

DYNAMIC MODELING OF SOIL-STRUCTURE INTERACTION FOR SEISMIC PERFORMANCE EVALUATION OF REINFORCED CONCRETE BUILDING

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ABSTRACT:

This study focuses on the effect of soil-structure interaction on the dynamic behavior of structures subjected to seismic movements. A 2D model of a simple minaret, 18.4 meters tall with a width and length of 3.5 meters, was analyzed using the SAP2000 V21 finite element software. Two types of seismic loading were applied: the response spectrum of Algerian seismic regulations (RPA 99 version 2003) for low seismicity (zone: Z1), and accelerograms measured at the Keddara site in Boumerdès, Algeria, in 2003. The soil foundation is classified as type S3 (loose soil), and the analysis included conditions both with and without soil-structure interaction. The results indicate significant impacts of soil-structure interaction: the inclusion of soil effects led to a 25% reduction in base shear and a 15% increase in the fundamental period of the structure compared to the reference model without soil interaction. Additionally, nodal horizontal displacements at the top of the building increased by 40% when accounting for soil-structure interaction, affecting the overall stability and design considerations. This study underscores the importance of incorporating soil-structure interaction in the design process, as neglecting these effects could lead to underestimating the seismic demand and potentially compromise structural integrity.

1. INTRODUCTION

Soil-structure interaction (SSI) significantly impacts the seismic response of structures, requiring a thorough understanding of soil properties and their interaction with buildings. Various studies, including those by Bielak et al. (2007), Prasad et al. (2017), Chen et al. (2019), Clouteau et al. (2012), Kramer and Stewart (2004), Liu et al. (2023), Rahman et al. (2024), and Hassan et al. (2022), highlight the importance of this interaction in designing safe and resilient structures. Despite the wealth of research conducted in this field, certain gaps remain, particularly regarding the behavior of concrete structures under seismic loading conditions.

Recent research has made significant strides in addressing these gaps by exploring various aspects of SSI. The works of Kausel (2010), Pitilakis et al. (2013), Stewart et al. (1999), and Mylonakis and Gazetas (2000) have examined how different soil types and characteristics influence the seismic response of structures, thereby contributing to a more comprehensive understanding of SSI.

For example, Zhang et al. (2020) analyzed the dynamic

interactions between soil and multi-story structures, underscoring the need to incorporate SSI considerations when evaluating the effectiveness of seismic interventions. Their study draws on foundational research by Veletsos and Meek (1974) and Wolf (1985), which laid the groundwork for understanding the dynamics of structures that interact with the underlying soil. This foundational research has been instrumental in shaping current methodologies in structural dynamics.

Additionally, studies like that of Wang et al. (2021) further emphasize the importance of various soil properties, including stiffness and damping, in achieving precise and reliable seismic design. Understanding these properties enables engineers and designers to create structures that are not only functional but also resilient in the face of seismic events. The findings of Lou et al. (2011) reinforce the necessity for rigorous modeling of SSI within structural design to ensure that potential vulnerabilities are adequately addressed.

The primary objective of our research is to advance the existing knowledge regarding dynamic soil-structure interaction, with a particular focus on the interaction between soil mass and foundation systems.

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This exploration is vital as it informs better design practices and enhances the safety of structures in seismic-prone areas. By building on recent results from researchers like Avilés and Pérez-Rocha (1998) and Torabi and Rayhani (2014), we aim to demonstrate the substantial significance of SSI in the analysis and design of structures exposed to seismic risks. To illustrate the practical implications of our research, we have chosen a case study involving a mosque minaret that stands 18.40 meters tall and is supported by a base measuring 3.50 x 3.50 meters. This specific case allows us to examine how different foundation models perform under seismic loading conditions. We employed 2D numerical simulations using SAP2000 V21 software to compare various foundation designs and assess their effectiveness in mitigating the impact of SSI on structural performance.

Through these simulations, we aim to generate accurate and relevant data to evaluate the impact of SSI on the design of similar structures. This analysis contributes not only to the academic body of knowledge but also has practical implications for engineers and designers in the field.

Our research is positioned within the ongoing investigations into SSI, striving to fill existing gaps related to its effects - especially within the Algerian context, where the nonlinear behavior of soil under seismic loads remains underexplored.

By highlighting the crucial role of soil plasticity and the conditions associated with cyclic loading in the dynamic response of structures, we hope to provide actionable insights that can lead to improved safety measures and design practices. The results of this study aim to offer practical information that can guide engineers and designers, fostering a greater understanding of the effects of SSI on concrete structures.

2. NUMERICAL SIMULATION METHODOLOGY

We modelled the dynamic effect using the response spectrum for an area of low type 1 seismicity and selected loose soil (type S3) for the foundation. In addition, we used the histogram of the Boumerdès earthquake in 2003 (Figure 1) in accordance with Algerian seismic regulations (RPA 99 version 2003). This

approach aligns with the methods used by Anastasopoulos and Gazetas (2007) in their study of soil failure for seismic protection of structures, and further developed by Gajan et al. (2010) in their analysis of nonlinear dynamic SSI effects.

Given the absence of a seismic histogram available for Zone 3, the Boumerdès histogram was chosen only for comparison with the calculations obtained using the response spectrum defined for this zone. This decision was informed by the work of Bao et al. (2016), who proposed simplified methods for evaluating seismic response considering soil-structure interaction, and further supported by the findings of Dutta et al. (2004) on seismic behavior of buildings with soil-structure interaction.

Our numerical simulations were conducted using SAP2000 V21 software, following the finite element approach outlined by Tabatabaiefar et al. (2013) in their study on the effects of dynamic soil-structure interaction on seismic behavior of mid-rise moment resisting frames. The modeling techniques we employed were inspired by the work of Ghandil and Behnamfar (2017) on the dynamic response of structures considering SSI effects, and the comprehensive analysis of SSI effects on the seismic performance of structures by Güllü and Karabekmez (2017).

We also incorporated insights from the studies of Hokmabadi et al. (2014) on the seismic response of mid-rise buildings on shallow and end-bearing pile foundations, and the work of Medina et al. (2013) on the influence of soil-structure interaction on the structural response of moment-resisting frame buildings. The importance of considering SSI effects in performance-based seismic design, as highlighted by Mahsuli and Ghannad (2009), further informed our approach.

Additionally, our methodology was influenced by the findings of Mahmoudpour et al. (2011) on the seismic behavior of structures with underground stories considering soil-structure interaction, and the work of Matinmanesh and Asheghabadi (2011) on seismic analysis of FRP-confined circular reinforced concrete columns.

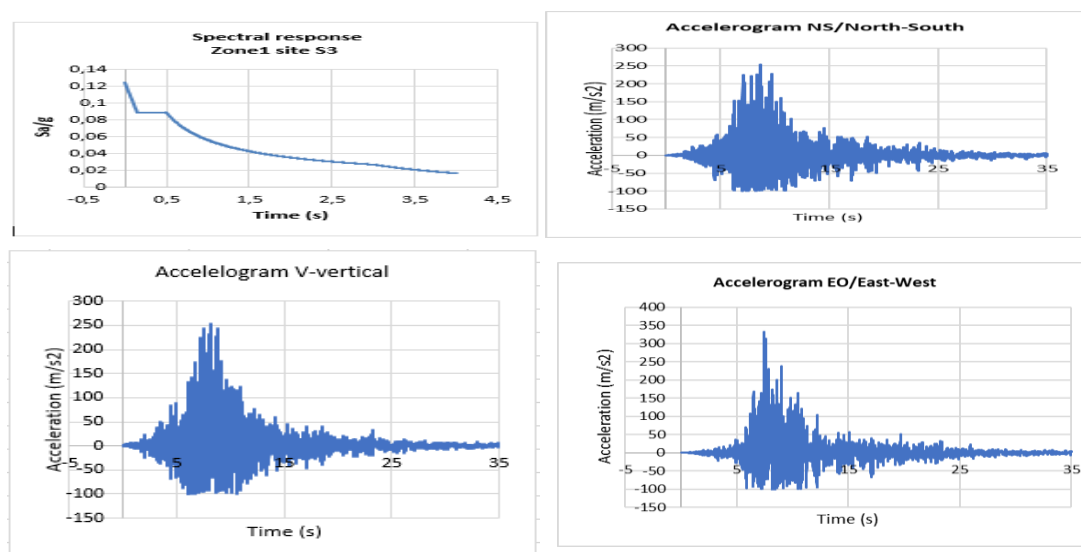


Figure 1. Spectral response (Zone 1 Site S3); Accelerograms (Boumerdès, 2003)

In this study, we present two foundation models for structures, taking into account the soil-structure interaction. The first model integrates the structure with insulated soles and is considered the reference model (Mod_Réf). The second model integrates the structure with a square raft foundation (Rad_Enct) (Figure 2a), measuring $4.90 \times 4.90 \text{ m}^2$. To take the ISS into account, we have proposed two different models with elastic springs, one with insulated soles (Sem_Ress) and the other with a raft foundation (Rad_Ress) (Figure 2b). Finally, for the ground mass, we chose three models. The first model represents only the ground mass (Massif) (Figure 2d), in an open field without any structure.

The second model consists of a gantry structure supported by insulated soles placed on the ground (Sem_Massif), the dimensions of which are $1.5 \times 1.5 \text{ m}^2$. The third model is a gantry on a raft foundation based on the ground mass (Rad_Massif) (Figure 2c), assuming that the ground is of the loose type.

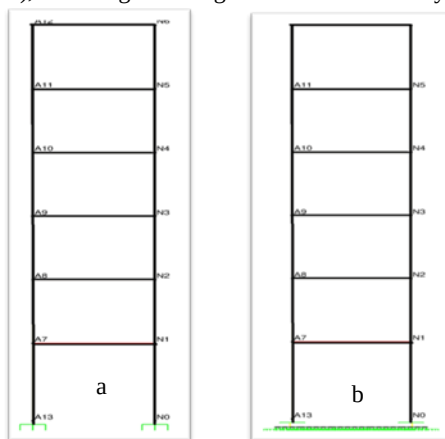


Figure 2a. a) Insulated insoles model, b) (Mod_Réf) Recessed raft model (Rad_Enct)

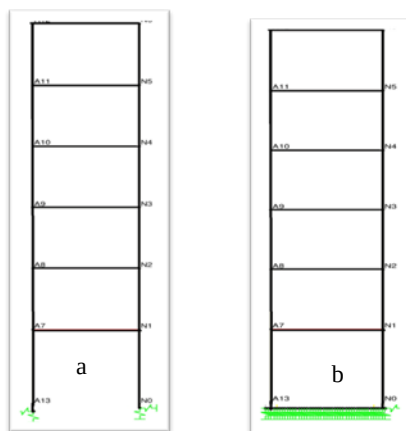


Figure 2b. a) Model insulated soles springs, b) (Sem_Ress) Spring raft model (Rad_Ress)

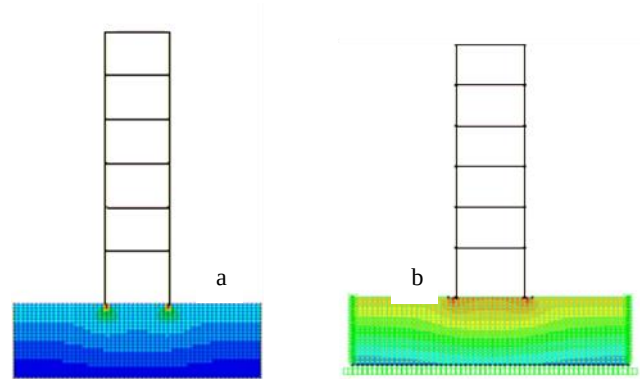


Figure 2c. a) Model insulated soles based ON solid (Sem_Massif), b) Massif-based raft model (Rad_Massif)



Figure 2d. Massive model without structure

3. INTERPRETATION OF THE RESULTS

To interpret the results of the calculations carried out, this article presents only the comparisons carried out for the period of the first mode, the cutting force and the displacement, which were found to be consistent. The comparison of the horizontal displacement of the different models was carried out at the nodes according to the height of the building.

Given the symmetrical nature of the structure, we only considered one side for the analysis.

3.1 Comparison of the periods of the first modes

Figure 3 shows that the Sem_Ress model, which incorporates the structure with elastic springs and insulated soles, has the highest T period (1.206 s), indicating that it is most sensitive to the effects of soil-structure interaction (SSI). The Rad_Ress model, which incorporates the structure with elastic springs and a raft foundation, has the lowest period T (0.541 s), indicating that it is the least sensitive to the effects of ISS.

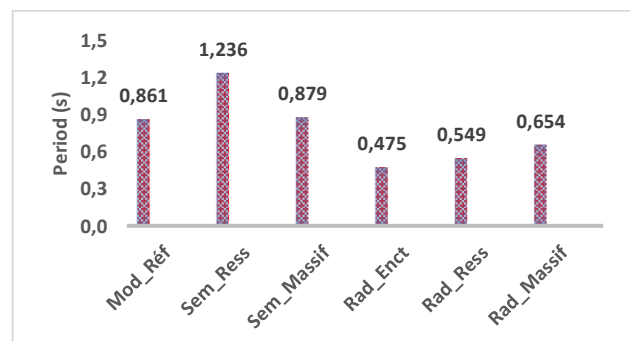


Figure. 3 First Mode Period

Figure 3, also shows that models with a raft foundation (Rad_Enct, Rad_Ress and Rad_Massif) have similar and lower T periods than models with insulated soles (Mod_Réf,

Sem_Ress and Sem_Massif). This suggests that the foundation raft reduces the effect of ISS by averaging soil displacements below the base of the structure.

Figure 3, finally shows that the Massif model, which represents the soil without structure, has a period T of 0.679 s, which is higher than that of the models with a raft foundation and lower than that of the models with insulated soles. This implies that the soil has a significant influence on the response of the structure, and that taking into account the ISS can be important for the seismic design of structures

3.2 Sharp Effort Comparison

According to table 1, which shows the response spectrum of the shear force, it can be observed that the distribution of the shear force with respect to the different levels is the same for all models. However, in terms of values, the SEM_Ress and Mod_Réf models have very high values compared to other models, reaching about three times higher

Height (m)	Sem Massif	Rad Massif	Sem Ress
0.00	4.84	5.65	12.63
3.40	4.84	5.65	12.63
6.40	4.38	5.19	11.35
9.40	3.75	4.63	9.71
12.40	3.06	3.85	7.74
15.40	2.13	2.68	5.38
18.40	1.10	1.44	2.57
Height (m)	Rad Ress	Rad Enct	Mod_Réf
0.00	6.13	6.44	14.41
3.40	6.13	6.44	14.41
6.40	5.73	6.05	67.55
9.40	5.03	5.33	11.94
12.40	4.05	4.27	9.77
15.40	2.78	2.91	7.00
18.40	1.23	1.27	3.51

Table 1. Maximum Shear Force T (kN) response spectrum

According to Table 2 which shows the Boumerdès EW accelerogram, it can be observed that the maximum shear force is almost identical for the Sem_Massif, Rad_Ress and Rad_Encast models, with a maximum value located at the first level. On the other hand, for the other models, the maximum value is at the base.

Height (m)	Sem Massif	Rad Massif	Sem Ress
0.00	6.76	10.34	8.78
3.40	8.47	8.99	9.98
6.40	7.45	8.47	7.99
9.40	5.78	8.08	8.68
12.40	6.68	7.26	8.80

15.40	4.85	8.58	7.84
18.40	2.13	8.94	4.72
Height (m)	Rad Ress	Rad Enct	Mod_Réf
0.00	14.25	26.24	24.95
3.40	15.80	25.79	20.38
6.40	12.72	22.51	18.34
9.40	13.60	18.23	14.55
12.40	14.05	14.12	15.55
15.40	11.83	9.65	14.14
18.40	6.35	4.95	10.05

Table 2. Maximum Shear Force T (kN) accelerogram EW

Regarding the values, we observe higher values at $T=25$ kN for the Mod_Réf and Sem_Ress models, while for the other models, they vary between $T=6$ kN and $T=15$ kN.

According to Table 3, which shows Boumerdès NS accelerogram, it can be observed that the shear force is almost identical for all models, with the exception of the Rad_Encast model where the maximum value is at the 3rd level. In all other models, the maximum value is at the first level

Height (m)	Sem Massif	Rad Massif	Sem Ress
0.00	5.13	11.37	8.58
3.40	5.31	10.97	10.19
6.40	4.26	7.89	6.61
9.40	4.02	7.68	6.94
12.40	3.96	8.56	8.67
15.40	4.78	8.36	8.84
18.40	3.57	6.40	4.80
Height (m)	Rad Ress	Rad Enct	Mod_Réf
0.00	10.02	18.03	17.53
3.40	7.96	20.89	21.62
6.40	6.81	16.41	12.28
9.40	10.44	11.10	11.97
12.40	10.22	12.61	10.47
15.40	9.57	10.36	9.27
18.40	4.89	6.67	7.48

Table 3. Maximum Shear Force T in NS accelerogram

3.3 Travel Comparison

The displacement is calculated as follows:

$$\delta_K = R\delta_{eK}$$

Where: δ_{eK} is the displacement due to seismic forces, F_i (including torsion), and R is the behavior coefficient.

The values calculated at each level k of the structure allow us to make a few remarks:

In the case of the response spectrum (Figure 4), it can be observed that the deflection varies between $\delta_k = 2.35$ cm for the Rad_Enct model and $\delta_k = 8.23$ cm for the Sem_Ress model, while for the reference model, $\delta_k = 5.29$ cm. Basically, the deflection value is zero for all models.

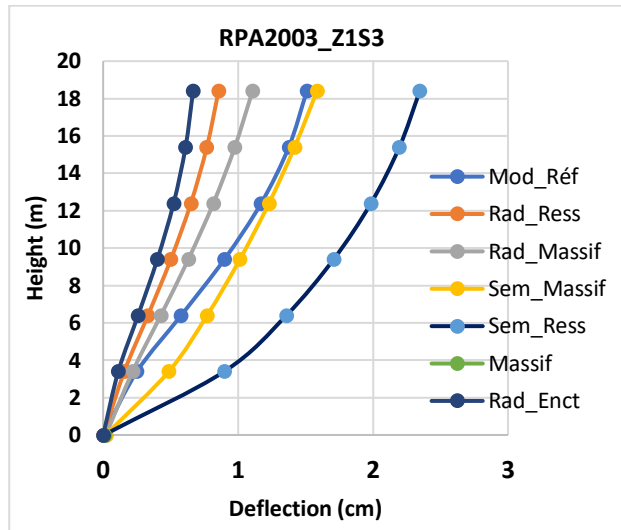


Figure 4. Deflection U_x response spectrum

In the case of the Boumerdès EW accelerogram (Figure 5), it can be observed that the value of the deflection varies between $\delta_k = 22.00$ cm for the Rad_Enct model and $\delta_k = 33.50$ cm for the Sem_Ress model, while for the reference model, $\delta_k = 24.85$ cm. In addition, we note that at the base, the deflection value is 20.05 cm for all models.

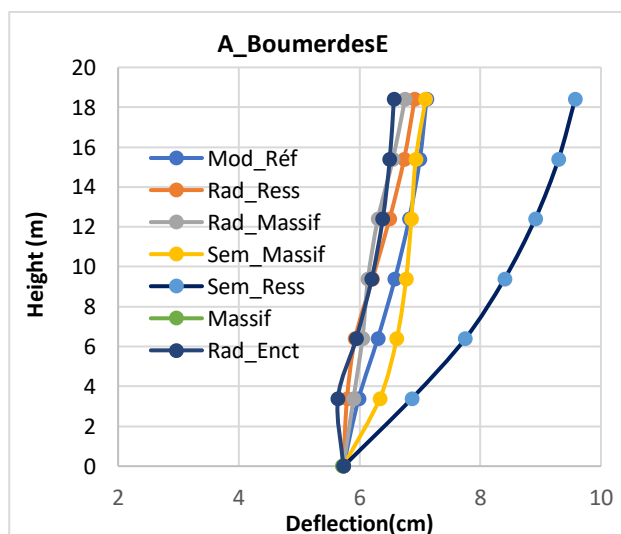


Figure 5. Deflection U_x EW accelerogram

4. CONCLUSION

This numerical study highlights the importance of soil-structure interaction (SSI) by demonstrating its significant impact on periods, stresses, and displacements, which depend on the type

of foundation and the seismic loading applied. The Sem_Ress model, with isolated footings, shows the longest period T , indicating increased sensitivity to SSI. In contrast, the Rad_Ress model, with a raft foundation, is less sensitive to SSI due to its shorter period T .

Models using a raft foundation show periods that are similar to or shorter than models with isolated footings, suggesting that raft foundations mitigate the effects of SSI. The Massif model, which represents only the soil, presents an intermediate period.

The shear force follows a similar pattern for all models and seismic loading cases, with a maximum value at the base or the first level of the structure. Compared to other models, the SEM_RESS model shows a 105% increase in shear force at the base and a 49% increase at the top compared to the reference model Mod_Ref. The Sem_Massif model shows a 27% increase. Horizontal displacements at the base are similar for all models and loading cases, except in the case of the V accelerogram of Boumerdès, where all displacements are zero except for the Rad_Enct model, which shows a displacement of 30.27 cm.

Regarding the variation of deflection curves with height, the difference can reach up to 8.61 cm between the SEM_Ress model and the reference model Mod_Ref, as observed in the seismic loading case of the EW accelerogram from Boumerdès.

In light of these results, we recommend that for designing structures in seismic zones with type S3 soils, raft foundations should be favoured over isolated footings, as they offer better performance in mitigating SSI effects. Design teams should account for a 15% increase in the fundamental period when calculating seismic forces and a 25% reduction in base shear when considering SSI effects. For horizontal displacement calculations at the top of the structure, a safety factor of 1.4 is recommended. These considerations can lead to substantial material savings, estimated at up to 20% in foundation design, while ensuring better seismic resistance.

It is also essential to use dynamic analysis software that explicitly considers SSI effects and to conduct site-specific geotechnical studies to accurately determine soil parameters. For critical structures in high-seismicity zones, the integration of base isolation systems should be considered. These recommendations should be incorporated into local building codes and design practices to ensure more resilient and economically efficient structures in seismic regions.

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