



Seismic Soil Structure Interaction of a Midrise Frame Structure

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Abstract. Earthquakes have occurred for millions of years and will continue in the future affecting millions of lives, thousands infrastructure and costing billions of dollars. Seismic soil structure interaction is the process in which the structure rested on the ground and subjected to an earthquake is affected by the response of the soil medium beneath it having its own characteristics. Thus, soil structure interaction response is dictated by the interaction between the structure, foundation and underlying soil or rock. To clarify the contribution of the seismic soil structure interaction, 3D time history finite element models of 15 story concrete frame building were performed using Abaqus under Kocaeli's Mw = 7.5 strong ground motion. The effects of soil boundary limits, mat thickness and soil linearity were investigated. To demonstrate the importance of modeling correct soil structure interaction problems, the numerical analysis was carried out for three cases: (1) a fixed-base structure, (2) a structure rested on silty sandy soil, and (3) a structure supported by raft foundation and rested on silty sandy soil. The results, presented in terms of the structural lateral deflection and base shear versus time, show that soil structure interaction effects should be evaluated when the maximum lateral deflection is obtained at top of the structure regardless when it occurred as well as at maximum absolute lateral deflection at each level. Moreover, excluding soil structure interaction effects may result in inadequate structural safety for the frame building rested on silty sandy soil and considering linear soil properties may result in non-economical structural design.

1 Introduction

Soil structures interaction (SSI) is a dynamic interaction problem between the structure, foundation and underlying soil or rock. It is the process in which the structure rested on the ground and subjected to an earthquake is affected by the response of the soil medium beneath it having its own characteristics. SSI affects the dynamic response of a flexible supported structure founded on soft soil by an increase in the structure's fundamental period, damping ratio, lateral displacement and a reduction or an increase in the structure's base shear depending on the soil spectral period response compared to a fixed-base structure (Kramer 1996).

Seismic SSI has been considered to be beneficial to structures founded on soft soils. Therefore, many seismic codes neglect SSI effect as a mean to improve the factor of

safety. Mylonakis and Gazetas (2000) discussed this subject by considering only inertial interaction in non-liquefiable soils. They found that using average spectral motions, like in all seismic codes, without considering proper normalization of periods may lead to unsafe designs. In addition, the authors proved that the concept that ductility demands of fixed-based structures decrease the structural period is not always true where an increase in structural period was obtained for structures founded on soft soils. As a result, the effect of SSI on structures founded on soft soils has been studied by Spyarakos et al. (1989), Veletsos and Prasad (1989), Safak (1995), Krawinkler et al. (2003), Galal and Naimi (2008), El Ganainy and El Naggat (2009), Iida (2012), Farghaly and Ahmed (2013), Hokmabadi et al. (2012a), Fatahi and Tabatabaiefar (2014), Tabatabaiefar et al. (2014a, b), Shehata et al. (2015), Nguyen et al. (2016, 2017) and many other researchers.

Recently, using finite element and finite difference software, the seismic SSI behavior of mid-rise building frames rested on soft soils has been considered by several researchers who using the direct method of analysis concluded that SSI must be considered in design. Using SAP 2000 and ETABs, Farghaly and Ahmed (2013) found that SSI increases the building's story displacement that gets amplified with the building height. Shehata et al. (2015) showed that seismic codes underestimate the structure period that is function of SSI. Moreover, the story number amplifies the SSI effects described by higher story displacement responses mostly affected at the lower stories. The story shear response depends on the foundation and soil type: as the soil stiffness decreases, the story displacement and drift increase. Using Flac2D, Hokmabadi et al. (2012a) found that although soil-structure interaction has less effect on piles than shallow foundation it decreases structure's base shear and interstory drift compared to the fixed base case. Fatahi and Tabatabaiefar (2014) verified that the equivalent linear method can predict the base shear of midrise buildings resting on soft soils considering SSI. However, this method underestimates the inelastic response (interstory drift and lateral deflection) compared to fully nonlinear method leading to underestimating the performance level. Tabatabaiefar et al. (2014a) showed that SSI can be neglected in sand but not in clay. The increase in SSI effects lead to an increase in structural displacement response that depending on the earthquake PGA may change the structure performance level from life safe to near collapse level. In addition, Tabatabaiefar et al. (2014b) proved that flexible base case's lateral deflection is amplified compared to the fixed base case while the base shear is reduced. The reason behind the reduction in base shear is the reduction in lateral distortions. This reduction leads to an increase in structure interstory drift that could affect the structure performance level. Finally, using Abaqus, Nguyen et al. (2016) showed that SSI interaction amplifies the lateral deflection of the structure and decreases the shear forces absorbed by the structure during the earthquake excitation. As the foundation size decreases, the lateral deflection, maximum interstory drifts and rocking experienced by the structure increase. Thus, the inertial forces decrease, the spectral acceleration gets reduced significantly due to the increase in structure's natural frequency. Moreover, Nguyen et al. (2017) found that increasing the length of piles caused the structure to undergo more lateral deflection which led to an increase in interstory drifts thus influenced the total shear forces absorbed by the structure during an earthquake.

Unlike previous studies, 3D time history finite element models of a 15 story midrise concrete frame building are performed using Abaqus under Kocaeli's $M_w = 7.5$ strong ground motion. The effects of soil boundary limits, mat thickness and soil linearity are investigated. Thus, linear and nonlinear soil models are considered in comparing the behavior of (1) a fixed-base structure, (2) a structure rested on silty sandy soil, and (3) a structure supported by raft foundation and rested on silty sandy soil. The results are presented in terms of structural lateral deflection, interstory drift and base shear versus time. This study demonstrates the importance of modeling correct SSI problems to aid engineers obtaining economic and safe designs.

2 Finite Element Model

2.1 Problem Definition

The finite element software, Abaqus (2017), was used to analyze the seismic behavior of 15 story mid-rise structures under Kocaeli's $M_w = 7.5$ strong ground motion. Figure 1 shows the variation of velocity with respect to time of Kocaeli earthquake. The 3D time history models were performed for linear and nonlinear cases for three cases: (1) a fixed-base structure (S-model), (2) a structure rested on silty sandy soil (SS-model), and (3) a structure supported by raft foundation and rested on silty sandy soil (SSF-model). The finite element models, consisting of the frame structure formed of beams, columns and slab, the soil and raft were hit by the earthquake load (V_x) at the bottom. The effects of soil horizontal boundary limits, soil linearity and raft thickness were varied in the analyses. The 3D models were simulated using the direct method of analysis: the entire structure-foundation-soil was modeled at the same time and the input earthquake load was specified at bedrock.

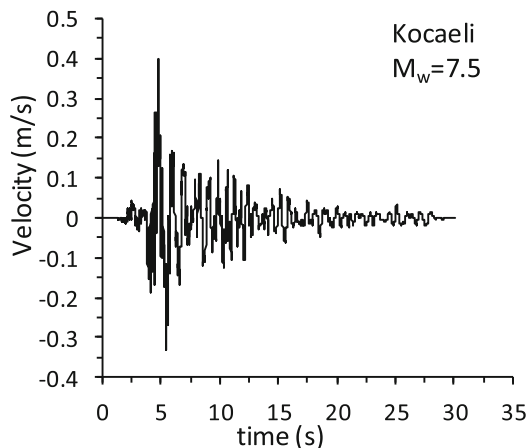


Fig. 1. Velocity with respect to time of Kocaeli earthquake

2.2 Model Characteristics

In this study, typical mid-rise concrete building frame of 15 stories was considered. The simulated frame structure is formed of three bays in both horizontal directions with a total width of 15 m and total story height of 3 m as detailed in Table 1. Dead (gravity load) and live loads were applied to the structural model in term of uniformly distributed load over the floors with a value of 2.5 kN/m². The inelastic behavior of structural elements was modeled using elastic-perfectly plastic material by defining the concrete yield stress and a structural damping ζ of 5% was adopted. Rayleigh modal coefficients $\alpha = 0.24$ and $\beta = 0.008$ were used and calculated based on the first and second structure's mode frequencies (f_i and f_j in rad/s):

Table 1. Finite element model configuration

Reference name	Number of stories	Raft dimension			Soil dimensions		
		Length (m)	Width (m)	Thickness (m)	Height (m)	Length (m)	Width (m)
SS-136-136	15	-	-	-	30	136	136
SS-136-76	15	-	-	-	30	136	76
SS-136-30	15	-	-	-	30	136	30
SS-106-106	15	-	-	-	30	106	106
SS-106-76	15	-	-	-	30	106	76
SS-106-30	15	-	-	-	30	106	30
S	15	-	-	-	-	-	-
SS-L	15	-	-	-	30	106	106
SSF-e-1 m-L	15	20	20	1	30	106	106
SSF-e-1.25 m-L	15	20	20	1.25	30	106	106
SSF-e-1.5 m-L	15	20	20	1.5	30	106	106
SS	15	-	-	-	30	106	106
SSF-e-1 m	15	20	20	1	30	106	106
SSF-e-1.25 m	15	20	20	1.25	30	106	106
SSF-e-1.5 m	15	20	20	1.5	30	106	106

Structures Dimensions

Number of Bays	Story Height (m)	Bay Width (m)	Total Width (m)	Column (cm)	Beam (cm)	Slab (m)
3	3	5	150	50 * 50	50 * 50	5 * 5 * 0.25

$$\zeta = \frac{1}{2f_n} \alpha + \frac{f_n}{2} \beta, \alpha = 2\zeta_i \frac{f_i f_j}{f_i + f_j} \text{ and } \beta = 2\zeta_i \frac{1}{f_i + f_j} \quad (\text{Chopra 2011}) \quad (2)$$

The fixed base structure (S-model) was then rested on a silty sandy soil medium (SS-models) having a shear wave velocity of 63 m/s. The properties of the concrete and silty sandy soil are listed in Table 2 noting that soil damping was not accounted for in this study. The soil model length and width used in studying the effects of the varied parameters are detailed in Table 1, while the vertical distance to the soil boundary was extended 30 m to the bedrock. Finally, the structure and the soil were connected to a 20 m width raft (SSF-models) with different thicknesses (Fig. 2 and Table 1); noting that every time history model took around 60 h to be completed using fast computational facilities at Université Saint-Joseph de Beyrouth.

Table 2. Properties

Silty Sandy Soil	E (MPa)	v	γ_d (kN/m ³)	e	φ°	ψ°	c (kPa)
		20	0.3	18.98	0.4	35	10
Concrete	E (GPa)	v	ρ (kg/m ³)	σ_y (MPa)	f'_c (MPa)	α	β
		20	0.2	2400	30	30	0.24

The beams (50–50 cm) and columns (50–50 cm) were built using 2-node linear beam elements B31 with around 9400 elements. Moreover, the slab (5–5 m) was built using 4-node doubly curved shell, reduced integration, hourglass control; finite membrane strains elements with around 100 elements. Whereas eight node linear brick, reduced-integration, hourglass control continuum solid elements C3D8R were used to model the soil with around 32000 elements and the raft with 4800 elements. Beams and floors slabs as well as raft bottom surface and soil top surface were tied in the numerical models. Moreover, embedded columns were inserted in the soil in structure-soil (SS) models and in the raft in structure-raft-soil (SSF) models. In static analysis, the bottom soil boundary was assumed fix to accommodate rigid conditions (rock) while movement along the soil boundaries was restrained axially (Fig. 2). In dynamic analysis, the soil wall boundaries were free to move in the horizontal directions but restrained to move in the upward direction to simulate absorbed boundary condition.

3 Numerical Results and Analyses

3.1 Effect of Soil Boundary Limits

To study the effect of artificial horizontal soil boundary limits, the soil was modeled as a semi-infinite medium in soil-structures models (SS-models). These models were formed of 15 story frame concrete structures and 30 m height silty sandy soil blocks as detailed in Fig. 2 and Table 1. Ghosh and Wilson (1969) showed that to obtain

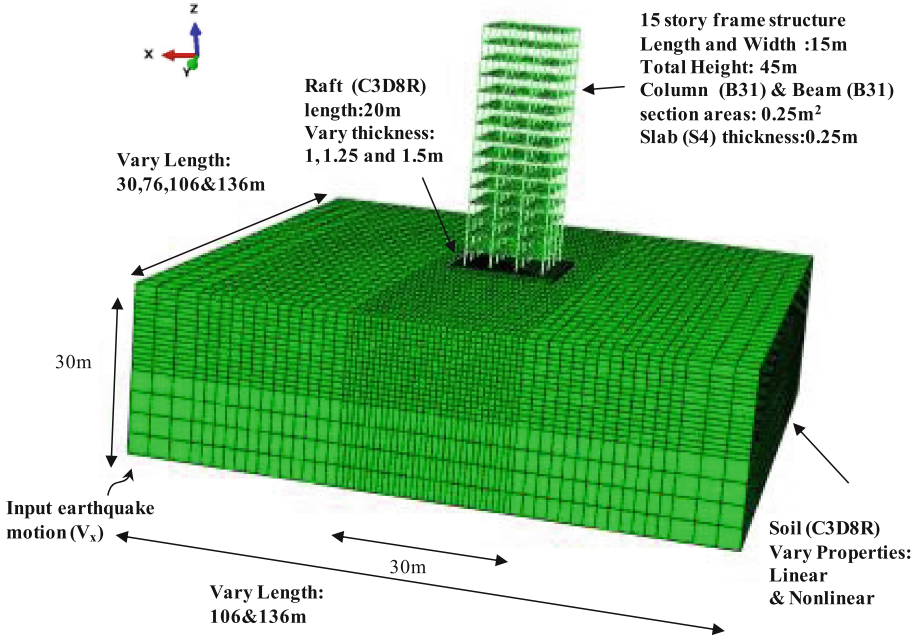


Fig. 2. Finite element model geometry, mesh distribution and varied parameters used in the numerical simulations

insignificant reflexive wave effects, the distance from the center of the foundation to the soil horizontal boundary should be 3–4 times the foundation radius and to the vertical boundary 2–3 times the foundation radius. Moreover, Rayhani and El-Naggar (2008) showed that most ground motion amplification occurs within the first 30 m of the soil profile and increasing the soil boundary from 5 to 10 times the width of the structure leads only to 5% difference in the results. Thus, based on these recommendations, soil boundary limits effects were investigated and the lengths (x-direction) and widths (y-direction) of the soil block (Fig. 2) were varied between 30, 76, 106 and 136 m corresponding to 2B, 5B, 7B and 9B respectively with B being the width of the structure. Moreover, Hokmabadi et al. (2012b) proved that lateral deflection results should be presented when the maximum is obtained at top of the structure (max top) regardless when it occurred while other studies present the lateral deflection results at maximum absolute lateral deflection value at each level. Therefore, the variation of lateral deflection and interstory drifts at maximum absolute value and at maximum lateral deflection at top (at maximum top) of the structure regardless of the time at each level for SS models under the influence of Kocaeli earthquake excitation (Fig. 1) were plotted in Figs. 3 and 4 for the effect of varying soil boundary limits noting that lateral deflection at each story was measured relative to the base of the structure.

The curves on Fig. 3(a, b) indicate that SS-136-30 and SS-106-30 models corresponding to 9B and 7B (x-direction) in lengths and 2B (y-direction) in widths respectively present unrealistic lateral deflection results compared to the other

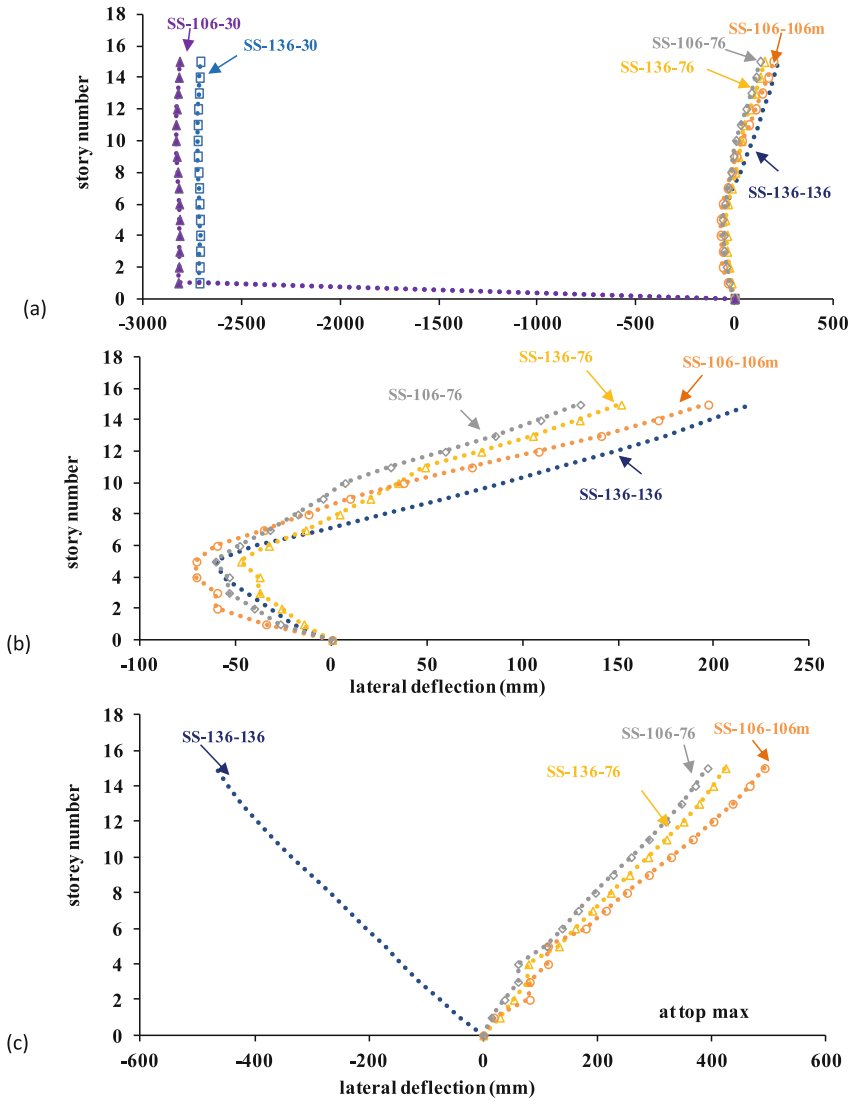


Fig. 3. (a & b) Maximum absolute lateral deflection and (c) maximum lateral deflection at top of SS boundary limits models

SS-models results. This is due to the reflexive wave's effect. Thus, the remaining SS-models were plotted in Figs. 3(b, c) and 4. All these models follow the same deformation pattern (they present the same deformation curve shape) at maximum absolute lateral deflection at each level: as the story level increases, the lateral deflection increases then reaches a peak at the 5th story, changes its direction and re-increases in a linear manner till the top of the structure (15th level) while at maximum top, the curves

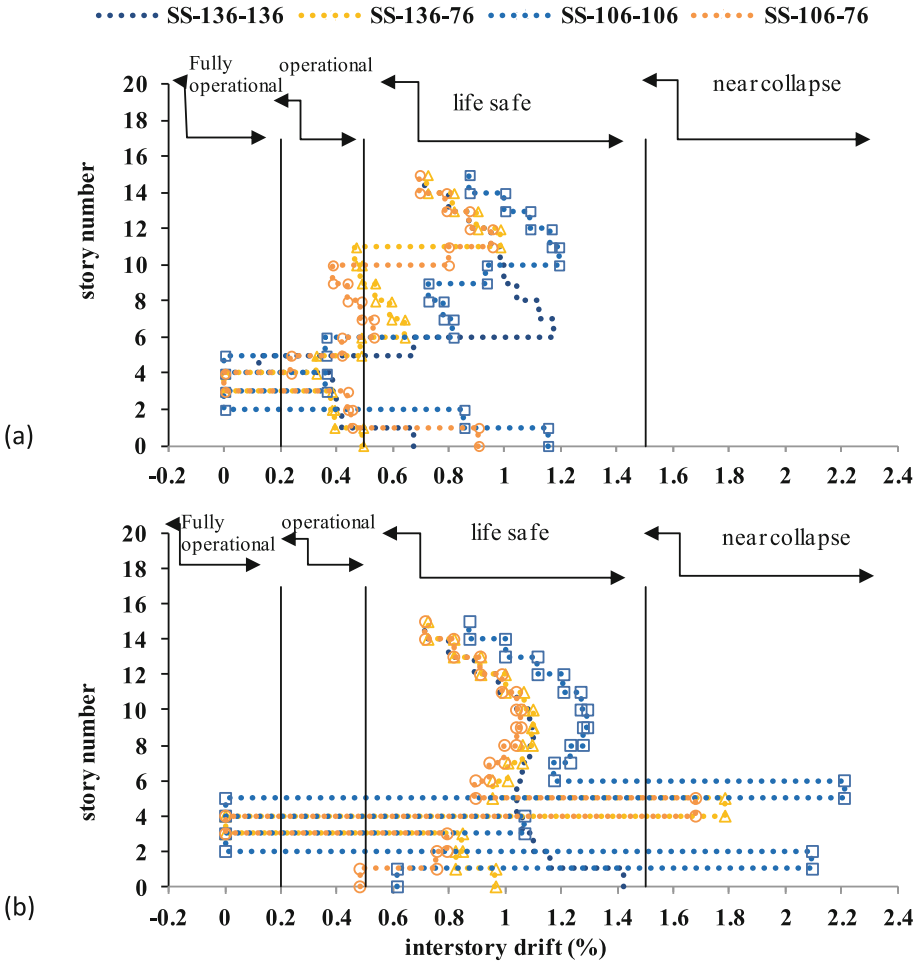


Fig. 4. Interstory drift at (a) maximum absolute lateral deflection and (b) maximum lateral deflection at top of SS boundary limits models

follow a more realistic pattern where the lateral deflection increases when moving to higher stories.

To express the level of damage of an earthquake on a structure based on safety and risk assessment, performance levels are used. Interstory drift, one of the most common damage parameters used, is the difference between the deflections of two stories when the building is subjected to an earthquake load normalized by the story height:

$$drift = (d_{i+1} - d_i)/h \tag{1}$$

where d_{i+1} and d_i are the deflections at $i+1$ and i levels respectively and h is the story height. Thus, performance levels are classified as: (1) fully operational if interstory drift $<0.2\%$, (2) operational if interstory drift <0.5 , (3) life safe if interstory drift $<1.5\%$,

(4) near collapse if interstory drift $<2.5\%$ and (5) collapse if interstory drift $>2.5\%$ (BSSC 1997, 2009). As shown in Fig. 4, even though the 4 models present the same performance level category “life safe” at maximum absolute value, performance levels of SS-136-136 and SS-106-106 models are shifted to higher values and reach “near collapse” category at maximum top noting that in most building codes the maximum allowable performance level category is “life safe”.

The maximum absolute lateral deflection and thus, interstory drifts are greater in the square soil blocks models having the same lengths and widths: SS-136-136 and SS-106-106 than in the rectangular soil blocks models: SS-136-76 and SS-106-76 noting that 76 m is the widths of the blocks in the y-direction while the input earthquake excitation is in the x-direction. Therefore, the average difference in maximum absolute lateral deflection at each level is 20, 10, 16 and 7% while at maximum top is 24, 5, 24 and 5% between SS-136-136 and SS-136-76, SS-136-136 and SS-106-106, SS-106-106 and SS-106-76 and SS-136-76 and SS-106-76 respectively. Therefore, since SS-106-106 presents 5% higher lateral deflection at maximum top while it presents 18% higher peak value at the 5th level and a 10% lower value at the 15th level than that of SS-136-136 and the variation of base shear is almost the same for these 2 models with time (Fig. 5), soil blocks having 106 m (7B) lengths and widths were used in the remaining analysis in this paper as detailed in Table 1.

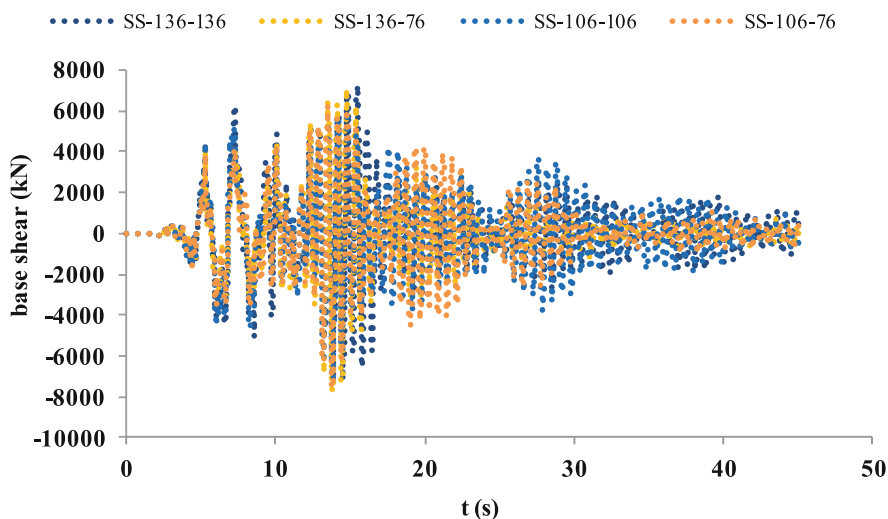


Fig. 5. Variation of base shear with time of SS boundary limits models

3.2 Effect of Soil Linearity and Mat Thickness

Previous studies, using the direct method of analysis, compared the effect of SSI of a structure founded on raft or pile foundation and soil to a fixed based structure adopted in most building codes (Hokmabadi et al. 2012a; Fatahi and Tabatabaiefar 2014; Tabatabaiefar et al. 2014a, b; Shehata et al. 2015; Nguyen et al. 2016, 2017, etc). In this

study, the effect of SSI was considered in various situations: linear and nonlinear silty sandy soil (Table 2) and 1, 1.25 and 1.5 m mat thicknesses for three model cases as shown in Fig. 2. These models included: (1) a fixed-base structure (S-model), (2) a structure rested on silty sandy soil (SS-model), and (3) a structure supported by 20 m width raft foundation and rested on silty sandy soil (SSF-model). The variation of lateral deflection and interstory drifts at maximum absolute value and at maximum lateral deflection at top of the structure regardless of the time at each level under the influence of Kocaeli earthquake excitation for the effect of soil linearity and mat thickness were plotted in Figs. 6, 7 and 8.

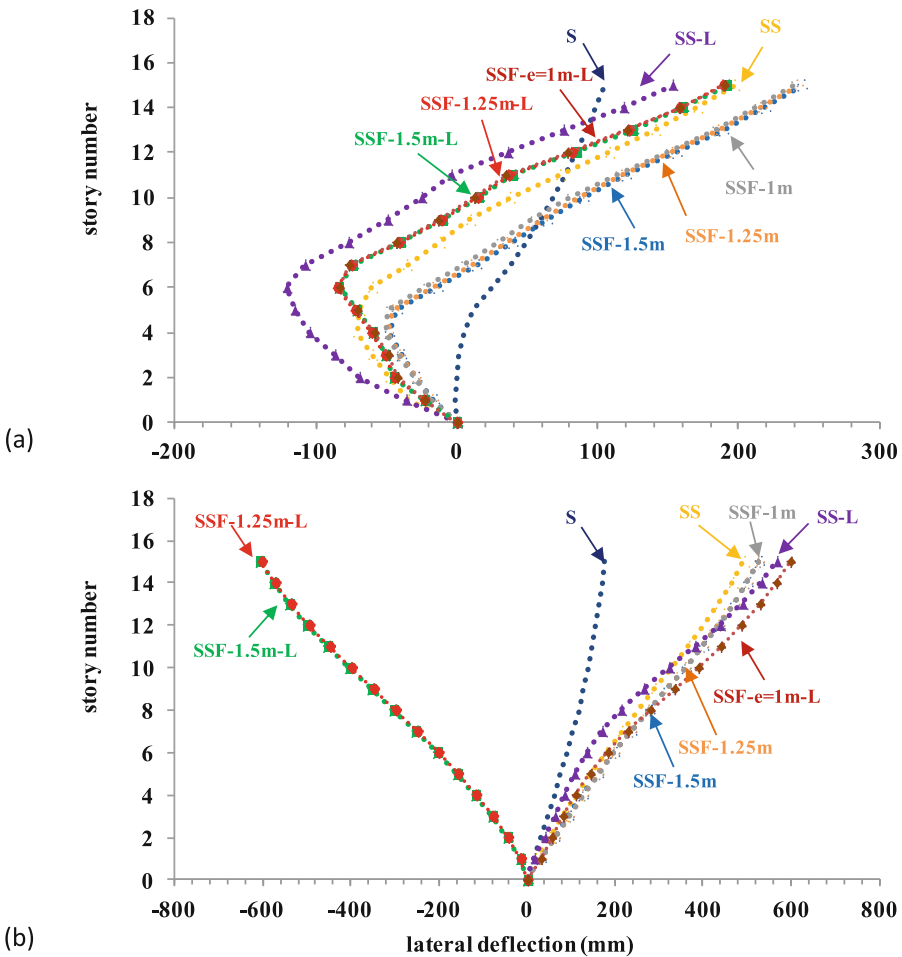


Fig. 6. (a) Maximum absolute lateral deflection and (b) maximum lateral deflection at top for linear and nonlinear S, SS and SSF Model cases

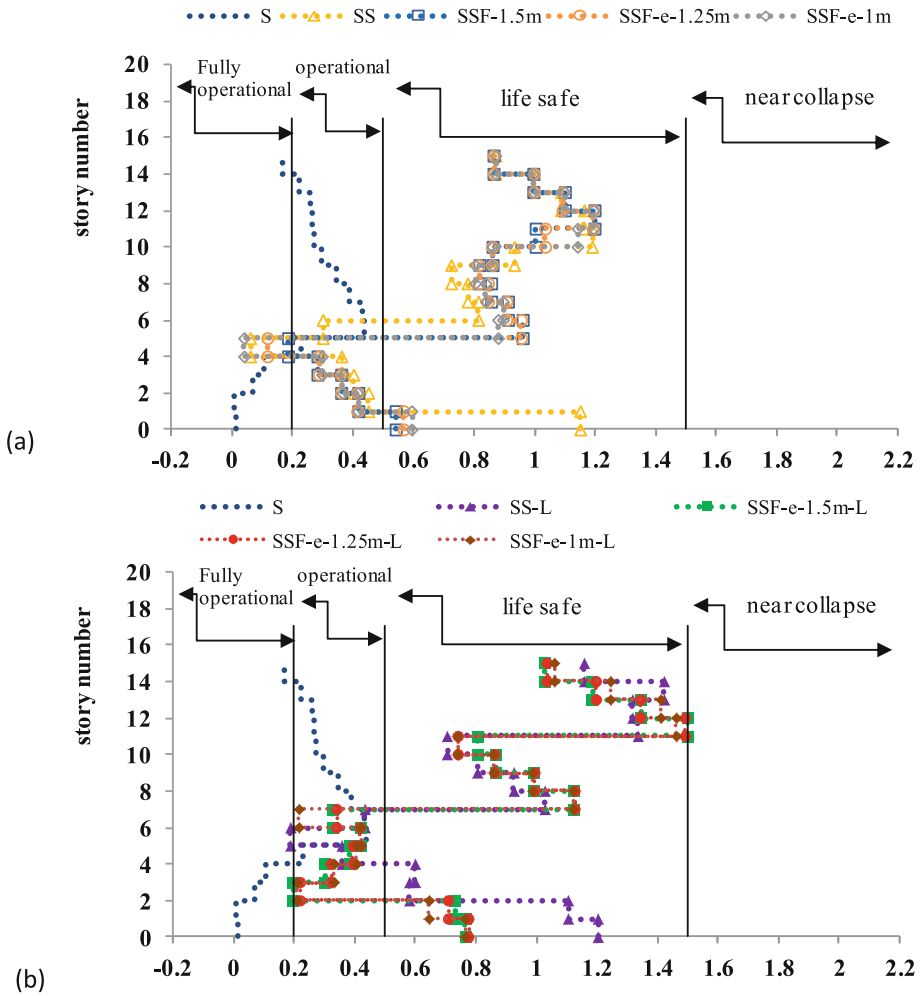


Fig. 7. Interstory drifts at maximum absolute lateral deflection of (a) nonlinear and (b) linear S, SS and SSF Model cases

The results show that mat thicknesses values used in this paper slightly affected the SSF-models lateral deflection and base shear results. This is due to the high mat thicknesses values adopted where a minimum mat thickness of 1 m ($0.7 N$ with N being the number of stories) was used. However, lateral deflections are greater in SSF than in SS and S-models. The amount of energy the raft and soil absorbed led to the increase in lateral deflection. SSF-models lateral deflection curves are similar to SS-models curves: they increase with moving to higher stories at maximum top while peaks are obtained at the 5th and 15th story levels at maximum absolute values. In addition, at maximum absolute value, lateral deflection values are greater at lower stories (<5 th level) and higher at higher stories in SS-models compared to SSF-models.

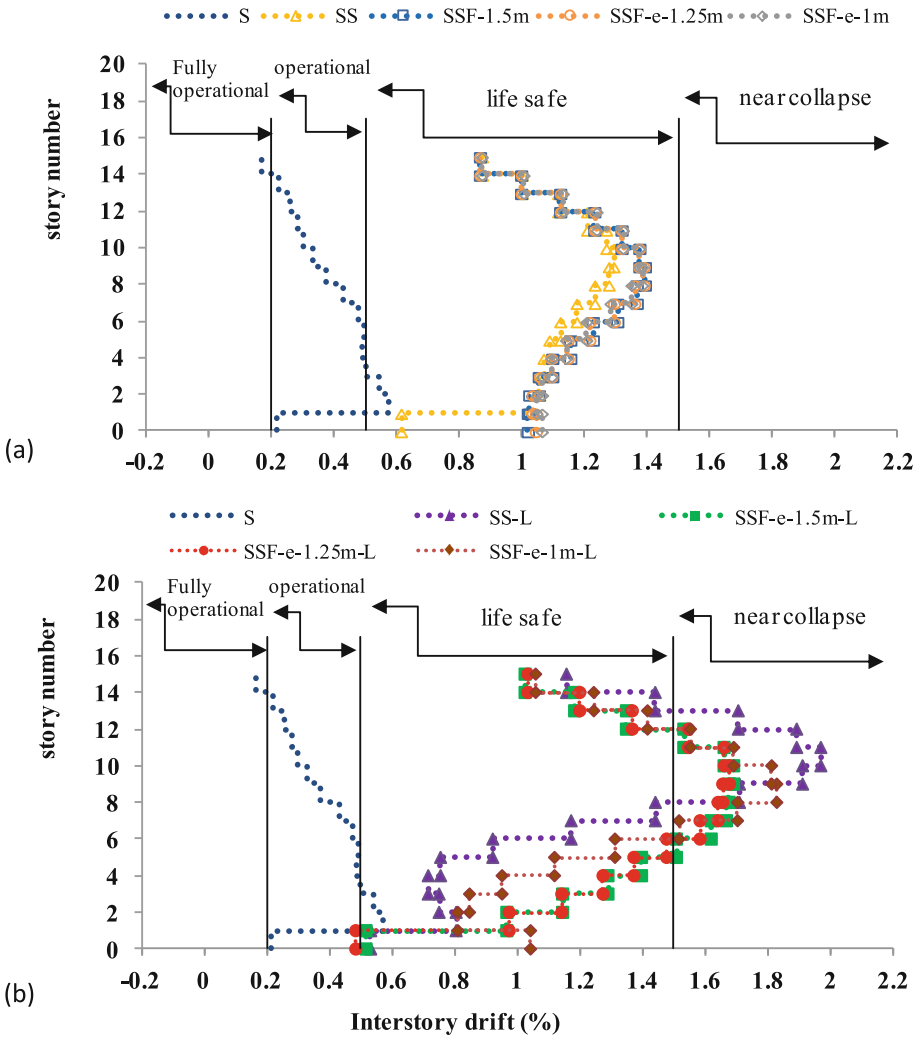


Fig. 8. Interstory drifts at maximum top lateral deflection of (a) nonlinear and (b) linear S, SS and SSF Model cases

The results are in accordance with Shehata et al. (2015) who showed that structure’s story number amplifies the SSI effects described by higher story displacement responses mostly affected at the lower stories.

Since soil properties affect earthquake motion characteristics at the base of the structure through amplification and SSI (Rayhani and El-Naggar 2008), lateral deflections were greater at lower stories and lower at higher stories at maximum absolute value while they increased with the number of stories at maximum top in linear models compared to nonlinear models. As shown in Fig. 6, at maximum top, SSF models lateral deflection values are 7% and 300% higher in linear and nonlinear

cases than SS and S-models values respectively. Also, at maximum absolute values at the 15th level, SSF models lateral deflection values are 25% and 200% higher in linear and 20% and 250% higher in nonlinear cases than SS and S-models values while at the 5th level, SSF models lateral deflection values are 38% lower and 600% higher in linear and 60% lower and 350% higher in nonlinear cases than SS and S-models values respectively.

Although both SS and SSF-models (flexible structures) are within “life safe” category in nonlinear soil cases, their performance levels are shifted to “near collapse” category in linear soil cases while S-model presents a much lower performance level value: “operational” level. SSF-models average interstory drifts values are 1 and 7% higher in nonlinear cases and 10 and 7% higher in linear cases than SS-models values at maximum absolute values and maximum top respectively.

In a similar manner, flexible structures (SS and SSF-models) base shears are almost the same (Fig. 9) and are 2 times as much as fixed base structure’s (S-model) base shear in linear cases and 1.4 in nonlinear cases. Therefore, structure’s base shear was amplified in both soil linearity models. This is related to the soil spectral response induced by Kocaeli earthquake excitation: each seismic excitation provokes different levels of shear strains in the soil block thus, induces different soil damping and modulus values (Kramer 1996). In addition, at the 5th level, level shear force is amplified in linear and nonlinear cases compared to the level shear value in fixed base structure. The ratio of level shear force of flexible to fixed base structures at the 5th level is 1.3 and 1.5 for SS and SSF-models respectively in nonlinear cases and 1.8 in SS and SSF-models in linear cases as shown in Fig. 10. Thus, in nonlinear cases, level shear force value at the 5th level is lower than that in fixed base structure while in linear cases, it is higher for SS and SSF-models.

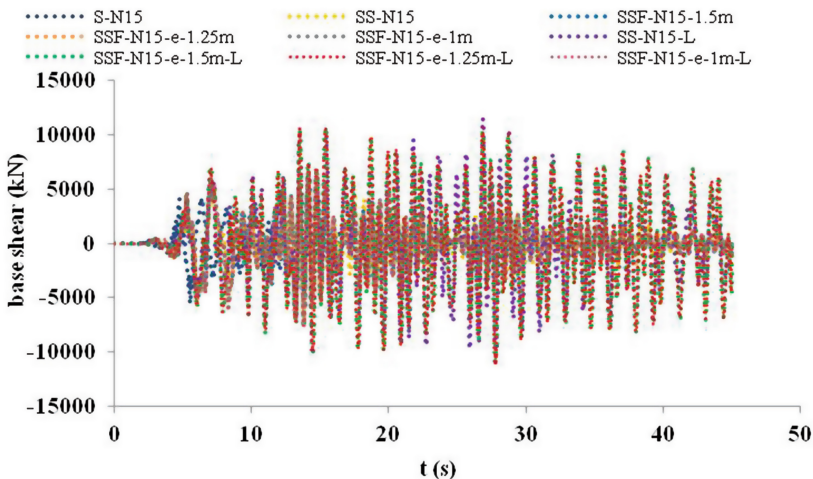


Fig. 9. Variation of base shear with time for linear and nonlinear S, SS and SSF Model cases

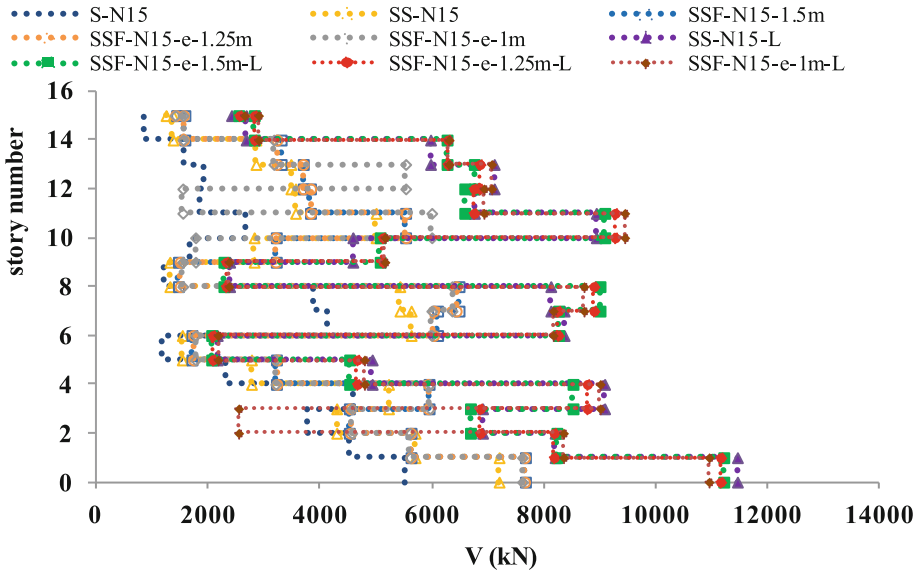


Fig. 10. Variation of level shear force at maximum absolute value for linear and nonlinear S, SS and SSF Model cases

4 Conclusions

3D time history linear and nonlinear finite element models of 15 story concrete building frame rested on silty sandy soils were performed using Abaqus under Kocaeli’s Mw = 7.5 strong ground motion. The effect of soil boundary limits, mat thickness and soil linearity were investigated and the results were presented in terms of structural lateral deflection, interstory drift and base shear versus time. The results showed that:

- Due to reflexive wave’s effect, SS-models having 30 m (2B) widths presented unrealistic lateral deflection results.
- Lateral deflection was found greater in square soil blocks models having the same lengths and widths than in rectangular soil blocks models.
- Increasing the soil boundary limits form 7 to 9 times the widths of the structure leads only to 10% difference in lateral deflection results.
- All flexible base models (SS and SSF-models) follow the same deformation pattern where at maximum absolute lateral deflection at each level, deflection increases with time to reach a peak at the 5th level then changes direction and increases linearly till top of the structure while at maximum top, deflection increases with the number of stories.
- SSI effects should be evaluated at structure’s maximum top lateral deflections regardless of the time because performance levels may be shifted to a higher category compared to the maximum absolute lateral deflection results.
- Lateral deflection was slightly affected by mat thicknesses values tested in this paper due to the high values used.

- At top of the structure, SSF models presented 25% in linear and 20% in nonlinear soil model cases higher lateral deflection than SS models. Nevertheless, flexible structures (SS-SSF models) gave higher story lateral deflections and structures base shear values than fixed base structure (S-model). Thus, higher interstory drifts that changed the performance level category and went beyond the safe limit given by structures code “life safe”.
- At the 5th level, level shear force is amplified in linear and nonlinear cases compared to the level shear value in fixed base structure. Moreover, in nonlinear cases, level shear force at the 5th level is lower than the value in fixed base structure while in linear cases, it is higher for SS and SSF-models.
- Linear cases presented higher story lateral deflection, interstory drifts and structures base shear than nonlinear cases. Thus, designing based on linear soil model properties may result in non-economical structural design.

Therefore, even though mat thickness values used slightly altered lateral deflection and base shear results in this study, engineers should model SSI problems in 3D using nonlinear SSF-models that lead to safe and economic results.

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