SEISMIC FRAGILITY EVALUATION OF MID-RISE RC STRUCTURES INCLUDING SOIL-STRUCTURE INTERACTION

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ABSTRACT

Seismic vulnerability assessment of mid-rise residential RC structures is critical for urban earthquake risk mitigation, especially in seismically active regions like Istanbul. Traditional fragility evaluations often treat structures as fixed-base systems, neglecting the significant influence of soil-structure interaction. This study aims to develop comprehensive seismic fragility curves for mid-rise residential RC structures that explicitly incorporate soil-structure interaction effects, providing a more accurate representation of structural vulnerability under various earthquake scenarios. Three different modeling approaches were employed: the fixed-base model, the sway-rocking soil springs model, and the finite elements model with solid elements for soil. The results indicate that the third model, which incorporates detailed soil-structure interaction, consistently shows higher probabilities of exceeding performance levels at lower PGAs compared to the other two models. This suggests that simplified models may underestimate the seismic vulnerability of structures. The study highlights the importance of considering SSI in seismic fragility assessments to achieve more accurate and realistic predictions of building performance. The methodology developed, including the semi-automated analysis process using programming languages, provides a robust framework for conducting large-scale seismic fragility assessments. This approach can be extended to evaluate a wider range of building types, heights, and soil conditions, contributing to more comprehensive seismic risk assessments for urban areas. The findings of this research contribute to the ongoing efforts to improve earthquake resilience in Istanbul and similar seismically active regions. By demonstrating the critical role of SSI in fragility assessments, the study calls for a reevaluation of current seismic design practices and risk assessment methodologies.

Keywords: Seismic Fragility Assessment, Fragility Curves, Soil-Structure Interaction, Soil Springs, Numerical Models.

1. INTRODUCTION

Seismic vulnerability assessment of mid-rise residential reinforced concrete (RC) structures is crucial for urban earthquake risk mitigation, particularly in seismically active regions. While traditional fragility evaluations often treat structures as fixed-base systems, this study recognizes the influence of soil-structure interaction (SSI) on the seismic performance of buildings. The dynamic reciprocation between the soil and the structure can substantially alter the overall system behavior, potentially leading to significant differences in structural response and damage probabilities. This research aims to develop comprehensive seismic fragility curves for mid-rise residential RC structures that explicitly incorporate SSI effects, providing a more accurate representation of structural vulnerability under various earthquake scenarios. By considering the local design code, the influence of soil conditions, and the structural properties of mid-rise residential buildings, this study seeks to enhance our understanding of seismic risk assessment for this important class of structures. The findings are expected to contribute to

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improved seismic design practices, more accurate risk assessments, and better-informed decision-making in urban planning and earthquake preparedness strategies for residential areas.

Relationships between the damage and the ground motion, also known as fragility curves, play an important role in estimating losses and analyzing structural risk. These relationships describe the likelihood of reaching or surpassing a specific damage level relative to earthquake intensity. The goal of fragility evaluations is to estimate the capacity of a building concerning ground motion parameters like peak ground acceleration (PGA) or spectral acceleration (Sa). Seismic hazards for a site are typically defined by PGA or Sa at various structural frequencies, so fragility estimates are always referenced to these ground acceleration measures.

This study aims to contribute to the earthquake risk mitigation efforts in Türkiye by conducting a seismic fragility assessment for a conventional mid-rise residential building designed according to the current seismic design code. Fragility assessment is performed on three models with different foundation boundary conditions, one of which is the widely preferred fixed-base (FB) model, as well as two SSI models (one with soil springs, SR and one with solid finite elements, FE). The effects of SSI on the fragility curves are investigated by comparing the results of these models (Figure 1). Thus, this study sheds light on the methods that enhance the accuracy of the fragility curves and increase the confidence in them.

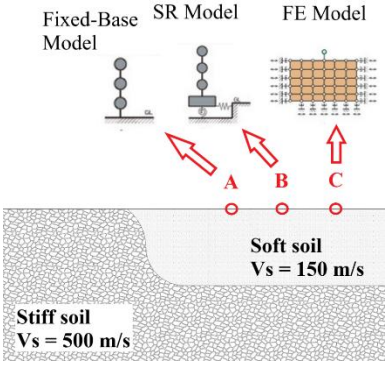

Figure 1. Depiction of the physical model

1.1 Study area

Istanbul is located near the North Anatolian Fault, which is along the seismically very active Alpine-Himalayan belt, making it highly susceptible to seismic activity. It encompasses a variety of soil types, including areas with a shear wave velocity of 150 m/s, which critically influence the seismic behavior of structures. Rapid urban growth and dense population further increase the risk of earthquakes disasters, emphasizing the need for rigorous seismic evaluations to safeguard the city's infrastructure (Ay & Demires Ozkul, 2021).

2. METHODOLOGY

To investigate the effects of SSI on seismic fragility evaluation, three types of analysis models are proposed. The first one is the most commonly used FB model that neglects the rotation of the foundation and assumes that ground accelerations are transferred to the structure completely and directly. This model has fewer degrees of freedom and requires less expertise (geotechnical part) and is therefore preferred over other models. The second model includes the SSI effect by modeling the soil as springs and dashpots. The last type models the soil with solid elements and considers the nonlinear behavior of the soil while simulating the SSI effects.

Herein, 14 earthquake records from the North Anatolian Fault and North Anatolian Fault (both are strike-slip faults) are used to perform incremental dynamic analysis (IDA) on mid-rise residential RC structures. The acceleration records are scaled for a peak ground acceleration (PGA) range of 0.1g–1.0g, covering a broad spectrum of seismic intensities. This comprehensive analysis aims to provide valuable insights into the seismic performance and fragility of typical mid-rise buildings in Istanbul, ultimately contributing to its urban resilience against earthquakes. This section describes the details of the numerical modeling for obtaining FC and implementing SSI into the analyses.

A conventional residential RC building with dimensions of 18–24 m on plan (each floor is laid on an equally spaced 3 × 4 grid) and six floors is designed according to the current seismic design code of Türkiye using the structural design software IdeCAD v10. This software facilitates the creation of a detailed structural model, including column and beam sizes, and rebar configurations. These details

are then used to model the 3D frame in STERA 3D, a Japanese structural analysis software known for its accuracy, user-friendly interface and computational efficiency.

After the initial modeling, a mass-spring model of the building is calibrated in ABAQUS using the analysis results obtained from STERA 3D. The calibration process includes conducting a pushover analysis for each story type to generate the backbone curve and capturing the relationship between lateral force and displacement. Subsequently, the entire structure is subjected to a gradual sinusoidal acceleration load (50 gal) to calibrate the elastic behavior of the springs. This load is then increased to 500 and 700 gal to assess the nonlinear response of the model.

2.1 Seismic fragility assessment

The selection of earthquake records for obtaining fragility curves is a critical step in seismic vulnerability assessment. The chosen earthquakes are specifically selected based on their relevance to the building's natural period of 0.478 s. The chosen earthquake records and the spectral acceleration plot provide a robust basis for calculating fragility curves. By focusing on spectral accelerations around the building's natural period, we can ensure a more accurate and reliable assessment of the building's seismic vulnerability. This approach aligns with previous research that emphasizes the use of spectral acceleration as a reliable intensity measure for mid-rise buildings. This ultimately contributes to improved seismic design practices and better-informed decision-making in earthquake preparedness and mitigation strategies.

2.2 Soil-structure interaction

Two approaches are investigated for the SSI part: 1) modeling the soil with springs and dashpots (sway-rocking (SR) model), 2) modeling the soil with solid finite elements (FE model). The former represents the elastic soil behavior with relevant stiffness and damping parameters, whereas the latter assumes the soil behavior is elastoplastic.

The SR model (Figure 2) is a simplified approach to represent SSI effects in seismic analysis. In this model, the soil beneath the structure is represented by a set of springs and dashpots that capture the translational (sway) and rotational (rocking) motions of the foundation, respectively. The springs represent the soil stiffness, whereas the dashpots account for radiation damping in the soil. Typically, horizontal and rotational springs are used for modeling the translational motions and rocking behavior, respectively. The properties of these springs and dashpots are derived from the soil properties and foundation geometry. This model allows for a more computationally efficient representation of SSI compared with full finite element modeling of the soil domain while still capturing key aspects of rotation of the foundation and energy dissipation through the soil. As the soil is assumed to be elastic in this model, four parameters that define the SSI are used, namely sway stiffness, sway damping coefficient, rocking stiffness, and rocking damping coefficient. These parameters are obtained by considering density, shear stiffness, and Poisson's ratio of the soil and the dimensions of the foundation.

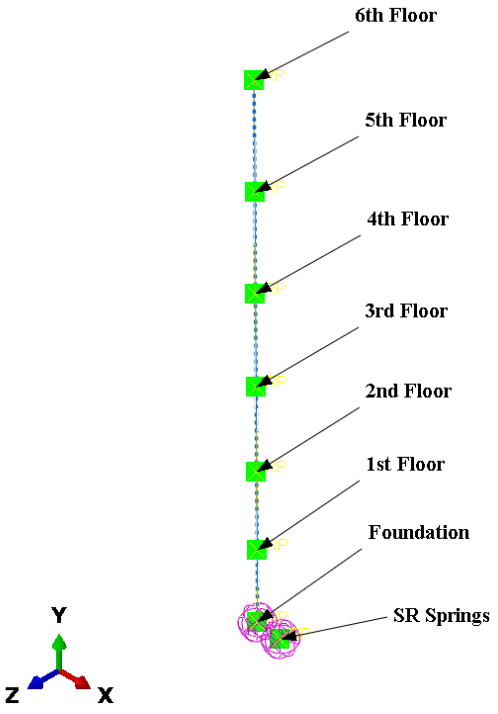

Figure 2. Assembly of the SR model in Abaqus

Full finite element (FE) modeling of the soil domain involves representing the soil-structure system in its entirety using a detailed numerical model.

The soil domain is discretized using solid elements while keeping the elements of the building the same as in the SR model. The coupled system of the FE model for both soil and structure is solved simultaneously via dynamic analysis in the time domain. The length of the soil part in the longitudinal direction is seven-fold that of the foundation in the same direction (Figure 3). Therefore, the far-field effect can be captured and then applied to the previously mentioned two models.

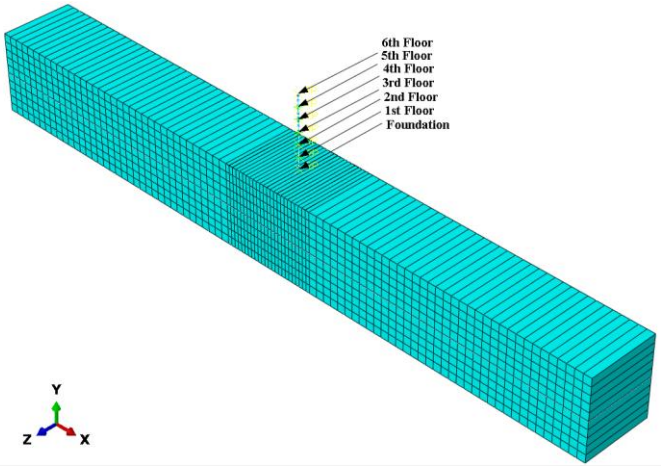

Figure 3. Mesh of the FE model

To reduce the computational cost of the model, the lateral direction is not divided into finite elements. A convergence check is performed to determine the optimum element sizes in the other directions. In the longitudinal direction, the element size is 1 m right under the foundation and 2 m in the rest of the model. In the depth direction, the mesh size is 2 m for the whole model. The structural model is placed on a rigid shell, which represents the rigid foundation. The boundaries of the soil at each end of the longitudinal direction is chosen as horizontal rollers.

3. RESULTS AND DISCUSSION

The results of this study provide a comprehensive analysis of the seismic performance of a mid-rise residential RC building designed according to the Turkish seismic design code. The building is modeled using three models, namely the FB model, SR model, and FE model with solid elements for soil. The model performances are evaluated using PGA as the seismic intensity measure and maximum interstory drift ratio (IDRmax) as the engineering demand parameter. The limit IDRmax values are determined as 1% for immediate occupancy, 2% for life safety and 2.5% for collapse prevention (Xue et al., 2008).

The fragility curves presented in Figure 4 show the probability of exceeding different performance levels (IO: Immediate Occupancy, LS: Life Safety, and CP: Collapse Prevention) as a function of PGA for the three models. These curves are essential for understanding the likelihood of various damage states under seismic loading. The fragility curves for the FE model show a higher probability of exceeding each performance level at lower PGAs compared with the other models, reinforcing the observation that the FB assumption may lead to risky estimates of seismic vulnerability. The fragility curves for the SR model indicate a lower probability of

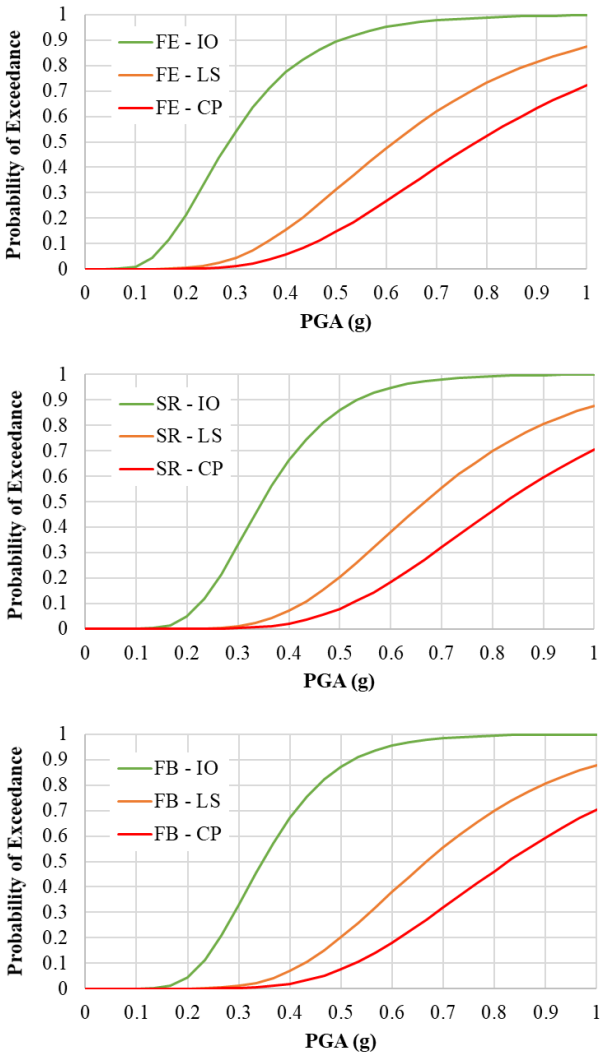

Figure 4. The fragility curves for each model

exceeding each performance level at a given PGA compared to the FE model, suggesting that the sway-rocking model may not provide an accurate assessment of the building's seismic performance by incorporating the effects of SSI. The fragility curves for the FE model show the highest probability of exceeding each performance level at a given PGA, underscoring the significance of using detailed SSI models to obtain reliable estimates of seismic vulnerability.

The next set of figures (Figure 5) compares the fragility curves of the three models for each performance level (IO, LS, and CP). The results show that the FB and the SR models exhibit similar probabilities of exceeding the IO performance level, whereas the FE model exhibits a higher probability. For the LS and CP performance levels, the finite elements model consistently shows the highest probability of exceedance, followed by the sway-rocking model and the fixed-base model. These findings highlight the importance of considering soil-structure interaction in seismic analysis to achieve more accurate and realistic predictions of building performance during earthquakes.

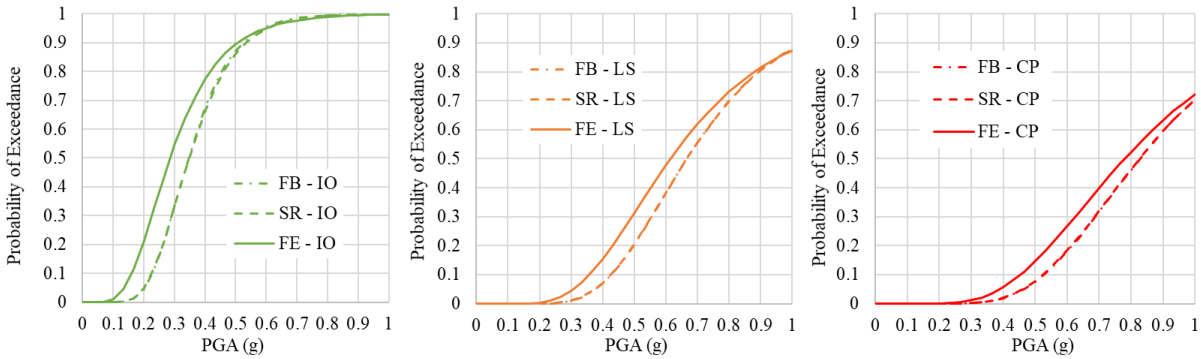

Figure 5. Comparison of IO, LS and CP fragility curves for each damage limit

In addition to these results, a set of analyses is conducted to investigate the influence of soil properties on the building response. Figure 6 shows the variation of the fragility curves depending on the elastoplasticity of the soil as well as the shear wave velocity. Because the plastic damages within the soil mostly occur at the bottom boundary of the top layer, the plasticity tends to decrease the probability of building damage, since it decreases the amplitude of the ground motion. Even though the stiffer soil (Vs = 200 m/s) yields smaller probabilities for lower PGA values, there is no considerable difference for the elastic soils with Vs = 150 m/s and Vs = 200 m/s for higher PGA values. These results emphasize the necessity of further investigation for various soil types and soil constitutive models.

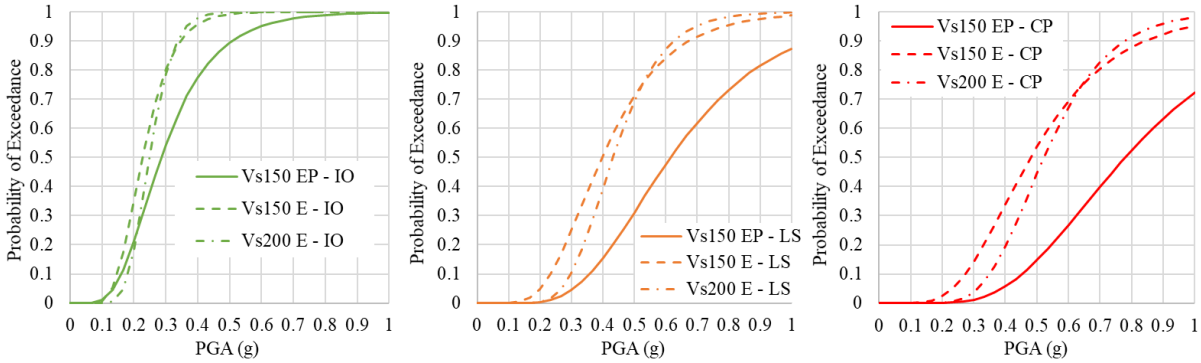

Figure 6. Comparison of various soil fragility curves for elastoplastic (EP) soil with Vs = 150 m/s, elastic (E) soils with Vs = 150 m/s and Vs = 200 m/s

4. CONCLUSIONS

For 14 earthquakes and 3 models (FB, SR, FE), a total of 504 analyses are made to obtain fragility curves. Such a large amount of analyses is run semi-automatically by using a set of MATLAB and Python scripts that are written for this study.

This study provides valuable insights into the seismic vulnerability of mid-rise residential RC structures in Istanbul, with a particular focus on the effects of soil-structure interaction (SSI). By comparing the three models, i.e., FB, SR, and FE, the considerable impact of SSI on seismic fragility assessments is investigated.

The FE model, which incorporates the most detailed representation of SSI, consistently showed higher probabilities of exceeding performance levels (IO, LS, CP) at lower PGAs compared to the other models. This suggests that simplified models may underestimate the seismic vulnerability of structures. The SR model, while accounting for some aspects of SSI, still provided lower estimates of vulnerability compared to the FE model. This indicates that even simplified SSI models may not fully capture the complex soil-structure interactions during seismic events. The commonly used FB model showed the lowest probabilities of exceeding performance levels, potentially leading to nonconservative estimates of the seismic risk.

These results underscore the importance of considering SSI in seismic fragility assessments, particularly for mid-rise RC structures in regions with soft soil conditions like parts of Istanbul. The significant differences observed between the modeling approaches highlight the need for careful consideration of SSI effects in seismic design and risk assessment practices.

The proposed methodology, including the semi-automated analysis process using MATLAB and Python scripts, provides a robust framework for conducting large-scale seismic fragility assessments. This approach can be extended to evaluate a wider range of building types, heights, and soil conditions, contributing to more comprehensive seismic risk assessments in urban areas.

In conclusion, this study contributes to the ongoing efforts to improve earthquake resilience in Istanbul and similar seismically active regions. By demonstrating the importance of SSI in fragility assessments, it calls for a re-evaluation of the current seismic design practices and risk assessment methodologies. Future studies should focus on further refining the SSI models, expanding the analysis to a broader range of structures and soil conditions, and integrating these findings into practical guidelines for seismic design and urban planning.

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