Performance - based design of soil – foundation – structure systems

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15 WCEE
LISBOA 2012

SUMMARY:
Soil - foundation - structure interaction (SFSI) is incorporated herein to the study of seismic performance of typical structural models. As opposed to traditional seismic design, soil - foundation system compliance is taken into account in the estimation of structural performance. The influence of several parameters on structural response, such as soil - to - superstructure stiffness ratio, structure slenderness, and soil - to - structure mass ratio, are incorporated in a series of parametric elastic time history analyses using the finite element method. The SFSI effects are examined in terms of performance point values, which are designated graphically at the intersection of the effective input motion demand spectrum and the SFSI system fundamental period. It is demonstrated that neglecting SFSI in performance-based design may lead to overestimation of the design forces, in terms of spectral acceleration and displacement.

Keywords: soil-foundation-structure interaction, demand, performance, earthquake engineering

1. INTRODUCTION

When analyzing the seismic response of structures it is common practice to make the assumption of a fixed-base structure and thus make use of the elastic design demand spectra for free-field conditions as proposed by seismic codes. However, in most cases foundation soil is flexible and the real demand spectra for every structure are affected by the soil-foundation-structure interaction (SFSI). Despite engineering practice did not consider SFSI effects - assuming that these effects are beneficial for the structures - many recent earthquakes showed and highlighted that in many cases SFSI effects play detrimental role to structural response (Mylonakis and Gazetas, 2000). The seismic codes (FEMA440, 2005) in many cases use practices that are not always very accurate. These practices are characterized by important simplifications. Some of the simplifications adopted by the seismic codes and affect the structural response are the smooth shape of design spectra, the impedances proposed, the way these impedances are estimated and finally the assumption of ignoring the kinematic effects of SFSI. The aim of the present study is to highlight and discuss the potential differences of the traditional approach in the case that we are considering the SFSI. The soil – foundation – structure system is more flexible than the traditionally assumed fixed-base model (Avilés, J. and Pérez-Rocha Luis, E., 2004, Aviles, J., Suarez, M., 2001, Aviles, J. and Perez-Rocha Luis, E., 2003). Since 1970's many researchers tried to estimate the elastic response of structures (Chopra, AK. and Gutierrez, JA., 1974, Veletsos, AS., 1997, 1974) taking into account the SFSI effects. The aim of this study is exactly to investigate the actual response of the structure under actual seismic excitations, taking into consideration the SFSI effects.

2. PERFORMANCE POINT FOR ELASTIC STRUCTURAL RESPONSE

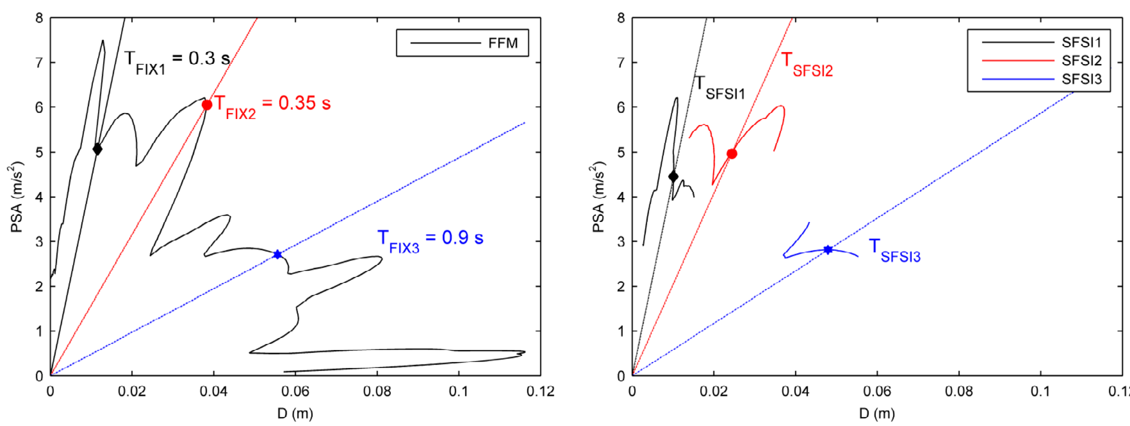
Conventionally, civil engineers evaluate the performance point (PP) for elastic structural response (using capacity demand diagram method) graphically, as the intersection of the demand spectrum in free-field conditions and the radial line that refers to the structural period for fixed-base conditions. The demand curve that occurs in this way from the free-field motion is the same for all structures (Fig.

2.1.a), because the foundation input motion is the same, irrespectively of structural materials, sections and dynamic proprieties. This assumption could be close to reality when the structure is founded on rock. FEMA356 (FEMA356, 2000) and ATC-40 (ATC-40, 1996) propose to include the SFSI effects by considering the stiffness and strength of the underlying soil, the so-called inertial interaction. However, these procedures do not propose anything for considering kinematic interaction although kinematic interaction modifies seismic input at foundation level. FEMA440 proposes a simplified procedure, which takes into consideration the whole SFSI phenomenon. According to FEMA440, kinematic interaction effect is composed of the foundation slab averaging, the wave scattering and the embedment effects. However, FEMA440 methodology neglects the effect of inertial interaction on the foundation input motion assuming that the effects of inertial interaction on the foundation input motion are concentrated near the first structural mode (Kim and Stewart, 2003).

In this study the demand spectrum is evaluated from the acceleration time history at the level of foundation which results from the analyses of the whole SFSI system. From now on we will refer to this motion as effective input motion (EIM). The use of FIM instead of EIM is rather simplifying, due to the fact that actual recordings in buildings include not only the kinematic, but part of the inertial interaction as well. Moreover inertial interaction is more significant to the first mode of the structure but on the other hand the first structural mode is the one that affects the most the structural response.

Using the direct method for analyzing the SFSI phenomenon, the ground motion (acceleration time history) at the centre of the foundation (EIM) differs from the one for free-field conditions, and therefore the demand spectrum for the structure will be affected. The difference between the two curves depends on the extent of SFSI effects. The demand spectrum curve that occurs from the compliant system response concerns only the specific dynamic characteristics and therefore only one point of this curve is conceptually 'correct', that is the point which corresponds to the SFSI system period (Fig. 2.1b). Another system with different characteristics will have a different pair of spectral ordinates. The flexible system fundamental period including interaction is calculated numerically by harmonic analyses.

In the following sections two cases are compared for the evaluation of PP. The first one is the conventional approach from the free-field motion (FFM) and the second one the approach we propose herein (SFSI). After presenting the data used in the analyses, the main differences of these approaches in terms of maximum acceleration and displacement structural response will be highlighted.



(a) (b)

Figure 2.1. (a) Conventional evaluation of P.P. (b) Evaluation of P.P in the present study

3. SOIL-FOUNDATION-STRUCTURE SYSTEMS AND EARTHQUAKE RECORDS FOR PARAMETRIC ANALYSES

The soil, the structure and the foundation compose the Finite Element Model. The soil is a homogeneous soil profile of 40m thickness. The soil deposit is simulated by 4-node linear elements. In all models there is also an extra layer that simulates the elastic bedrock. The elastic bedrock has a shear wave velocity equal to V_s=800m/s and density equal to ρ=2000kg/m^3. Plane strain conditions are assumed for both soil layer and bedrock. The foundation is a surface, rigid foundation and simulated by 4-node linear elements. The structure represents a typical single-column bridge pier having a cyclic cross section, which is a common choice for bridges in both Europe and other areas. The structure is simulated by linear elastic beam elements. The structural mass is assumed to be lumped at the top of the pier. The column is considered massless. The damping for both soil and structure is equal to 5% for the first mode of the system (according to Rayleigh). Three models of different material and geometrical characteristics concerning the soil, the foundation and the structure were selected to elucidate the effects of the soil-foundation-structure interaction on the system response. These three models concern structures that respond at high, medium and low period range.

The properties of these three models are depicted in Table 3.1. All three models have a bridge column diameter equal to 2m and height equal to 15m. The equivalent foundation widths (2B) utilized in the analyses occur from the radius (r) which is equal to 15m, 5m and 3m for the high, medium and low period range model respectively (Table 3.1). The concrete elasticity modulus is equal to E=29GPa for all three models. The structural mass is equal to 1012.5Mg, 112.5Mg and 40.5Mg. The shear wave velocity of the underneath soil profile ranges between 71m/s and 640m/s for the three models studied (Table 3.2). Due to the big number of different soil profiles, the resulted soil to structure stiffness ratio, σ factor, has values between 0.05 and 0.15. The density of the soil is in all cases stable and equal to 2000 kg/m^3.

Table 3.1. Structural characteristics of the three soil foundation structure interaction systems studied

	High period	Medium period	Low period
d (m)	2	2	2
h (m)	15	15	15
r (m)	15	5	3
h/r	1	3	5
m (kg)	1012500	112500	40500
E (Pa)	2.90E+10	2.90E+10	2.90E+10
T_{FIX}	1.405	0.468	0.281

Table 3.2. Vs values structural and soils periods of the three soil foundation structure interaction systems studied

High period

1/σ	0.05	0.06	0.07	0.10	0.12	0.15
V_s (m/s)	231.50	177.97	152.50	106.77	88.96	71.17
$T_{1,soil}$ (s)	0.75	0.90	1.05	1.50	1.80	2.25
T_{SFSI} (s)	1.50	1.52	1.64	1.82	2.13	2.40

Medium period

1/σ	0.05	0.07	0.1	0.12	0.15
V_s (m/s)	640.52	457.51	320.26	266.88	213.51
$T_{1,soil}$ (s)	0.25	0.35	0.50	0.60	0.75
T_{SFSI} (s)	0.50	0.53	0.59	0.64	0.73

Low period

1/σ	0.10	0.12	0.15
V_s (m/s)	533.77	444.81	355.84
$T_{1,soil}$ (s)	0.30	0.36	0.45
T_{SFSI} (s)	0.36	0.38	0.43

Five acceleration time – histories are used as input motions (Table 3.3). Two of these motions are the acceleration records of Greek earthquakes and were recorded during the Kozani M_w=6.4 earthquake (Greece 1995) and the Aegion M_w=6.5 earthquake (Greece 1995). The other three motions were recorded during the Northridge M_w=6.7 earthquake (California 1994), the Kobe M_w=6.9 earthquake (Takatori site, Japan 1995) and finally the El Centro, M_w=7.0 earthquake (Northridge 1940). All input motions that are used in the parametric analyses are scaled to maximum acceleration at the level of bedrock of $3m/s^2$. The predominant periods of the input motions are: Aegion: T_p=0.72s, El Centro: T_p=0.84s, Kozani: T_p: 0.2s, Northridge: T_p: 0.20s and Takatori: T_p: 1.22s (Table 3.3).

Table 3.3. Selected earthquake records

	T_p (s)
Aegion (Greece)	0.72
El Centro (California)	0.84
Kozani (Greece)	0.20
Northridge (California)	0.20
Takatori (California)	1.22

4. RESULTS

Using the data presented above a set of dynamic time history analyses were performed. For each combination of structural characteristics – Vs value – earthquake record we examine two approaches to evaluate the performance of the structure. In the first approach we apply the conventional methodology to determine the PP and thus the PP is the intersection of the demand curve for FF (free-field) conditions with the T_{FIX} (structural period for fixed-base conditions). In the second approach, SFSI approach, the PP is the intersection of demand spectrum from the EIM with the T_{SFSI} fundamental period of the SFSI system. The results of the parametric analyses performed are depicted in Fig. 4.1, which shows the average value curves from the 5 records for each value of 1/σ ratio, in terms of e_{acc} (Eqn. 4.1) for the accelerations and e_{dis} (Eqn. 4.1) for the displacements.

$$e_{acc} = \frac{SFSI_{acc} - FF_{acc}}{FF_{acc}} (\%) \quad (4.1)$$

$$e_{dis} = \frac{SFSI_{dis} - FF_{dis}}{FF_{dis}} (\%) \quad (4.2)$$

In Fig. 4.1 the horizontal axis depicts the relative soil-to-structure stiffness ratio 1/σ. The vertical axis refers to the comparison of conventional (fixed-base) evaluation of the PP to the evaluation using the flexible system. Fig. 4.1 shows the results if the structure is categorized according to the period range it responds, while Fig. 4.2 depicts all results independently the structural dynamic characteristics. With the abovementioned categorization we examine the effect of the soil profile, the structure and the selected methodology to the structural demand. The results and conclusions that arise are very interesting and will be discussed in the next paragraphs.

For structures that respond at high period range, SFSI effects reduce the seismic input in terms of accelerations for all 1/σ values at an average value of 50% (Fig. 4.1a). On the other hand, the displacements for the SFSI system are reduced (by a mean value of 10%) for 1/σ≤0.12 (Fig. 4.1b), that is for soil profiles with shear wave velocity 213.5m/s < Vs ≤ 88.96m/s (Table 3.2). For soil profiles that consist of softer materials (1/σ>1.2) the displacement values for the SFSI system occur up to 100% greater (1/σ=0.15) than the values with the FFM assumption.

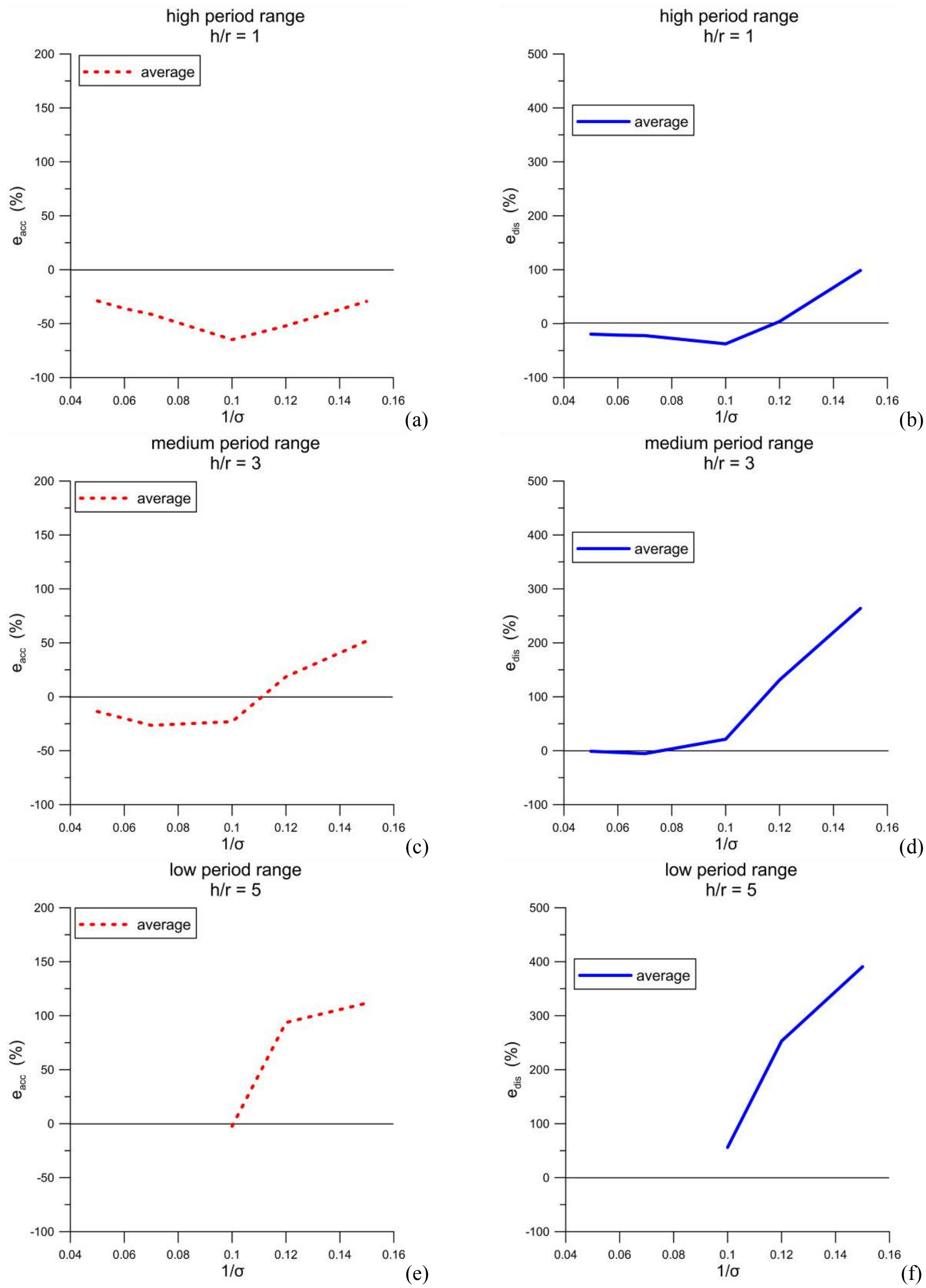


Figure 4.1. Percentile modification of structural response in terms of acceleration (a, c, e) and displacement (b, d, f) values using the conventional and proposed approach for structures that respond at (a, b) high (c, d) medium and (e, f) low period range according to the relative soil to structure stiffness ratio 1/σ.

For structures that respond at medium period range the SFSI reduce the seismic demand in terms of accelerations for soil profiles with Vs≥320.25m/s. This reduction is equal to 20%-40% (Fig. 4.1c). For more soft soil profiles (Vs<320.25m/s) the spectral acceleration values result greater when considering the SFSI effects up to an average value equal to 50% (Fig. 4.1c). For structural response at medium period range the displacements for the SFSI are almost equal to the FFM assumption for $1/\sigma \leq 0.1$, while for $1/\sigma > 0.1$ there is almost linear increase of the SFSI displacements with the increasing of the soil profile shear wave velocity (Fig. 4.1d). This increase of the displacement values for the softer soil studied profiles ($1/\sigma = 0.15$) reaches the value of 300% (Fig. 4.1d).

For structures that respond at low period range, the values in terms of both accelerations and displacements occur higher for the SFSI system (Fig. 4.1e and Fig. 4.1f). The above-mentioned comments on the results refer to the average value occurred for the five different earthquake input motions studied.

Fig. 4.2 depicts all the results of Fig. 4.1 independently the structural response period range and the earthquake input motion. For soil profiles with $1/\sigma < 0.11$ acceleration demand is lower for the SFSI system, while for $1/\sigma > 0.11$, acceleration demand for the SFSI system is higher that FFM system. The displacements of the SFSI system are equal to the FFM when $1/\sigma < 0.1$, while when $1/\sigma > 0.1$ the displacements of the SFSI system are greater.

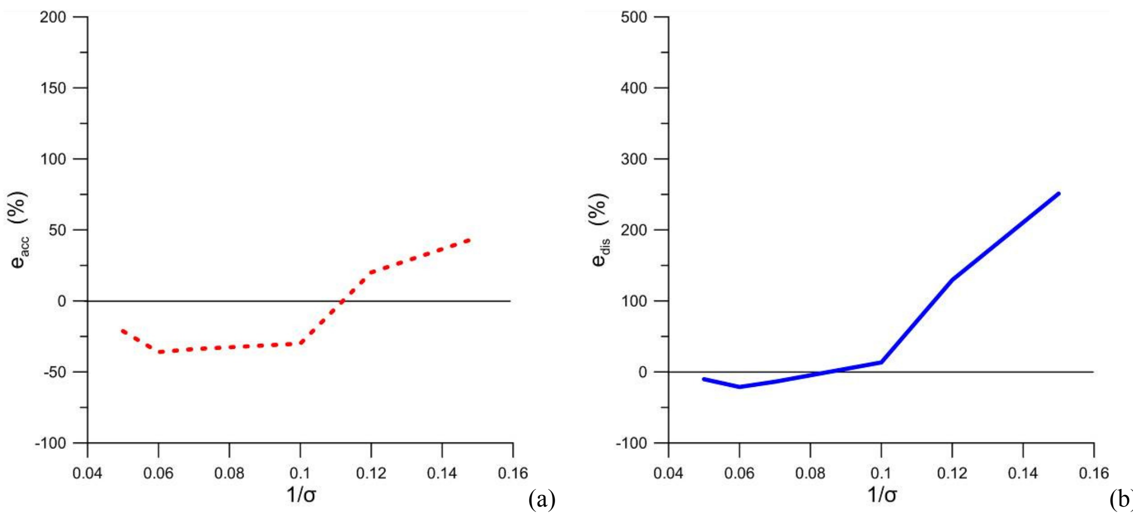


Figure 4.2. Percentile modification of structural response in terms of (a) acceleration and (b) displacement values using the conventional and proposed approach according to the relative soil to structure stiffness ratio $1/\sigma$.

5. CONCLUSIONS

In the present study two methods are investigated to estimate the elastic structural response in terms of accelerations and displacements, when including SFSI effects. These methods are the conventional methodology neglecting interaction effects and the direct analysis of the whole flexible soil-foundations-structure system. The studied SDOF systems that simulate typical bridge piers are subjected to five earthquake ground motions of different frequency range but scaled to the same maximum acceleration at the level of bedrock. The comparison concerns the free-field and fixed-base system and the flexible system. The results of the whole study provide some interesting conclusions which are summarized as follows:

- The shape of demand spectra and thus the structural response depends on the local geology at the examined site and the frequency domain of earthquake input motion.
- SFSI seems to be in favor of the structure for high period response, reducing the seismic input in terms of accelerations.
- On the contrary, acceleration demand increases for structures that respond at low period range.
- The displacements seem to be almost equal to or greater for the SFSI system comparing to the FF system.

- SFSI is not always in favor of the structure reducing the seismic input for the superstructure.
- SFSI effects seem to be more intense for soft soil profiles and for structures that respond at low period range.
- The effect of the seismic input motion on the structural demand increases with the decreasing of shear wave velocity value of the soil profile.
- Finally, results are very sensitive to the earthquake input motion for structures that respond at high period range and the methodology one follows for structures that respond at high period range.

AKCNOWLEDGEMENT

Part of this work was performed in the framework of the European project "Performance-based approach to earthquake protection of cultural heritage in European and Mediterranean countries (PERPETUATE)", Grant agreement 244229.

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