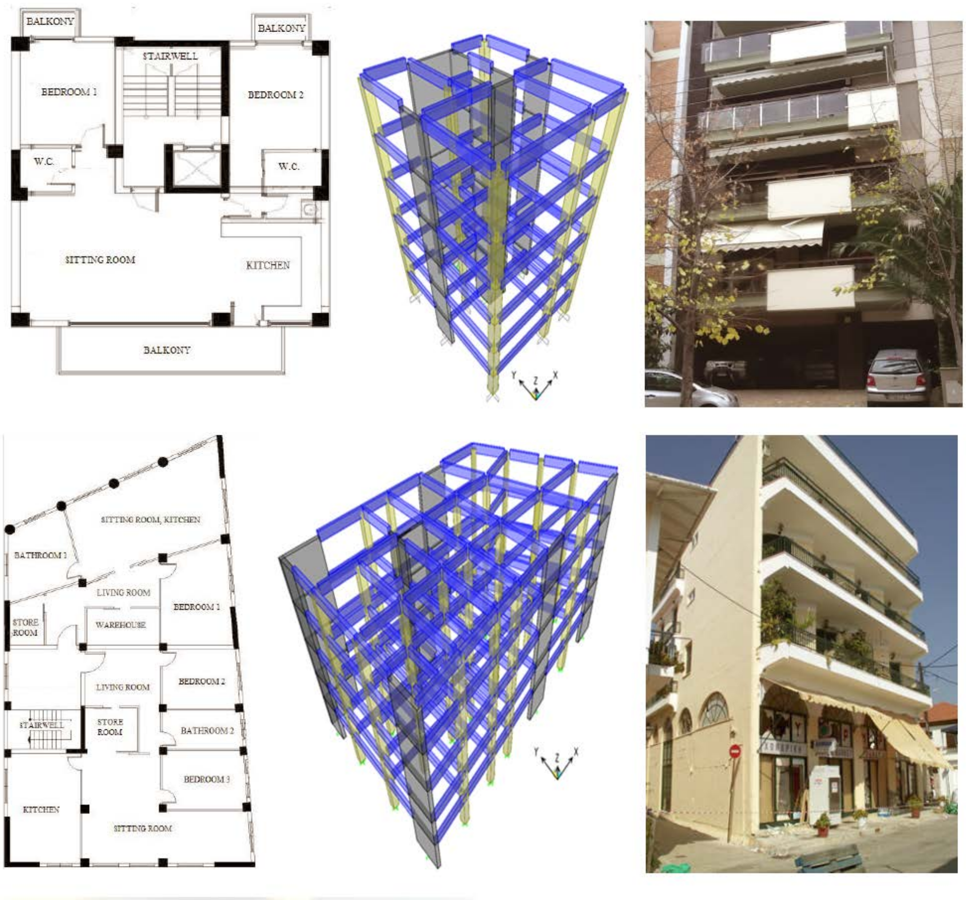


Figure 1. Overview of the two RC buildings studied

Equivalent Single Degree of Freedom Systems

In order to investigate SFSI effects on inelastic seismic demand of a wider range of structures, the framework of the equivalent non-linear SDOF oscillator was employed. It was deemed necessary, however, these oscillators to be representative of real multi-storey buildings. Therefore, transparent formulation, based on Fajfar N2 method (Fajfar and Gašperšič 1996, Fajfar 2000), was utilized in order to transform the Building I described above, into an equivalent inelastic SDOF system, with an elastic period Tel = 0.538 s.

Next, all additional oscillators were developed under the assumption (a) of a 150t storey mass, (b) an effective mass (M_{eff}) and height (H_{eff}) corresponding to the first mode of vibration, calculated according to SEAOC "Blue Book" (1999), (c) the same strength (C_y = 0.25) and hardening ratio (9.28%) as resulted from the transformation of Building I, (d) identical foundation conditions to the (9.5x11m) mat foundation of Building I and (e) a foundation mass M_f equal to 20% of structure's mass with a mass moment of inertia calculated as $I_f = M_f \times (2L)^2/12$. The inelastic behavior of the aforementioned SDOFs was described using a bilinear backbone curve and utilizing the modified Takeda hysteretic rule for the hysteretic response as shown in Figure 2. The characteristics of the equivalent SDOF oscillators are summarized in Table 1 (oscillator 6 corresponding to Building I), while the non-linear soil – foundation – structure system is also presented in Figure 2. It is noted that this system is a 3DOF system, considering the top structural translational DOF, as well as the foundation's horizontal and rocking motion.

Table 1. Equivalent SDOF oscillators' characteristics

	Period T (s)									
	0.1	*0.2*	*0.3*	*0.4*	*0.538*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*
Number of Storeys	1	2	3	4	6	7	8	9	10	11
Effective Mass M_{eff} *(t)*	150	270	382.5	510	637.2	787.5	900	1012.5	1125	1237.5
Effective Height H_{eff} *(m)*	3	5	7	9	13	15	17	19	21	23
Stiffness K (MN/m)	592.2	266.5	167.8	125.8	86.9	89.4	72.5	62.5	54.8	48.9
Yield Strength F_y *(kN)*	368	662	938	1251	1650	1931	2207	2483	2759	3035
Yield Displacement d_y *(cm)*	0.06	0.25	0.56	0.99	1.90	2.24	3.04	3.98	5.03	6.21
Base-shear coefficient $C_y = F_y/M_{eff}g$	0.25									

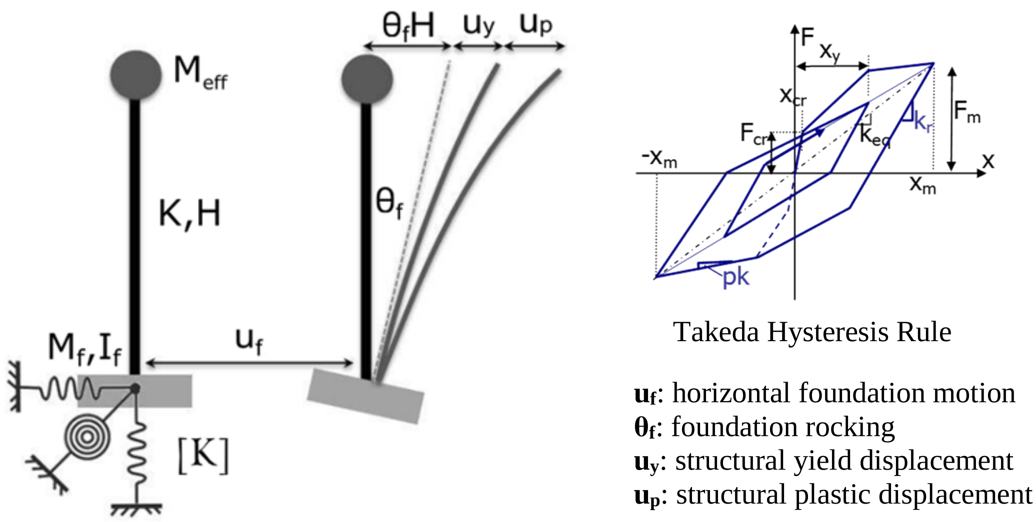


Figure 2. Soil – foundation – structure model for horizontal and rocking foundation motions

Soil-Structure Interaction Modelling

Foundation's dynamic impedance stiffness

Inertial interaction was considered by evaluating the foundation dynamic stiffness matrix using formulas for surface foundation resting on a homogeneous halfspace according to (Mylonakis et al. 2006). The aforementioned calculated impedance stiffness was incorporated in the numerical model using springs and dashpots with appropriate frequency-dependent coefficients calibrated to the predominant frequency of the excitation.

Soil nonlinearity

To incorporate soil nonlinearity into the soil-foundation system, the conventional equivalent linear method was utilized. This approach is based on approximating the nonlinear stress-strain curve of soil by a secant stiffness, G_{sec}, and an equivalent damping, ξ_{eq}, that are compatible with the strain in the soil induced by the ground shaking. The modification factors provided by EC8-5 (2004) associating G, V_s and ξ with Peak Ground Acceleration, were used herein to calculate the values of G_{sec} ($G_{sec} = V_{sec}^2\rho$) and equivalent damping ξ_{eq}.

Input Ground Motions

The symmetric Ricker wavelet (2nd derivative of Gaussian, also called "Mexican Hat") with different amplitude and frequency content was employed in this study, as shown in eq. (1).

$$\psi\left(\frac{t-\xi_t}{s}\right)=\left[1-\left(\frac{t-\xi_t}{s}\right)^2\right]e^{\left[-\frac{1}{2}\left(\frac{t-\xi_t}{s}\right)^2\right]} \tag{1}$$

where: s is the scale parameter that controls the dilation or contraction of the wavelet, ξ_t is the translation time (i.e., the movement of the wavelet along the time axis) and $\psi(t, s, \xi_t)$ is the Ricker wavelet function.

Parametric scheme

MDOF Structures

For the aforementioned two real RC buildings, a total number of 160 non-linear response history analyses were conducted for the cases of (a) fixed base conditions and compliant soil of three different types with shear wave velocity V_s equal to 350, 250 & 150 m/s, (b) two levels of PGA equal to 0.10g and 0.50g and (c) 10 different predominant periods of the exciting pulse, ranging from 0.1–1.0s at a step of 0.1s. The excitation was bi-directional and simultaneously applied, while the combination was performed according to the 30% rule.

SDOF Structures

For the ten idealized SDOF oscillators a total number of 1600 non-linear response history analyses were performed corresponding to: (a) fixed base condition and compliant soil of three different types with shear wave velocity Vs equal to 350, 250 & 150 m/s, as previously, (b) four levels of PGA equal to 0.05g, 0.20g, 0.35g and 0.50g and (c) 10 different predominant periods of the excitation again ranging from 0.1–1.0s at a step of 0.1s.

SFSI EFFECTS ON SEISMIC DEMAND

The results from the non-linear response history analyses performed are presented in the following figures illustrating SFSI effects on seismic demand for the different cases of ground motions and soil compliance considered in the present study.

MDOF structures results

The effect of foundation flexibility on inter-storey drift demand for Buildings I and II is illustrated in Figure 3 and Figure 4, respectively. In these figures, the variation in the inter-storey drift ratio between the SFSI and the fixed-base system is shown as function of the normalized predominant period of the pulse to the building's first mode's period (T_p/T_s). The response of the fixed-base structure is denoted with the subscript "fixed", while the response of the flexibly-base structure is denoted with the subscript "sfsi". The maximum drifts d(%) are calculated from the displacement response histories in the y-y direction. The ratio of the response of the two systems illustrates whether the SFSI effects in fact amplify (d_{sfsi}/d_{fixed} > 1.0) or reduce (d_{sfsi}/ d_{fixed} < 1.0) seismic demand and the associated damage.

At first, it is observed for Building I that the SFSI effects amplify the inter-storey drift for pulses with predominant period larger than the fundamental structural period T_s (i.e., $T_p/T_s > 1.0$) and reduces it when $T_p<T_s$ holds. This limit is slightly different for Building II, where detrimental amplification is seen for $T_p/T_s>0.8$. Interestingly, these amplification threshold limits show only a minor dependence in PGA and soil compliance. On the contrary, as anticipated, the magnitude of the variation is highly related to both PGA and soil compliance. As far as the soil compliance is concerned, it is observed that for softer soils (smaller values of shear wave velocity), SFSI effects are more profound. For example, the inter-storey drift ratio for Building I corresponding to PGA = 0.10g and T_p/T_s=2 are 1.25, 1.55 & 2.2 for Vs = 350 m/s, 250 m/s & 150 m/s, respectively. However, the aforementioned dependence is inherently related to PGA and to the structure's degree of inelasticity. As a result, for higher levels of PGA, more damage is induced in structures resulting to larger structural period elongation and greater hysteretic damping thus leading to a decrease of SFSI effects.

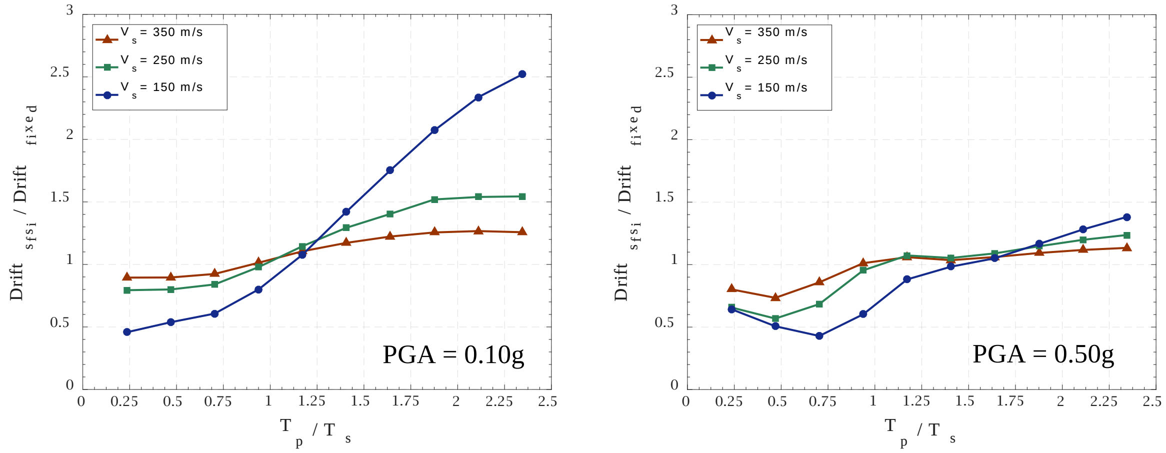


Figure 3. SFSI effects on inter-storey drift demand for Building I versus the predominant period of the pulse (T_p) normalized to the structural period (T_s=0.427s) for PGA = 0.10g (left) and PGA = 0.50g (right).

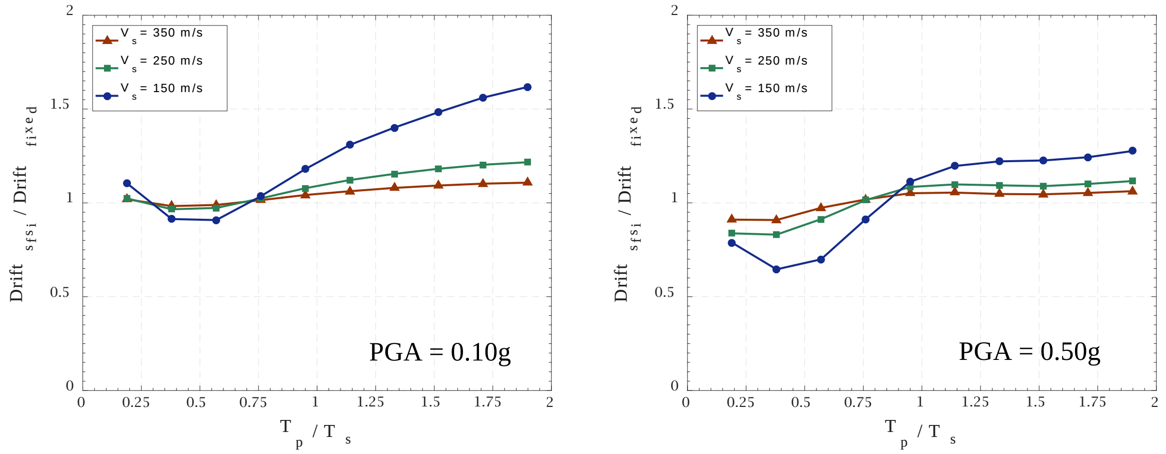


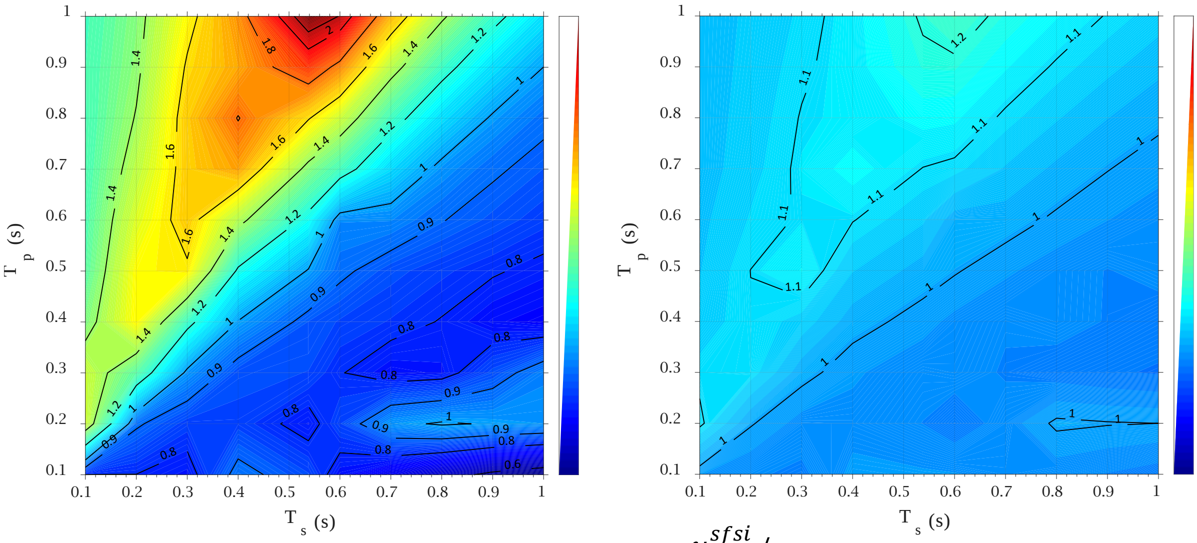
Figure 4. SFSI effects on inter-storey drift demand for Building II versus the predominant period of the pulse (T_p) normalized to the structural period (T_s=0.527s) for PGA = 0.10g (left) and PGA = 0.50g (right).

SDOF system results

The assessment of SFSI effects on SDOF oscillators is performed in terms of structural ductility demand imposed and is formulated for the flexible-base systems as $\mu_d{}^{sfsi} = u_d{}^{sfsi} / u_y$, where $u_d{}^{sfsi}$, is the maximum structural displacement after substracting the rigid body component due to translation and rotation of the foundation and u_y, is the yield displacement of the structure. The ductility demand of the fixed-base systems is calculated in a same manner by substituting $u_d{}^{sfsi}$ with $u_{max}{}^{fixed}$, i.e., the maximum horizontal displacement at the top. Consequently, the response ratio in ductility terms, $\mu_d{}^{sfsi} / \mu_{fixed}$, is defined as $u_d{}^{sfsi} / u_{max}{}^{fixed}$, on the assumption of a constant yield displacement, u_y.

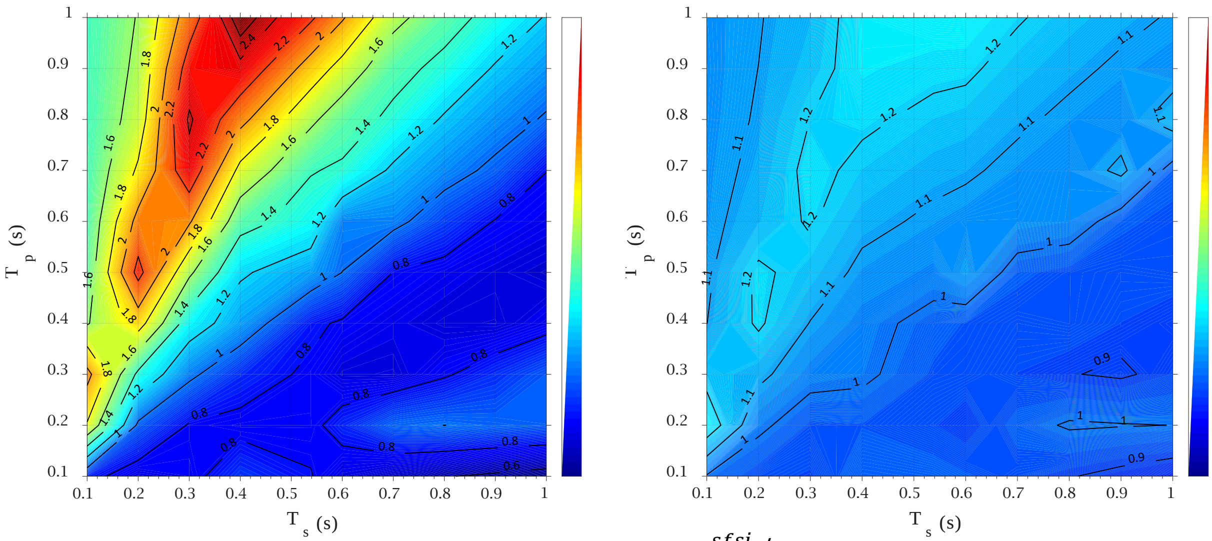
Figures 5 and 6 plot this response ratio in terms of structural displacement and ductility, respectively, as a function of the structural period (T_s) and the predominant period of the pulse for different values of shear wave velocity 350 & 150 m/s. Figure 5 corresponds to PGA level of 0.05g, where, as anticipated structural response remained linear elastic, whereas Figure 6 corresponds to PGA level of 0.20g. Firstly, from both figures, it can be clearly observed that SFSI effects are more significant (i.e., lead to larger magnitudes of seismic demand) for shear wave velocity V_s equal to 150m/s (left) than 350m/s (right) under the same level of PGA. In other words, the more compliant the soil, the more profound the SFSI impact, as anticipated. Furthermore, by comparing these two figures for the case of V_s = 150m/s (i.e., Figures 5 and 6, left) it can be seen that SFSI effects may be benefial (i.e., response ration remains below 1.0) approximately for all structures below the diagonal (T_p/T_s<1.0 or more accurately, T_p/T_s<0.8). For cases where the pulse period exceeds that of the structure T_p/T_s>0.8, both the elastic (Figure 5) and the inelastic demand (Figure 6) may be amplified due to SFSI by a factor of up to 2.0 and 2.6, respectively. This can be attributed to the fact that for structures where

T_s<T_p, the period elongation associated with SFSI leads to resonance effects, which are of course more profound when additional yielding (and further elongation of structural period) take place.



Displacement demand ratio: $u_d^{sfsi} \big/ u_{max}^{fixed}$

Figure 5. Structural displacement demand ratio between SFSI and fixed-base nonlinear systems for PGA a_g=0.05g, V_s=150m/s (left) and V_s=350 m/s (right) for all the examined structural (T_s) and predominant pulse periods (T_p).



Ductility demand ratio: $\mu_d^{sfsi} \big/ \mu_{fixed}$

Figure 6. Structural ductility demand ratio between SFSI and fixed-base nonlinear systems for PGA a_g=0.2g, V_s=150m/s (left) and V_s=350 m/s (right) for all the examined structural (T_s) and predominant pulse periods (T_p).

Figure 7 shows the variation of the ductility demand ratio as a function of normalized structural period to predominant period of the pulse (T_s/T_p). It can be observed that for higher levels of PGA, SFSI effects tend to decrease and become less significant. Finally, Figure 8 illustrates the specific conditions under which neglecting SFSI leads to non-conservative estimates of ductility demand, (or else, that SFSI effects are *detrimental*) for PGA = 0.20g. As previously, it can be derived that for this level of PGA, SFSI adversely affects the response of slender structures for $T_s/T_p < 1.25$. It is noted herein that, these kind of diagrams may be useful in the preliminary design of structures, as a rough guide for the engineer to decide whether or not SFSI should be taken into consideration.

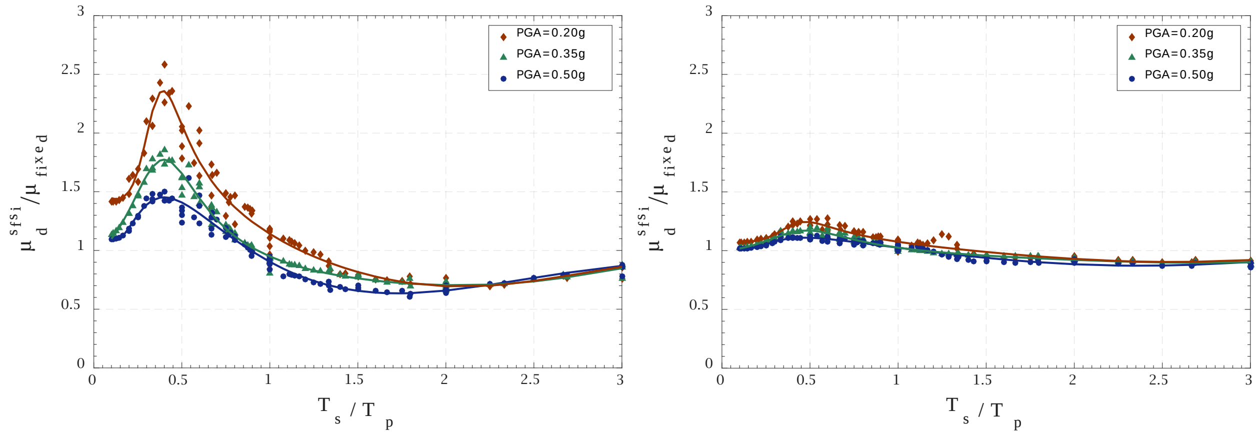


Figure 7. Structural ductility demand ratio between SFSI and fixed-base nonlinear systems for soil shear wave velocity Vs =150 m/s (left) and Vs = 350 m/s (right)

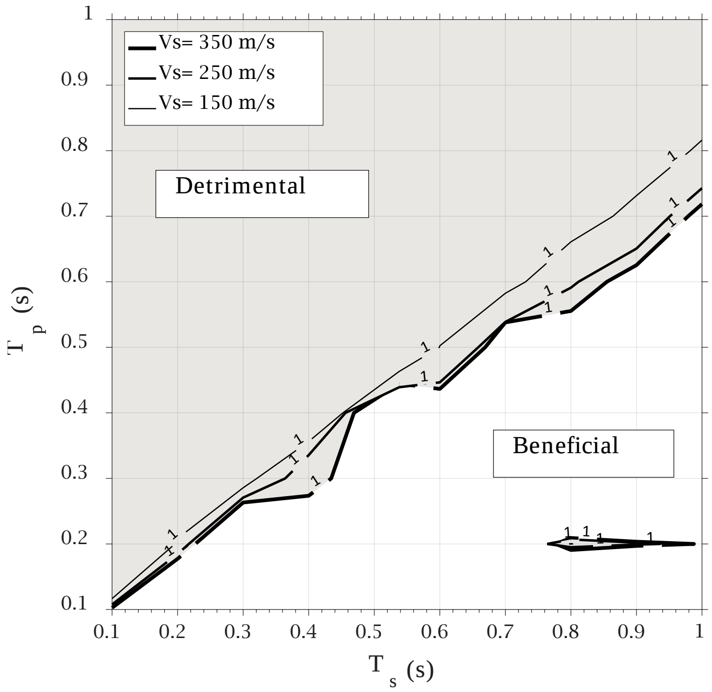


Figure 8. Areas of SFSI effects on seismic demand for PGA = 0.20g as a function of structural period (T_s) and predominant period of the pulse (T_p).

CONCLUSIONS

This study aimed to identify the cases that the simplified assumption of support fixity underestimates seismic demand of RC buildings. Along these lines, a parametric analysis was performed for two real buildings and ten equivalent SDOF oscillators representative of real multi degree of freedom structures. Three different soil types were adopted with shear wave velocity V_s equal to 350, 250 & 150m/s. The seismic response of the oscillators under multiple Ricker pulses of different amplitude and frequency was identified through non-linear response history analysis that takes into account material nonlinearities in both the soil and the superstructure. The conclusions drawn are summarized as follows:

- SFSI effects were found to be detrimental, i.e., leading to larger inter-storey drift or ductility demand, for structures with fixed base natural period shorter than approximately 1-1.25 times the predominant period of the pulse (T_s/T_p<1.0-1.25 or T_p/T_s<0.8-1.0) and beneficial for structures with longer natural period.

- In cases where SFSI effects lead to an amplification in seismic demand, it was found that the magnitude of this amplification depends highly on the degree of structural nonlinearity. In particular, the more inelastic the oscillator behavior the less profound the SFSI effects on the modification of seismic response.
- The variation in inter-storey drift for the MDOF structures and ductility demand for the SDOF oscillators, when SFSI is considered, is also depended on soil compliance. The more compliant the soil becomes the more significant the variation in seismic demand.

Despite the fact that the conclusions drawn cannot be easily generalized, it is an attempt to quantify the effects of SFSI on the complex dynamics and seismic response of real RC buildings and identify the case that support fixity may lead to non-conservative estimates of specific Engineering Demand Parameters. Further analytical work is required to investigate the effects of SFSI on non-linear structures with different dynamic and inelastic characteristics, as well as different foundation types and soil conditions.

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