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Soil-Structure Interaction in Nonlinear Pushover Analysis of Shear Wall-Frame RC Structures: Nonhomogeneous Soil Condition

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Abstract :

Determining the real displacement demand and seismic force resisting capacity of structures get importance to obtain performance level of structures when considering soil-structure interaction. Pushover analysis, a method of nonlinear static analysis, is generally used in assessment of existing buildings. Pushover analysis gives more accurate results when compared to linear analysis methods to evaluate seismic performance level of structures. In the study, three-dimensional soil structure interaction problem stemming from soil inhomogeneity is carried out with nonlinear pushover analysis. In this analysis, an investigation of effect of story number on performance level of five and eight-story reinforced concrete (RC) structures designed as shear wall-frame systems is performed. Inhomogeneity of soil is considered by impedance functions, which represent static stiffness of foundations for elastic soil behavior. These functions are calculated by considering shear wave velocity, shear modulus, depth of soil and poisson ratio for saturated normally and slightly over consolidated clays for spread foundation. For each foundation horizontal and vertical translations, and rocking stiffness are calculated with these impedance functions. Analysis results are compared in terms of target displacements, story drifts, plastic hinge mechanisms and rotations obtained from pushover analysis of superstructure. According to the results, displacement demand and plastic hinge rotations increase if soil inhomogeneity is considered. In other words, if impedance functions are employed in the analysis, plastic deformations can be observed in elastic deformation regions due to soil-structure interaction.

Key words: Soil-structure interaction, RC shear wall-frame systems, nonlinear pushover analysis

1. Introduction

One of the best used method to evaluate nonlinear performance of reinforced concrete structures under earthquake loads is pushover analysis. In this analysis technique, displacement demand of a structure is determined by increasing monotonically lateral load which is adaptable with first free vibration mode. This increase of seismic displacement demand should been proceed until a reliable target displacement. Force distribution due to lateral earthquake load is taken into account in a compatible form of fundamental first mode to the structure at story levels [1]. Besides a pushover analysis method can be applied for different numerical analysis to solve structural engineering problems. One of the most complicated problem is soil-structure interaction (SSI) due to the inhomogeneity. The nonlinear analysis of structures can be used only if an accurate numerical modelling technique is performed considering SSI effect. [2]. Moreover, due to the modeling difficulties of defining the effect of soil condition SSI effect is generally neglected in nonlinear pushover analysis. In some recent studies, to suggest an alternative

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solution for the SSI effect, is used impedance functions for foundations proposed by [3]. That proposed impedance functions can be directly represented by shear modulus which decreases with depth of nonhomogeneous soil. [4]. Due to the inhomogeneity of soil, the stiffness of soils are evaluated according to the some specified impedance functions to determine deformations of soils. To determine static and dynamic deformations of soils due to the dynamic stiffness of soil can reach critical values [5] when soils are multilayered and nonhomogeneous [6]. In this study, an incremental single mode pushover analysis is achived to define behavior of a three-dimensional RC frame and a shear wall-frame systems considering SSI. The effect of number of story and inhomogeneity of soil are taken into account in these analysis. Pushover analysis of the structure having five and eight stories are conducted by using SAP2000 [7] finite element software.

2. Numerical Modelling and Parametric Study

In the study, a nonlinear pushover analysis is applied to calculate real nonlinear displacement demand under earthquake loads. Nonlinear deformations of structural elements are evaluated with that displacement demands. In nonlinear analysis determining plastic hinge properties of cross sections is very crucial to define nonlinearity of structures. In this section, modelling details of superstructure and substructure are given to perform numerical model in pushover analysis. In this research eight pushover analyses are applied for five and eight stories RC frame-Shear Wall 3D structures considering nonhomogeneous soil conditions. The analysis results are compared in terms of nonlinear force-displacement relationship, story drifts, plastic hinge rotation and variation of first fundamental vibration mode of structure.

2.1. Modelling Superstructure

Three dimensional and two different type RC structures are used in analysis. They are designed according to the minimum design conditions given by Turkish Earthquake Code 2007 (TEC2007) as five and eight-story RC structures. In analysis plastic hinges can be assigned to only frame elements. Therefore RC Shear walls are defined with mid-pier frame approach [8] and connected to the structural system with infinite rigid beams (Figure 1). It is provided that the structures are constructed in first seismicity risk degree zone and have high ductility. The soil conditions are chosen saturated normally and slightly over consolidated clays (Z4 soil class) defined in TEC 2007 for all structural models. In TEC 2007 the peak ground acceleration (A0) is defined as 0.4g for first degree seismicity risk. Elastic-perfectly plastic model is defined for stress-strain relationship of steel reinforcement. Mander confined and unconfined approach are assumed for nonlinear behavior of concrete. Plastic hinge properties are evaluated according to the moment –curvature relationship of each cross section are defined by considering longitudinal and transverse reinforcements. These plastic hinges are defined at the each end points of RC structural elements. The frame in red box is chosen as a reference axis to compare between analysis results. Dimensions of each cross section, material properties and reinforcing details of the structural elements are given in Table 1 and Figure 2. General layouts and plan views of three dimensional structures are presented in Figure 3.

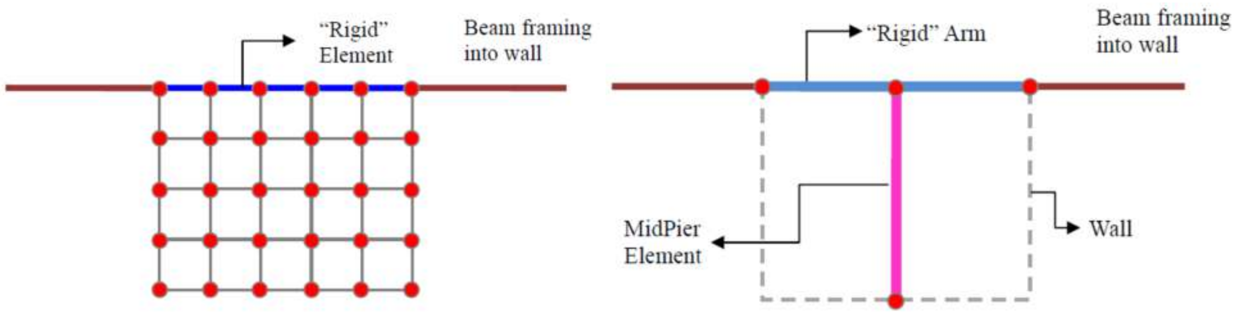

Figure 1. Plan view and 3D model of structural model [8]

Table 1. Material and section properties of superstructure

Name	Element	Concrete - Reinforc.	Mod. of Concrete (Mpa)	Mod. of Reinfor. (Mpa)	Yield Strength of Reinforc. (Mpa)	Dimensions (mm)	Long. – Trans. Reinforc.
C1	Column	C25 – S420	30000	210000	420	600x250	10Φ16–Φ10/10
C2	Column	C25 – S420	30000	210000	420	250x600	10Φ20–Φ10/10
C3	Column	C25 – S420	30000	210000	420	600x250	10Φ20–Φ10/10
B1	Beam	C25 – S420	30000	210000	420	250x500	6Φ16–Φ10/10
B2	Beam	C25 – S420	30000	210000	420	250x500	6Φ20–Φ10/10

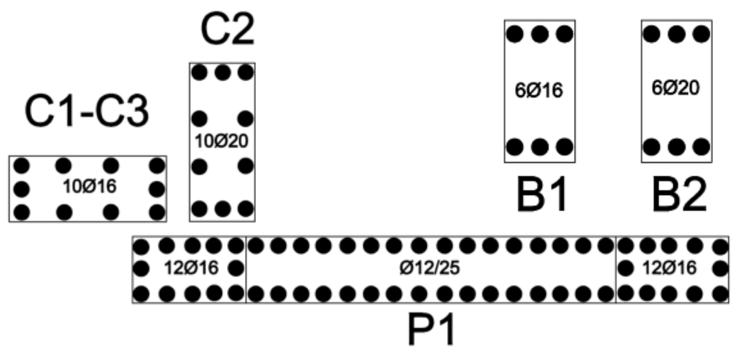

Figure 2. Reinforcement details of structural elements

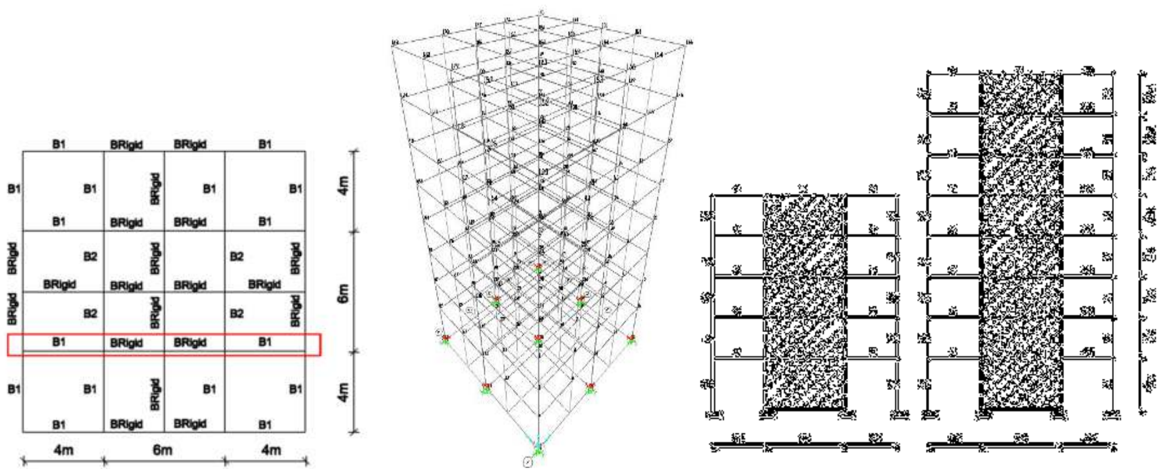

Figure 3. Plan view, 3D model and General layout of structural model

2.2. Modelling substructure

Soil structure interaction for nonhomogeneous soils is defined by using impedance functions proposed by Gazetas (1991). The interaction between soil and superstructure is determined due to the foundation impedance functions. These functions represent static stiffness of nonhomogeneous elastic soil behavior, can be applied to any solid foundation shape on the surface of a nonhomogeneous half space soil. In the study, translational and rocking static stiffnesses are calculated for spread footing proposed by Gazetas (1991). The impedance functions which can be used both dimensions of the footing evaluated by Gazetas (1991). To define SSI effect of nonhomogenous soil conditions shear modulus is changing with depth in these functions. They are also evaluated by taken into account shear wave velocity and poisson ratio of soil. Shear modulus changing with depth is defined in Eq. 1. Translational, rocking and torsional spring stiffnesses are calculated by using Equations 2&3, 4, 5 respectively for nonhomogeneous soil class and they are given in Table 2. These equations are determined for the saturated normally and slightly over consolidated clays whose shear modulus can increase relatively fast at large depths. In Eq. 1, to fit test result x parameter is determined by fitting. The numerical model where SSI effect of nonhomogeneous soil conditions is determined using in Sap2000 is shown in Figure 5.

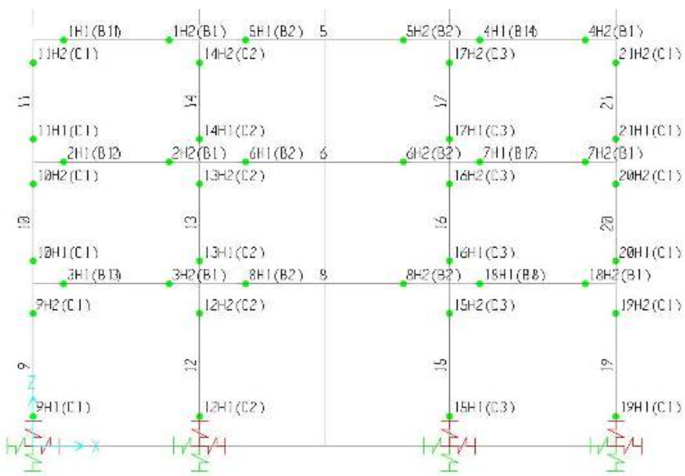

Figure 5. Finite element model of superstructure considering SSI with plastic hinge assignments

$$G = G_0 (1 + x\frac{z}{B})^{1/n} \quad (1)$$

$$K_{z,vertical} = \frac{4.54}{1-\nu} G_0 B [1 + \alpha]^n \quad (2)$$

$$K_{x,horizontal} = \frac{9}{2-\nu} G_0 B \left[1 + \alpha \frac{z}{B}\right]^n \quad (3)$$

$$K_{x,rocking} = \frac{36}{1-\nu} G_0 B^3 [1 + \alpha]^n \quad (4)$$

$$K_{torsion} = 7.93 G_0 B^3 \left[1 + \frac{1}{10}\alpha\right]^n \quad (5)$$

Table 2. Translation and rocking stiffness of springs represent nonhomogeneous soil conditions

Shear Modulus G_0 (kN/m^2)	Shear Wave Velocity (m/s)	Poisson Ratio	Stiffness (kN/m^2)					
			Translation Along			Rocking About		
			x	y	z	x	y	z
10368	70	0.49	63741	63741	98029	74729	74729	82742

3. Results

The structural models are designed as two different structural systems to compare analysis results. It is aimed determining effect of number of story and inhomogeneity of soil in nonlinear analysis. By means of these analysis it can be evaluated effect of nonhomogenous soils on the nonlinear structural performance. Foundation geometry is chosen 2 m by 2 m square for columns and 2m by 6 m for shear walls respectively. Shear modulus, translational and rocking stiffnesses using in these analysis are defined by using Gazetas (1991) formulas which are evaluated for nonhomogeneous soils. To compare analysis result eight nonlinear incremental single mode pushover analysis are completed by using SAP2000. To determine effects of inhomogeneity and number of story target displacements, story drifts values and plastic hinge mechanisms formations are compared for nonhomogenous and rigid soil conditions.

3.1. Pushover Curve

Pushover curve is defined as the relationship between base shear force and roof displacement. In the study to determine pushover curves are used in nonlinear analysis. In the analysis structural the variation of displacement and force demand which are taken form pushover curves, are shown in Figure 6 considering inhomogeneity of soil and structural height. Moreover to evaluate for performance level of each structural system the pushover curves obtained from nonlinear analysis are used. When the analysis result are compared that the nonlinear displacement demand increases when nonhomogeneous SSI effect is taken into account in RC shear wall-frame systems. Additionally, rigidity of the structural system decreases and the structural system performs more ductile behavior when SSI is considered.

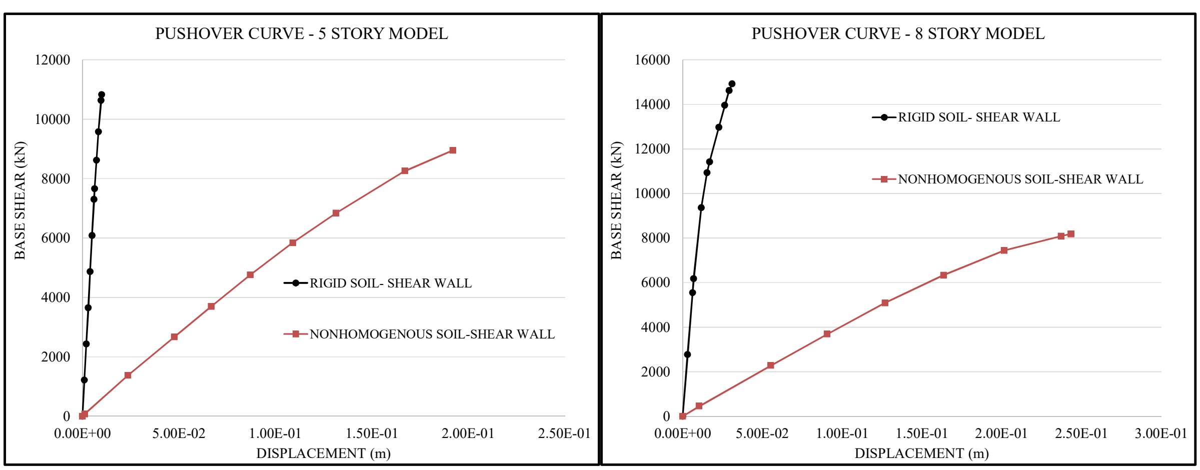

Figure 6. Pushover curves

3.2. Structural demands

Target displacement values are determined to evaluate the plastic hinge rotations. These plastic deformations are very crucial to calculate the real nonlinear performance level of a structure. Target displacements are obtained from the analysis results by means of measuring horizontal deflection value at the top of structural models. The variation is a ratio that is calculated by dividing the difference between rigid and nonhomogeneous soils to the rigid soil condition values. The difference of base shear, roof displacement and period of fundamental mode for different structural models are shown Table 3 considering soil structure interaction due to the inhomogeneity of soil.

Table 3. Variation of structural demands

Soil Type		Rigid	Nonhomogenous	Variation (%)
5 Storey	Base Shear (kN)	10830.32	8953.00	-17.33
	Roof Disp. (m)	0.01	0.19	1820.00
	Periyod T (s)	0.164	0.741	351.83
8 Storey	Base Shear (kN)	14919.38	8187.331	-45.12
	Roof Disp. (m)	0.05	0.35	620.41
	Periyod T (s)	0.222	1.123	405.86

3.3. Story drifts

Story drift is calculated by dividing the difference in horizontal deflection of top and bottom of a story to the height of this story. These drifts are used to evaluate the nonlinear performance level of a structure. In different earthquake codes of different countries some limitations are defined for story drifts when determining performance level of structures. In the study, the limitations of American Society of Civil Engineers (ASCE41-06) are used and they are defined for immediate occupancy, life safety and collapse prevention performance levels as 2%, 3% and 5% respectively. The variation of story drifts which are calculated according to the story displacement for each structural model are shown in Figure 7 and 8.

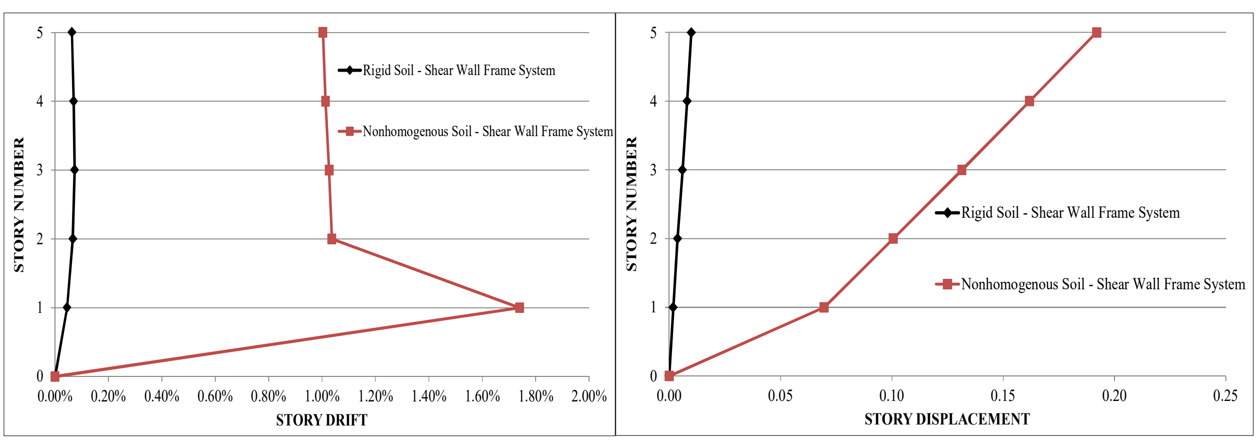

Figure 7. Story displacements for five story structures

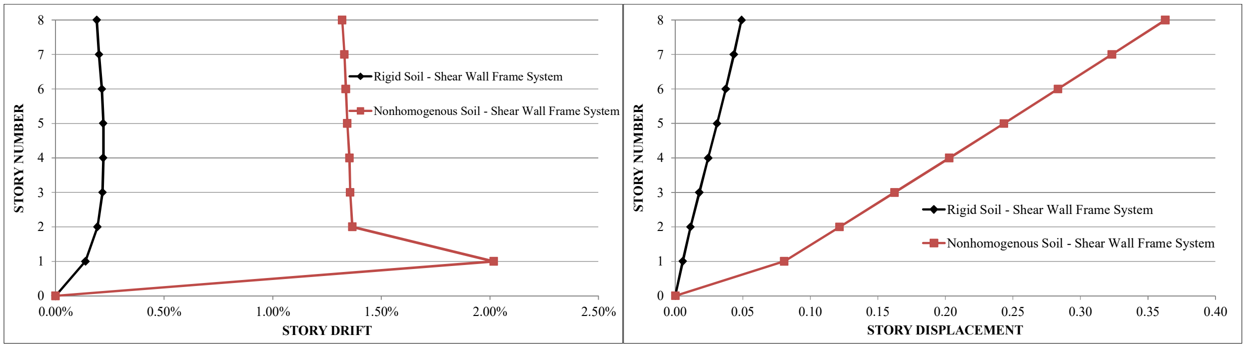

Figure 8. Story displacements for eight story structures

3.4. Plastic Hinge Mechanisims

In earthquake codes there is a crucial design rule for column-beam connection. Strong column - weak beam approach is generally accepted to design more ductile behaviour in RC structures. In the study results obtained from pushover analysis showed that this analogy couldn't be provided if SSI due to the inhomogeneity of soil is taken into account. Moreover, new plastic hinge mechanism can occur in a structural system when SSI is considered. Additionally, these plastic hinge rotations can increase due to the effect of SSI when results of rigid soil condition are compared. For instance, the variation of plastic hinge mechanisms are given in Figure 9 for five and eight-story RC structures which are designed as shear wall-frame systems.

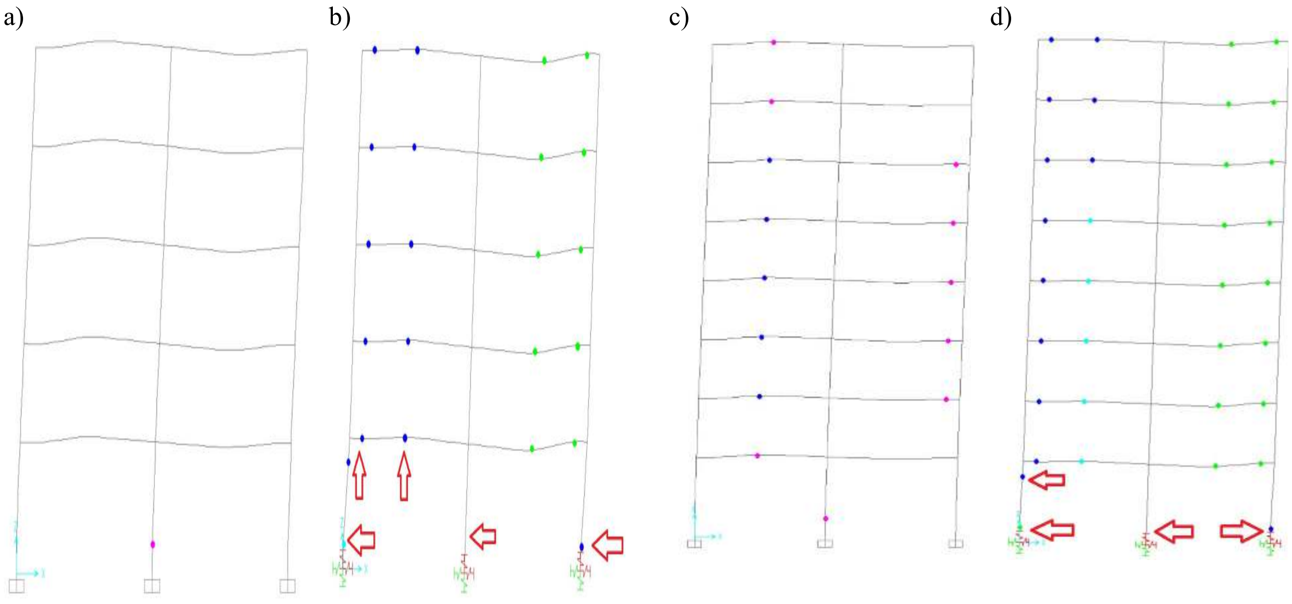

Figure 9. Plastic hinge formation 5&8-story a) Rigid soil condition-5-story b) Nonhomogeneous soil-5-story c) Rigid soil condition-8-story d) Nonhomogeneous soil-8-story

4. Conclusions

The effect of SSI is seemed in nonlinear analysis should be considered when soil rigidity decreases. As the soil rigidity decreases due to the inhomogeneity of soil, performance levels of structures can change in numerical models negatively. Moreover, the effect of SSI get more crucial as the depth of soil increases. From analysis results, the following conclusions can be concluded:

1-) When pushover curves are compared, due to SSI effect, the shear-wall system becomes less rigid.

2-) It is seemed that the roof displacement and the displacement demand can become bigger values as the soil rigidity decreases. Moreover, the difference between numerical models of rigid soil and SSI also gets higher with the increasing number of story.

3-) The story drift, which can use directly to determine performance level in design codes, can reach critical limit values. When the number of story increases whereas the soil rigidity decreases because of the inhomogeneity of soil, the story drift values can change in an unconservative way.

4-) when the effect of SSI is taken account into in nonlinear analysis, plastic hinge mechanism change to column hinge mechanism for numerical models. Plastic hinge rotations can reach high values with the increasing of roof displacement.

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