Evaluation of Settlement and Seismic Response of High-Rise Buildings Considering Soil–Structure Interaction Based on Static Loading Results and Continuum Modeling

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ABSTRACT

High-rise buildings have always been important subjects for researchers and structural designers. While seismic analysis of these structures is critical in engineering, the effects of soil-structure interaction often receive less attention. However, considering soil-structure interaction in seismic analyses provides more accurate and realistic estimates of structural performance during earthquakes. This study investigates the impact of soil-structure interaction on the seismic behavior of high-rise buildings with mat and pile (deep) foundations. The main goal is to evaluate foundation settlement considering soil-structure interaction and compare it with the fixed-base condition, which ignores soil effects. A 33-story high-rise building with a core frame structural system was modeled, analyzed, and designed using ETABS software. For a more precise analysis of the soil-structure-pile-mat interaction, the continuum soil modeling software MIDAS GTS NX was used to calculate foundation settlement under continuum conditions. Comparing these results with those using the Winkler spring model in non-continuum software shows that foundation settlement considering soil-structure interaction is greater than that predicted by the Winkler model. Furthermore, accounting for soil effects reduces foundation settlement compared to the fixed-base condition. Additionally, including soil effects in seismic analysis increases inter-story displacement. These findings emphasize the critical importance of incorporating soil-structure interaction in the analysis and design of high-rise buildings.

KEYWORDS

seismic interaction of pile soil and structure, seismic performance of buildings, continuous environment modeling, finite element, tall structure

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1. Introduction

Attention to the seismic and wind resistance of tall buildings is one of the most important challenges in civil engineering, especially considering geotechnical hazards. Recent earthquakes have shown that many buildings suffer severe damage; therefore, revising standards and using new materials and construction methods are crucial. Studies indicate that soil-structure-pile-foundation interaction (SSI) has a significant impact on the seismic performance of buildings and must be considered in design and analysis. During an earthquake, the soil beneath the structure undergoes deformations, and its behavior affects the dynamic response of the building. Thus, the structure, foundation, and soil act together as a unified system.

Numerous studies, including research by Dorrinia et al. (2025) studied the seismic behavior of structures in two conditions: fixed-base and considering soil-structure interaction. Their research results indicated the necessity of including soil-structure interaction for realistic outcomes [1]. Other studies, such as those by Tahghighi and Mohammadi (2020), also emphasize the importance of SSI in the vulnerability of structures [2].

Advanced software like PLAXIS 3D and MIDAS have facilitated more accurate modeling of soil-structure-pile-foundation interactions, enabling dynamic and seismic load analyses. These models, capable of simulating nonlinear soil and structural behavior, have been validated against static load testing results. Findings from these studies highlight the necessity of incorporating SSI effects in the seismic design of tall buildings to improve analysis accuracy as well as structural safety and performance. This innovative approach can be an effective step toward enhancing performance-based design methods for tall buildings.

2. Structural and soil properties

The studied building is a 33-story tall residential structure located in Babolsar city, which is classified as having a relatively high risk. The lateral load-resisting system consists of a core frame system. The height of the first floor is 4 meters, while the other floors have a height of 3.5 meters. The total height of the structure is 116 meters. Beams and columns are modeled using frame elements, although most seismic codes do not account for longitudinal slip of reinforcement in the plastic hinge region due to difficulties in interpretation. The thickness of the waffle concrete slab is 0.3 meters. The live load on residential floors is considered as 2200 kg/m², and an additional dead load of 160 kg/m² is applied to the slabs. Considering the building weight and soil strength, the use of a deep pile combined with a raft foundation (pile cap) with adequate stiffness for load distribution is necessary. Without considering settlement, the bearing capacity of this raft foundation is reported as 4.2 kg/cm² under gravity loads and 6.5 kg/cm² under seismic loading, with dimensions of 30 m by 46 m and a depth of 4 m. Also, without settlement considerations, the allowable soil bearing capacity beneath the raft exceeds the existing stress (3.75 kg/cm² seismic and 2.9 kg/cm² gravity). However, the existing settlements of the raft foundation—without accounting for piles exceed the allowable code limits, reaching approximately 40 cm. Therefore, this structure uses a combined raft foundation and piles, which has been incorporated in the modeling performed by MIDAS software. For geotechnical investigation, three boreholes reaching a depth of 60 m below the ground surface were drilled mechanically by a consulting company. During drilling, soil samples were taken at various depths for testing, and Standard Penetration Tests (SPT) were conducted according to ASTM-D1586. Near the surface, testing intervals were closer, increasing with depth. After stopping drilling, the SPT sampler was inserted to the desired depth and struck by a 63.5 kg hammer falling from a height of 76.2 cm. The number of blows required to penetrate 15 cm of soil was recorded, repeated three times for a total penetration of 45 cm. The blows counted for the last two 15 cm increments constitute the SPT value. In this study, borehole BH3 was used to determine soil parameters. Shear wave velocity and SPT data were used to calculate the soil elastic modulus Es. These calculations were carried out down to a depth of 60 meters.

3. Numerical modeling

The structure under study was first designed in ETABS software according to the Iranian Standard 2800 and the Ninth Chapter of the National Building Regulations. The structural system is a moment-resisting frame combined with a special shear wall. To model the soil-structure system and solve complex equations and boundary and geometric conditions, the finite element software MIDAS GTS NX was used. This software is employed for modeling the structure together with the soil and foundation to analyze interaction issues [3].

In the geotechnical MIDAS software, three soil layers with thicknesses of 12 m, 12 m, and 36 m were modeled over an area of 100 m × 100 m. Considering the construction site location, structural specifications, and consultant reports, the raft foundation alone did not provide sufficient bearing capacity; therefore, 100 piles were used in the design. The piles, with diameters of 1.2 m and lengths of 30 m and 25 m as per the construction drawings, were modeled accordingly. The soil is fine-grained at depths around 8 m and 17 m, coarse-grained at other depths, and the groundwater table is located at a depth of 5 m with relatively good bearing capacity.

The raft foundation has a settlement depth of 2.2 m below street level and dimensions of 30 m by 46 m. Figure 1. illustrates the modeled building and the soil layers.

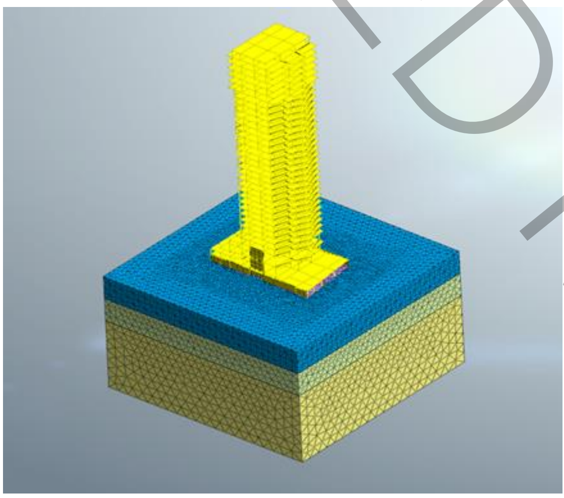

Figure 1 .Structure and soil layers modeled in MIDAS GTS NX software

4. Engineering Demand Components

For the selected structure and ground motion model, Engineering Demand Parameters (EDPs) were evaluated to quantify potential differences. Figure 2. shows the average calculated values of maximum inter-story drifts. These curves represent the average results from eight earthquakes for each hazard level, corresponding to return periods of 72 and 475 years. As seen in the figure, the average inter-story drifts for the fixed-base and SSI conditions at the 72-year return period show negligible differences. Therefore, according to the calculations in this study, soil effects on average inter-story drift can be disregarded.

On the other hand, the comparison at the 475-year return period, especially in the lower stories, is different. For the fixed-base condition, the average maximum inter-story drift is 0.65% (in stories 15 to 18), whereas in the SSI condition, it reaches 0.75% at stories 12 and 13. Earthquakes with a return period of 475 years or more cause such differences that increase the maximum inter-story drift. Hence, neglecting SSI can lead to unrealistic analysis results.

Regarding the base shear, according to FEMA P-2091, tall buildings in seismic zones exhibit spectral responses affected by soil-structure interaction (SSI), which alters the natural period by increasing it, resulting in a reduction of base shear. In this study, the base shear was calculated as 1713 tons for the fixed-base case and 1548 tons considering soil-structure interaction.

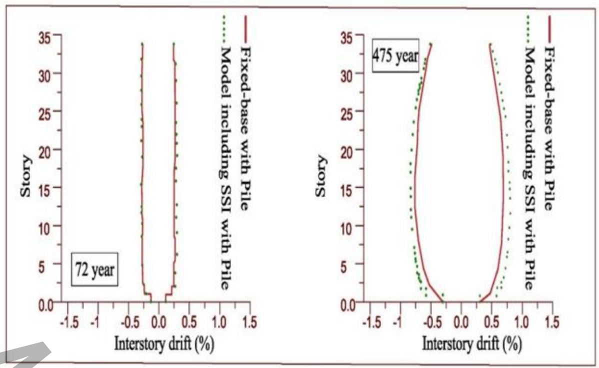

Figure 2. Calculated seismic EDPs along the height for each hazard level: Maximum inter-story drifts

5. Results and Discussion

In this study, the settlement of the foundation of a tall concrete building with a core frame system was examined under two conditions: considering soil-structure interaction (SSI) and fixed base. To this end, the 33-story concrete building and the surrounding soil were modeled using MIDAS software, which is based on a continuous environment. Then, the building model was analyzed in both the SSI and fixed base conditions, and the results were compared.

The analysis results showed that the foundation settlement in the presence of piles and considering soil-structure interaction differs significantly from the fixed base condition. For the building under study, the maximum settlement in the SSI condition was 14 cm, while it was 19 cm in the fixed base condition. Similarly, the minimum settlement was calculated as 3 cm for SSI and 5 cm for the fixed base. These differences emphasize the importance of accounting for soil-structure interaction effects in the analysis of tall buildings, as it leads to more accurate and realistic results.

Additionally, to investigate the seismic behavior of the structure under fixed base and SSI conditions, nonlinear dynamic analyses were performed. Two earthquake sets with return periods of 72 years and 475 years were applied to the structure. The results indicated that the maximum inter-story drift under the 72-year return period earthquakes showed little difference between the fixed base and SSI conditions. However, for earthquakes with a 475-year return period, the results differed, with the inclusion of soil effects resulting in increased drift. Furthermore, the overall displacement of the building differed between the two conditions; the displacement under SSI was less than that under the fixed base. This difference increased with the building height, reaching a maximum of 20% at the 33rd floor.

6. Conclusions

Overall, the findings of this study indicate that considering soil-structure interaction has a significant impact on the foundation settlement of the building, and results from fixed base analysis may lead to unrealistic estimates. Additionally, soil effects influence the structural response during earthquakes, especially for earthquakes with a 475-year return period. Considering the type of structure (core frame system) and the soil investigated, it is recommended that similar studies be conducted for other structural systems and soil types to enable a more comprehensive comparison and the development of more optimized solutions.

References

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