INFLUENCE OF SOIL-STRUCTURE-INTERACTION IN SHEAR-WALL RC BUILDINGS FRAGILITY CURVES

M. Rodríguez\(^1\), C. Magna-Verdugo\(^2,3\) and J. Abell\(^4\)

ABSTRACT

It has been widely recognized that soil-structure interaction (SSI) can have a significant effect on structural performance during seismic response. This effect varies depending on structural and local site characteristics, meaning that general conclusions, relevant to a large class of structural and site characteristics, cannot be drawn. In this study, the seismic performance of a typical Chilean shear-wall reinforced concrete (RC) building is assessed. The geometric and material characteristics of the building are chosen to be representative of a 20-story RC residential building. Its design followed the Chilean seismic code provisions. The numerical model of the prototype RC building was developed using the program OpenSEES, wherein fiber-based beam elements using non-linear materials were considered. SSI effects were incorporated by modeling the site using a linear continuum approach discretized by two-dimensional quadrilateral finite elements. Materials were chosen consistent with a class B site (Vs30 > 500 m/s), according to the Chilean site classification of the seismic. Fragility curves were obtained through incremental dynamic analysis, using a set of 34 acceleration ground-motion records obtained from the Chilean National Seismic Center. Different damage measures were extracted from the simulations, e.g.: inter-story drift, floor acceleration, axial load levels measured in the walls, among others. Two sets of fragility curves were obtained considering the inter-story drift of the first floor, one for a fixed-base model and the second, for a model including SSI. The results shown in this study showcase the importance of SSI effects in the structural response of shear-wall RC buildings in Chile. The inclusion of SSI effects in fragility curves is of importance to damage evaluation and risk assessment studies, which use the fragility curves as an input.

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ABSTRACT

It has been widely recognized that soil-structure interaction (SSI) can have a significant effect on structural performance during seismic response. This effect varies depending on structural and local site characteristics, meaning that general conclusions, relevant to a large class of structural and site characteristics, cannot be drawn. Therefore, SSI must be considered on a case-by-case basis. In this study, the seismic performance of a typical Chilean shear-wall reinforced concrete (RC) building is assessed, considering fixed-base and SSI response, using a two dimensional numerical model. The geometric and material characteristics of the building are chosen to be representative of a 20-story RC residential building. Such characteristics include wall density, story weight per unit area, inter-story height, length and width of walls, reinforcement ratio for the boundary elements and wall web, among others. Its design followed the Chilean seismic code provisions. The numerical model of the prototype RC building was developed using the program OpenSEES, wherein fiber-based beam elements using non-linear materials were considered. SSI effects were incorporated by modeling the site using a linear continuum approach discretized by two-dimensional quadrilateral finite elements. Materials were chosen consistent with a class B site (Vs30 > 500 m/s), according to the Chilean site classification of the NCh433 seismic code, which is common in some populated cities in Chile, such as Santiago. Also, a fixed-base model was developed for comparison. Fragility curves were obtained through incremental dynamic analysis (IDA), using a set of 34 acceleration ground-motion records obtained from the Chilean National Seismic Center. Different damage measures were extracted from the simulations, e.g.: inter-story drift, floor acceleration, axial load levels measured in the walls, among others. Two sets of fragility curves were obtained considering the inter-story drift of the first floor, one for a fixed-base model and the second, for a model including SSI. The results shown in this study showcase the importance of SSI effects in the structural response of shear-wall RC buildings in Chile. The inclusion of SSI effects in fragility curves is of importance to damage evaluation and risk assessment studies, which use the fragility curves as an input.

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Introduction

Typical Chilean residential buildings are composed of a lateral resistant system based on reinforced concrete (RC) walls [1,2], as shown in Figure 1. The walls are usually continuous in elevation, and can be found in the central axis and the perimeter of the buildings. Due to the damage reported after the 2010 Chilean earthquake [3-5], the Chilean seismic standard [6] was modified to include: a special design detailing for wall boundary elements, a limit was placed on the maximum level of axial load in the walls permitted [7], and a modification to the classification of soil types, among others [8]. Previous studies have assessed the performance of old Chilean RC walls [9-10] and generated fragility curves for fixed based models following a similar procedure as the present study [9]. Given all the changes introduced by the new seismic code, a re-assessment of the RC building fragilities and implied risk is needed. Furthermore, with the advances in computing, including the effects of soil-structure interaction (SSI) in the fragility curves through direct simulation has become feasible. Comparing the performance of buildings with and without SSI will help to gain a deeper understanding of the overall behavior of RC shear-wall structures.

Figure 1. Plan view of a typical residential reinforced concrete building in Chile (dimensions in meters).

The effect of SSI is evaluated by comparing the response of a fixed-base model subjected to ground motions which have been modified to consider free field site response, with a flexible-base model which directly models the site in question and is subjected to the same records without the site effects. The soil is modeled using a linear constitutive model within a 2-D continuum approach. A type B soil site, as defined by the Chilean seismic standard classification (Vs30>500 m/s) [6-8] was considered in this study. This is a common foundation soil in the most populated city of Chile, Santiago. This type of soil tends to be considered favorable for high-rise buildings, but there is little information about how SSI effects might influence the seismic performance of these structures. Moreover, the code classifies the site class considering only the value of Vs30 and disregarding the site-specific resonant period, which can possibly further
enhance the site response and SSI effects making the seismic demands on the building more severe.

To achieve the goals of this research, two models were developed in the OpenSEES platform [11]. The first one is a 2D model of a residential high-rise building considering a fixed based (FB) support condition, and the second model is the same building model founded on a linear-elastic continuum site model. Both models were subjected to incremental dynamic analysis (IDA) [12], which involves nonlinear time history analysis using scaled ground motions. The horizontal components of seventeen ground motion records were selected to construct the IDA record database. From these analyses, the performance of building is assessed by considering the first floor inter-story drift as damage state parameter, following the definition included in the Hazus manual [13]. The fragility curves derived from this IDA for both models are compared to assess the effect on the behavior of the structure when SII is included.

Prototype Building

The fragility curves derived from this study were obtained from a reduced model of the RC building illustrated in Figure 1. For simplicity and for lowering computational cost a 2D model was selected, similar to the model presented in previous studies [9, 14]. A representative axis of a 20-story reinforced concrete shear-wall building was selected for the analysis (Figure 2 b)). This axis has two rectangular walls with of 6.7 m in length, with thickness of 0.3 m (minimum required by the design code), and 2.5 m of inter-story height, resulting in a total of 50 m of total building height. The two walls are connected through a flexural element representing a portion of the slab, estimated to have a depth of 0.2 m according to reference [15]. As shown in Figure 2, the walls are separated by a corridor of width 1.6 m, where the effective stiffness of the slab is related to a 0.5 times separation of the two rectangular walls [16]. Since this horizontal connector does not provide enough coupling, it is assumed that the behavior of the walls is dominated by flexure. The tributary area for the analyzed axis is 82 m², which implies a wall density in the direction of analysis of 4.91%.

![Figure 2. Plan and elevation views of prototype building: a) Plan view with tributary area, b) Elevation with building height](image-url)

With respect to the materials, common properties for concrete and steel were used in the design of the prototype building. A compressive strength of $f'c=25$ MPa and yield and ultimate strengths of 420 MPa and 630 MPa, were used for concrete and the steel, respectively. Following the guidelines established in Chilean seismic code NCh433.Of1996mod2009 [6] and the documents Decretos Supremos 60 [7], and 61 [8], a modal-spectral and an elastic analysis using
a design spectrum was performed in ETABS [17]. The ETABS model does not consider soil-structure interaction, and it was fixed at the base. From the modal analysis, the fundamental period obtained is 1.14 sec, similar to the periods of real RC residential buildings with in Chile [2]. From the design procedure an ultimate design shear value of 4558 kN was obtained, which is equivalent to 4.8% of the seismic weight of the prototype building. The longitudinal reinforcement ratio of the boundary element is estimated to be 0.13%, resulting in 10 $\phi$ 16 mm and its transverse reinforcement is comprised by hoops hooks of $\phi$ 8 mm with spacing of 7 cm, along the wall height. The web reinforcement was designed with $\phi$ 10 mm bars spaced at 20 cm in the longitudinal directions and axis and $\phi$ 8 mm bars spaced at 10 cm for the transversal direction. Details of wall reinforcement are shown in Figure 3.

After the building design is completed, a model was built using the OpenSEES platform [11] and the fundamental period obtained was of 1.06 sec. The differences presented in the reported period with respect to the period obtained from ETABS might be attributed to numerical discrepancies in solvers, constitutive relations of the materials, among others. Nevertheless, the differences of the periods do not translate in large discrepancies of the final overall response of the building.

**Numerical model**

The nonlinear model of the prototype building was implemented in OpenSEES, and the walls were modeled following the Pugh model [18], which can be based on a Displacement-Based or a Force-Based Beam-Column element. An RC wall model calibration program was carried out and can be found elsewhere [14]. In that reference, three wall models were compared with experimental cyclic tests reported in the literature [14]. Variation of the material definition, and confinement models was included. Finally, the wall model that showed better computational stability, modeling simplicity, and accuracy was the Pugh model, with Chang & Mander concrete model [19], constitutive based model for steel (SteelMPF), Saatcioglu & Razvi confinement concrete model [20] and Yassin [21] constitutive model for concrete (Concrete02). The Pugh model for RC walls was modeled using a Displacement-Based Beam-Column element because it presented a better stability and convergence in the non-linear time history analysis with respect to Force-Based Beam-Column model. Each wall at every floor was modeled using 5 elements along the height and 5 integration points (iPs). The shear component of the walls was considered throughout the section aggregator command for including the defined material with shear properties recommended by Pugh reference [18]. For modeling the connecting slab between the walls, a beam-with-hinges model was used. The effective stiffness of the coupling slab was accounted by including plastic hinges [22] in the boundary elements, along the corridor.
length. The connection between the slab element and the walls elements was completed by the command constrain rigidLink, and equalDOF, representing the rigid diaphragm expected to form in this type of buildings. Additionally, for improving stability and computational cost, a truss element [23] was included at the center of each wall, to finally generate the rigid diaphragm provided by the concrete slab. The modeling configuration showing all the mentioned elements is presented in Figure 4.

![Figure 4. OpenSEES model of RC shear-wall frame, first floor elevation.](image)

Two boundary conditions were considered at the base of the building. First, a fixed base condition where both translations and the rotation of the bottom nodes are fixed. In this case the earthquake is input into the model as a base acceleration, resulting in inertial forces along the height of the building, using the ground motion records modified to include site effects. The second case is the building founded over a flexible model of site soil, where the soil is modeled like a continuum. Figure 5 illustrates the model with SSI and establishes all boundary conditions, the reader interested in details is referred elsewhere [24].

![Figure 5. Prototype building model including SSI.](image)
Ground motion database and site response

A set of ground motion records was obtained from the website of the national seismological center at Universidad de Chile. Records were selected to have epicentral distances between 100 km and 250 km and magnitudes in the range 6.5 <= Mw <= 9.0. This selection covers a range of durations from about 19 s to 125 s and PGA values as small as 0.01 g and as large as 0.56 g. From this initial selection, a suite of 17 records were chosen such that they are all within similar hypocentral distances (between 150 km and 180 km) and cover a wide range of magnitudes, PGA, and significant durations. The specifics of the chosen records along with their relevant metrics can be found elsewhere [17]. For IDA analysis, both horizontal components of these records are used independently for a grand total of 34 records.

All records in the database were obtained on rock or very hard sites, with surficial shear wave speeds in excess of 800m/s. The class B site of the Chilean seismic code [6-8] is characterized by a shear wave speed averaged over the first 30 m of soil (Vs30) greater than 500m/s. In order to introduce the site effects into the seismic records, a 1-D linear site response analysis was performed. The shear wave speed was modeled increasing in depth following $V(z)=V_0 \left(1 + z^\alpha\right)$, where $V_0$ and alpha were chosen to produce an average Vs30 > 500m/s in the first 30 m of depth. The parameters $V_0 = 150$ and alpha=0.5 were chosen in this case. The site was prolonged in depth up to a total depth $H$ until a site period which matches the fixed-base period of the structure was obtained. In the present case $H=52.5$m. Care was taken to to ensure proper frequency resolubility and dissipation of out-going waves was provided using Lysmer-Kuhlemeyer boundary conditions [24]. The response at the free surface was recorded and used then for the following fixed-base IDA analysis. Figure 6 shows the 5%-damped response spectra of the chosen records without site-effects (left) and with the incorporated site effects (right). Inclusion of site effects resulted in increases in spectral accelerations at the fundamental building period between 11% and 74%, while peak ground accelerations saw anywhere between 2% and 44% increases for the records in the database.

![Figure 6](image-url)

Figure 6. 5%-damped response spectra of records database: a) without site-effects and b) with the incorporated site effects.
Fragility curves show the probability of reaching a particular damage state as a function of intensity measure. In this work, fragility curves were constructed from incremental dynamic analysis (IDA) [12]. IDA is a parametric analysis method used to estimate structural performance under seismic loads. It involves subjecting a structural model to one or more ground motions records, scaled to achieve increasing levels of earthquake intensity measure (IM). At each demand level, one or more engineering demand parameters (EDP) are computed. Then, one or more curves of response parameterized versus intensity level are plotted in what is called an IDA curve.

The 5%-damped spectral acceleration ordinate at the fixed-base fundamental period (Sa(T₁)) was chosen as seismic intensity measure parameter (IM). This is a commonly used parameter since it correlates strongly with the dynamic behavior of structures dominated by the first mode [12]. The first floor inter-story drift and roof drift of the building were chosen as damage measure parameters (DM), and were obtained from the analysis results.

“Slight”, “moderate”, “extensive”, and “complete” damage states were defined for this DM following the recommendations given in the Hazus-MH2.1 manual [13] for a type C2 high-rise building and a high-code design level (equivalent to the Chilean seismic code including modifications after 2010 event). Thus, threshold values in mm/mm are 2‰ for “slight”, 5‰ for “extensive, 15‰ for “moderate” and 4‰ for “complete” damage states.

The IDA analysis was performed by scaling the 17 records selected and both their respective horizontal components were scaled from 0.05g to 2.5g spectral acceleration (Sa(T₁)) levels, using increments of 0.05g. This generates a total of 1,700 nonlinear time-history analysis cases which were run in parallel using the HPC infrastructure at the National Laboratory for High-Performance Computing (NLHPC) at Universidad de Chile. Figure 7 presents the IDA curves obtained considering the maximum roof displacement as the DM value for both models, fixed based (a) and SSI model (b). Additionally, the plot show the level at which the limit states are exceeded for each record.

Figure 7. Incremental dynamic analysis curves for the roof displacement (ur). Dots mark exceedance of limit states; green for “slight”, blue for “moderate”, yellow for “severe” and red for “complete”.
For the fixed base model, the displacement of the first floor relative to the base and the absolute displacement of the first floor are the same. In the case of soil structure interaction, in order to obtain the relative displacement of the first floor with respect to the base, the absolute displacement of the base and the effect produced by the rocking of the building must be subtracted from the absolute displacement of the first floor. This numerical correction must be performed to extract the rigid body rotation of the building which leads to increases in relative story drift without deformation of the walls and, hence, no damage. This modification is necessary to prevent the overestimation of the relative displacements. From figure 7 it can be observed that both models attain the first three limit states, slight, moderate, and extensive for some records. For the “complete” limit state, the fixed base model does not report exceeding the threshold, contrasting the SSI model, which shows the exceedance of the limit value in several ground motion records.

The fragility curves are constructed from the IDA curves by counting the number of cases that exceed a given threshold value for each intensity measure. Following the procedure described by Baker [25], a lognormal probability distribution curve with 95% confidence is fitted to these curves. The adjusted parameters obtained for each damage state for the two cases studied (FB and SSI) are found in Table 1. The fragility curves obtained are plotted in Figure 8, where the effect of including SSI to the model is evident.

Table 1 Mean and standard deviation of the adjusted fragility function for fixed-base model and model including SSI.

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Fixed-Base Model</th>
<th>SSI Model</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Slight</td>
<td>-0.798</td>
<td>0.305</td>
</tr>
<tr>
<td>Moderate</td>
<td>-0.066</td>
<td>0.321</td>
</tr>
<tr>
<td>Extensive</td>
<td>1.116</td>
<td>0.317</td>
</tr>
<tr>
<td>Complete</td>
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Figure 8. Fragility curves for the maximum first-floor inter-story drift ratio for all damage states with and without SSI.
From Figure 8 it can be observed that the probability of exceedance of all 4 damage states increases when considering SSI. The probability of exceeding the “slight” damage state reaches 50% at $Sa(T1)=0.48g$ and $Sa(T1)=0.32g$ for the models without and with SSI, respectively. For 50% of exceeding the “moderate” state the intensities values of $Sa(T1)=1.11g$ and $Sa(T1)=0.48g$ are computed, respectively. For the “extensive” damage state, the 50% exceedance is achieved at $Sa(T1)=1.25g$ for the SSI model, while for the maximum intensity measure considered in this study, only a 28% of probability is estimated for the fixed-base model. The “complete” damage state is only achieved with 48% probability of exceedance in the SSI case and was not achieved for the fixed-base model.

Conclusions

The goal of this research was to estimate the influence that SSI effects can have on building performance, even on a competent site class, when the site fundamental period closely matches that of the fixed-base building system. This was achieved by constructing fragility curves by means of IDA analysis of fixed-base and flexible base RC shear-wall building non-linear numerical models. The results show that significant differences appear in the selected damage measure, and is further reflected in the damage states achieved in the IDA analysis. Notably, the fixed base model never achieve the complete damage state for the maximum intensity measure ($Sa(T1) = 2.5g$), while the model with SSI does achieve this state at the same IM level. Across all damage states, it is shown that SSI can severely increase the probability of exceedance of damage states referring to interstory drift, even in a competent soil, given the right conditions. This work shows that not only is it necessary to classify sites using soil rigidity parameters such as $Vs_{30}$, it is also necessary to include site dynamic properties such as fundamental site period as well as SSI effects.

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