Soil-structure interaction effects on seismic behaviour of reinforced concrete frames

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ABSTRACT:
It is often the case that soil beneath the structure is ignored in numerical analyses. In most cases there are two reasons for neglecting the soil in analyses: complexity in modelling of the soil and, as mostly believed, beneficial effects of the soil on structures. The paper discusses three different approaches on numerical modelling of fixity of structures with the soil beneath: conventionally fixed structure, structure on Winkler springs and structure on half-space. Linear elastic analysis was carried out on three-, seven- and ten-story three-bay reinforced concrete frames using time history analysis. All of the structures were founded on soft soil as defined according to Eurocodes. Ground motions used were selected from the European Strong-Motion Database. Also, the paper gives outline of recommendations on including soil-structure interaction in structural models according to European and American seismic regulations and highlights detrimental effects of soil-structure interaction on low-rise buildings.

Keywords: soil-structure interaction, seismic behaviour, reinforced concrete, numerical model, soft soil

1. INTRODUCTION

The well estimated seismic behaviour of structures is of great importance when designing new structures or when making retrofit of the existing ones. In practice fixed based models of structures in dynamic analyses are an often assumption. While in most cases this is a valid assumption, and to a certain point a codified rule, there has been continuous research which states that in some special cases fixed base models can lead to an underestimation of response under seismic demand.

During an earthquake event, the structure interacts with the foundation soil causing it to deform. The soil deformations, in turn, cause the motion of the supports or the interface region of the soil and the structure to be different than that of the free field ground motion. Such ongoing interactions cause a substantial change in the response of both the structure and the soil. For very stiff soils or when the stiffness of the foundation soil is relatively high compared to the stiffness of the structure, this change is extremely small and can be neglected. Therefore, consideration of base fixity remains a valid assumption for the superstructure constructed on firm soil. On the other hand, in the case of medium firm to loose soils, it is known that flexibility of foundation is usually accompanied with lengthening of the fundamental period of the soil-structure system and an increase in damping. Using typical code spectra, it is usual to assume that this may always lead to a reduction in the spectral acceleration and consequently, lower seismic demands for the superstructure. Hence, fixed based models are assumed to be too conservative.

Some findings however reveal that the latter may not be the case for some soil sites and under specific earthquake motions with particular properties (for example frequency content) (Fardis, 2010; Gazetas, 2010; Mylonakis and Gazetas, 2000). Coupled with these findings, the questionable code based design spectra and lack of code recommendations for SSI are taken under a loop in order to establish some ground work for investigation of this usually neglected phenomenon.

The main objective of this paper is to evaluate the effect of soil-structure interaction on the behaviour of reinforced concrete frames subjected to European earthquake motions and analysed according to European regulations. Also, the aim of this paper is to put additional light on importance of including soil in numerical analyses of structures. Linear elastic analysis was carried out on three different types of structures founded on two different soil profiles. Three different soil modelling techniques were employed in order to show the sensibility of results and to give some rough recommendations in the framework of seismic design codes.

2. SOIL-STRUCTURE INTERACTION WITH EMPHASASIS ON SEISMIC REGULATION

European regulation for seismic design of structures (CEN, 2004b; 2004c; 2005) contains very few information for including soil-structure interaction in numerical calculations. According to CEN (2004c) the effects of dynamic soil-structure interaction should be taken into account only in: a) structures where 2nd order effects play a significant role; b) structures with massive or deep-seated foundations; c) slender tall structures and d) structures supported on very soft soils, with average shear wave velocity less than 100 m/s.

On the other hand, FEMA (2000 and 2005) gives simplified procedures for including the effects of soil-structure interaction in a structural model. FEMA (2000) implies that soil-structure interaction may modify the seismic demand on a building. Furthermore, according to FEMA (2000) the effects of soil-structure interaction must be evaluated for near-field and soft soil sites and also for buildings in which an increase in fundamental period due to the effects will result in an increase in spectral acceleration. Good estimate of fundamental period of a building is of great importance for a new approach in design called Performance Based Design that is under continuous development and which have become a contemporary tool in the field of earthquake engineering (Džakić, Kraus and Morić 2012).

In order to properly assess the problem of soil-structure interaction in the context of seismic analysis one must be familiar with the dynamic properties of both the structure and the foundation soil. Dynamic characteristics of the structure are clearly defined through the principles of structural dynamics, and so are partly the properties of the soil. In addition to this, dynamic properties of the soil are highly dependent on wave propagation through the soil medium. Firstly, the knowledge of wave propagation through the soil medium is essential to understand ground motion modifications due to soil properties. Secondly, the knowledge of the vibration characteristics of the soil medium due to wave propagation is important in relation to the determination of the soil impedance functions when using multi-step methods. Once one is familiar with the above mentioned, the mechanism of soil-structure interaction can be defined through two main effects which take place in earthquake excitation (Stewart, Fenves and Seed, 1999).

There are two types of interaction (FEMA 2005): inertial Interaction and kinematic interaction. Inertial forces induced by foundation motion during the earthquake can cause the compliant soil to deform which in turn affects the super-structure inertial forces. This deformation propagates away from the structure in six degrees of freedom of the foundation motion. In other words, the dynamic response of the superstructure decreases. When the earthquake ground motion in the free-field is varying over the area corresponding to that of a stiff foundation, then it can be constrained and modified by the stiff foundation. This deviation from free field motion is called kinematic interaction between the soil and foundation. Kinematic interaction can be significant in cases with very stiff or embedded foundations (Kramer, 1996), thus this paper is focused only on inertial effects.

3. NUMERICAL MODELS

For the purpose of this research a 2D linear elastic analysis was carried out on three-, seven-, and ten story three-bay reinforced concrete facade frames using time history analysis. The frames are part of residential buildings regular in plan and elevation which are located in a high seismically active area. The buildings are assumed to be founded on shallow strip foundations that rest on soft soil.

The numerical analysis was performed using the general-purpose structural analysis program SAP2000 (CSI 2009 Version 14.1.0). Reinforced concrete beams and columns were modelled using elastic frame elements assuming gross section properties. The beams were modelled having T-cross section to account for the effective width of the slab according to CEN (2004a). Damping ratio of the buildings is taken equal to 5 %. Rayleigh damping was included in the analysis.

A parametric investigation was carried out assuming three cases of building fixity to the ground: a) building is conventional fixed at the ground level; b) building is founded on flexible base represented by Winkler springs; c) building is founded on uniform, viscoelastic half-space (Fig. 1.).

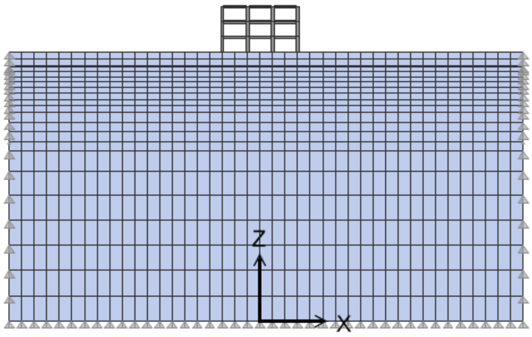


Figure 1. Half-space represented using finite element model of soil with primary boundaries.

As noted by Tabatabaiefara and Massumi (2010), the distance of the structure centre to the soil finite element model boundaries should be within three to four times the foundation radius in horizontal direction and two to three times the foundation radius in the vertical direction, to make the effects of the reflexive waves negligible. Therefore, horizontal distance between soil boundary and centre of building has been adopted equal to 50 m, while vertical distance between soil boundary and foundation of building has been adopted equal to 100 m as this is the bedrock depth of soil profiles observed provided from Book 13 (2008) (see Fig. 2. where γ is soil specific weight and v_s is shear wave velocity).

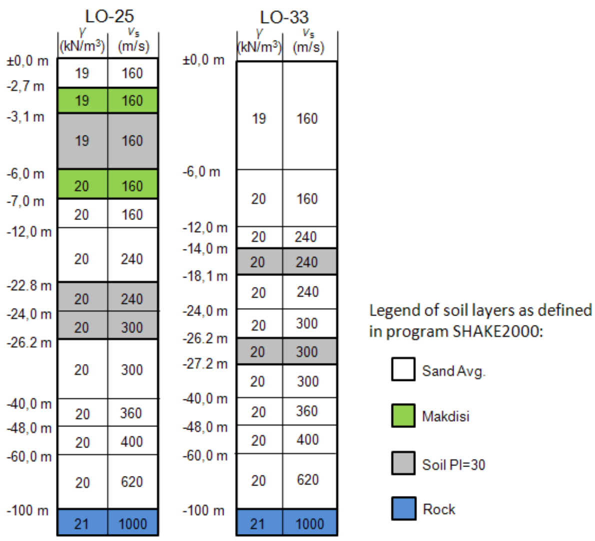


Figure 2. Two soil profiles taken in Osijek, Croatia used in analysis (Book 13, 2008)

The soil finite element model was modelled using quadrilateral shell elements having thickness equal to 1 m. The width of the shell elements is equal to 2,5 m, while the height (i.e. depth) of the shell elements vary from 0.5 to 5 m depending on the thickness of specific layer of the soil profile provided in Book 13 (2008).

The stiffness and damping of the translational and rotational Winkler springs were calculated as suggested by Stewart, Fenves and Seed (1999) and Arefi (2008). For calculating those parameters, strip footing 1 m wide and 16 m long was assumed.

For all soil layers damping of 8 % is assumed, except for rock, i.e. half-space, where damping is assumed equal to 2 % (Book 13, 2008). Furthermore, Poisson's coefficient of 0,2 is assumed for all soil layers (Book 13, 2008). It is worth noting that the soil profiles selected for the analysis corresponds to ground type C as described by CEN (2004b).

Tilting of the building was not observed within this paper, also, it was assumed that the height of the water table is zero.

3.1. Materials

The frame elements, as well as floor and roof slabs, are assumed to be normal weight concrete of class C25/30 (CEN, 2004a) with characteristic compressive cylinder strength at 28 days f_c = 25 MPa, secant modulus of elasticity E_{cm} = 31000 MPa and specific weight γ_c = 25 kN/m^3 which includes the weight of the reinforcement.

3.2. Geometry

The frames are assumed to have a span length of L_b = 5,0 m, while the story height is taken to be L_c = 3,0 m, which are in the usual range for residential buildings. The cross sectional properties of beams and columns corresponding to the three-, seven- and ten-story frame are shown in Tab. 1. Floor and roof solid reinforced concrete slabs are assumed to satisfy all criteria to be treated as rigid diaphragms CEN (2004b).

Table 1. Geometry of structural elements

Building height (floors)	Beams				Columns		
	b_b [cm]	h_b [cm]	b_{eff} [cm]	L_b [cm]	b_c [cm]	h_c [cm]	L_c [cm]
3	30	50	170	500	40	40	300
7	30	50	170	500	60	60	300
10	30	50	170	500	70	70	300

3.3. Loading on frames

The gravity load includes both dead and imposed loads. The structural analysis program SAP2000 (CSI 2009 Version 14.1.0) calculates the self-weight of the structure automatically. Additional dead load added to floor and roof slabs is equal to 2,5 kN/m^2 and 3,5 kN/m^2 respectively. Imposed loads for floors and roof was taken equal to 2,0 kN/m^2, which is the code value for residential buildings (CEN 2002b). The value of the mass which should produce inertial effects during earthquake excitation is taken according to CEN (2004b) and is equal to:

$$\sum G_{k,j} \text{"+"} \sum \psi_{E,i} \cdot Q_{k,j}\,, \tag{1}$$

where $\psi_{E,i}$ represents the ratio of the participating live load during a seismic event and is taken as 0,15 according to CEN (2004b) with floors occupied independently.

3.4. Earthquake loading

The ground motions were selected from the European Strong-motion Database, all to match target response spectrum of ground type A defined according to CEN (2004b). Those ground motions were modified using SHAKE2000 (Ordóñez, 2011), a computer program for equivalent-linear site response analysis. Original motions were applied to the base of the numerical models with soil modelled using shell elements while modified motions, i.e. motions taken from the top of the soil profiles modelled using SHAKE2000 (Ordóñez, 2011) were applied to the base of the numerical models with fixed base conditions and with soil modelled using Winkler spring elements.

Using freely available computer aided code-based program REXEL (Iervolino, Galasso and Cosenza, 2010) seven real ground motions were selected for conducting the analysis (Fig. 3.).

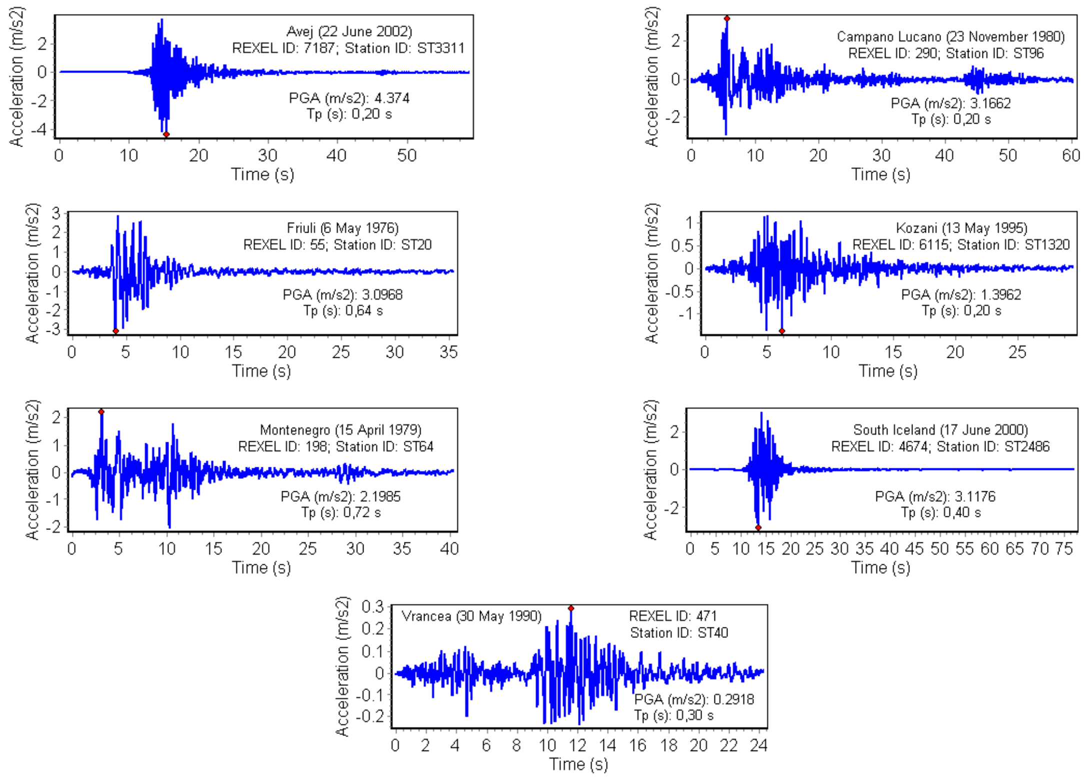


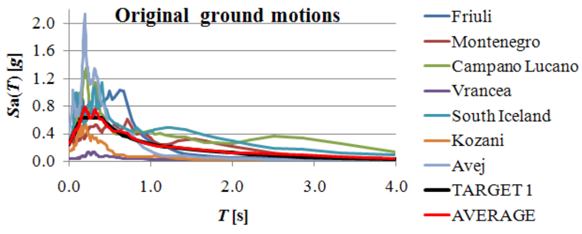
Figure 3. Ground motions obtained from program REXEL

Selection of ground motions was conducted using the anchoring value of the spectrum a_g set to 0,25. Also the limits for magnitude M and source to site distance R was set equal to 6,5 - 7,0 and 0 km - 35 km respectively. Spectrum matching was done by setting maximum deviations, i.e. lower tolerance and upper tolerance to 10 % and 30 % respectively between periods T_1 and T_2 equal to 0,15 s and 2 s respectively.

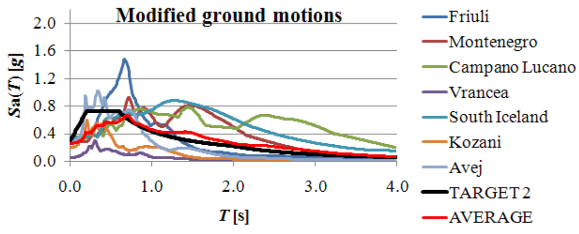
4. RESULTS AND DISCUSSION

Average spectrum calculated using ground motions recorded on ground type A (TARGET 1) and modified using program SHAKE2000 shows good match with spectrum for ground type C (TARGET 2) defined according to Eurocode 8 (2004b) (see Fig. 4.). The matching is especially good for periods after 0,6 s.

Fundamental periods of vibration of buildings for different soil models are shown in Tab. 2. It has been observed that the building models with soil included, compared to conventional fixed base models, have 70 % higher fundamental periods of vibration, except for buildings higher than three stories having modelled using finite elements which have up to 120 % higher fundamental periods of vibration.



a)



b)

Figure 4. Spectral functions obtained from: a) original ground motions and b) modified ground motions

Table 2. Fundamental periods of vibration of buildings for different soil models

Building height (floors)	Fundamental period of vibration of a building (s)		
	Soil model		
	Fixed	Spring	Half-space
3	0,4	0,7	0,7
7	0,7	1,2	1,5
10	1,0	1,7	2,2

Results of the performed analyses are summarized in form of diagrams and shown in Fig. 5. and Fig. 6. as total story shear V_{story} to total weight of building W_{EQ} ratios and as storey drifts respectively. Since seven ground motions were used to observe seismic behaviour of the models of buildings and as recommended by CEN (2004b) and Čaušević (2010), only average results are shown.

Even at the early phase of soil response analyses it was assumed that the two soil profiles analyzed (LO-25 and LO-33) would not impose much difference in response of the structures. Distribution of total story shear V_{story} to total weight of building W_{EQ} ratios and storey drifts is quite the same for both soil profiles. Results obtained from models with soil LO-33 are 5 % smaller when compared to results obtained from models with soil LO-25.

The response of the three-storey frame, i.e. low-rise building, shows that the fixed base assumption is far from the safe side since the base shear (Fig. 5.) and the storey drifts (Fig. 6.) are much higher in the case when soil-structure interaction effects are included in structural model. First storey drifts are usually the most critical ones and the difference between the three modelling approaches are significant.

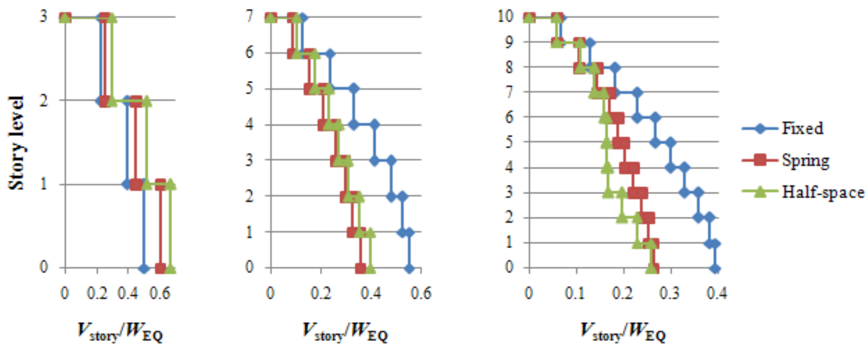


Figure 5. Distribution of story shear

Most significant difference, when referring to story drifts, can be seen for the three-storey frame. When compared the fixed base model and the model on half-space this difference approaches almost

500 % (Fig. 6.). For the same frame the difference for story drifts between the fixed base model and the Winkler model is about 100 % which is still more than significant. The difference in base shears varies about 10 % for the fixed base model and models with soil included which is not much and can be neglected.

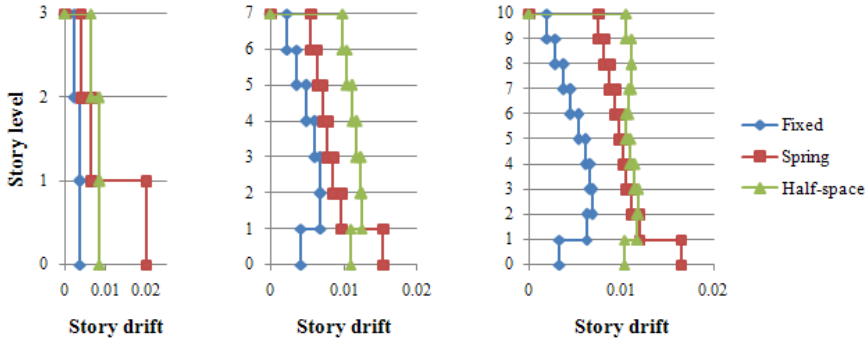


Figure 6. Distribution of story drift

On the other hand, the seven- and ten-storey frames, when compared to the three-story frames, have an opposite trend when observing the distribution of base shear. The fixed base model is the critical one having up to 64 % higher base shear for the seven- and 65 % higher base shear for the ten-storey frame when compared to models with soil. Storey drifts however show that the soil flexibility has significant impact on seismic behaviour of buildings, pointing out differences up to 400 % in the critical first storey for both the seven- and ten-storey frames.

Furthermore, when observing the story drifts, the upper stories of the three storey frame are not as much affected as are those of the seven- and ten-storey frames are, showing differences up to 100 % and 400 % respectively.

As far as the soil modelling choice is concerned there is not much difference between the Winkler and half-space model in terms of base shear for any of the three frames observed. The mentioned difference does not exceed 10 % and shows good correspondence between the two modelling approaches. In terms of storey drifts however the two approaches vary up to 60 % for the seven- and ten-storey frames, while for the three storey frame this difference exceeds 100 %. However the before mentioned concerns only the first storey drifts while the upper stories show much less difference. Although in the case of the seven-storey frame the drifts are much more amplified and reach 100 % in favour of the half-space model.

Weighing the time and cost factors the Winkler model can be adopted as a more satisfactory approach, at least when relatively simpler structures are of concern. Approximately the same amount of time is needed for modelling soil using Winkler springs and finite elements, i.e. shell elements but calculation of model with Winkler springs, when compared to model with finite elements, is up to five times faster.

5. CONCLUSION

The paper shows that including soil in a model of structure does not always have beneficial effects, as often believed. Analyses conducted shows that structure models with soil included have much higher values of story drifts, especially when the soil is modelled using Winkler springs. Furthermore, a common assumption that including soil to a model of structure would elongate fundamental period of structure and thus reduce internal forces shows to be wrong. This research shows that this assumption is not valid for low-rise buildings founded on soft soil. The models with soil included, compared to conventional fixed base models, have 70 % higher fundamental periods of vibration but also up to 400

% higher base shear. Since this research was conducted using linear-elastic models, further investigation on nonlinear models is underway.

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REFERENCES

Arefi, M.J. (2008). Effects of soil-structure interaction on the seismic response of existing R.C. frame buildings. A dissertation submitted in partial fulfilment of the requirements for the Master Degree in Earthquake Engineering and Engineering Seismology. Istituto Universitario di Studi Superiori di Pavia, Università degli Studi di Pavia. Available online at: www.roseschool.it/files/get/id/4458, accessed 28 April 2013

Book 13: Geotechnical project, No. 120-S-038 (2008). University of Zagreb, Faculty of civil engineering, Department of Geotechnics. (in Croatian)

Čaušević, M. (2010). Dinamika konstrukcija, Golden Marketing, Tehnička knjiga, Zagreb (in Croatian)

CEN - European Committee for Standardization (2002a). Eurocode - Basis of structural design

CEN – European Committee for Standardization (2002b). Eurocode 1 – Actions on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings

CEN – European Committee for Standardization (2004a). Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings

CEN - European Committee for Standardization (2004b). Eurocode 8 - Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

CEN - European Committee for Standardization (2005). Eurocode 8: Design of structures for earthquake resistance - Part 2: Bridges. European Committee for Standardization, Brussels, Belgium

CEN - European Committee for Standardization (2004c). Eurocode 8: Design of structures for earthquake resistance - Part 5: Foundations, retaining structures, geotechnical aspects. European Committee for Standardization, Brussels, Belgium

Computers and Structures Inc. (CSI) (2009). SAP2000, structural analysis program. Version 14.1.0. Berkeley, California

Džakić, D., Kraus, I., Morić, D. (2012). Direct displacement based design of regular concrete frames in compliance with Eurocode 8. Technical Gazzette **19: 4**, 973-982. Available online at: www.hrcak.srce.hr/file/137752, accessed 21 April 2013

Fardis, M.N. (2010). Advances in Performance-Based Earthquake Engineering, Springer

Federal Emergency Management Agency (FEMA) (2000). Prestandard and commentary for the seismic rehabilitation of buildings. FEMA 356, prepared by American Society of Civil Engineers, Reston, Virginia prepared for Federal Emergency Management Agency, Washington, D.C., USA

Federal Emergency Management Agency (FEMA) (2005). Improvement of nonlinear static seismic analysis procedures. FEMA 440, prepared by Applied Technology Council (ATC-55 project), Redwood City, California prepared for Department of Homeland Security, Federal Emergency Management Agency, Washington, D.C., USA

Gazetas, G., Ziotopoulou, A. (2010). Bi-normalized Response Spectrum for a Rational Soil-Structure Interaction Analysis, Workshop on Soil Structure Interaction (SSI) Knowledge and Effect on the Seismic Assessment of NPPS Structures and Components, Otawa, Canada, 6-8

Iervolino, I., Galasso C., Cosenza, E. (2010). REXEL, computer aided record selection for code-based seismic structural analysis. Bulletin of Earthquake Engineering 8, 339-362. Available online at: http://wpage.unina.it/iuniervo/papers/Iervolino_et_al_REXEL_BEE.pdf, accessed 6 April 2013

Kramer S. L. (1996). Geotechnical earthquake engineering, Prentice Hall

Mylonakis, G. Gazetas, G. (2000). Seismic soil structure interaction: Beneficial or Detrimental? Journal of Earthquake Engineering **4: 3**, 277-301

Ordóñez, G.A. (2011). SHAKE2000, a computer program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems. User's Manual. Available online at: http://www.geomotions.com/Download/SHAKE2000Tutorial.pdf accessed 5 April 2013

Stewart, J. P., Fenves, G. L., Seed, R. B. (1999). Seismic soil-structure interaction in buildings. I: Analytical methods. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **125: 1**, 26-37

Tabatabaiefara, H.R., Massumi, A. (2010). A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil-structure interaction. Soil Dynamics and Earthquake Engineering **30: 11**, 1259-1267