Soil-Foundation-Structure Interaction Effects on Nonlinear Seismic Demand of Structures

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ABSTRACT: Investigating the seismic demand of structures including soil-foundation-structure interaction (SFSI) effects is a demanding task due to the complexity of the coupled dynamic problem. This task is significantly burdened by uncertainty in the soil and structural parameters and randomness in earthquake characteristics. The objective of this research is to highlight SFSI effects on the seismic demand of nonlinear structures in the presence of these uncertainties and to thus quantify the risk of exceeding response design specifications. This goal is accomplished through a probabilistic Monte Carlo methodology. In the analyses, various soil and structural parameters selected from expected or realistic ranges were combined to generate a large number of simplified analytical models. These models were then subjected to a range of earthquakes with different spectral characteristics. Specifically, 1.36 million nonlinear time-history simulations were run over: (*i*) models consisting of a single-degree-of-freedom (SDOF) superstructure and a rheological soil-shallow foundation element; and (*ii*) their corresponding fixed-base models. The demand modification in structural distortion, drift and total displacement due to consideration of SFSI are compared to the results of the corresponding fixed-base systems and are quantified through a comprehensive statistical presentation. The results contradict prevailing views of the beneficial role of SFSI on the structural response and thus show the resulting design guideline assumptions do not hold for all cases. In fact SFSI effects can only be safely ignored with 50% confidence. The rigorous statistical Monte Carlo analysis presented is a significant first step towards reliability-based seismic design procedures incorporating foundation flexibility.

1 INTRODUCTION

Soil-foundation-structure interaction (SFSI) effects on seismic demand of structures could be defined as a discrepancy in the structural response, when considering flexible-foundation instead of ideal fixed-base model. These coupled systems are a complex, nonlinear analysis problem. The combined impact of the uncertainty in soil and structural parameters, and inherent randomness of the input ground motion makes the problem even more complex for analysis and design.

Modification of the seismic demand of elastic SDOF structures was first introduced by the extensive efforts of (Jennings and Bielak 1973), (Veletsos and Meek 1974) and (Veletsos and Nair 1975). They showed that the effect of inertial interaction on the structural response can simply be investigated from the response of an equivalent SDOF system. This system consists of an increase in the fundamental natural period and a change in the associated damping of a fixed-base structure. They also recognized that SFSI consideration can either increase or decrease the seismic demand of the structures depending on the parameters of the system and the characteristics of the input motion. Later, the presented replacement oscillator approach formed the basis of today's seismic design provisions (e.g., ATC-3-06 1984, FEMA 440 2005). In the design code using an idealized smooth design spectrum with a constant acceleration up to a certain period and a decreasing branch thereafter, it has been suggested that consideration of SFSI results in a decrease in structural seismic demand.

The response of yielding structure-foundation systems has been examined by (Veletsos and Verbic 1974) and it was suggested that structural yielding also decreases the effects of interaction since it increases the flexibility of the system. Ciampoli and Pinto (1995) also have shown that the inelastic seismic demand of a SDOF representation of structures essentially remains unaffected by SFSI, even showing a tendency to decrease the response. However, numerical results presented by (Bielak 1978) indicated that for non-linear hysteretic structures compliance of the foundation may lead to a larger displacement demand than what would be expected for a fixed-base system. Further confirmation was mentioned by (Miranda and Bertero 1994) based on analyses accomplished for motions recorded on soft soils. They demonstrated that in certain frequency ranges, period lengthening can result in an increase in the structural seismic demand. Recently, it was stated by (Avilés and Pérez-Rocha 2003) that the interaction effects for yielding systems are as important as for elastic systems.

The controversy regarding the role of SFSI on the seismic demand of structures raises the important question of whether SFSI is beneficial or detrimental (Mylonakis and Gazetas 2000), and, further, should it be considered in every day design procedures or not. Given the wide range of uncertainties, a rational way for achieving a rigorous evaluation of the SFSI effects on seismic demand of structures is to make use of a probabilistic approach. This methodology was utilized previously by the authors to quantify the SFSI effect on the response of elastic structures (Moghaddasi et al. 2009a) and yielding systems (Moghaddasi et al. 2009b). This paper extends those results to investigate the modification in structural distortion, system drift and structural total displacement seismic demand of SDOF systems with nonlinear behaviour supported by an equivalent viscoelastic half-space.

In this paper, the associated variation in the seismic demands was investigated via spectral format. The variation was demonstrated in terms of fundamental period of corresponding fixed-base (FB) superstructure. Following this quantification, the demand modification factors were scrutinized in terms of combined soil-structure key parameters at three levels of confidence: 50, 75 and 95%. Furthermore, for the 50% confidence level (commonly adopted design level), a curve was fitted to the corresponding data. Finally, the obtained demand modification curves were utilized to suggest a modification scheme to the current seismic design codes in order to incorporate the effect of SFSI.

2 STOCHASTIC SEISIMC DEMAND INVESTIGATIN

While the analysis of a SDOF soil-foundation-structure (SFS) system is relatively straightforward, significant uncertainty in: (a) input ground motion and (b) parameters of the coupled SFS system can result in a wide range of structural seismic demand. This variation also exists for an ideal fixed-base assumption, but due to upper-bound consideration that is implicitly included in the spectral analysis (i.e., seismic design code procedure) it generally does not result in an un-conservative design. For the SFSI phenomenon, this variation cannot be simply ignored.

To explain this, Figure 1 illustrates the effect of aleatory (inherent randomness in input ground motion) and epistemic (randomness in the model parameters) uncertainty on the seismic force demand of a flexible-base structure, as an example.

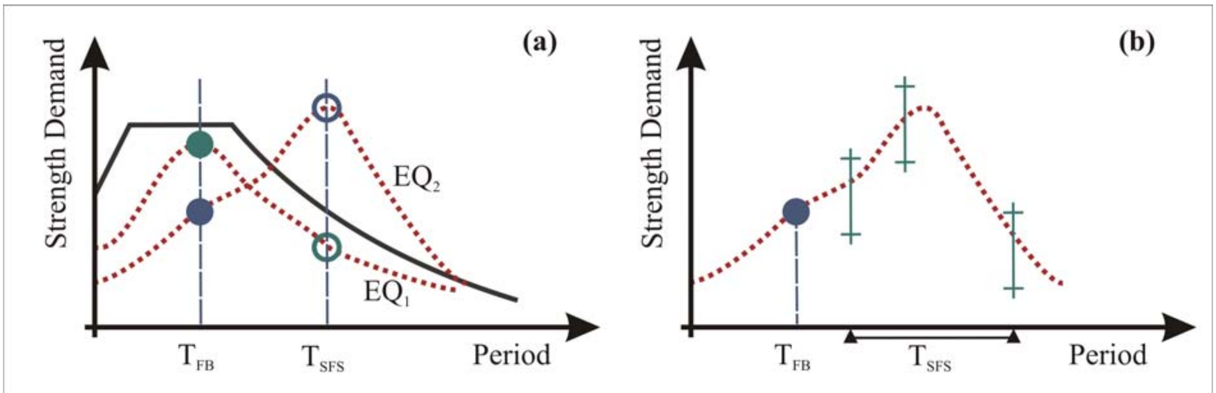

Figure 1. Schematic illustration of SFSI effects on structural response: (a) the effect of aleatory uncertainty, (b) the effect of epistemic uncertainty

Along with the earthquake response spectrum, the response of a FB system and its flexible-base counterpart are shown in this figure. Clearly, if a presumed structure with a fundamental natural period of T_{FB} is subjected to two different earthquake ground motions, the demand ratio between FB and SFS system could be different (Figure 1a). The demand for the SFS system can be either increased or reduced compared to the reference FB system, depending on the structural and earthquake characteristics. Furthermore, as shown in Figure 1b, for an earthquake ground motion with a specific spectrum shape, depending on the relative configuration of structural parameters, foundation radius, and soil characteristics, significant variation in the strength demand ratio is expected. Depending on the location of the SFS system's response within this variation boundary, SFSI may result in beneficial or detrimental role. However, in contrast to this demonstration, it has been concluded from the current design code approach that any increase in the natural period of the structures due to SFSI effect may lead to a decrease in the strength demand of structures.

Therefore, a rigorous investigation of any modification to the structural seismic demand due to SFSI requires: (*i*) considering all sources of uncertainty in analysis; (*ii*) computing the response of randomly generated scenarios that span and reasonably cover a realistic range; and (*iii*) presenting the results in a comprehensive and concise statistical demonstration to quantify the risk of exceeding the expected design level.

3 METHODOLOGY AND MONTE CARLO SIMULATION

An established rheological soil-shallow foundation-structure model was considered for this comprehensive probabilistic analysis. Its parameters were systematically defined randomly through a Monte Carlo simulation by carefully ensuring to satisfy the requirements of realistic model parameters. The generated SFS models along with their FB counterparts were then subjected to a suite of earthquake ground motions via nonlinear time-history analyses.

3.1.1 *Dynamic soil-foundation-structure model*

The interacting soil-structure system investigated in this study is illustrated in Figure 2. It consists of a SDOF yielding superstructure supported by a rigid circular shallow foundation located on an equivalent linear viscoelastic soil stratum. The SDOF superstructure is an approximate representation of a FB multi-story building vibrating in its fundamental natural mode. This structure is characterized by height (h_{eff}), mass (m_{str}), lateral stiffness (k_{str}) and damping (c_{str}). To represent the nonlinear behaviour of the structure, a force-deflection relationship of the Takeda type (elastoplastic with strain hardening and stiffness degradation) was used. Finally, 5% viscous damping was assumed.

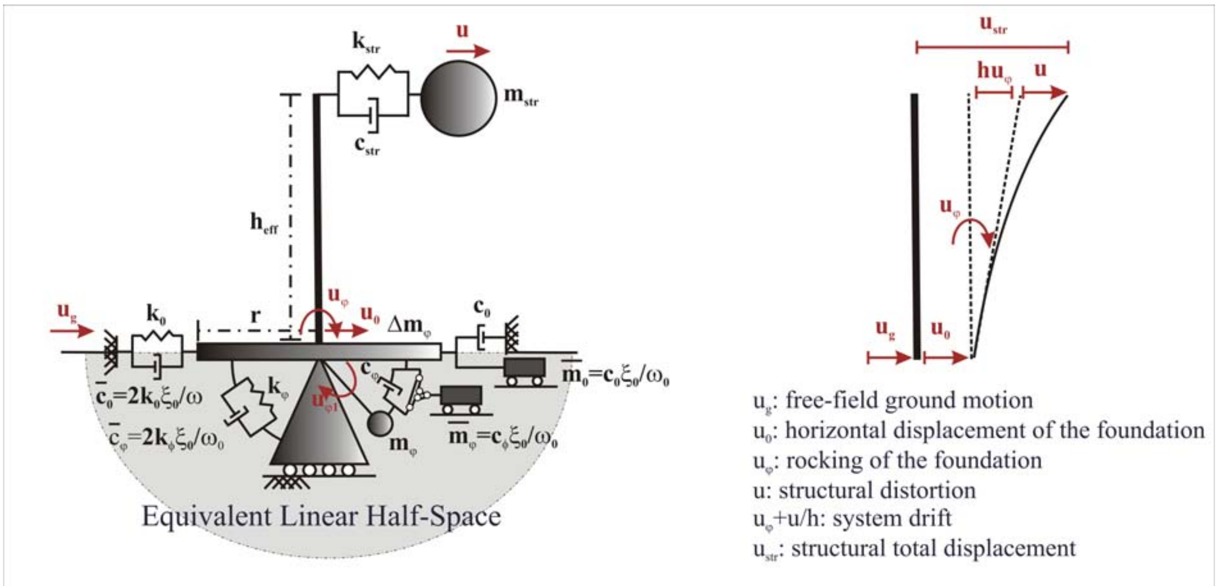

Figure 2. Dynamic soil-shallow foundation-structure model for horizontal and rocking foundation motions

The soil-foundation element was modelled by a lumped-parameter model representing a rigid circular footing resting on the soil surface and having a perfect bond to the soil. Moreover, the foundation was assumed to have no mass and mass moment of inertia about the horizontal axis. For evaluating the soil dynamic impedances incorporating soil nonlinearity, the frequency-independent coefficients of a rheological Cone model (Wolf 1994) was modified based on conventional equivalent linear method (Seed and Idriss 1970). In this model, the soil stratum is assumed to be a viscoelastic half-space. The parameters needed to quantify the dynamic impedances for the horizontal (index 0) and rocking components (index φ) are presented in Table 1.

Table 1. Parameters of soil-foundation element based on the Cone model concept

<table>
<tr><th colspan="2">Motion</th><th>Stiffness</th><th>Viscous damping</th><th>Added mass</th></tr>
<tr><td colspan="2">Horizontal</td><td>$k_0 = \frac{8Gr}{2-\nu}$</td><td>$c_0 = \rho V_s A$</td><td>-</td></tr>
<tr><td rowspan="5">Rocking</td><td>$\nu \le 1/3$</td><td rowspan="2">$k_\varphi = \frac{8Gr^3}{3(1-\nu)}$</td><td>$c_\varphi = \rho V_p I_r$</td><td>-</td></tr>
<tr><td>$1/3 \le \nu \le 1/2$</td><td>$c_\varphi = \rho(2V_s)I_r$</td><td>$\Delta m_\varphi = 1.2(\nu - 1/3)\rho I_r r$</td></tr>
<tr><td colspan="4">Internal mass moment of inertia</td></tr>
<tr><td>$\nu \le 1/3$</td><td colspan="3">$m_\varphi = \frac{9\pi}{32}\rho I_r r(1-\nu)(\frac{V_p}{V_s})^2$</td></tr>
<tr><td>$1/3 \le \nu \le 1/2$</td><td colspan="3">$m_\varphi = \frac{9\pi}{8}\rho I_r r(1-\nu)$</td></tr>
<tr><td colspan="2" rowspan="3">Material damping</td><td colspan="3">Additional parallel connected element (i=0 or φ)</td></tr>
<tr><td colspan="2">Viscous damping to stiffness ki</td><td>Inertial mass to damping ci</td></tr>
<tr><td colspan="2">$\overline{c}_i = 2k_i(\xi_0/\omega_0)$</td><td>$\overline{m}_i = c_i(\xi_0/\omega_0)$</td></tr>
</table>

The parameters utilised in this table are defined as:

r, A and I_r: Equivalent radius of the foundation, area of the foundation ($A=\pi r^2$) and mass moment of inertia for rocking motion ($I_r=\pi r^4/4$).

ρ, υ, V_s, V_p and G: Soil mass density, Poisson's ratio, soil shear wave velocity, soil longitudinal wave velocity and soil shear modulus.

ξ_0 and ω_0: Equivalent soil material damping and effective frequency of SFS system.

3.1.2 *Realistic randomly generated soil-foundation-structure models*

A systematic scheme was utilized to generate random models with realistic parameters (Moghaddasi et al. 2009b). A period range of 0.2, 0.3 … 1.8 sec was selected to: (i) represent the fixed-base superstructures with total height of 3-30 m and (ii) satisfy the period-height relationship introduced in New Zealand Standard (NZS1170.5 2004). To cover the variability of model parameters at each considered fixed-base period (T_{FB}), 1000 system configurations representing random, but still realistic, structural and soil conditions with the same T_{FB} were considered. The number 1000 was chosen with the intention to: (i) give the best fit uniform distribution for the randomly selected parameters and (ii) increase the accuracy of the Monte-Carlo simulation compared to the exact expected solution (Fishman 1996).

3.1.3 *Seismic input*

A suite of 40 ground motions (i) recorded on stiff/soft soil (specifically, type C and D based on USGS classification) and (ii) scaled to have reasonably distributed PGAs within the range of 0.3-0.8g were used as an input for the adopted time-history simulations. The number 40 was chosen to obtain an estimate of median response within a factor ±0.1 with 95% confidence (Shome et al. 1998).

3.1.4 *Nonlinear time-history analysis*

The Newmark constant average acceleration scheme was used to integrate the equations of motion in nonlinear time-history analysis using a FEM code (Carr 2009).

4 RESULTS AND DISCUSSION

Maximum values for three measures of structural seismic demand were examined: (*i*) structural distortion (u), (*ii*) system drift (dr) and (*iii*) structural total displacement (u_{str}). Structural distortion is the horizontal displacement of the superstructure relative to the foundation and represents the transmitted displacement/force to the superstructure. It also stands for the displacement ductility demand of the structure (μ), since ductility is the ratio between the maximum experienced displacement and the yield displacement that is constant for a certain system. System drift is defined as the summation of drift value induced by structural distortion and structural lateral displacement due to rocking of the foundation. Large drift values can cause second-order P-Δ effects. Representative of top floor displacement, structural total displacement includes structural distortion, structural lateral displacement due to rocking of the foundation and horizontal displacement of the foundation. Hence, u (or μ) and dr are parameters that must be considered for design of the structural elements, while u_{str} must be controlled to prevent pounding between adjacent buildings.

To simplify the presentation of the results from numerous time-history simulations, the maximum values for SFS systems were presented as normalized ratios with respect to the FB system results. This ratio is called the demand modification factor. Hence, SFSI is detrimental when the demand modification factor is greater than unity.

The response quantities will be presented and discussed as functions of: (*i*) fundamental period of the fixed-base superstructure ($T_{FB}=2\pi/\omega_{str}$), (*ii*) structural aspect ratio (h_{eff}/r), (*iii*) structural-to-soil stiffness ratio ($\omega_{str}h_{eff}/V_s$) and (*iv*) SFS-to-FB period ratio (T_{SFS}/T_{FB}). To represent the existing variation in the demand modification factor in terms of T_{FB}, box and whisker plots are utilized. The box has lines at 25th percentile (bottom line), median (middle line), and 75th percentile (top line) values. Whiskers extend from each end of the box to the 5th percentile and 95th percentile respectively. Outliers are the data with values beyond the whiskers. The effect of h_{eff}/r, $\omega_{str}h_{eff}/V_s$ and T_{SFS}/T_{FB} on the demand modification factors is characterized through 50th, 75th and 95th percentile boundary lines representing different levels of confidence. To provide a closed-form formula for the 50% confidence level, as the lowest acceptable design level, a curve is fitted to this median data.

4.1.1 *The effect of SFSI on structural distortion demand*

The effect of foundation flexibility on structural distortion demand is illustrated in Figure 3. Clearly, the demand modification factor (u_{SFS}/u_{FB}) for 5th-95th percentile of the examined cases varies within the range of 0.3-1.2 depending on the fixed-base period (Figure 3 top-left). Based on this probabilistic quantification, SFSI can only be neglected with 50% confidence for stiff structures (T_{FB}<0.5 sec) and with 75% confidence for structures with longer periods (T_{FB}>0.5 sec). In other words, there is 50% likelihood for stiff structures and 25% likelihood for structures with longer periods that the structural distortion due to SFSI effects will be increased with respect to the FB response. The expected increase with 95% confidence is limited to 20% for stiff structures and to 10% for other structures.

The demand modification factor for structural distortion is also demonstrated for h_{eff}/r in Figure 3 (top-right), $\omega_{str}h_{eff}/V_s$ (bottom-left) and T_{SFS}/T_{FB} (bottom-right). The variation in the ratio of u_{SFS}/u_{FB} is presented for three confidence levels: 50, 75 and 95%. In addition, a regression line is assigned to the data corresponding to the confidence level of 50%. When 50% is considered as the expected confidence level, as already has been seen for the case of T_{FB}, the SFSI appears to be beneficial. Furthermore, it may be concluded that an increase in h_{eff}/r slightly reduces the ratio of u_{SFS}/u_{FB}, while an increase in either $\omega_{str}h_{eff}/V_s$ or T_{SFS}/T_{FB} result in a significant reduction. If higher confidence levels (e.g. 75% or 95%) are required, the detrimental SFSI effect needs to be taken into account for any values of h_{eff}/r and some ranges of $\omega_{str}h_{eff}/V_s$ and T_{SFS}/T_{FB} since the modification factor is greater than unity. The critical range of variation for $\omega_{str}h_{eff}/V_s$ and T_{SFS}/T_{FB} will be enlarged when the expected confidence level increases. Also in this case, the variation effect of h_{eff}/r on the structural distortion demand modification factor is negligible.

4.1.2 *The effect of SFSI on system drift demand*

Figure 4 shows the effect of foundation flexibility on system drift demand. As mentioned earlier, it

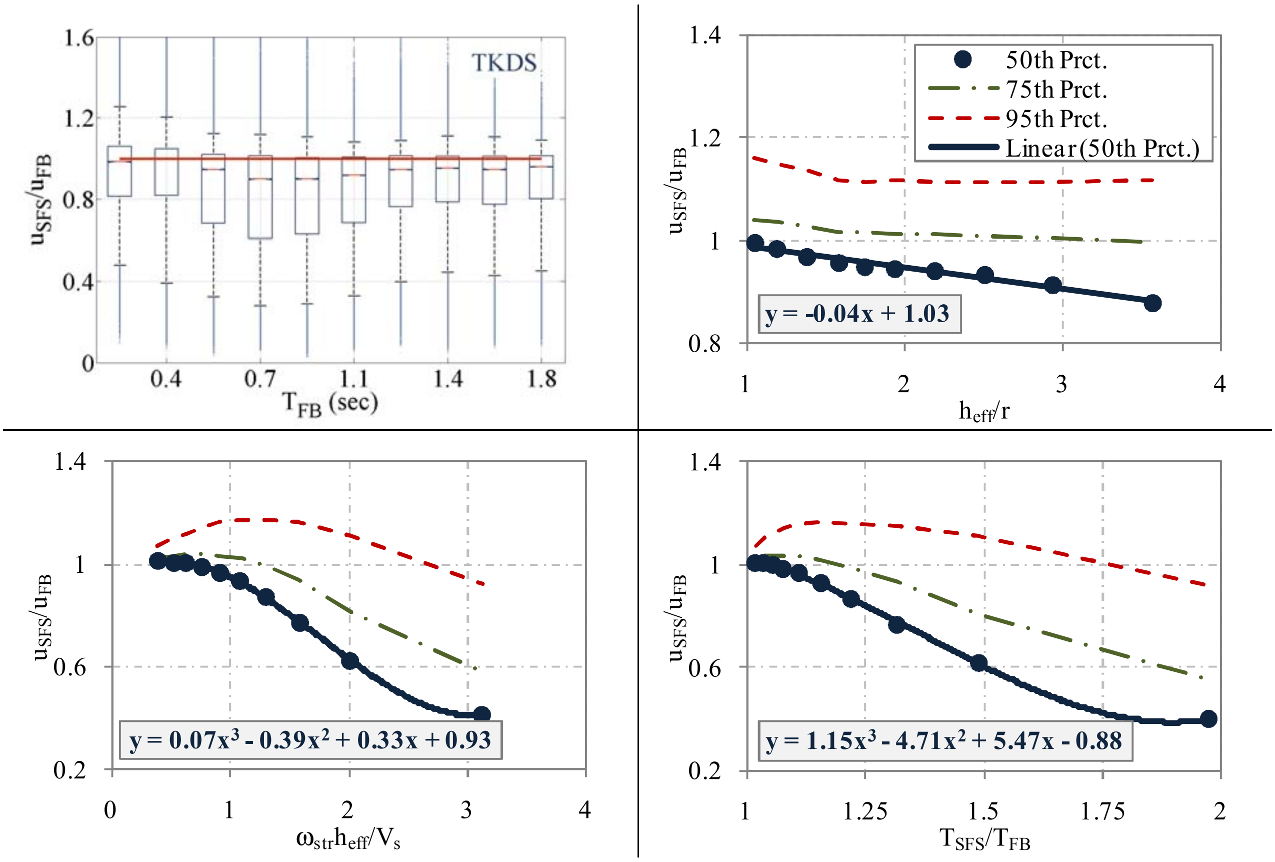

Figure 3. The effect of SFSI on structural distortion demand

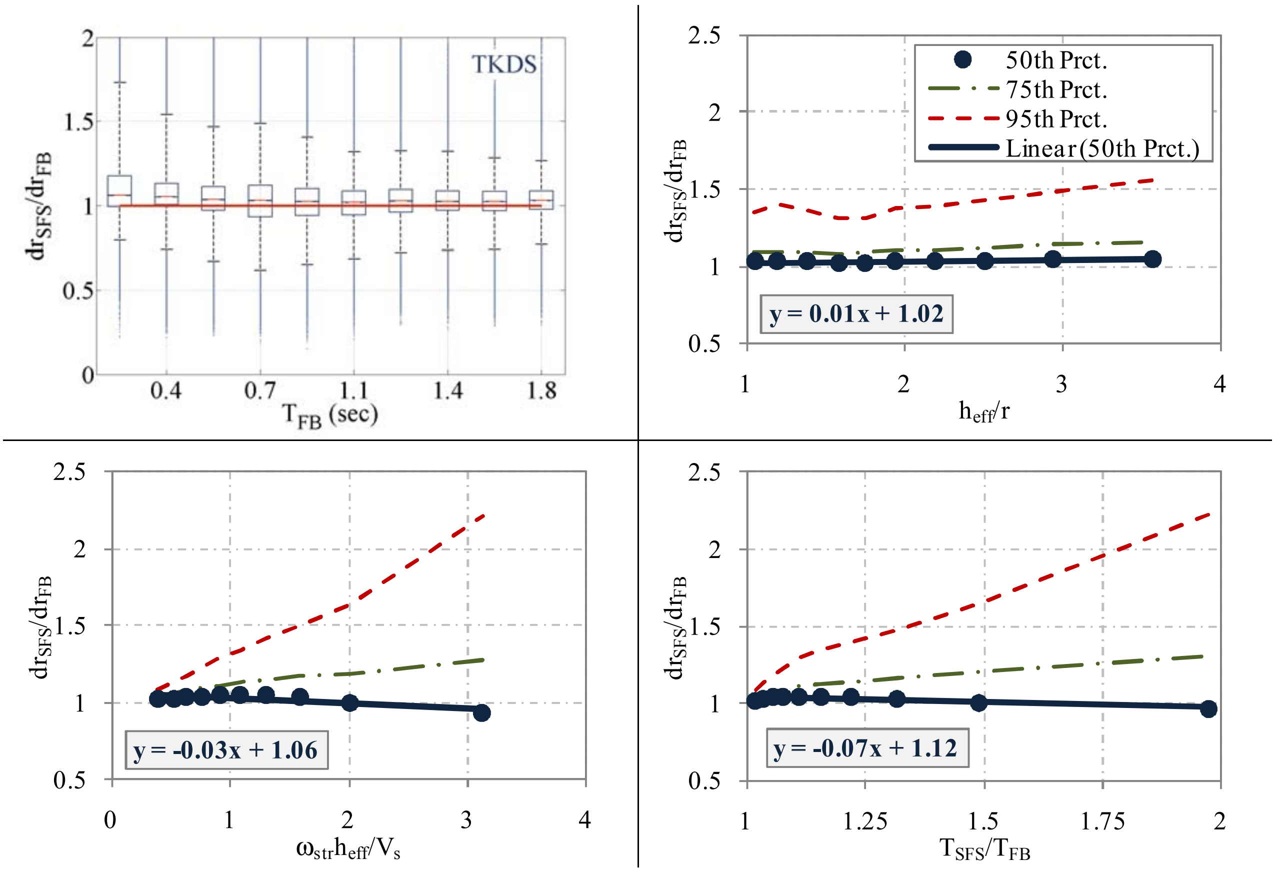

Figure 4. The effect of SFSI on system drift demand

includes the effect of rotational rigid body motion of the foundation on the system displacement. The drift demand modification factor (dr_{SFS}/dr_{FB}) for 5th-95th percentile of the examined cases varies within the range of 0.6-1.7 depending on the fixed-base period (Figure 4 top-left). Clearly, even at 50% confidence level, dr_{SFS}/dr_{FB} is greater than unity and thus SFSI effect on the system drift demand cannot be neglected. However, the increase is less than 10-20%. It should be noted that the demand modification factor increases for higher levels of confidence (75th and 95th percentile) and in this case the increase could be significant. The expected increase in the response with 95% confidence varies from 100% to 40% when the T_{FB} (fundamental period of the fixed-base superstructure) increases.

Figure 4 also shows the demand modification factor for structural drift as a function of h_{eff}/r (top-right), $\omega_{str}h_{eff}/V_s$ (bottom-left) and T_{SFS}/T_{FB} (bottom-right). The nearly horizontal trend of the regression line at 50th percentile shows that the drift demand is only weakly sensitive to all three variables. Furthermore, the constant value of the regression line is almost unity, suggesting that adding flexibility to the foundation has little effect on structural drift demand at 50% confidence level. However, when higher levels of confidence are considered different interpretations appear. For an increase in any of the three selected parameters that regulate SFSI phenomenon, the demand modification factor tends to increase, and the observed rising trend is more noticeable for higher level of confidence. This fact confirms that for design of systems with higher levels of importance, consideration of SFSI may result in higher system drift levels.

4.1.3 *The effect of SFSI on structural total displacement demand*

Figure 5 shows the demand modification factor, $(u_{str})_{SFS}/(u_{str})_{FB}$, when the effect of both rigid motions caused by foundation flexibility on the structural displacement response is accounted for. The observed trend in this case is similar to that for drift demand, except that the variation of $(u_{str})_{SFS}/(u_{str})_{FB}$ for the 5th-95th percentile has slightly higher range of 0.7-2. This increase is not unexpected since one additional rigid body motion is included. Following this fact, when pounding effects need to be accounted for, SFSI should be considered in the analysis of structures.

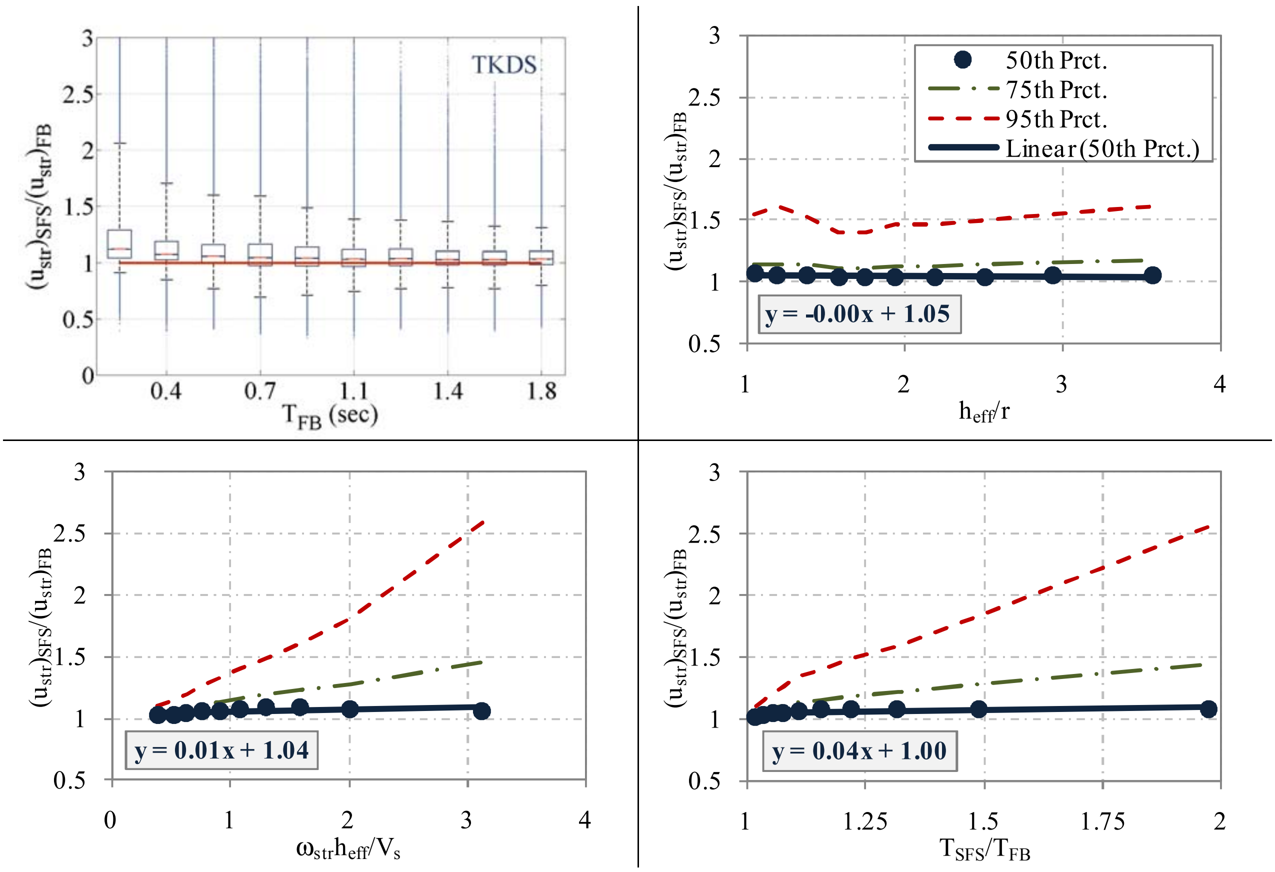

Figure 5. The effect of SFSI on structural total displacement demand

5 PROPOSAL FOR DESIGN PROCEDURES

On the basis of this robust statistical study, a simplified modification to the current seismic design procedures can be suggested in order to incorporate SFSI effects. It is noted that the suggestion should be taken into account respecting the scope of this study.

To include or neglect the SFSI effects in a design procedure, first, the designer or the owner should decide on the desired level of confidence. If a design with 50% confidence (most commonly accepted level) is required, then SFSI effect on structural response can be neglected. On the other hand, if a higher confidence level needs to be considered, depending on the design parameter and the certain situation of structure and the soil, the seismic demand obtained for a FB system can simply be modified by a factor to incorporate SFSI effect.

The SFS-to-FB period ratio (T_{SFS}/T_{FB}) is a unified variable combining the structural and soil parameters. Therefore, it is selected as the variable that should be used to define the demand modification factors. While the ratio of T_{SFS}/T_{FB} is known for a certain structure and soil scenario, the modification factor for any of the three introduced structural seismic demands can be extracted from the graphs presented through Figures 3-5 (bottom-right), respecting the confidence levels of 75 and 95%. This modification factor is then used as a multiplier to present the expected change in seismic demand of a FB system due to SFSI consideration.

6 CONCLUSION

A comprehensive Monte Carlo simulation was undertaken with the purpose to quantify the effects of SFSI on the seismic demand of structures. The most common soil-structure-earthquake scenarios were covered through consideration of a large number of models with wide ranges of soil, foundation and structural parameters and a suite of earthquake ground motions with different spectrum. The results indicate that:

SFSI effects on structural distortion seismic demand can only be neglected with 50% confidence for stiff structures (T_{FB}<0.5 sec) and with 75% confidence for structures with longer periods (T_{FB}>0.5 sec). The variation in structural distortion seismic demand due to SFSI effects is independent of h_{eff}/r ratio, nevertheless, is influenced by $\omega_{str}h_{eff}/Vs$ and T_{SFS}/T_{FB} ratios significantly. An increase in the value of $\omega_{str}h_{eff}/V_s$ and T_{SFS}/T_{FB} ratios corresponds to a sharp reduction in the demand modification factor.

In most cases SFSI produces an increase in the structural drift and maximum displacement demand. The increase level is not very significant for 50% confidence level, however, cannot be neglected for higher confidence levels. This increase only results from the rigid body components arising from the foundation motion, and is not because of the greater inelastic demand of structure. The increase level rises due to an increase in the ratio of h_{eff}/r, $\omega_{str}h_{eff}/V_s$ and T_{SFS}/T_{FB} with sharper trends for higher confidence levels.

For higher confidence levels, a demand modification factor can be introduced based on SFS-to-FB period ratio (T_{SFS}/T_{FB}) to adjust the response of a FB system for SFSI effects.

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