Structure – Soil – Structure Interaction (SSSI) effects on seismic response of low-, mid- and high-rise steel moment resisting frame structures

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Abstract

Unknown situations or factors in design of a structure such as underlying soil characteristics and presence of adjacent structures can affect the reliability, and consequently, the cost of the project. Therefore, the effects of soil-structure interaction as well as the simultaneous effects of this interaction in the presence of adjacent structures on the seismic response of 3, 9 and 20-story benchmark steel moment resisting frame structures are investigated, including six different adjacency cases of the structures in three different distances. The effect of soil-structure interaction is considered by using a hybrid method, in which the stiffness matrix of soil system is obtained through analysis of a two-dimensional model in Abaqus considering a plain strain condition. Then, the obtained stiffness matrix is added to the nonlinear 2D model of the structure by using a set of pre-defined and a new developed element in OpenSEES. The results obtained from the time history analysis under ten far-field earthquake records show that the effect of soil-structure interaction on the response of a 20-storey structure is more significant than the other two structures and leads to a maximum increase of 9 percent in the maximum average drift ratio and decrease of 6.99 percent in the average base shear in this structure compared to fixed base. In addition, the presence of high-rise and mid-rise structures increase the maximum average drift ratio of low-rise structures by 10.44 and 9.36 percent and the average base shear in this structure by 2.87 and 3.93 percent, respectively, compared to the flexible base.

Keywords

Soil-Structure Interaction (SSI), Structure – Soil – Structure Interaction (SSSI), Substructure Method, Finite Element Method (FEM), Steel moment resisting frame.

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Introduction

The development of urbanization and the increase in the population of cities have made human to build tall structures densely and side by side in urban areas. In these conditions, Unknown situations or factors such as subsoil and the presence of adjacent structures can affect the design reliability in the classical case and, consequently, the cost of the project. The effects of soil and adjacent structures on each other which is studied in the field of civil engineering called dynamic Structure- Soil-Structure Interaction (SSSI).

The first studies in this field conducted in 1970s. Mulliken & Karabalis [1] developed discrete models to evaluate the effects of SSSI using masses, springs and frequency-independent dampers. Alexander et al. [2], used a simple structural model and a rotational spring to obtain a certain formulation for considering the effects of SSSI. Madani et al. [3] investigated the effects of pounding and SSSI on seismic responses of 3, 5, 6 and 12-story steel frames considering nonlinear behavior for structures and soil and five different adjacency cases with three different distances. Aldaikh et al. [4] estimated the effects of SSSI on the response of a scaled structure adjacent to one and two other structures using a set of shaking table experiments. Liang et al. [5] modeled two identical shear walls with solid foundation embedded in the soft soil layer on the elastic bedrock under the effect of the out-of-plane horizontal shear wave using indirect boundary element method to study SSSI phenomena. Vicencio and Alexander [6] studied the effects of SSSI between two linear structure using nonlinear Bouc-Wen model and a rotational spring for modeling soil and adjacent structure effects, respectively. Cilsalar and Cadir [7] investigated the seismic response of a 4-story steel structure considering SSSI with nonlinear behavior for soil and structure and soil layering effects under time history analyses and in the form of fragility curves.

The purpose of this article is to investigate Soil-Structure Interaction (SSI) and also, simultaneous effect of this interaction in the presence of the adjacent structure considering six different adjacency cases between low-, mid- and high-rise (3, 9 and 20-story) steel structures. In this study, the substructure method is used to model SSI and SSSI systems to decrease the limitations of other methods such as inability of considering the relation between responses of horizontal and vertical components of soil and increase in analysis time of complicated models, while maintaining the acceptable accuracy.

Modeling

Modeling of Structures

The three 3, 9 and 20-story benchmark steel moment frames in Ref. [8] are selected as case studies. The structures are modeled in OpenSees framework using RembergOSgood uniaxial material [9] and nonlinearBeamColumn element with distributed plasticity and fiber sections. The inherent damping of the steel structures is considered 2% and applied as Rayleigh damping in the software. These frames are shown in **Fig.1**.

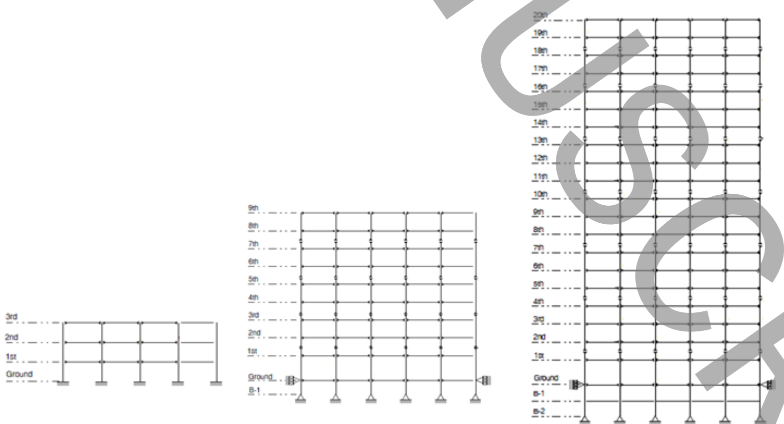

Fig 1.The frames in this study

Modeling of SSI and SSSI

The effects of SSI and SSSI are considered using substructure method. For this purpose, soil medium modeled in Abaqus software using finite element method. Then, the reduced or condensed stiffness matrix of the soil-foundation or foundation- soil-foundation systems in different adjacency cases are evaluated using a series of static analyses

$$\begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} = \begin{bmatrix} k_{11}+k_{12}+k_{13} & 0 & 0 \\ 0 & k_{22}+k_{21}+k_{23} & 0 \\ 0 & 0 & k_{33}+k_{31}+k_{32} \end{bmatrix} + \begin{bmatrix} -k_{12}-k_{13} & k_{12} & k_{13} \\ k_{21} & -k_{21}-k_{23} & k_{23} \\ k_{31} & k_{32} & -k_{31}-k_{32} \end{bmatrix} \quad (1)$$

Based on Equation (1), This matrix for a system with three degree of freedom can be written as sum of two matrix. The first matrix is a diagonal matrix that added to structural models in OpenSees by transitional springs as zeroLength element in two horizontal and vertical directions. The schematic diagram of the springs under the foundation are shown in **Fig.2**. But about the second matrix, please consider that the sum of the elements of each column or row equals to zero. So, one concludes that, this matrix is related to the relative translation between the common nodes considered in the boundary of soil and foundation. This matrix is added to the structural models by a new developed element in OpenSees framework. In fact, this element can assemble a pre-defined matrix to global stiffness matrix of the model.

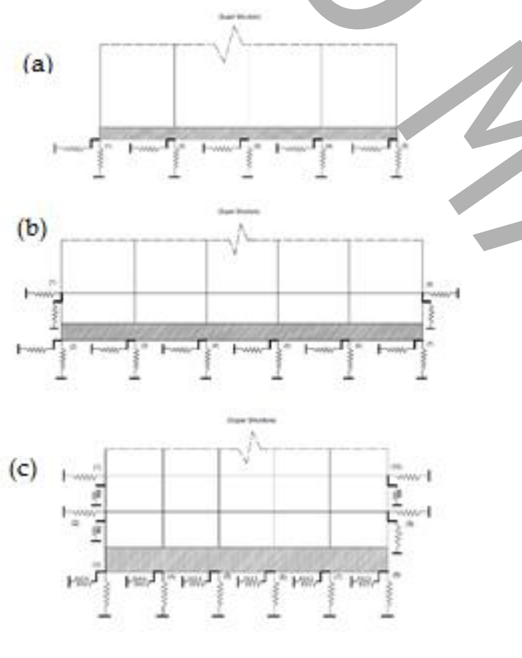

Fig 2. Schematic diagram of soil and foundation modeling in (a) 3-story (b) 9-story (c) 20-story structures

Analysis process

In this study, the results are obtained in the form of maximum of the average drift ratio and base shear of the fixed-based models and the models considering SSI and SSSI using 240 time-history analyses under ten far-field earthquakes listed in **Table 1**. The earthquakes are selected from PEER ground motion records dataset, based on shear wave velocity between 200 to 375 m/s in depth of 30 m of soil, earthquake magnitude between 6.5 to 7.5 Richter and 20 to 50 km distance from fault.

Table 1. Parameters of earthquakes used in this study

No.	Earthquake Name	Station	PGA (g)
1	San Fernando	L.A. - Hollywood Stor FF	0.225
2	Loma Prieta	Hollister City Hall	0.246
3	Loma Prieta	Palo Alto - 1900 Embarc.	0.215
4	Landers	Yermo Fire Station	0.245
5	Northridge	L.A. - Baldwin Hills	0.239
6	Kobe	Abeno	0.221
7	Kobe	Morigawachi	0.214
8	Kocaeli	"Duzce"	0.312
9	El Mayor-Cucapa	El Centro Differential Array	0.507
10	Darfield	Pages Road Pumping Station	0.223

Conclusion

This study investigates the effect of SSI and SSSI on the seismic response of 3, 9 and 20-story benchmark steel moment frames considering six different adjacency cases. The behavior of underlying soil is considered elastic but nonlinearity is considered for the steel frames. The drift ratio and base shear of the frames under ten far-field earthquakes are compared between fixed based, SSI and SSSI cases.

The results show that the SSI effect on responses of high-rise structure is more than two other structure. Moreover, the presence of 9 and 20-story adjacent structures increases the response of the 3-story structure as a consequence of SSSI effect.

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