COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

PERFORMANCE-BASED SEISMIC DEMAND OF SOIL-FOUNDATION-STRUCTURE SYSTEMS

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Keywords: soil compliance, seismic demand, FEMA440, effective foundation motion

Abstract. *Seismic demand of soil-foundation-structure systems is evaluated herein in the light of performance-based design approaches, accounting for soil-foundation compliance effects. Due to kinematic and inertial interaction, structural response may be substantially different from the traditionally calculated fixed-base-structure-on-free-field approach. When soil-foundation-structure interaction (SFSI) is accounted, seismic demand of a system is identical to the notion of performance point, the latter being unique for every linear elastic SFSI system. We evaluate seismic demand using three distinct approaches: a) the traditional fixed-base-on-free-field approach, b) a finite element numerical code and c) the analytical approach proposed in FEMA440. In the current study, we utilize the exact ground motion at the foundation level and we propose a practical method to account for soil-foundation-structure interaction effects on seismic structural performance. We then highlight and quantify the discrepancies between our approach and the traditional approach and FEMA440 methodology. We propose use of effective foundation motion (EFM), which is affected by both kinematic and inertial interaction. Until now, no such index has been proposed, since relevant notions, such as the foundation input motion proposed in FEMA440, do not take into account both inertial and kinematic interaction. Moreover, EFM is measurable directly from actual records and field measurements. Using the graphical capacity spectrum method, intersection of the spectrum, expressed in acceleration-displacement format, that results for the acceleration time-history at the foundation level with the radial, which refers to the SFSI structural period, gives good estimation of structural response, compared to the direct method. Finally, for systems affected by interaction, FEMA440 seems to become un-conservative compared to numerical solutions and the deviation of EFM compared to the free-field motion can be from -60% up to +35%.*

1 INTRODUCTION

When analyzing the structural seismic response it is common in practice to assume the base of the structure to be fixed, which is only an assumption since in most cases the foundation soil is flexible. Recent earthquakes showed and highlighted the importance of SFSI to actual structural response [1]. The assumption of a fixed-base structure is realistic only when the structure is founded on solid rock. In all other cases, compliance of the soil can induce two distinct effects on the response of the structure, that is the modification of the free-field motion at the base of the structure (kinematic interaction), and the introduction of deformation from dynamic response of the structure into the supporting soil (inertial interaction). There are two main ways to analyze the SFSI phenomenon: the direct approach, in which the whole SFSI system is modeled in one step, and the substructure approach [2], in which the SFSI problem is divided in two distinct mechanisms, notably the inertial and the kinematic interaction.

The aim of this paper is to elucidate the effects of SFSI on system response, in context of performance-based design. Performance-based design is the design or assessment of a structure, to meet a specified performance level. The performance level is affected by several and important parameters and one of them is certainly the soil foundation structure interaction. So, a realistic consideration of interaction phenomenon is in some cases unavoidable.

One of the widely used methods to evaluate structural response in the light of performance-based design is the capacity spectrum method, originally developed by Freeman, 1998 [3] and extended later by Fajfar and Gaspercic, 1996 [4]. In both approximations, performance of a structure is evaluated as the intersection of the capacity curve with the demand spectrum in Acceleration-Displacement Response Spectrum (ADRS) coordinates. The capacity curve is obtained by standard nonlinear static procedures. The demand spectrum is usually estimated from free-field motion recordings. The above-mentioned methodologies have been used mainly to predict the structural performance ignoring the SFSI effects.

Most of the available methodologies to account the SFSI effects propose the increase of the structural period and the increase of the damping of the system. The available methodologies are based on response spectrum approach [5]. Based on the shape of the design spectra that are proposed by the codes for normal structures (i.e. structures not responding at very low periods), the SFSI effects work in favor of the structure's response. However, The ADSR spectra that result from actual records are not smooth in shape like the ones proposed in building codes and have spikes at the predominant response periods [3]. Aviles and Perez Rocha, 2003 [6] proposed that for structures with fixed-base periods, shorter than the soil resonant periods, a detailed study of the SFSI effects is needed.

Kinematic interaction effects, and thus the effect of SFSI on FIM (foundation input motion), in most of the abovementioned studies are neglected. When kinematic effects are neglected, FIM is equal to the FFM (free-field motion). However, there are two available simple approximations in order to consider the effect of kinematic interaction on structural response. Kim and Stewart, 2003 [7] proposed a methodology for shallow foundations, while Kurimoti and Iguchi, 1995 [8] proposed a methodology for both shallow and embedded foundations. The method proposed by Kurimoti and Iguchi is taking the weighted average of the free-field displacements along the foundation interface, adding the displacements caused by the resultant force and moment associated with the free-field tractions along with this surface. The abovementioned methods are easy to implement when the substructure method is used. Foundation input motion (FIM) is not probably a proper index of the whole soil foundation structure interaction phenomenon [9]. According to Iguchi et al. 2001 [10], an appropriate index that expresses the effects of SFSI effects on seismic input is the effective input motion

(EIM) that will be named as effective foundation motion (EFM) in this study. This motion includes effects of both inertial and kinematic interaction, and thus can be an index of the whole SFSI phenomenon. Effective foundation motion is really useful when studying SFSI using actual earthquake records at the level foundation, or when the whole SFSI phenomenon is being simulated with a one-step method (direct method). According to Iguchi et al. 2001 [10], the magnitude of the horizontal effective input motion greatly depends on the frequency content included in the free-field motion. The numerical evaluation of the effective foundation motion seems to be in good agreement with the records from field observations. Recently, Givens et al., 2012 [11] study kinematic interaction effects by comparing field tests with simplified analytical solutions.

The main objective of this paper is to highlight effects of SFSI on structural response for the simplest case of linear systems. For linear elastic systems, soil-foundation compliance affects directly seismic demand. Moreover, as it will be further explained, for flexible-base linear elastic structures, spectral demand and performance are notions practically identical, as only one pair of demand spectral coordinates exists, a unique performance point for any soil-foundation-structure system.

2 EVALUATION OF ELASTIC PERFORMANCE OF STRUCTURES

In the following paragraphs three different approaches are presented for the estimation of seismic performance of structures. All three methods have been used herein.

2.1 Fixed-base structure with free-field motion

In engineering practice, seismic demand to dynamic excitation is calculated directly from the free-field motion (FFM). Free-field response is not influenced by the presence of structures and thus the demand for all systems is the same irrespectively the dynamic characteristics of the soil-foundation-structure system. Such an approximation is irrelevant for structures founded on actual soil profiles. This approximation is relevant only when the structure is founded on solid rock which in most cases is far from reality.

2.2 Direct FEM

Direct finite-element approach can be used to calculate the response at the foundation level in a single step. The performance point of the flexible-base system is estimated from the intersection of the demand curve resulting from the time-history response at the foundation level with the radial line that concerns effective period of the system T_{SFSI}. It is worth mentioning here that something important is the T_{SFSI} value and the way this value is estimated. Moreover, using the direct method the structural response at the top can be estimated directly as output of the analysis.

When considering the SFSI effects, spectral demand and performance are notions practically identical and the performance point is unique for any soil-foundation-structure system. The demand curve changes its shape when the superstructure's characteristics change. This is the main difference between direct FEM and the traditional fixed-base system approach.

2.3 FEMA440 methodology

A simplified approach for including SFSI effects in seismic assessment is proposed in FEMA440 [12]. More specifically, kinematic interaction and foundation damping effects are approximately taken into consideration in estimating the FIM. Inertial interaction effects are partially addressed in FEMA356 [13] and ATC 40 [14] procedures for including foundation stiffness and strength of the geotechnical components of the foundation in the structural analysis model. It is important to mention that the FEMA440 methodology does not consider the effect of inertial interaction on FIM. However, in reality the foundation level response changes comparing to free-field motion due to both inertial and kinematic interaction.

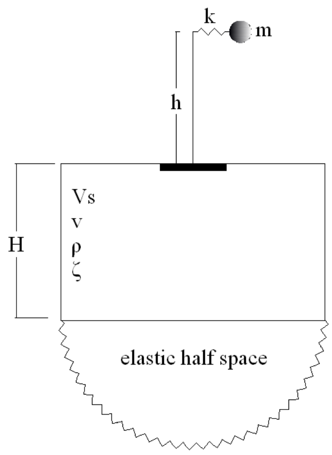
3 SOIL-FOUNDATION-STRUCTURE SYSTEM

A set of dynamic analyses is performed in order to investigate the effect of soil structure interaction on seismic demand evaluation. As first step, dynamic analysis is performed for the soil system only, and in a second step for the complete soil-foundation-structure system.

Elastic demand spectra that result from the obtained free-field motion and the response at the foundation level are then depicted in the same graph, together with the demand spectrum that results when following the methodology proposed by FEMA440 for accounting SFSI effects. All demand spectra are presented graphically by elastic spectra with equivalent viscous damping ratio equal to 5%. The performance points that result for the fixed-base - free-field system and the complete systems are then compared.

Soil-foundation-structure system is modeled using the finite element method. The soil domain is homogeneous with thickness of H=50m. The soil deposit is simulated by 4 node linear elastic elements. The elastic bedrock is simulated using Lysmer-Kuhlemeyer, 1969 [15] dashpots at the base of the soil profile. The bedrock has shear wave velocity equal to V_s=1500m/s and density equal to ρ=2400kg/m^3. Plane strain conditions are assumed for both soil and bedrock. The foundation is a surface, rigid foundation and simulated by 4 node linear elastic elements and its width is equal to 2B. The structure represents a typical single-column bridge pier having a cylindrical cross section, which is a common choice for bridges in both in Europe and other areas. The structure is simulated by linear elastic beam elements and its height is equal to 6m.

The structure's mass is assumed to be lumped at the top of the pier. The damping for both soil and structure is five per cent for the first mode of both structure and soil profile (Rayleigh damping). The properties and the geometry of the studied models are depicted in Fig. 1. The concrete elasticity modulus is equal to E=32GPa for all models. The soil's density in all cases is stable and equal to ρ=2000kg/m^3 and the Poisson's ratio equal to ν=0.333. All models are triggered at the level of bedrock by the Northridge 1994 earthquake record (NGA_1011) with fundamental period T_p=0.16s and peak ground acceleration equal to a_{max}=0.95m/s^2.



Model 1:
h = 6 m
2B = 6m
Vs = 100, 200, 300, 400, 450 m/s
ρ_{soil} = 2 t/m^3
m = 100 Mg, 200 Mg, 400 Mg, 800 Mg, 1200 Mg
ν=0.333
ν_{str}=0.25
H = 50m
d = 0.8, 1.2, 1.6, 2.0, 2.2 m

Figure 1: Soil foundation structure systems studied

4 CONCEPTUAL EXAMPLE

We consider for example Model 1 with shear wave velocity V_s=300m/s^2, mass at the top of the structure equal to m= 400Mg and pier diameter d= 2.2m. The elastic demand spectra that occur from the obtained free-field motion from analysis of the soil profile only (FFM) and the SFSI motion at the foundation level using the direct method (EFM) are depicted at the same graph, together with the demand spectrum that occurs when following the FEMA440 methodology. All demand spectra are depicted graphically by elastic spectra with an equivalent viscous damping ratio equal to 5%. Fig. 2 depicts the performance points (PP) which are the intersection of the following curves:

- PP1 is the intersection of the free-field demand spectrum with fixed-base structural period T_{FIX}.
- PP2 is the pair of values of the total (maximum) acceleration and displacement relative to the foundation that result directly at the top of the structure from the analysis. This pair of values gives also T_{SFSI} from Eq. 1. It is worth mentioning here that PP2 is almost identical to the one that results using the capacity spectrum method with the demand curve being the EFM curve and the radial the effective period of the system that stems from the division of the Fourier spectrum at the top of the structure to the one at the level of foundation. This combination of demand curve and effective period gives in all studied cases a very good approximation of the performance results using the direct method where the pairs of acceleration-displacement values are estimated directly from the analysis.
- PP3 is the intersection of the FFM demand spectrum with T_{SFSI}.
- PP4 represents the PP which is the intersection of the demand curve that results after utilizing the FEMA440 methodology with the T_{SFSI}.

For each analysis the output is in terms of accelerations and displacements at the top of the structure, at free-field and at the level of foundation. Moreover u_t (total displacement), u_{FFM}(displacement at free-field conditions), u_{fnd} (foundation's displacement), u_θ (displacement due to foundation's rocking) and u_{sb} (displacement due to structural bending) are also estimated (Fig.3). Most of the results of this study are depicted in terms of u_{str}, which is the displacement at the top of the structure relative to the foundation level, and it is the sum of the displacements due to rocking of the foundation and structural bending. Finally, each analysis gives the results in terms of drift values at the top and foundation's rotation values.

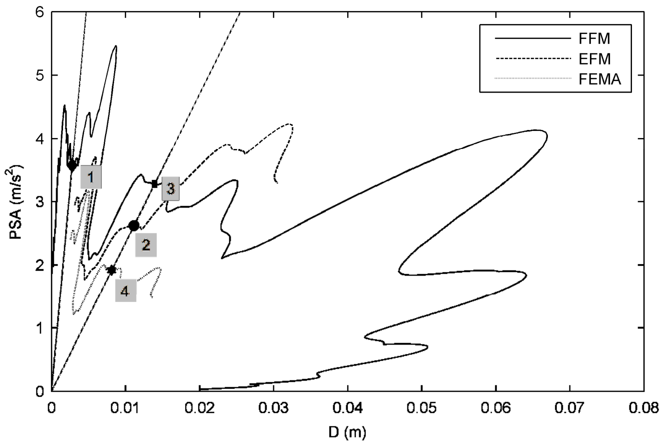


Figure 2: Performance points using different approximations. PP1 concerns the performance of the structure when using the traditional approach, PP2 concerns the performance when using the direct method for the whole SFSI system, PP3 is the structure's performance when considering demand curve for free-field conditions with the effective period of the system T_{SFSI}.

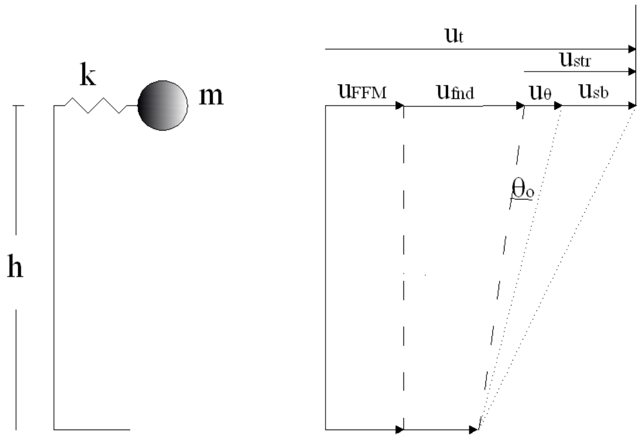


Figure 3: Response at the top of the structure when considering soil-foundation-structure interaction effects in terms of displacements.

5 RESULTS

The results of the parametric study conducted herein are depicted in Fig. 4 to Fig.8. The results are expressed in terms of relative soil to structure stiffness ratio 1/σ (Eq. 2) and normalized mass ratio m_{norm} (Eq. 3), and concern the same value for the normalized height ratio h_{norm}=h/B=2.

Fig. 4 shows the resulted effective to fixed-base period (T_{SFSI}/T_{FIX}) values, in three (Fig4a) and two (Fig4b) dimensional plot, in terms of 1/σ and m_{norm}. As expected, the T_{SFSI}/T_{FIX} ratio is increasing with either decreasing the soil stiffness or increasing the slenderness of the structure. As stems from the graphs, for actual soil profiles the effective period of the system including SFSI is up to 4 times the fixed-base period. This is a value that stems also from literature for bridge piers and normalized height equal to h_{norm}=2 [16].

Another important point to mention is what exactly the effective period of the system represents when estimated by different approaches. More specifically in Fig.5 the resulting from Eq.1 values of effective period T_{SFSI} are compared with three different approximations (a) the effective period the occurs when dividing the Fourier spectrum at the top of the structure by the one at the level of foundation, (b) the effective period that results when dividing the Fourier spectrum at the top of the structure to the one at free-field conditions and (c) the effective period that results from theoretical expressions that exist in literature [17]. It seems that T_{SFSI} is in good agreement with $T_{SFSI(FOUND)}$, while $T_{SFSI(FFM)}$ is in good agreement with $T_{SFSI(THEO)}$. This could be explained by the fact that T_{SFSI} and $T_{SFSI(FOUND)}$ include only to the relative to the foundation level displacement at the top u_{str} (Fig.3), while $T_{SFSI(FFM)}$ and $T_{SFSI(THEO)}$ include also the horizontal displacement of the footing u_{fnd} (Fig.3).

$$T_{SFSI} = 2 \cdot \pi \cdot \sqrt{\frac{u_{str}}{\ddot{u}_{str}}} \tag{1}$$

$$1/\sigma = \frac{h}{T_{FIX} \cdot V_s} \tag{2}$$

$$m_{norm} = \frac{m}{B^3 \cdot \rho} \tag{3}$$

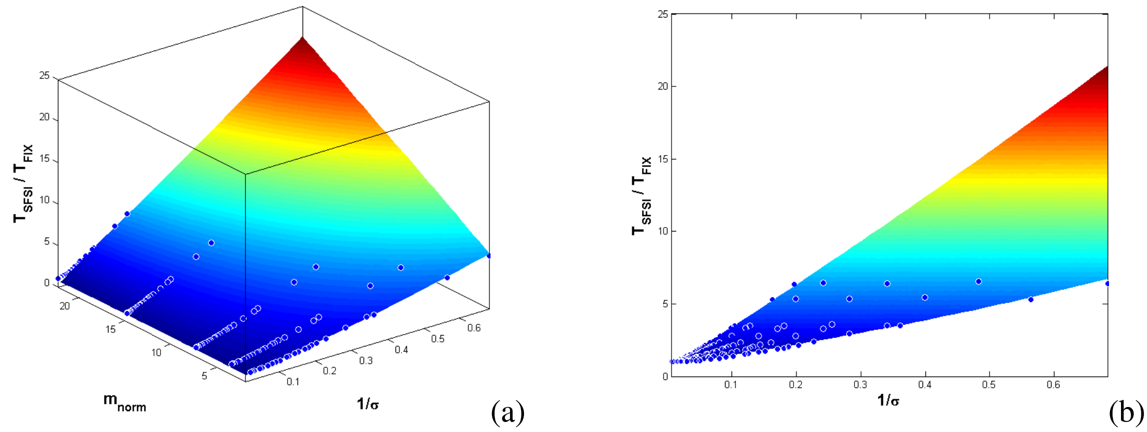


Figure 4: Effective system's period to fixed-base period (T_{SFSI}/T_{FIX}) values in terms of soil to structure stiffness ratio 1/σ and normalized mass m_{norm} in (a) three dimensions plot and (b) two dimensions plot.

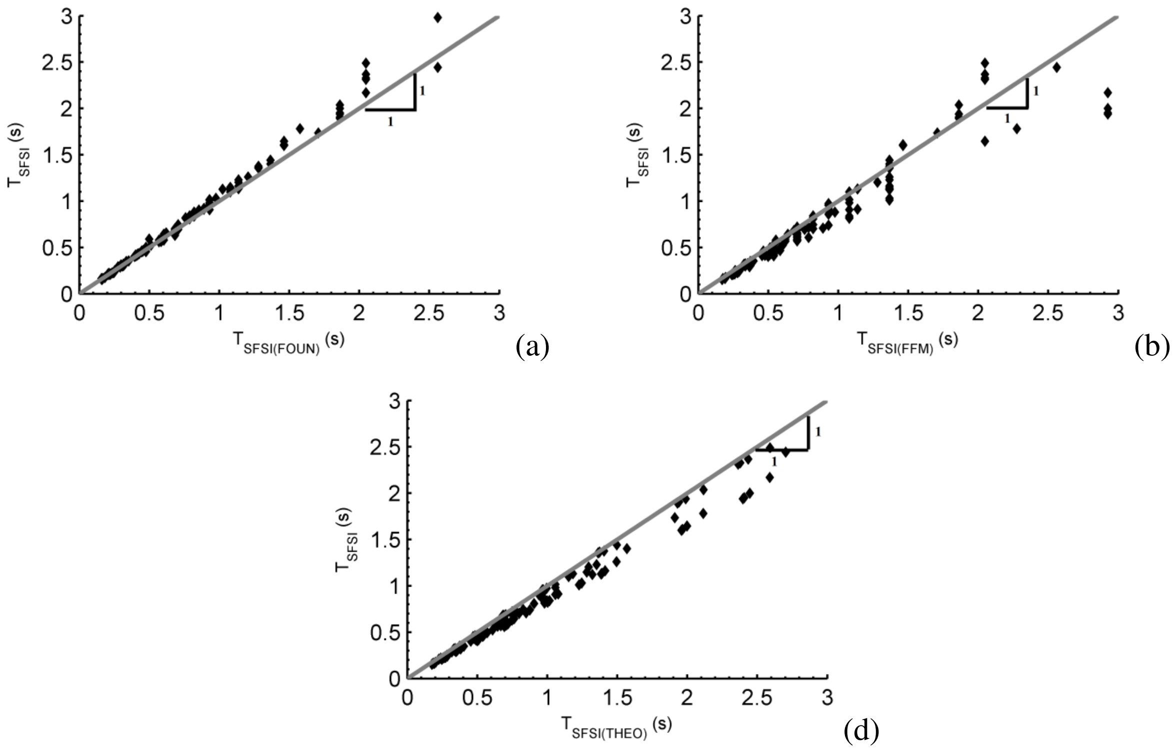


Figure 5: Effective period T_{SFSI} compared with three different approximations (a) the effective period the occurs when dividing the Fourier spectrum at the top of the structure to the one at the level of foundation $T_{SFSI(FOUND)}$, (b) the effective period that results when dividing the Fourier spectrum at the top of the structure to the one at free-field conditions $T_{SFSI(FFM)}$ and (c) the effective period that results from theoretical expressions that exist in literature $T_{SFSI(THEO)}$.

Fig. 6 shows the maximum acceleration values at the top of the structure that occur when using the direct method ($\ddot{u}_{str}$) together with the maximum acceleration values that result by the intersection of free-field demand curve with T_{SFSI} radial line ($\ddot{u}_{strf}$). Additionally, in the same graph it is depicted the 1:1 radial line and the radial line that results after linear regression of the results. In most cases the acceleration value at the top of the structure for the SFSI system ($\ddot{u}_{str}$, see PP2 in Fig. 2) is smaller than the acceleration at the top of a structure with effective period equal to T_{SFSI} triggered by the free-field motion ($\ddot{u}_{strf}$, see PP3 in Fig. 2). After linear regression the $\ddot{u}_{str} / \ddot{u}_{strf}$ ratio is equal to 0.7573 (Fig. 6). The relation between $\ddot{u}_{str}$ and $\ddot{u}_{strf}$ gives more or less the relation between the EFM and the FFM motion in terms of spectral values at the effective period of the system.

The displacement at the top of the structure (u_{str}) is composed by two parts the displacement due to foundation's rocking (u_θ) and the displacement due to structural bending (u_{sb}). Fig. 7 and Fig. 8 show in two and three dimensional plot the u_θ/ u_{str} and u_{sb}/ u_{str} ratios respectively in terms of 1/σ and m_{norm} ratios. As the soil becomes softer and the structural mass value greater the u_θ/ u_{str} values are greater (Fig. 7). This in other words means that for very soft soil profiles the structure's response is defined mainly by rocking. On the other hand, as the soil becomes softer the u_{sb}/ u_{str} values are smaller.

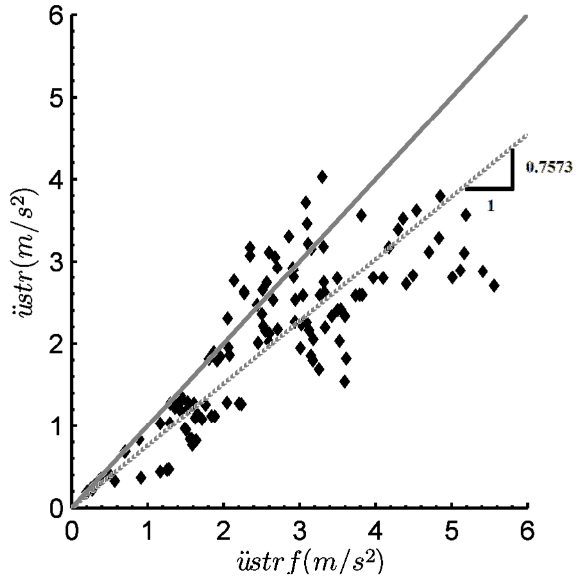


Figure 6: Maximum acceleration at the top of a structure with T_{SFSI} subjected to EFM ($\ddot{u}_{str}$) and to FFM ($\ddot{u}_{strf}$).

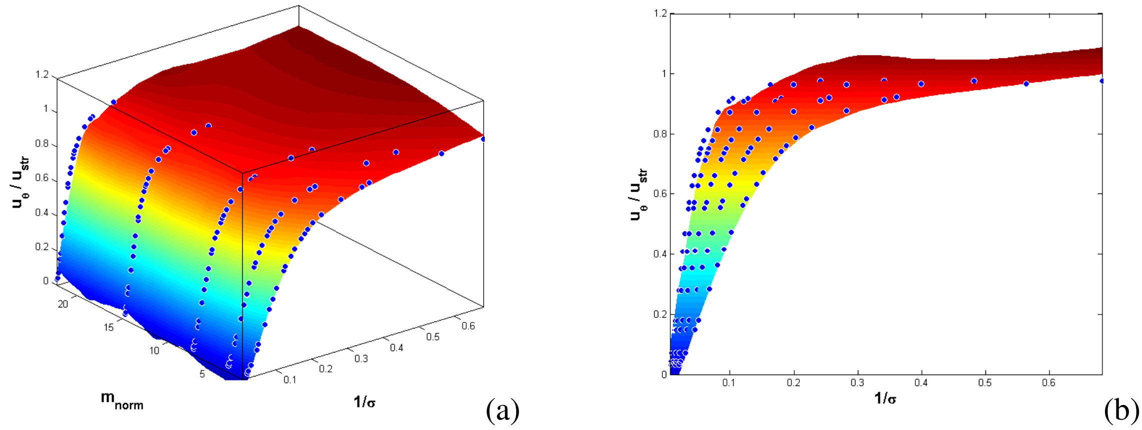
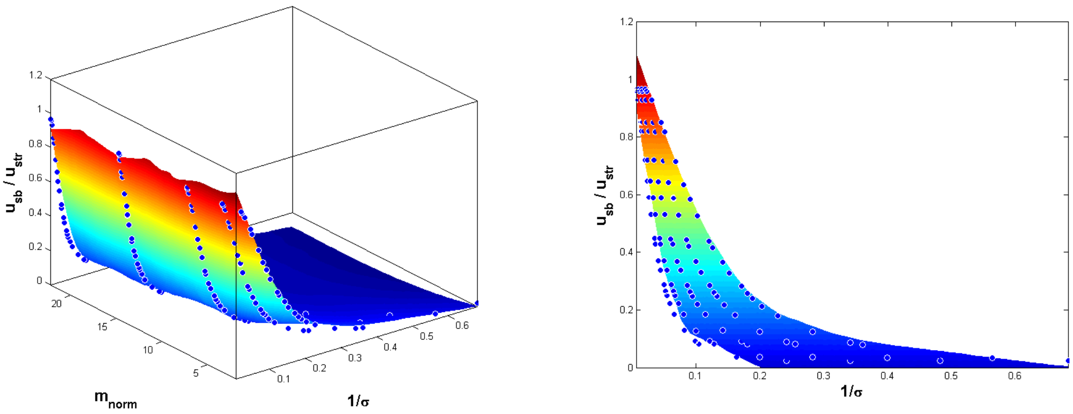


Figure 7: Rocking to relative displacement ratio u_θ/ u_{str} in terms of soil to structure stiffness ratio 1/σ and normalized mass m_{norm}.



(a) (b)

Figure 8: Structural bending to relative displacement ratio u_{sb}/u_{str} in terms of soil to structure stiffness ratio $1/\sigma$ and normalized mass m_{norm}.

6 PROPOSED METHODOLOGY AND ITS APPLICATION

The methodology that is proposed herein could be described by the following steps:

1. Estimate the dynamic and geometrical characteristics h, m, Vs, 2B of the soil and structure and soil response acceleration at free-field conditions.
2. Evaluate $1/\sigma$, m_{norm}, T_{FIX}, h_{norm} using the Eq.2 and the Eq.3.
3. Estimate the T_{SFSI}/T_{FIX} ratio in terms of $1/\sigma$ and m_{norm} (Fig. 4).
4. Estimate $\ddot{u}_{str}$ using the proposed in terms of $\ddot{u}_{strf}$ modification value (Fig. 6).
5. Calculate u_{str} from the T_{SFSI} period value combined with the $\ddot{u}_{str}$ value.

The u_{str} value is the sum of the u_θ and u_{sb}. The values of both two parts could be estimated by the proposed curves in Fig. 7 and Fig. 8. The resulting values, when applying the proposed methodology, are in a very good agreement with the ones from the time history analysis.

As an example for the model described in paragraph 4, $m_{norm}=7$, $1/\sigma=0.113$, $T_{FIX}=0.176s$. For these values according to Fig.4, $T_{SFSI}/T_{FIX}=2.36$ and thus $T_{SFSI}=0.42s$. The intersection of T_{SFSI} with the FFM demand curve gives the $\ddot{u}_{strf}$ value that is equal to $3.27 m/s^2$. According to Fig.6, $\ddot{u}_{str} = 0.7573 \cdot 3.27 = 2.48 m/s^2$. From Eq.1 u_{str} is estimated equal to 0.011m and using Fig.7 and Fig.8, the rocking displacement is equal to 0.009m and the displacement at the top due to structural bending is equal to 0.002m. These values are in a very good agreement with the ones resulted from the time history analysis.

The main advantage of the proposed methodology is that, in order to calculate the structure's response considering SFSI effects (kinematic and inertial), one needs only to know the main characteristics of the system and the ground response at free-field conditions.

7 COMPARISON BETWEEN FEMA AND FEM

The comparison of PP2 and PP4 for all the analyses in terms of per cent acceleration modification factor $(PP_{FEMA}-PP_{FEM})/PP_{FEM}$ % are depicted in Fig. 9. The trend line shows that for stiff soil profiles ($1/\sigma<0.1$) FEMA440 gives from 0% up to 50% higher values, while for soft soil profiles FEMA440 gives up to 100% smaller values comparing to the direct methodology that is proposed herein. In other words, FEMA440 seems to be un-conservative when $1/\sigma > 0.1$ and this could be attributed to the fact that when T_{SFSI}/T_{FIX} takes values greater than two, normal values for bridge piers that are characterized by important masses, the FEMA440 overestimates system's damping. The FEMA440 methodology is more appropriate for buildings.

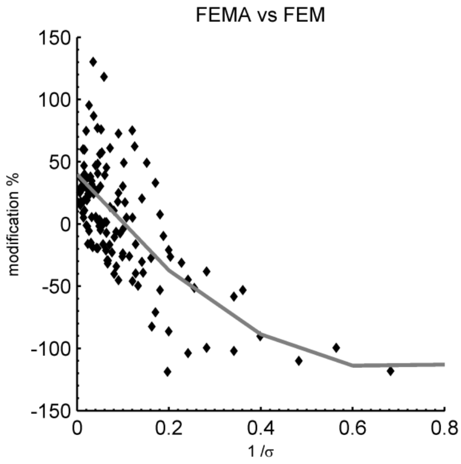


Figure 9: Comparison between FEMA440 and FEM methodologies in terms of per cent spectral acceleration modification.

8 CONCLUSIONS

Based on the results presented the following conclusions could be deducted:

- For the SFSI system we propose the demand curve calculated from the effective foundation motion combined with the $T_{SFSI(FOUN)}$ that stems from the division of the Fourier spectrum at the top of the structure with the one at the level of foundation. This combination gives results in good agreement with the response from the direct method. The abovementioned seismic performance concerns total relative to the foundation level lateral displacement at the top. However, both parts of total displacement are easily evaluated by the proposed methodology. Final performance depends on the limit state to be considered.
- Structural response can be calculated only if the main characteristics of the system and the motion at free filed conditions are known. The final result considers both kinematic and inertial interaction.
- T_{SFSI}/T_{FIX} values are up to 4 for actual soil profiles.
- The maximum acceleration values at the top of the structure that occur when using the direct method ($\ddot{u}_{str}$) divided to the maximum acceleration values that result by the intersection of free-field demand curve with T_{SFSI} radial line ($\ddot{u}_{strf}$) give after linear regression a ratio equal to 0.7573.
- For very soft soils the main part of u_{str} is u_θ, while for stiff soils and slender structures the main part of u_{str} is u_{sb}.
- For typical soil profiles, FEMA seems to be un-conservative and overestimates damping when SFSI effects are important.

ACKNOWLEDGEMENTS

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, as well as in the framework of the European project "Seismic engineering research infrastructures for European synergies (SERIES)", Grant agreement 227887.

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