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Soil-Structure Interaction in Nonlinear Pushover Analysis of Frame and 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 more important to obtain performance level of structures when considering soil-structure interaction. Pushover analysis, one method of nonlinear static analysis, is generally used in the assessment of existing buildings. Pushover analysis gives more realistic results when compared to linear analysis methods to achieve seismic performance level of structures. In this study, three-dimensional soil structure interaction due to the soil inhomogeneity problem is carried out with nonlinear pushover analysis to determine the effect of story number on the performance level of RC structures which are designed as frame and shear wall-frame structural systems with five and eight stories. Inhomogeneity of soil is taken account into with impedance functions, which represent static stiffness of foundations for elastic soil behavior. These functions are calculated by taking shear wave velocity, shear modulus, depth of soil and poisson ration for a soil type can be given as saturated normally and slightly over consolidated clays for spread foundation. At each foundation horizontal translation, vertical translation and rocking stiffness is calculated with these impedance functions. Shear wall are modeled with mid-pier frame approach. These are connected to the structural system with infinite rigid beams. Sap2000 finite element software package is employed in all the numerical analysis. Target displacements, story drifts, plastic hinge mechanisms and rotations obtained from pushover analysis of superstructure are compared according to the analysis results. All these results from rigid soil behavior are compared with those obtained from five and eight story and nonhomogeneous soil conditions. Displacement demand and the plastic hinge rotations increase when soil inhomogeneity considered. The difference between rigid and nonhomogeneous soil conditions is more apparent when the number of story increases. In other words, an elastic deformation in the structure can change into a plastic deformation when impedance functions are employed in the analysis.

Keywords: Pushover analysis, soil-structure interaction, nonhomogeneous soil, RC structures

1. Introduction

Determining of the nonlinear capacity of structures under seismic forces is extensively made by pushover analysis. In this analysis methods seismic demands of structure are calculated by increasing lateral seismic effect monotonically until a real target displacement is reached. Force distribution between the stories is applied in a form like fundamental first mode. (Chopra A.K. et al., 2001). Soil-structure interaction (SSI) system in nonlinear analysis can also be used by pushover method if it is adopted and represented precisely for the nonlinear seismic analysis (Liping L. et al., 2012). However, in pushover analysis SSI is generally neglected because of the modeling difficulties of defining the effect of soil condition, using SSI by employing foundation impedance functions given by Gazetas (1991) can be a solution to determine the SSI behavior in nonlinear analysis. The SSI is related shear modulus of soil directly. The shear modulus decreases with depth of soil faster in nonhomogeneous soil conditions (Vrettos, C., 1999). Static and dynamic deformations of soils can be larger due to the dynamic stiffness of soil (Wolf J.P, and Meek J.W., 1994) when soils are multilayered and nonhomogeneous (Gazetas G., 1980). In this research, effect of number of story and inhomogeneity of soil in nonlinear pushover analysis is applied to find out by considering three-dimensional soil structure interaction in different structures which have five and eight stories Reinforced Concrete (RC) frame and shear wall-frame systems with finite element software package, SAP2000.

2. Numerical Modelling and Parametric Study

Pushover analysis is important in this research to determine real nonlinear displacement demand is required to represent the real behavior of structure under seismic loads. Plastic deformation of structural element of superstructures are calculated with this displacement demands. Plastic hinge properties of cross sections, which are needed to define nonlinearity of structures, is very essential. Modelling method of superstructure and substructure is given in detail in this section.

2.1 Modelling superstructure

Three dimensional five and eight story, RC structures are designed according to the the minimum design conditions required by Turkish Earthquake Code 2007 (TEC2007). Shear walls are connected to the structural system with infinite rigid beams are modeled with mid-pier frame approach. Stress-strain relationship of steel reinforcements are accepted as elastic perfectly plastic. Confined and unconfined concrete behavior is modeled by considering Mander approach. Plastic hinge properties of each cross section is defined by considering longitudinal and transverse reinforcements given in Table 1. These plastic hinges are assigned at the end points of shear walls, columns and beams. General layouts of three dimensional structures are presented in Figure 1. Cross section details of the structural elements are given in Table 1.

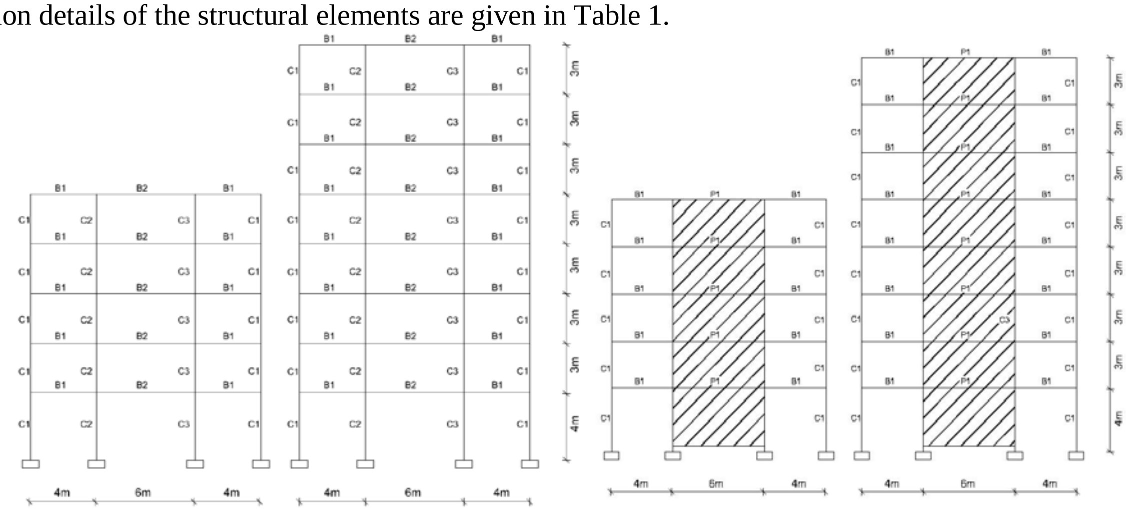

Figure 1– General layout of structural systems

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
P1	Shear Wall	C25 – S420	30000	210000	420	250x6000	12Φ16 – Φ12/15-Φ10/10

2.2 Modelling substructure

Soil structure interaction for nonhomogeneous soils is considered by using spring stiffness solutions that are applicable to any solid basement shape on the surface of a nonhomogeneous half space studied by Gazetas (1991). The relationship between soil and superstructure is defined by means of foundation impedance functions, which represent static stiffness of nonhomogeneous elastic soil behavior. In this research, translational and rocking stiffness for spread footing given by Gazetas (1991) is considered for. Gazetas (1991) calculated these impedance functions by using both dimensions of the footing and shear modulus which changes with depth, defined by using shear wave velocity of soil along with its Poisson's ratio. Shear modulus changing with depth is given in Eq. 1. Horizontal spring stiffness by using equation 2&3 and rocking and torsional spring stiffness by using equation 4&5 are determined for nonhomogeneous soil class and they are tabulated in Table 2. These equations are represents saturated normally and slightly over consolidated clays whose shear modulus can increase relatively faster at large depths. In Eq. 1 x parameter should be determine by fitting with the test results. The numerical model using in Sap2000 software package is shown in Figure 2 considering soil structure interaction for nonhomogeneous soil conditions.

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

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

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

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

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

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

Shear Modulus G_0 (kN/m^2)	Stiffness (kN/m^2)					
	Translation Along			Rocking About		
	x	y	z	x	y	z
10368	63741	63741	98029	74729	74729	82742

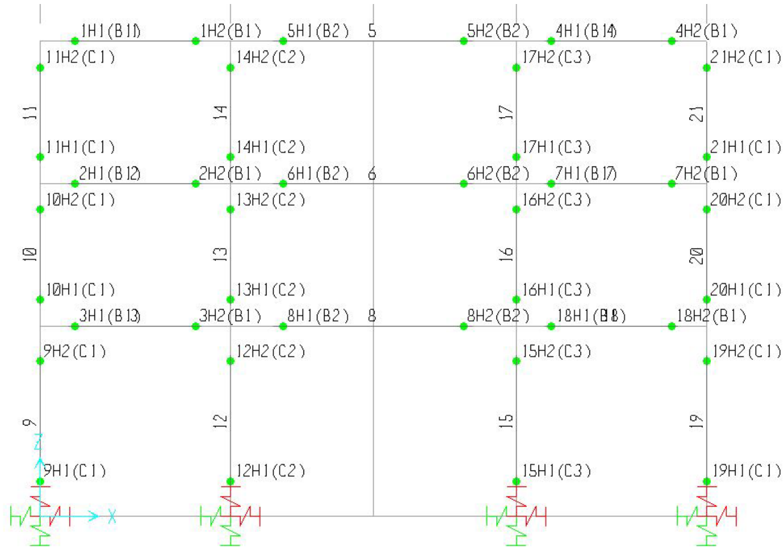

Figure 2 – Finite element model of superstructure considering SSI with plastic hinge assignments at member ends

3. Results

Two different structural heights and structural system are compared to find out the effect of number of story and inhomogeneity of soil on the pushover analysis of three dimensional structure. Foundation geometry is selected 2 m by 2 m square. Shear modulus, translational and rocking stiffness are calculated by using Gazetas (1991) formulas which are given for nonhomogeneous soil conditions.The nonlinear incremental single mode pushover analysis are completed by using finite element software package firstly, the effects of inhomogeneity and number of story are determined by comparing of target displacements, story drifts and plastic hinge mechanisms formation resulted from both considering rigid and nonhomogeneous soil conditions with impedance function.

3.1 Pushover Curve

The relationship between base shear force and roof displacement is defined by using pushover curves in pushover analysis. Pushover curves are used to calculate structural displacement and force demand in nonlinear analysis. Variation of pushover curves considering inhomogeneity of soil and structural height are given in Figure 3. Also the variation of pushover curves is observed as different values according to the structural systems.

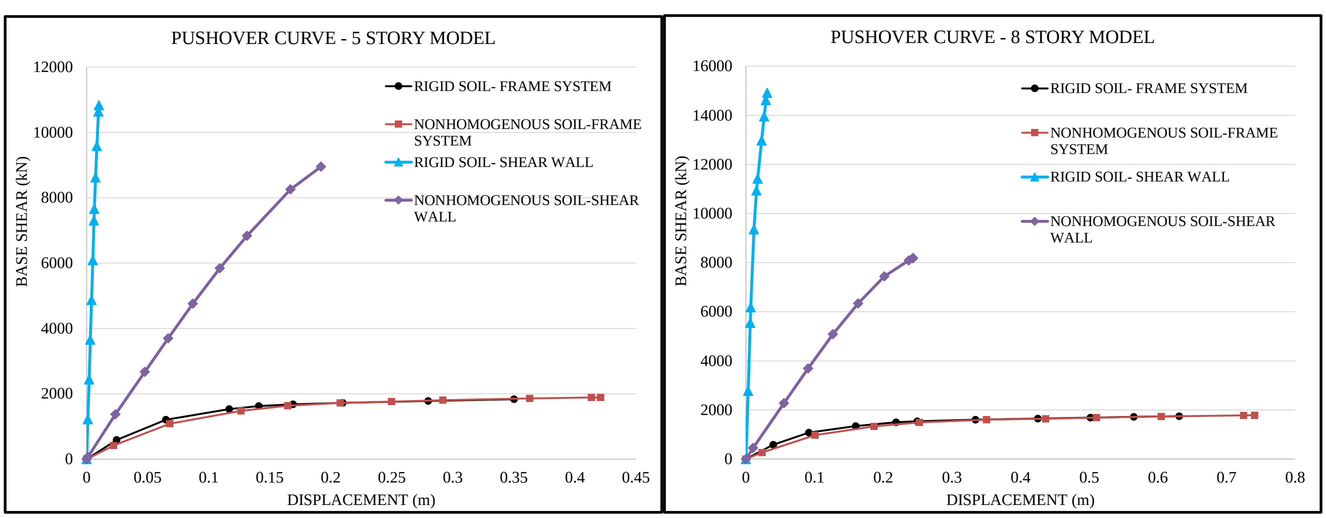

Figure 3 – Pushover curves

3.2 Structural demands

Target displacement values are used to calculate the plastic hinge rotations. These plastic deformations are very essential to determine the real nonlinear performance level of a structure. Target displacement which is called roof displacement is the horizontal deflection value at the top of structures. The variation of target displacement demand for different structural heights and structural systems considering soil structure interaction due to the inhomogeneity of soil are given Table 3&4.

Table 3 – Variation of structural demands for 5 story structure

5 STOREY				
Soil Type		Rigid	Nonhomogeneous	Variation (%)
Frame System	Base Shear (kN)	1838.20	1888.55	2.74
	Roof Disp. (m)	0.36	0.42	16.95
	Periyod T (s)	1.199	1.364	13.76
Shear Wall	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

Table 4 – Variation of structural demands for 8 story structure

8 STOREY				
Soil Type		Rigid	Nonhomogeneous	Variation (%)
Frame System	Base Shear (kN)	1838.20	1888.55	2.74
	Roof Disp. (m)	0.36	0.42	16.95
	Periyod T (s)	1.199	1.364	13.76
Shear Wall	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 defined as the difference in horizontal deflection of top and bottom of a story, used to determine the nonlinear performance level of a structure. There are some limitations for story drifts in different earthquake codes. In American Society of Civil Engineers (ASCE41-06) for Immediate Occupancy performance level 2%, for the Life Safety performance level 3%, for the Collapse Prevention performance level 5% story drift value are defined to find out performance level of the structures. Story displacements and story drifts which is calculated according to the story displacement for each numerical model of structure are plotted in Figure 4 and Figure 5 respectively.

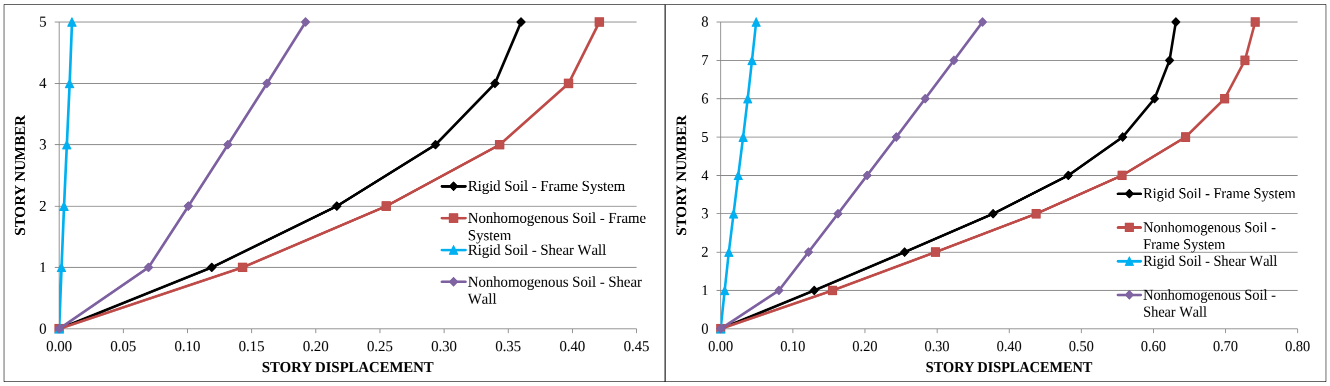

Figure 4 – Story displacements for five and eight story structures

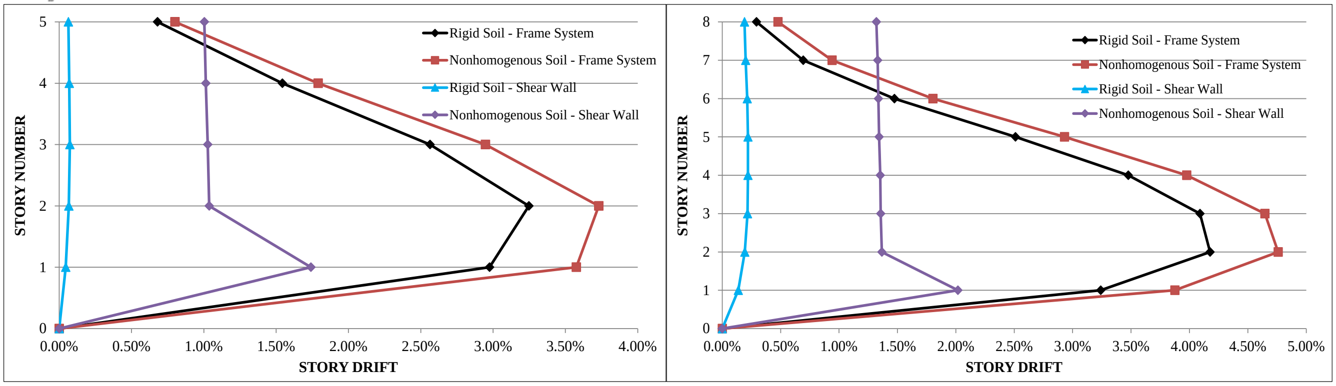

Figure 5 – Story drifts for five and eight story structures

3.4 Plastic Hinge Mechanism

Plastic mechanism at beam edges for achieving beam mechanism rather than frame mechanism. Results showed that hinge formation could be changed when soil-structure interaction due to the inhomogeneity of soil is considered. Additionally, a plastic hinge rotation in a model with soil structure interaction can increase in a model with rigid soil condition. For instance, the variation in the plastic hinge formation are shown in Figure 5 and in Figure 6 for five and eight story RC structures which are designed frame and shear wall-frame systems.

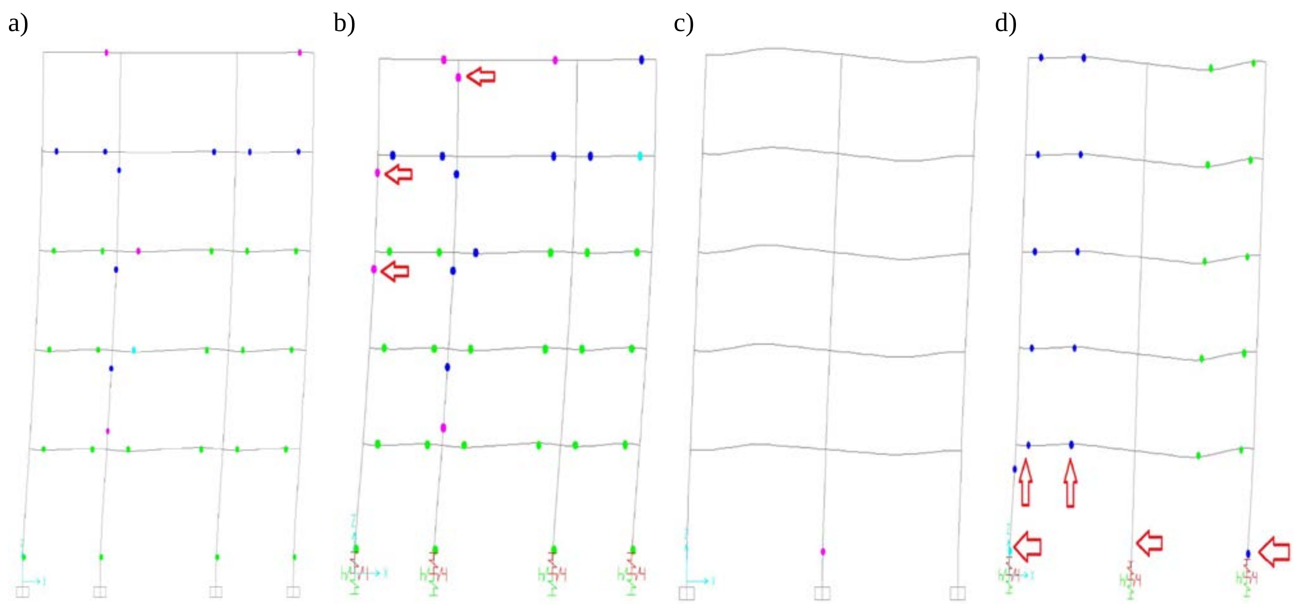

Figure 5 – Plastic hinge formation 5 story a) Rigid soil condition-frame b) Nonhomogeneous soil-frame c) Rigid soil condition-shear wall-frame d) Nonhomogeneous soil-shear wall-frame

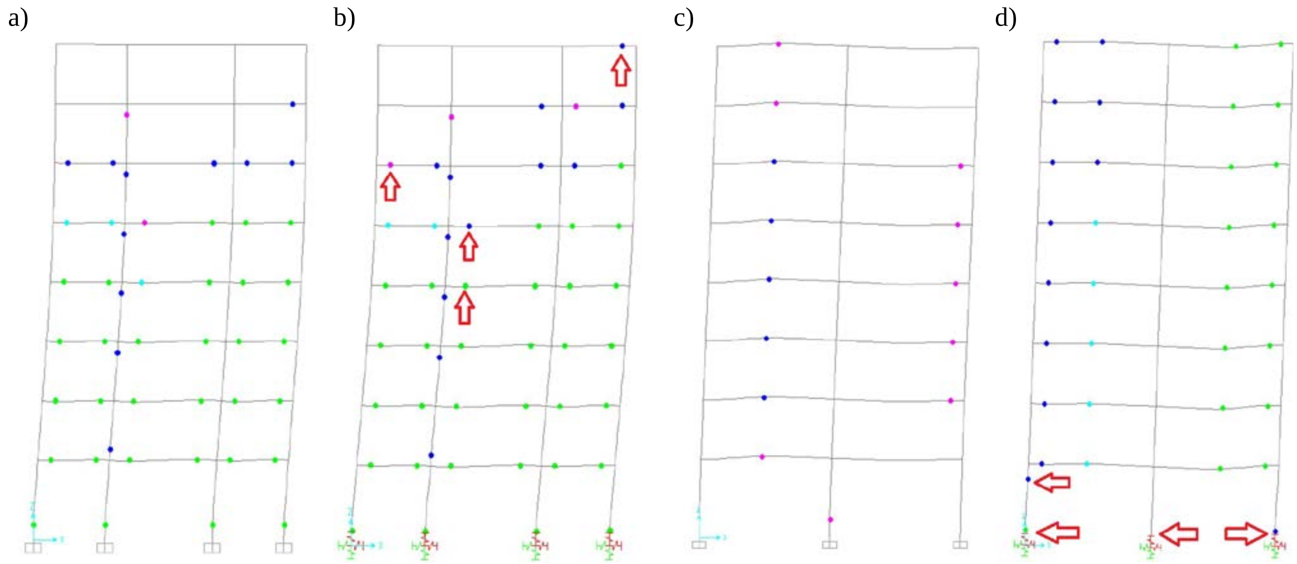

Figure 6 – Plastic hinge formation 8 story a) Rigid soil condition-frame b) Nonhomogeneous soil-frame c) Rigid soil condition-shear wall-frame d) Nonhomogeneous soil-shear wall-frame

4. Conclusions

Soil-structure interaction behavior in pushover analysis must be considered especially when soil rigidity decreases such this model. Ignoring soil structure interaction especially inhomogeneity in numerical model can change performance level in unconservative way. Furthermore, as the depth of soil increases, the SSI effect gets more apparent than other situations. From analysis results, the following conclusions can be summarized:

1-) The roof displacement and the displacement demand gets bigger values as the soil rigidity decreases when pushover analysis is used considering soil-structure interaction due to the inhomogeneity of soil. When models are compared, the difference between results when impedance functions are not ignored is obtained for shear wall-frame system. Moreover, the difference also gets higher with the increasing number of story.

2-) The story drift, which are used to determine performance level in ASCE 41-06, reaches critical limit values when the number of story increases whereas the soil rigidity decreases because of the inhomogeneity of soil especially in frame systems.

3-) When plastic hinge rotation are compared, plastic hinge formation mechanism changes especially in columns of five and eight story RC shear wall-frame systems when soil structure interaction is taken account into. Plastic hinge rotation values gets higher as the roof displacement increases.

5. References

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