The effects of soil-foundation interface nonlinearity on seismic soil-structure interaction analysis

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ABSTRACT: This research presents the impact of base fixity on seismic analysis including soil-structure interaction (SSI) considering linear and nonlinear soil-foundation interface conditions. A set of inelastic time history analyses using a yielding single-degree-of-freedom structural system with different fixity conditions at the base are used. The base fixity configurations considered are: 1) fixed-base; 2) linear flexible-base; 3) nonlinear flexible-base without uplift; and 4) nonlinear flexible-base with uplift. A suite of 40 ground motions with large-magnitude and moderate-distance is chosen to ensure robustness of the results across realistic ground motions. The examination of SSI effects on the structural response under a design base earthquake (DBE) level, i.e. 500-year return period event, is carried out for all considered scenarios. In addition, the effects of an increase in the seismic intensity up to a maximum credible earthquake (MCE) level, i.e. 2500-year return period event, are also studied for the case of nonlinear flexible-base with uplift. The results illustrate the degree of residual foundation deformation as well as the impact of SSI on structural acceleration, total displacement and ductility. In this context, the importance of SSI effects for a design procedure as well as the difference between linear and nonlinear SSI considerations is highlighted.

1 INTRODUCTION

Consideration of soil-structure interaction (SSI) during an earthquake in a dynamic analysis or a design procedure has been a controversial topic for the last three decades [1]. In principal, when SSI is included in a dynamic analysis, the response of three linked and interacting systems, namely: 1) the soil stratum surrounding the foundation; 2) the foundation; and 3) the structure has to be simultaneously considered. In this context, instead of applying the seismic forces directly to the structure assumed to be fixed at the base, a modified input excitation by the coupled dynamic behaviour of the soil, foundation and structure has to be used [2]. As a result, the induced deformations and forces in the structure are altered from their corresponding values when the structure is assumed to be fixed at the base.

Neglecting SSI effects on structural response is currently being suggested in many seismic codes [3-6]. However, there are some studies showing that SSI can result in either beneficial or detrimental effects depending on the soil-structure system parameters and input ground motion characteristics [7, 8].

Most studies on soil-structure interaction in addition to the current design procedures are based on the assumption that the soil adjacent to the foundation behaves as a linear or at most an equivalent linear viscoelastic material [9-12]. In addition, the foundation is assumed to be fully bonded to the soil underneath. However, geotechnical investigations after the Northridge 1994, Kobe 1995, Kocaeli 1999 [13] and Christchurch 2010 earthquakes [14] have shown that significant nonlinear action in the soil and soil-foundation interface can be expected due to high levels of seismic excitation and spectral acceleration. Therefore, it is very important to investigate the influence of soil-foundation interface nonlinearity on the effects of soil-structure interaction [15]. Principally, neglecting such phenomena...
prohibits the effects and consequences of: 1) energy dissipation due to soil yielding; 2) large foundation deformation as well as residual settlement and rocking; and 3) foundation toppling on the structural response.

In this regard, Gandomzadeh et al. [16] carried out a parametric study for an elastic structural system supported on a nonlinear soil stratum. The structure was modelled as a single-bay, single-storey 2D frame having different masses, and the soil was modelled using the Iwan’s constitutive nonlinear model. The soil-structure systems considered were then enforced to Ricker wavelet with various amplitudes. They concluded that due to soil nonlinearity and, consequently, an additional energy dissipation to the system, structural response decreases if SSI is considered. This reduction is more pronounced for the systems having a fundamental frequency close to the natural frequency of the soil. In addition, it was stated that soil nonlinearity changes fundamental frequency of the system and this change is significantly affected by the mass of the system.

Saez et al. [17] also studied the effect of elastic and inelastic soil-structure interaction on seismic demand of single-degree-of-freedom (SDOF) structures. In this study, two inelastic SDOF structures, representing low-rise and mid-rise reinforced concrete moment resisting frame buildings, and two soil conditions, representing a dry and a saturated homogenous dense Toyoura sand profile of 30m depth overlaying bedrock, were considered. The soil was modelled using elastic and elasto-plastic constitutive models. The soil-structure systems generated were then excited by a suite of ground motions comprising different earthquake selections and strong-motion parameters. It was concluded that when the soil is in a dry condition, the elastic and inelastic SSI result in a similar effect on structural response. However, when the soil is in a saturated condition, a significant variation exists between elastic and inelastic SSI effect. This variation is obviously due to pore pressure generation that cannot be captured by linear soil models. In addition, it was indicated that the influence of SSI on the structural response when low-rise structural systems on dry soil are considered, might be either beneficial or detrimental. However, SSI is beneficial for other scenarios considered.

Finally, the effects of SSI on structural response for linear and nonlinear soil-foundation interface conditions were studied by Pecker and Chatzigogos [18] following an incremental dynamic analysis (IDA) approach. The analyses were facilitated using a new dynamic macro-element specifically developed to represent soil-foundation interface nonlinearity [19, 20]. This study covered a typical highway bridge pier excited by a suite of ground motions representing relatively large-magnitude earthquakes with moderate distances and no effects of directivity. In the soil-structure model used, both soil and structure were considered to be nonlinear. It was concluded that nonlinear SSI is always beneficial and significantly reduces the structural ductility demand. However, large displacements and rotations at the foundation are also resulted that might be unacceptable. Therefore, care must be taken into account before moving towards a design philosophy where the ductility demand can be transferred from the structure to the foundation (e.g. [21]).

Following that has been presented in the literature, an attempt was made in this research to expand those works and specifically: 1) investigate the effects of linear and nonlinear SSI on structural response; 2) compare the SSI effects for linear and nonlinear soil-foundation interface conditions; and 3) examine the effects of soil-foundation nonlinearity at the maximum credible earthquake (MCE) level. In this context, an idealised inelastic SDOF structural system attached to a soil-foundation interface element representing either: 1) a linear condition; 2) a nonlinear condition without uplift; or 3) a nonlinear condition with uplift was used. The soil-structure models generated were then enforced to a suite of 40 ground motions scaled to a desired hazard level. Finally, the trends and behaviours were comprehensively quantified and presented.

This study is the first step towards a more comprehensive probabilistic analysis and design guidelines using nonlinear soil-structure models covering existing uncertainties in model parameters and ground motions.

2 SOIL-STRUCTURE MODEL DESCRIPTION

The soil-structure system investigated in this research (Figure 1) denotes a typical highway bridge pier supported by a rigid circular shallow-foundation and enforced to seismic excitation [18]. It was
designed based on a direct displacement-based design (DDBD) approach specifically introduced to take into account the soil-structure interaction effects [22]. The design was based on the Eurocode 8 design spectrum-Type 1, considering a firm soil condition and a peak ground acceleration (PGA) of 0.5g. The design performance criteria considered are:

- System drift limit, $\Delta_d = 0.03h$
- Maximum foundation rotation, $\theta_{lim} = 0.01$
- Maximum structural ductility demand, $\mu = 3$

![Soil-structure system studied: (a) physical; (b) model.](image)

This system was then modelled in the finite-element program Ruaumoko 3D [23] using: 1) a yielding SDOF structure representing the bridge pier; and 2) a mass-spring-dashpot assembly or a macro-element representing the linear or nonlinear soil-foundation interface condition, respectively. Clearly, this modelling approach follows the substructure technique introduced for SSI analysis.

2.1 Structural system

The yielding SDOF structural system used is characterised by its height $h$, mass $m$, lateral stiffness $k$, and equivalent structural viscous damping $c_s$. The damping ratio of 5% was also assumed. In addition, to cover structural nonlinearity, a stiffness-degrading force-deformation hysteresis rule as Takeda (bilinear envelope with strain hardening and stiffness degradation) was considered with 5% post-elastic stiffness and unloading and reloading parameters of $\gamma = 0.3$ and $\delta = 0.2$, respectively ($\gamma$ and $\delta$ are defined in Figure 1). This force-deformation behaviour was then assigned to the spring representing the lateral stiffness of the system. The numerical parameters defining the structural system are given in Table 1.

2.2 Linear soil-foundation interface

To represent the dynamic behaviour of soil-foundation interface assuming a linear response, the commonly used mass-spring-dashpot assembly [24] was attached to the base of the SDOF structural system considered. In this approach, the soil is assumed to behave linearly and the foundation is considered to be fully bonded to the soil. The springs in this assembly represent the static stiffness of the soil-foundation system and the dashpots represent the radiation damping. The formulations and the corresponding numerical parameters used to define this element are given in Table 1.
Table 1. Properties of the soil-structure model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formulation/Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Parameters:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. height, $h$</td>
<td>effective height to centre of the mass</td>
<td>20 m</td>
</tr>
<tr>
<td>2. mass, $m$</td>
<td>including the mass of the deck and pier</td>
<td>1.22 kt</td>
</tr>
<tr>
<td>3. initial lateral stiffness, $(k_i)$</td>
<td>-</td>
<td>25 MN/m</td>
</tr>
<tr>
<td>4. coefficient of viscous damping, $c_i$</td>
<td>$c_i = 2(5%)\sqrt{m_i(k_i)}$</td>
<td>0.55 MN.s/m</td>
</tr>
<tr>
<td>5. yield strength, $f_y$</td>
<td>-</td>
<td>1.27 MN</td>
</tr>
<tr>
<td>6. yield displacement, $\delta_y$</td>
<td>$\delta_y = f_y/(k_i)$</td>
<td>0.051 m</td>
</tr>
<tr>
<td><strong>Soil-Foundation Interface Parameters:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Soil and Foundation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. soil mass density, $\rho$</td>
<td>-</td>
<td>1.6 t/m$^3$</td>
</tr>
<tr>
<td>2. Poisson’s ratio, $\nu$</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>3. soil shear wave velocity, $V_s$</td>
<td>-</td>
<td>255 m/s</td>
</tr>
<tr>
<td>4. soil shear modulus, $G$</td>
<td>-</td>
<td>104 MPa</td>
</tr>
<tr>
<td>5. soil cohesion, $c_0$</td>
<td>-</td>
<td>0.15 MPa</td>
</tr>
<tr>
<td>6. foundation radius, $r$</td>
<td>-</td>
<td>3.75 m</td>
</tr>
<tr>
<td>7. foundation mass, $M_f$</td>
<td>-</td>
<td>0.22 kt</td>
</tr>
<tr>
<td>8. foundation mass moment of inertia, $M_{fi}$</td>
<td>-</td>
<td>0.78 kt.m$^2$</td>
</tr>
<tr>
<td>• Mass-Spring-Dashpot Assembly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Vertical stiffness, $K_v$</td>
<td>$K_v = \frac{4Gr}{1-\nu}$</td>
<td>2229 MN/m</td>
</tr>
<tr>
<td>2. Horizontal stiffness, $K_h$</td>
<td>$K_h = \frac{8Gr}{2-\nu}$</td>
<td>1835 MN/m</td>
</tr>
<tr>
<td>3. Rocking stiffness, $K_r$</td>
<td>$K_r = \frac{8Gr^2}{3(1-\nu)}$</td>
<td>20893 MN.m</td>
</tr>
<tr>
<td>• Macro-Element</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Plasticity parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Maximum cantered vertical force, $N_{max}$</td>
<td>$N_{max} = 6.06c_eA$</td>
<td>40 MN</td>
</tr>
<tr>
<td>2. Maximum normalized horizontal force, $Q_{max}$</td>
<td>$Q_{max} = \frac{c_eA}{N_{max}}$</td>
<td>0.165</td>
</tr>
<tr>
<td>3. Maximum normalized moment, $Q_{max}$</td>
<td>$Q_{max} = \frac{0.67c_eAD}{DN_{max}}$</td>
<td>0.11</td>
</tr>
<tr>
<td>4. Numerical parameter expressing the extent of initial plastic stiffness, $p_i$</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>5. Numerical parameter expressing the extent of stiffness degradation in reloading, $p_{ir}$</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>b) Uplift parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. $\alpha$</td>
<td>$Q_{u,i} = \frac{Q_{u}}{\alpha} \exp(-\beta Q_{u})$</td>
<td>6</td>
</tr>
<tr>
<td>2. $\beta$</td>
<td>$\alpha = \frac{1}{(1 - \frac{Q_{u}}{\alpha})^{1/2}}$</td>
<td>1.5</td>
</tr>
<tr>
<td>3. $\zeta$</td>
<td>$\mathcal{R}<em>{\zeta} = \left{ \begin{array}{l} 0, \quad \mathcal{R}</em>{\zeta} \leq 0 \mathcal{R}_{\zeta} &gt; 0 \end{array} \right}$</td>
<td>$\zeta(1 - \frac{Q_{u}}{\alpha})$</td>
</tr>
</tbody>
</table>
Table 1. Continued.

| 4. δ | $g_r^\text{el} = \left\{ \begin{array}{ll} g_r, & |q_r^\text{el}| \leq |q_u| \\ 0.5 & \end{array} \right.$ |
| 5. γ | $Q_c/Q_{c,ss} = 3 - 2 \left( \frac{q_u}{q_v} \right)$ |

- Radiation Damping

1. Vertical damping, $C_v$  
   
   $C_v = \rho \left[ \frac{3.4}{\pi (1 - \nu)} \right] V_s A$, $A = \pi r^2$  
   
   28 MN.s/m

2. Horizontal damping, $C_h$  
   
   $C_h = \rho V_s A$  
   
   18 MN.s/m

3. Rocking damping, $C_r$  
   
   $C_r = \rho \left[ \frac{3.4}{\pi (1 - \nu)} \right] I^r$, $I = \pi r^4/4$  
   
   98 MN.s/m

For detailed description of the macro-element formulation and its parameters refer to [19]. Because of space limitation, the full explanation of the model is avoided herein.

2.3 Nonlinear soil-foundation interface

The dynamic behaviour of the soil-foundation interface with nonlinear condition was included in the model by a link element, denoted as macro-element, introduced by Chatzigogos et al. [19, 20]. This macro-element is specifically formulated to reproduce all nonlinearity expected at the foundation level including: 1) soil material nonlinearity (yielding); and 2) interface nonlinearity (uplift). It principally uses a nonlinear constitutive law linking force parameters to displacement parameters. These parameters are selected such that to be directly linked to those related to the structure supported by the foundation. The interested reader is referred to the original work by Chatzigogos et al. for complete details. In addition, the macro-element is coupled with the same dashpot as for the linear soil-foundation model to cover radiation damping. The formulations and the corresponding numerical parameters used to define macro-element are given in Table 1.

3 GROUND MOTIONS AND SCALING SCHEME

To cover the uncertainties resulting from record-to-record variability, the generated soil-structure model was subjected to a large number of ground motions with different characteristics. An ensemble of 40 earthquake ground motions recorded on stiff/soft soil (soil type C, $V_s = 180 – 360$ m/s, and D, $V_s < 180$ m/s to a depth of 30 m, based on USGS classification) was used in the analyses. All selected records are from earthquakes with magnitude of 6.5-7.5 and have source-to-site distance (closest distance to fault rupture) in the range of 15-40 km. Detailed information about the selected suite of ground motions can be found in [8].

The selected ground motions were then scaled using the method introduced in New Zealand Standard [25] to match the target spectrum over the period range of interest. The target spectrum chosen represents a 5% damped elastic acceleration response spectrum for: 1) soil class C; 2) hazard factor (Z=PGA) of 0.4g; 3) return period factor of 1.0 corresponding to a design based earthquake (DBE) level. The period range of interest considered is 0.5-2.2 s covering periods between $0.4T_{FB}$ and $1.3T_{SS}$. where $T_{FB}$ is the fundamental period of the fixed-base system and $T_{SS}$ is the fundamental period of the corresponding soil-structure system. Scaled acceleration response spectra are presented in Figure 2.

In addition, to investigate the effects of soil-foundation nonlinearity on the response of soil-structure systems when the maximum credible earthquake (MCE) level is considered, the ground motions selected were also scaled for the return period of 2500 years. It should be noted that these scaled records were only used for the results presented in Section 4.4.
Figure 2. Scaled acceleration response spectra for the ground motions selected.

4 SSI EFFECTS ON STRUCTURAL RESPONSE

4.1 Typical result of a dynamic analysis

A typical dynamic response of the fixed-base model and the corresponding nonlinear flexible-base model with uplift is shown in Figures 3 and 4, respectively. The quantities depicted are: 1) structural acceleration $a_s$, that is the total acceleration of the structural mass representing the base shear; 2) total displacement $u_{tot}$, that is a measure of the displacement at the roof level including lateral displacement resulted from foundation motion and structural distortion, which can cause the pounding between adjacent structures; and 3) structural force-deformation hysteretic behaviour $F_{s,el}$ vs. $u_s$ that shows the maximum structural force and distortion in addition to the degree of structural nonlinearity experienced. The other quantities only considered for the flexible-base mode are: 4) horizontal foundation displacement $u_u$; 5) foundation rocking $u_r$; and 6) vertical foundation displacement $u_v$.

These parameters are all defined at the foundation centre. It should be noted that when $u_s < 0$, the foundation centre moves downwards (settles), and when $u_s > 0$, a separation between the foundation centre and the ground surface occurs. However, this separation does not mean toppling.

Figure 3. Example of a dynamic structural response of the fixed-base model subjected to EQ 6.
Figure 4. Example of a dynamic structural response of the nonlinear flexible-base model subjected to EQ 6.

As illustrated in these figures, the inclusion of nonlinear soil-structure interaction in dynamic analysis results in a residual foundation deformation that, in turn, causes a more significant residual total displacement compared to that for the fixed-base model. In addition, foundation settlement exists as a result of this integration that cannot be captured in a traditional fixed-base model. Finally, the nonlinear behaviour of the foundation most probably makes the system to show a smaller structural acceleration and less degree of nonlinearity.

4.2 SSI effects presentation

To illustrate SSI effects on structural response for the different soil-foundation interface conditions examined, the maximum values of: 1) structural acceleration \( a_s \); 2) total displacement \( u_{tot} \); and 3) normalized structural distortion by the yield displacement \( u_r/\delta_s \) are compared for the fixed-base (FB) and flexible-base (SSI) models. In addition, the residual foundation settlement \((u_f)_rs\) and rocking \((u_f)_rs\) are also illustrated for flexible-base models.

4.3 Linear SSI effects

The results of the numerical simulations using models with linear soil-foundation interface are presented in Figure 5. Clearly, as the foundation behaves linearly and the vertical and rocking foundation responses are independent, the foundation settlement under the total weight of the system is constant for all ground motions considered, and no residual foundation rocking is observed. Furthermore, in terms of structural acceleration, in contrast to the current design provisions, SSI can either decrease or increase the response. In this context, the probability of amplification is 25%, a percentage value that cannot be simply neglected. However, it should be noted that the degree of
reduction is higher than the degree of amplification. The maximum reduction in the structural acceleration due to SSI is about 40%, while the maximum amplification is about 20%. In addition, at the 84th percentile level, a linear SSI model appears to reduce the structural acceleration by about 10%.

The response amplification effects of SSI are more pronounced when total displacement is considered. Specifically, for almost 95% of the cases, SSI results in an amplified total displacement, with a maximum amplification of about 90%. Moreover, at the 84th percentile level, SSI increases the total displacement by almost 20%. The risk of such non-negligible level of amplification emphasizes that SSI should be always considered in studies where pounding effects are of concern. Finally, if structural distortion is considered, SSI can also result in either a reduction or an amplification in the response. In this case, the probability of amplification is about 45% with the maximum reduction and amplification being in the order of 40%. Note that the structural distortion is reduced at the 84th percentile level by about 10% when a linear SSI model is used.

Figure 5. SSI effects on structural response for models with linear soil-foundation interface.

Figure 6. SSI effects on structural response for models with nonlinear soil-foundation interface without uplift.
d, different trends and conclusions are observed. In the case of linear SSI, structural acceleration and structural distortion always decrease due to SSI consideration. The maximum reduction in the response is 60% for structural acceleration and similarly for structural distortion. This high degree of reduction in the response is obviously due to a large amount of energy dissipation occurring at the soil-foundation interface level. In addition, consideration of soil material nonlinearity can reduce structural acceleration and structural distortion at the 84th percentile level by almost 30% and 50%, respectively. It is also interesting to note that although foundation yielding decreases structural ductility level, it cannot totally prevent the structure from yielding.

Furthermore, in contrast to what observed in the case of linear SSI, structural acceleration and structural distortion always decrease due to SSI consideration. The maximum reduction in the response is 60% for structural acceleration and similarly for structural distortion. This high degree of reduction in the response is obviously due to a large amount of energy dissipation occurring at the soil-foundation interface level. In addition, consideration of soil material nonlinearity can reduce structural acceleration and structural distortion at the 84th percentile level by almost 30% and 50%, respectively. It is also interesting to note that although foundation yielding decreases structural ductility level, it cannot totally prevent the structure from yielding.

However, when total displacement is considered, different trends and conclusions are observed. SSI increases total displacement for almost 70% of the cases. In addition, the amplification in the response...
at the 84th percentile level is about 20% with the possibility of an increase up to 100%. It highlights that the beneficial role of SSI in decreasing structural acceleration and ductility demand is compensated by large foundation displacement and rocking that might become totally unacceptable.

4.5 Nonlinear SSI effects considering material and geometrical nonlinearity

Obviously, material and geometrical soil-foundation interface nonlinearity are two inseparable phenomena. Thus, their combined role on SSI effects should be investigated when soil-foundation interface nonlinearity is included in the SSI analysis. In this regard, the macro-element with an activated uplift option was used in the simulations adopted. Note that when foundation uplift is considered, an extra type of foundation failure, referred to as toppling, is introduced. Principally, foundation toppling occurs when the separation between the soil and foundation exceeds a predefined limit. The results of the numerical analyses considering both material and geometrical nonlinearity are presented in Figure 7.

As foundation uplift is included in the dynamic analysis, the soil-structure system considered experiences a larger degree of nonlinearity at the foundation level. Specifically, foundation failure due to soil yielding occurs in 6 cases, where the foundation motion is getting very large without being stabilized. Having larger degree of nonlinearity also can be distinguished in terms of residual settlement and rocking at the foundation level. As shown in Figure 7, residual foundation rocking can increase up to 0.015 rad compared to 0.005 rad when foundation uplift has been neglected. Due to this large foundation rocking, the centre of foundation even may experience a residual separation from the ground level. In addition to the cases of failure due to due to soil yielding, 1 toppling failure was also observed. Therefore, 7 cases out of 40 scenarios investigated experienced foundation failure. These failure cases are not shown in the graph presenting 

\[
(u_p)_{res} \text{ vs. } (u_p)_{res}.
\]

Similar trends and conclusions to those described for the case of nonlinear SSI without uplift are valid in the case of nonlinear SSI with both material and geometric nonlinearity. More specifically, nonlinear SSI with uplift also always decreases structural acceleration and normalized structural distortion. The maximum reduction in the response is also 60% with the reduction at the 84th percentile level being 40% and 60% for structural acceleration and structural distortion, respectively. It implicitly concludes that foundation uplift does not have a significant effect on the original structural response. However, when total displacement is considered, the effect of foundation uplift is notable. This is due to the fact that the total displacement includes foundation motion as a rigid body that, in turn, is significantly affected by foundation uplift. Nonlinear SSI with uplift increases the total displacement for almost 75% of the cases, and the maximum amplification in the response can be up to 200%, even before showing foundation failure due to soil yielding. Note that the cases with the largest values of total displacement (6 in total) correspond to the cases where the foundation failure is due to soil yielding. Nonlinear SSI with uplift at 84th percentile level increases the total displacement by about 180%.

An attempt is also made to better illustrate and compare SSI effects when different soil-foundation interface conditions are considered. In this regard, Figures 8 and 9 compare the previously defined response parameters for the cases of nonlinear SSI vs. linear SSI and nonlinear SSI vs. nonlinear SSI without uplift, respectively.

When nonlinear SSI effects on soil-structure system response are compared with the linear SSI effects (Figure 8), it is clear that residual foundation rocking, which might have a significant consequence in terms of design and recovery after earthquake event, is not taken into account in linear SSI. In addition, it can be concluded that linear SSI overestimates structural acceleration and structural distortion. This overestimate is in the range of 30-80% for structural acceleration and in the range of 30-150% for normalized structural distortion. Therefore, using a linear SSI analysis to define structural reactions and deformations when soil-foundation interface nonlinearity is probable to occur, can lead to misleading results and conclusions. On the other hand, if total displacement is considered, soil-foundation interface nonlinearity can result in either reduction or amplification in the response compared to the case when linear SSI is considered. For almost 50% of the cases considered, soil-foundation interface nonlinearity results in larger total displacement. The maximum amplification in
the response, ignoring failed scenarios due to soil yielding, is about 120%, while the maximum reduction is about 40%. It clearly demonstrates that soil-foundation interface nonlinearity also plays an important role in terms of total displacement.

If the results from nonlinear SSI analyses are compared with those from nonlinear SSI without uplift, as shown in Figure 9, it is noticeable that foundation uplift has a significant effect on the foundation rocking and, consequently, total displacement. For almost all the cases considered foundation uplift result in an equal or a larger residual foundation rocking and total displacement. However, the effects of foundation uplift on structural acceleration and structural distortion is not significant. Principally, considering both material and geometrical nonlinearity only slightly reduces structural acceleration and structural distortion as compared to the case when foundation uplift is ignored.

Figure 8. Comparison of dynamic structural response between models with nonlinear and linear soil-foundation interfaces.

Figure 9. Comparison of dynamic structural response between models with nonlinear and nonlinear without uplift soil-foundation interfaces.
4.6 The role of earthquake design level

As shown in the Christchurch earthquake sequence in 2010-2011, structures designed for the DBE level might be subjected to extreme events during their life time. Therefore, from a design point of view, it is important to assure that structures can resist the higher seismic demand without collapsing or, where possible, without being damaged beyond reparability level. In this regard, to investigate the role of earthquake design level on the response of soil-structure systems with nonlinear soil-foundation interface, the suite of ground motions selected were scaled up to the maximum credible earthquake (MCE) level, i.e. with a 2500-year return period, and the dynamic simulations previously described were repeated with the records scaled to MCE. The results of these simulations are summarised in Figure 10.

As expected, pushing foundation with larger forces will result in a larger number of failure cases. In this regard, 16 cases failed due to foundation toppling, 18 cases failed due to soil yielding, and only 6 cases avoided any foundation failure. Large foundation motion obviously results in a very large total and residual displacement that is further out of the acceptable range. However, large soil-foundation interface nonlinearity was in favour of structural response in terms of structural acceleration and structural distortion. Specifically, nonlinear SSI, in general, reduced structural acceleration by a factor of 2 and structural distortion by a factor of 2.5. It implicitly means that soil-foundation nonlinearity can act as an isolation mechanism preventing the damage to be transferred to the structure.

The statistics presented gives the crude impression that, using nonlinear SSI as an isolation mechanism in extreme events can result in system collapse due to foundation toppling with 40% probability, structural protection but with large foundation movement with 45% probability and full structural protection with 15% probability.

Figure 10.SSI effects on structural response for models with nonlinear soil-foundation interface considering MCE hazard level.

5 CONCLUSIONS

This study aimed to investigate the role of soil-foundation interface nonlinearity on the seismic soil-structure interaction analysis. With this purpose, a comparative analysis was performed between soil-structure models with four different base fixity conditions, including: 1) fixed-base; 2) linear flexible-base; 3) nonlinear flexible-base without uplift; and 4) nonlinear flexible-base with uplift. In this context, the structure was modelled as a yielding single-degree-of-freedom system with Takeda type force-deformation behaviour, and the soil-foundation interface was modelled either with a spring-mass-dashpot assembly (for linear case) or macro-element (for nonlinear cases). The generated models
were then subjected to a suite of recorded ground motions representing large-magnitude, moderate-distance earthquake events. The results of the simulations adopted can be summarised as:

- In contrast to what typically believed in practice, linear SSI can result in beneficial or detrimental effects on the structural response depending on the soil-structure-earthquake scenario considered.

- The role of soil material nonlinearity on the SSI effects is significant. Specifically, this role is favourable in reducing the structural response compared to that of the fixed-base condition. However, this beneficial role might be compensated with large foundation displacement and rocking that might be totally unacceptable.

- Foundation uplift increases the degree of nonlinearity on the foundation behaviour and, consequently, causes larger foundation displacement and rocking. In this context, foundation might fail due to excessive soil material nonlinearity or toppling, while it would not captured if the uplift was not considered. However, the effects of foundation uplift on the structural response are negligible compared to the effects of soil material nonlinearity.

- Soil-foundation interface nonlinearity in the extreme events can be used as a damage prevention mechanism if the toppling and large rigid body deformation can be appropriately treated.

- Finally, it should be noted that this study only covered a simplified SDOF system. Thus, the differential movement of the individual foundations was not taken into account. These individual foundation movements, and possibly failures, might introduce large deformations/stresses in the structure above and, consequently, cause greater damage than that predicted in fixed-base analysis. Therefore, a further study is required to investigate these effects in more detail.

REFERENCES:


