Seismic Displacement Demand of a Mid-Rise RC Building Considering Soil Structure Interaction

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ABSTRACT

This study aims to evaluate the effect of soil structure interaction and the differences in linear and nonlinear modelling of the structure on seismic response. For this purpose, SSI and fixed base models of 7-story building were used. Both linear and nonlinear behavior of the building are taken into account for comparison.

The findings obviously indicate large variation in displacement demands depending on ground motion record, soil type, consideration of soil structure interaction and linear and nonlinear structure modelling. The displacement demands tend to increase for softer soils except few cases, especially for fixed base models. Significant differences are obvious for linear and nonlinear building models of fixed base case. The evaluation of obtained results and observations in the current study clearly indicate that the effects of SSI approach depend on dynamic characteristics of soil and structure. While soil deformations influence the seismic demands of structure in positive way for linear models, these effects are more complex for nonlinear models. It is difficult to mention about certain trend for nonlinear models. It should be also kept in mind that linear fixed base models are inappropriate for dynamic analysis due to high sensitivity of dynamic amplification and the use of fixed base linear models may cause inaccurate seismic demand estimates.

The outcomes and observations emphasize that the demand estimates are independent from the fixed base or SSI approaches and linear or nonlinear models for stiffer soils. All combinations provide reasonable demand estimates. However, the modelling approach becomes extremely important for softer soils. The best approach seems to be SSI with nonlinear modelling. The fixed base with nonlinear modelling also provides acceptable estimates.

Keywords: Fixed Base; Linear Analysis; Nonlinear Analysis; RC Building; Seismic Demand; Soil Structure Interaction (SSI); Time History Analysis

INTRODUCTION

Seismic response of structures is directly influenced by soil behavior under dynamic loads. Soil deformations and rotations at the base of structure may change the dynamic behavior of buildings. It is well known that building input motion and free-field motion can differ due to the presence of structure as well as the frequency content and amplitude of motion. These effects are more pronounced for softer soil profiles and stiffer superstructures.

The interaction between soil and structure is generally neglected with the fixed base assumption. However, soil structure interaction is an important issue for the behavior of structures on soft soils. Soil Structure Interaction (SSI) approach includes much more complexity compared to fixed base assumption inherently [1-3]. Soil properties, characteristics of input motions and transmitting boundary conditions are significantly effective parameters in modelling. Therefore, it is important to define SSI problem with minimum error and as simple as possible.

This study aims to evaluate the effect of soil structure interaction and the differences in linear and nonlinear modelling of the structure on seismic response. For this purpose, SSI and fixed base models of 7-story building were used. Both linear and nonlinear behavior of the building are taken into account for comparison.

The selected 7-story building was designed according to modern Turkish Earthquake Code [4] considering both gravity and seismic loads. 7 ground motion records and 4 soil types with different stiffness were taken into account during linear and nonlinear time history analyses.

METHODOLOGY

In this study, direct approach with finite element method (FEM) was preferred and three-dimension linear and nonlinear time history analysis has been performed using general-purpose structural analysis program Sap2000 [5]. Schematic illustration of a direct method model of soil-structure interaction problem is given in Figure 1a. Three dimensional frame system of building and Solid FEM model of soil were simultaneously taken into account in mathematical model and analysis in single step [6]. The equation of motion can be written as follows:

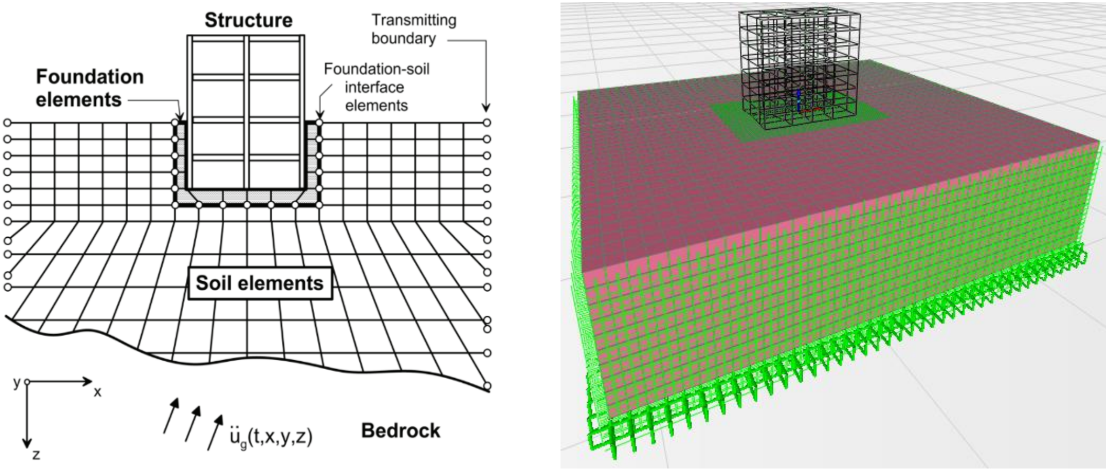
$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{\ddot{u}_g\}$$

where $\{\ddot{u}_g\}$ represents the input motion of model, $[M]$, $[C]$ and $[K]$ are respectively the mass, viscous damping and stiffness matrix of the total system, $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are respectively acceleration, velocity and displacement vectors.

Viscous boundary approach was used to eliminate propagating waves [7] and the bottom of soil layer is assumed to be on the rock as defined as fixed at the bottom in the models. Mesh length of soil is taken as 0.5 m and 2 m at adjacent to building and distant locations, respectively.

Four different soil types were considered during analyses by taking into soil classification of FEMA. Soil dimensions are taken as 80 m in X, 70 m in Y directions and 20 m in depth. Although there might be differences, soil layer profile was assumed to be uniform throughout depth. Detailed information about soil properties are given in Table 1. The 3-D view of soil-structure model is shown in Figure 1.b.

Free-field motions recorded on rock were used in the current study. The records were applied at the bottom of soil layer were processed to obtain soil amplified records at the top layer. This is an accepted assumption as mentioned in literature; SAP2000 program, using the SOLID element, can be used to calculate either the one, two or three dimensional free-field motions at the base of a structure if the soil material is considered as linear [8]. The amplified records were used for the fixed base models as input motion while the records were directly applied at the bottom of soil layer for SSI cases.



(a) (b)

Figure 7 (a)Schematic illustration of a direct approach [9], (b) 3D view of soil-structure model

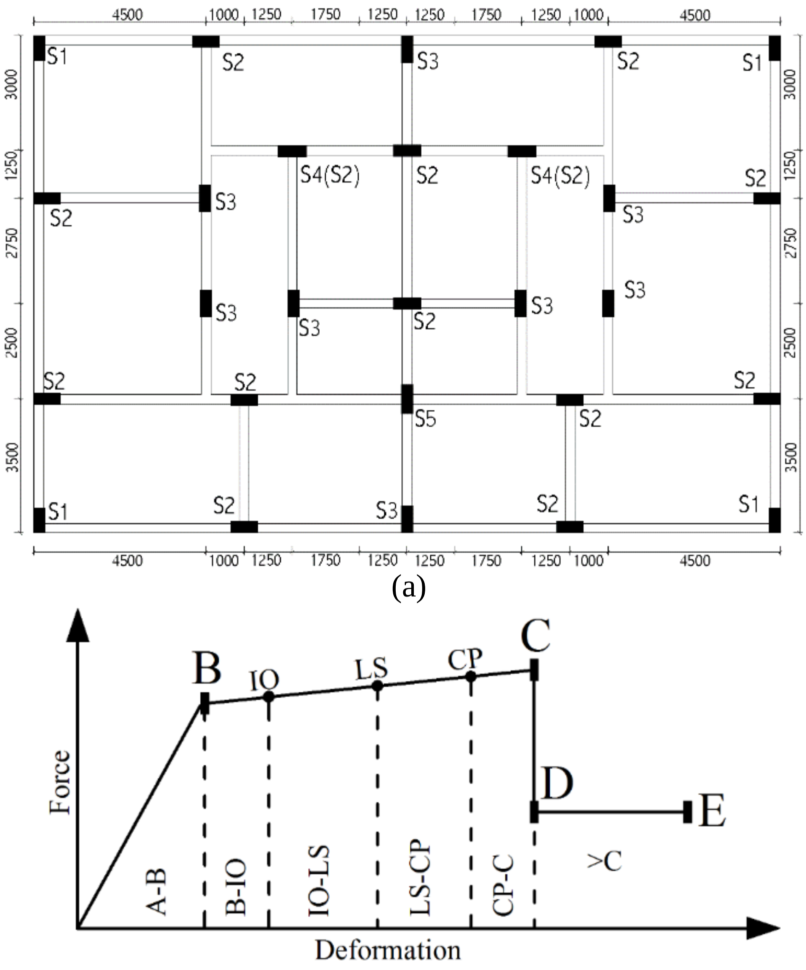
Table 2 Soil Properties

Soil:	Shear Wave Velocity, Vs (m/s)	Soil Profile Type (FEMA)	Densitiy (kN/m^3)	Poisson Ratio	Damping (%)
S1	800	B	2.25	0.25	%5
S2	400	C	2.15	0.30	%5
S3	200	D	1.80	0.40	%5
S4	150	E	1.60	0.40	%5

Building Models

A 7-story RC building was selected to represent mid-rise residential buildings located in the high seismicity region of Turkey in the current study. Building model is typical beam-column RC frame building with no shear walls. Plan view of model can be seen in Figure 2a. The selected reference model was designed according to modern Turkish Earthquake Code considering both gravity and seismic loads. A design ground acceleration of 0.4 g and soil class Z3 that is similar to class C soil of FEMA-356 [10] was assumed.

Nonlinearity of structural models was defined with lumped plasticity by defining plastic hinges at both ends of beams and columns. As shown in Figure 2b, five points labelled A, B, C, D and E define force-deformation behaviour of a typical plastic hinge. The typical nonlinear static analysis has a decrease in lateral load carrying capacity at point C. In this study the decrease at point C is ignored for numerical problems in SAP2000. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element. Plastic hinge length is assumed to be equal to half of the section depth as recommended in 2007 Turkish Earthquake Code [11] and other documents (such as ATC-40 [12], FEMA-356 etc.). Also, effective stiffness values are obtained per the code; 0.4EI for beams and values between 0.4 and 0.8EI depending on axial load level for columns. Shear hinges were also defined at the middle of columns to reflect brittle behaviour of members. Shear hinges were not effective on results in the scope of this study since none of column members reached the shear capacity.



(b)

Figure 8 (a) Plan view of the 7-story building, (b) Force-deformation relationship for a typical plastic hinge

Ground Motion Records

Ground motions recorded on rock soil were used during dynamic time history analyses. For this purpose, 7 records were taken from the stations with shear velocity values greater than 750 m/s. Table 2 lists the records considered in this study [13,14].

Results

Roof displacement demands and displacement profiles of SSI and fixed base approaches are compared for both linear and nonlinear models to understand the effects of soil structure interaction and linear or nonlinear modelling of structures on seismic behavior. Table 3 illustrates roof displacement demands of 7-story building models with fixed base and SSI approaches for linear and nonlinear cases. The table obviously indicates large variation in displacement demands depending on ground motion record, soil type, consideration of soil structure interaction and linear and nonlinear structure modelling. The displacement demands tend to increase for softer soils except few cases, especially for fixed base models. Significant differences are obvious for linear and nonlinear building models of fixed base case.

Table 2 Information about ground motion records used in the study

Identifier	**Earthquake**	**Date (dd/mm/yy)**	**Magnitude**	**Station**	**Comp. (º)**	**PGA (g)**	**PGV (m/s)**	**Dist. (km)**
IR80STUR.000	Irpinia Italy	23.11.1980	M_W= 6.5	Sturno	360º	0.251	0.37	32.00
IR80STUR.270	Irpinia Italy	23.11.1980	M_W= 6.5	Sturno	270º	0.358	0.527	32.00
KB95KBU.000	Kobe	16.01.1995	M_W= 6.9	Kobe Univ.	360º	0.29	0.53	0.90
KC99IZT.090	Kocaeli	17.08.1999	M_W= 7.4	Izmit	90º	0.22	0.298	4.80
LP89G01.090	Loma Prieta	18.10.1989	M_W = 6.9	Gilroy Array 1	90º	0.473	0.339	11.20
LP89G01.000	Loma Prieta	18.10.1989	M_W = 6.9	Gilroy Array 1	360º	0.411	0.316	11.20
NR94GPO.270	Northridge	17.01.1994	M_W = 6.7	USGS Griffith Park Obs.	270º	0.246	0.211	23.80

Table 3 Roof displacement demands of the 7-story building (mm)

Linear								
Record:	SSI				Fixed Base			
	S4	S3	S2	S1	S4	S3	S2	S1
IR80STUR.000	95.7	91.1	61.4	53.7	259.1	144.5	64.4	53.8
IR80STUR.270	87.2	70.2	56.5	43.6	171.4	104.3	61.0	42.5
KB95KBU.000	152.5	113.4	96.1	85.6	272.4	123.5	85.2	79.8
KC99IZT.090	82.8	60.8	54.6	43.7	203.4	80.0	56.5	42.8
LP89G01.000	83.9	85.3	60.2	39.4	155.2	147.5	75.2	39.8
LP89G01.090	75.6	148.0	69.3	61.3	187.3	263.6	84.6	64.7
NR94GPO.270	157.7	137.6	99.5	88.1	294.4	198.2	92.7	85.5
Nonlinear								
Record:	SSI				Fixed Base			
	S4	S3	S2	S1	S4	S3	S2	S1
IR80STUR.000	129.9	91.0	60.5	49.6	129.6	128	63.7	51.5
IR80STUR.270	109.9	100.9	84.7	53.2	112.5	105.5	101.5	65.8
KB95KBU.000	315.8	194.2	131.9	113.9	266.9	161.5	114.8	100.9
KC99IZT.090	104.4	60.8	54.0	39.7	104.4	59.8	61.9	47.0
LP89G01.000	75.7	87.0	53.7	35.4	61.7	86.1	54.6	37.2
LP89G01.090	101.9	160.4	85.8	54.6	126.0	141.1	87.5	63.2
NR94GPO.270	176.9	96.9	76.8	67.8	157.8	110.4	65.1	57.1

Figure 3 plots displacement demand ratio of SSI and fixed base cases for linear and nonlinear models, separately. The scatter in linear building model is evident indicating significant differences between fixed base and SSI models. The fixed base model estimates are extremely higher than the SSI estimates except Kobe and Northridge records for S1 and S2 soils. This means that the fixed base model tends to overestimate displacement demands especially on softer soils for linear behavior. The fixed base and SSI models give reasonable estimates only for stiffer soil S1. As the soil gets softer, the discrepancy in estimates of the fixed base and SSI models increases for linear building behavior.

The average displacement demand ratios of SSI and fixed base models for 7 ground motions are also plotted on the figure. It is interesting that the average ratios of linear behavior is close to unity for S1 and S2 soils, indicating similar demand estimates of both models. This is expected behavior because as the soil gets stiffer it approaches to the fixed base model. However, the average of fixed base model estimates exceeds twice of SSI estimates for S4 soil type. Figure 3 obviously illustrates that both variation and the difference between fixed base and SSI approach estimates tend to decrease with increasing soil stiffness in linear behavior. It is well accepted that SSI approach in linear models estimates smaller displacement demands for softer soils due to energy dissipated by soil movement and base rotations. The observations in Figure 3 are compatible with the common view about soil structure interaction effects.

Although similar scatter to linear behavior is observed in nonlinear behavior, the ratio of SSI and fixed base estimates ranges around unity, having values of about 0.7 to 1.2. It is hard to mention about the positive influence of SSI approach for nonlinear behavior. It is also interesting that the average ratios of 7 records are very close unity meaning that both SSI and fixed base approaches give similar displacement demand estimates in average sense. It is hard to conclude a clear tendency related to the performance of SSI or fixed base approach for nonlinear behavior. Besides, there is no clear soil type dependence in estimates. Nevertheless, fixed base model displacement demand estimates is acceptable in average sense when nonlinear behavior of building is considered.

Plastic deformations change seismic response of structure and phase shift due to deviation of dynamic response may cause increment or decrement on relative structure displacement demands. Thus, the effect of SSI for nonlinear models is a much more complex problem compared to linear models. This phenomenon is highly depended by soil and structural properties as well as frequency content of input motion.

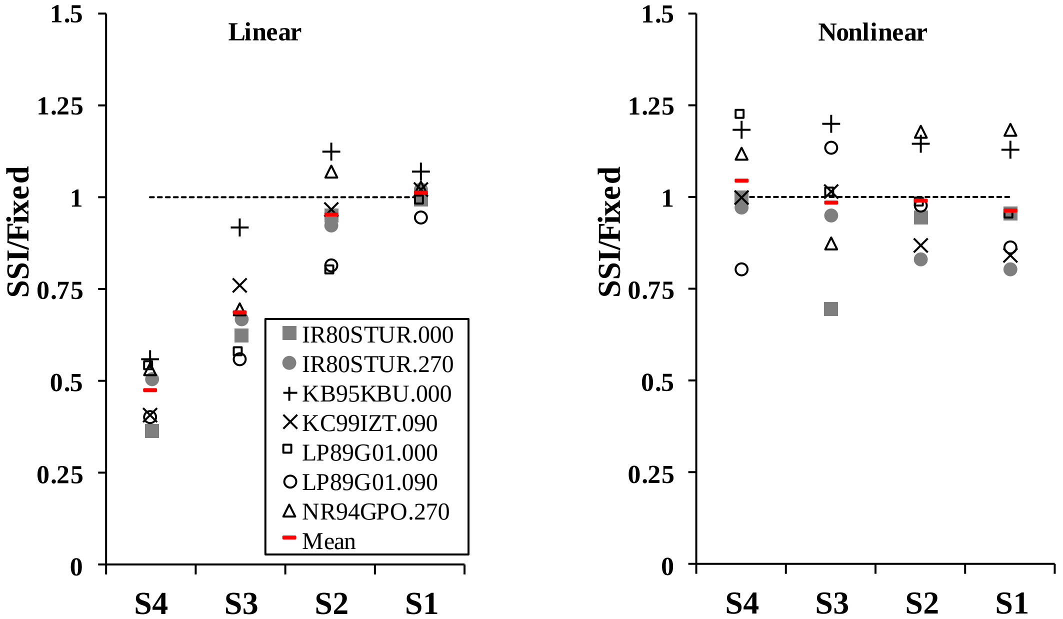


Figure 9 Comparisons of roof displacement demand ratios of SSI and fixed base approaches for linear and nonlinear models

Figure 4 compares linear and nonlinear model estimates of the fixed base and SSI approaches. The linear model tends to give lower estimates for softer soils when soil structure interaction is taken into account. The ratio of linear to nonlinear model estimates vary below and above unity with relatively good average values for stiffer soils. The meaning of this observation is that both linear and nonlinear models provide reasonable demand estimates when SSI is accounted in modelling. Similar observation is valid for the fixed base model when the soil type is S1 or S2. However, the variation significantly increases as the soil gets softer. All estimates of linear model with the fixed base approach are greater than nonlinear model estimates for soil type S4, having ratios up to 2.5. Figure 4 obviously illustrates that linear models give extremely higher estimates for soil types S3 and S4.

The outcomes and observations from Figure 4 indicate that the demand estimates are independent from the fixed base or SSI approaches and linear or nonlinear models for stiffer soils. All combinations provide reasonable demand estimates. However, the modelling approach becomes extremely important for softer soils. The best approach seems to be SSI with nonlinear modelling. The fixed base with nonlinear modelling also provides acceptable estimates.

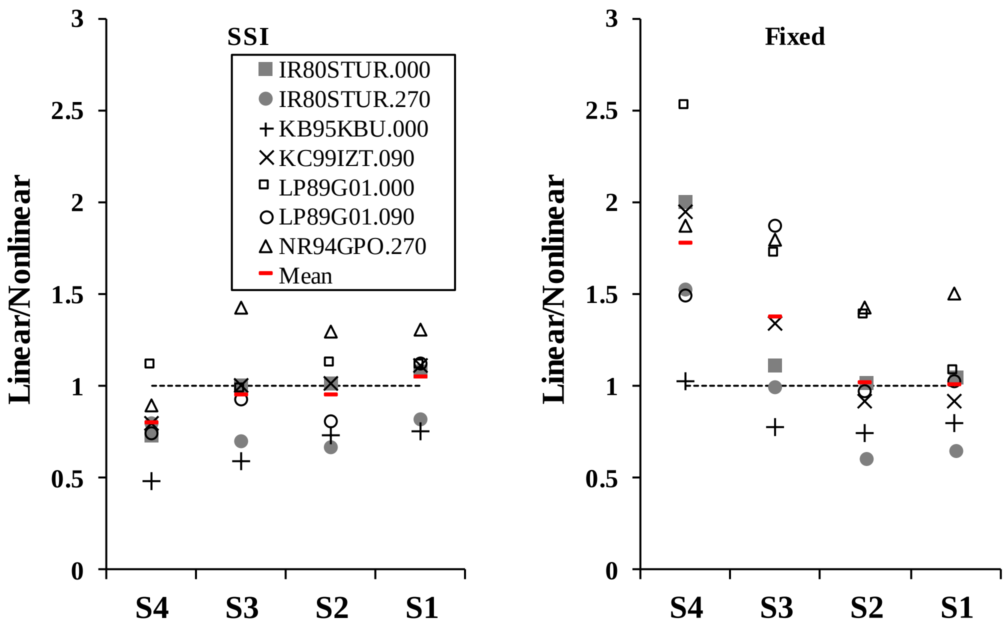


Figure 10 Comparisons of roof displacement demand ratios of linear and nonlinear models for SSI and fixed base approaches

Displacement profile along the building height is an indicator for interstory drift ratios. It also shows sudden changes of story displacement for irregular structures. The displacement profiles of the selected building are compared for the fixed base and SSI approaches at maximum roof displacement. Figures 5 and 6 plots the average displacement profiles of 7 records for linear and nonlinear models, respectively. The displacement profiles of the fixed base and SSI approaches are similar for S1 and S2 soil types for linear models. The profiles start to deviate for softer soils due to extremely higher estimates of the fixed base case. Similarity of average displacement profiles of SSI and fixed base approaches is obvious for nonlinear models. The observations for average displacement profiles point out that the linear fixed base models are more sensitive to dynamic amplifications for softer soils (i.e. S3 and S4 soil types).

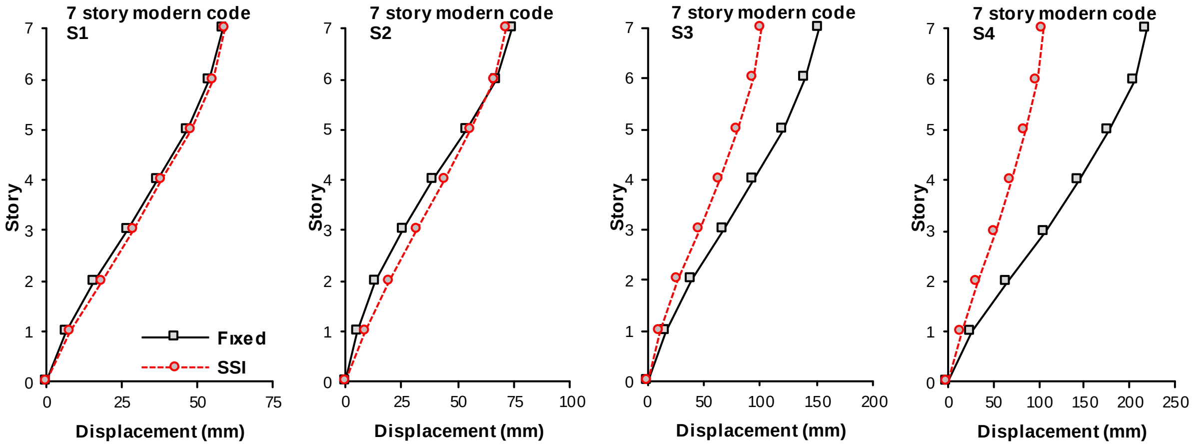


Figure 11 Comparisons of average displacement profiles of linear 7-story modern code building for SSI and fixed base approaches

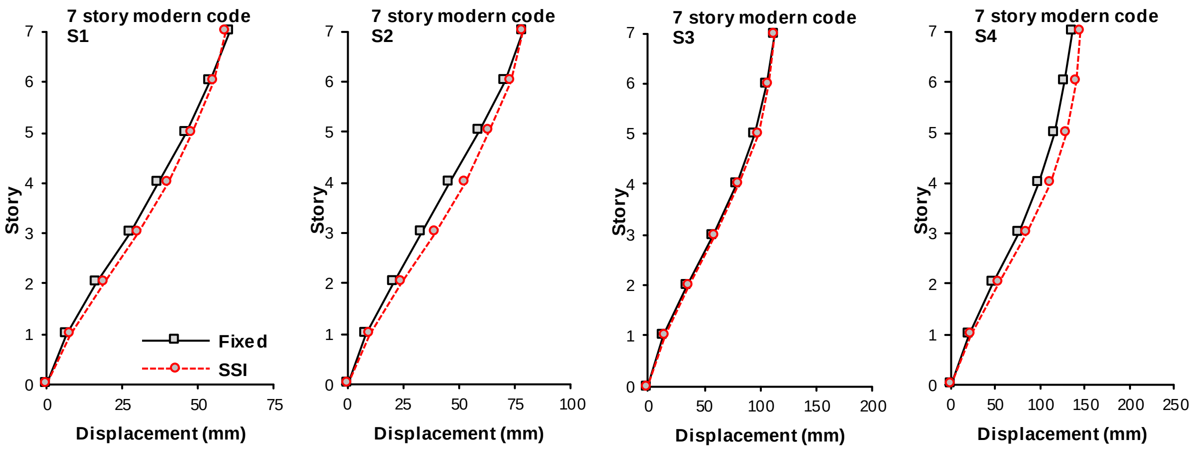


Figure 12 Comparisons of average displacement profiles of nonlinear 7-story modern code building for SSI and fixed base approaches

Although the average displacement profiles of fixed base and SSI approaches match reasonably well for nonlinear models, there are differences for individual records. Figure 7 shows the displacement profiles for KB95KBU.000 and IR80STUR.000 records on soil type S4 and S3 respectively. The differences and opposite trend are obvious for the considered records.

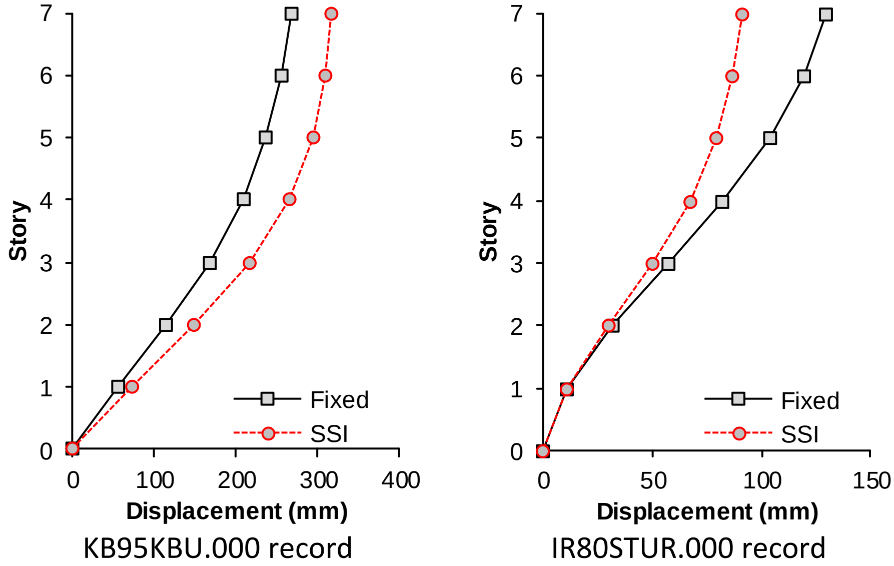


Figure 7 Comparison of displacement profiles of nonlinear for SSI and fixed base approaches subjected to KB95KBU.000 and IR80STUR.000 records

CONCLUSION

This study evaluates the effect of soil structure interaction and the differences in linear and nonlinear modelling of the structure on seismic response. For this purpose, SSI and fixed base models of 7-story building were used. Both linear and nonlinear behavior of the building were taken into account for comparison.

Roof displacement demands and displacement profiles of SSI and fixed base models were compared for both linear and nonlinear models to understand the effects of soil structure interaction and linear or nonlinear modelling of structures on seismic behavior. The findings obviously indicate large variation in displacement demands depending on ground motion record, soil type, consideration of soil structure interaction and linear and nonlinear structure modelling. The displacement demands tend to increase for softer soils except few cases, especially for fixed base models. Significant differences are obvious for linear and nonlinear building models of fixed base case.

The evaluation of obtained results and observations in the current study clearly indicate that the effects of SSI approach depend on dynamic characteristics of soil and structure. While soil deformations influence the seismic demands of structure in positive way for elastic models, these effects are more complex for nonlinear models. It is difficult to mention about certain trend for nonlinear models.

It should be also kept in mind that linear fixed base models are inappropriate for dynamic analysis due to high sensitivity of dynamic amplification which is not compatible with nonlinear behaviour since the dynamic properties change by plastic deformations. Therefore, the use of fixed base linear models may cause inaccurate seismic demand estimates. Another important point is that the average dynamic analysis results do not reflect characteristic properties of the records. This may mislead to understand the effect of specific ground motion like near fault or forward directivity. Even the average values tend to be in similar range for nonlinear models, seismic demands vary in a wide range for ground motion records.

As concluding remarks, the outcomes and observations emphasize that the demand estimates are independent from the fixed base or SSI approaches and linear or nonlinear models for stiffer soils. All combinations provide reasonable demand estimates. However, the modelling approach becomes extremely important for softer soils. The best approach seems to be SSI with nonlinear modelling. The fixed base with nonlinear modelling also provides acceptable estimates.

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