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EFFECT of FOUNDATION GEOMETRY and SOIL CLASS in NONLINEAR PUSHOVER ANALYSIS of TWO DIMENSIONAL RC FRAMES CONSIDERING SOIL STRUCTURE INTERACTION

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ABSTRACT

In this study, effect of foundation geometry and soil class in nonlinear pushover analysis is investigated by considering two-dimensional soil structure interaction. Nonlinear incremental single mode pushover analysis is used for the purpose of modeling three stories and three bay Reinforced Concrete RC frames with commercial finite element software package, SAP2000. Soil condition effects on super structure performance are taken into account by considering foundation impedance functions. These impedance functions, which are calculated from American Society of Civil Engineering (ASCE) 41-06, determine static stiffness of surface foundations for elastic soil behavior. Effects of foundation geometry are considered by choosing the spread foundation cross section as rectangular and square. Effects of soil class are considered by employing three shear wave velocities for each soil types, which are defined in ASCE 41-06. It is shown that soil-structure interaction gets more important in soft soil conditions and it becomes significant when aspect ratio of rectangular spread foundation increases.

INTRODUCTION

With the help of recent studies carried out lately, pushover analysis which is one type of nonlinear static analysis is used in the assessment of existing buildings for being easy to implement and giving faster results (Liping L. et al., 2004). Pushover analysis gives more realistic results than other linear analysis methods for obtaining seismic performance of structures. Although pushover analysis is widely used in determining the seismic performance of structures most of the current researches are carried out for the cases in which support of the structure is assumed rigid connected to the bedrock. (Aydınoglu N., 2007). Modeling difficulties of defining the effect of soil condition to the superstructure, which is also known as soil-structure interaction can be the reason for such disregarding. Defining soil-structure interaction by employing foundation impedance functions given in ASCE 41-06 can be a solution to define the soil-structure interaction behavior in pushover analysis.

In recent years, there are some limited pushover analysis related researches in which impedance functions are employed. They used pushover analysis to determine seismic performance level of plane frame-shearwall structure of tall building. They used impedance functions to define soil-structure interaction in their analysis. They reported that the story peak displacement and story drift are reduced when soil-structure interaction is reflected in the model. They also found that plastic hinge order and distribution is changed between the models where impedance functions are included and not included

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(Liping Liu et al., 2008). Some researchers used nonlinear impedance functions defined by Gazetas (1990) to model the seismic behavior of low-rise steel framed structures. He found that as the nonlinearity of foundation increases the displacement demand decreases (Raychowdhury P. et al., 2011). Some investigators conducted a research for a structure located at hill side. In their research they used different soil classes for the columns located at different levels of the hillside. They defined equivalent spring stiffness to describe different soil class behavior for detecting the change in the total base shear force, total displacement demand and response correction factor (Pandey et al., 2011).

In this study, effect of foundation geometry and soil class in nonlinear pushover analysis is investigated by considering two-dimensional soil structure interaction. Nonlinear incremental single mode pushover analysis is used for the purpose of modeling three stories and three bay Reinforced Concrete RC frames with commercial finite element software package, SAP2000.

NUMERICAL MODELLING

Numerical modelling of structure is constructed by employing commercial software package, SAP2000, which can handle pushover analysis. Nonlinear incremental single mode pushover analysis is essential in this study because nonlinear displacement demand is required to represent the real behavior of structure excited with earthquake loads. Performance level of structures are addressed with this displacement demands. Defining plastic hinge properties of cross sections, which are needed in pushover analysis, is very important. Modelling strategies of superstructure and substructure is given in detail in this section.

Modelling of Superstructure

General layout of the frame used in this study is presented in Figure 1. Three bay-three story, reinforced concrete frame is designed with the minimum cross section design conditions required by Turkish Earthquake Code 2007 (TEC2007).

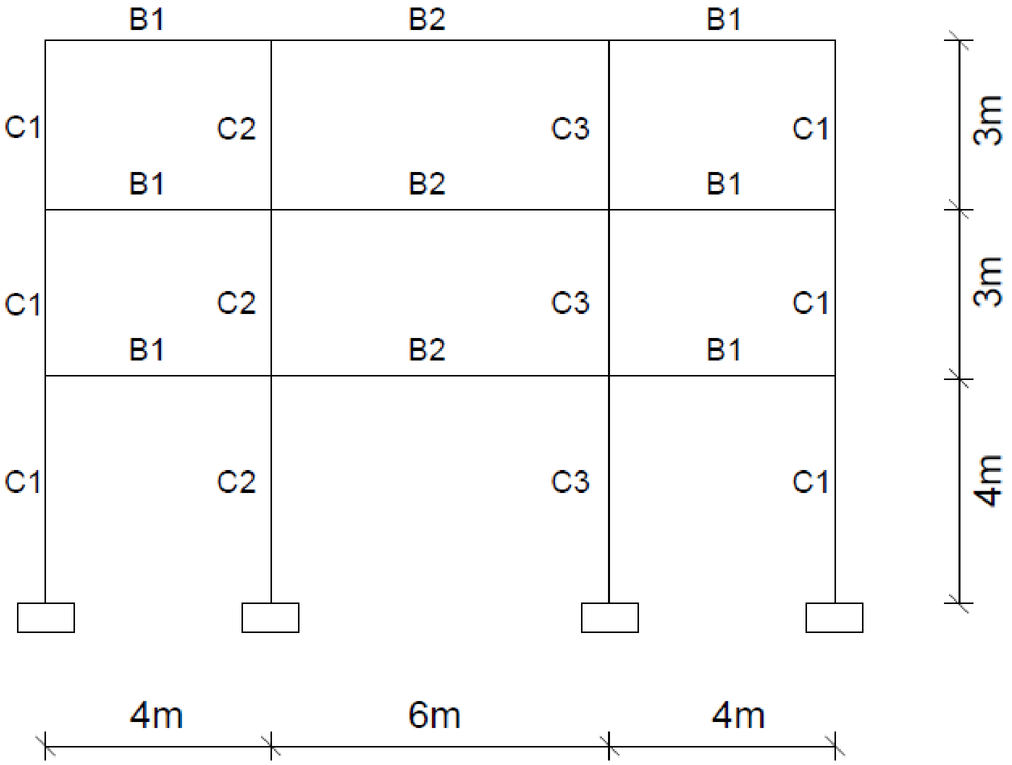

Figure 1. General layout of three bay-three story super structure

Cross sectional details along with material properties of the structural elements are given in Table 1. Steel reinforcements are modelled as elastic perfectly plastic. Concrete material behavior is modelled by employing Mander approach. Plastic hinge property of each confined cross section is determined by considering longitudinal and transverse reinforcement given in Table 1 by calculating moment-rotation capacity. Once these plastic hinges are determined then they are assigned at the end points of columns and beams.

Table 1. Material and section properties of superstructure

Section Name	Element	Material Concrete – Reinforcement	Modulus of Concrete (Mpa)	Modulus of Reinforcement (Mpa)	Yield Strength of Reinforcement (Mpa)	Dimensions (mm)	Longitudinal – Transverse Reinforcement
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

Modelling of Substructure

Soil structure interaction is modelled by using spring stiffness solutions that are applicable to any solid basement shape on the surface of a homogeneous half space studied by Gazetas (1991). Thus, soil-structure interaction is modelled by means of foundation impedance functions, which represent static stiffness of surface foundation for elastic soil behavior. In this study translational and rocking stiffness for spread footing given in American Society of Civil Engineering (ASCE) 41-06 is considered. Gazetas (1991) defined these impedance functions by using both dimensions of the footing and shear modulus calculated by using shear wave velocity of soil along with its Poisson's ratio. Stiffness expressions used in this study are in the form given in equation (1) and (2). These equations represent stiffness values for translational and rocking degree of freedoms for one axis. In the following equations *G* is the shear modulus, *L* and *B* are the dimensions of foundation. Same equations can be used for different axis.

$$K_{x,translation} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right] \tag{1}$$

$$K_{xx,rocking} = \frac{GB}{2-\nu}\left[0.4\left(\frac{L}{B}\right) \; + 0.1\right] \tag{2}$$

PARAMETRIC STUDY AND RESULTS

Three different soil classes and three different foundation geometry are used to find out the effect of foundation geometry and soil class on the pushover analysis of structure. Authors think that soil-structure interaction is more evident in soft soils. Thus, C, D and E soil classes are selected from ASCE 41-06 for having lower shear velocities. Foundation geometry is selected with different aspect ratios. Aspect ratio of 0.25, 0.50 and 1 is selected to see the effect of foundation geometry. For each soil classes and foundation geometry shear modulus, translational and rocking stiffness are calculated and tabulated in Table 2. These stiffness values are used to define the spring properties used in finite element modeling.

Table 2. Translation and rocking stiffness of springs represent different soil classes

Foundation Dimensions (m)	Soil Class	Shear Wave Velocity (m/s)	Shear Modulus (kN/m^2)	Stiffness (kN/m^2)					
				Translation Along			Rocking About		
				x	y	z	x	y	z
2.0x0.5	C	564	572573	1640881	1846596	2215115	181600	1402278	1169068
	D	275	136125	390107	439015	526627	43174	333381	277937
	E	120	25920	74282	83594	100277	8221	63480	52923
2.0x1.0	C	564	572573	2240637	2377780	2911387	769128	2149007	1950187
	D	275	136125	532695	565300	692161	182854	510911	463642
	E	120	25920	101432	107641	131797	34818	97284	88284
2.0x2.0	C	564	572573	3154294	3154294	4016557	3418346	3445693	4763807
	D	275	136125	749910	749910	954907	812687	819188	1132560
	E	120	25920	142793	142793	181827	154746	155984	215654

Finite element model of the structure considering soil structure interaction constructed in SAP2000 is depicted in Figure 2. Plastic hinges defined at member ends, springs defining soil-structure interaction and member id's are shown in the figure.

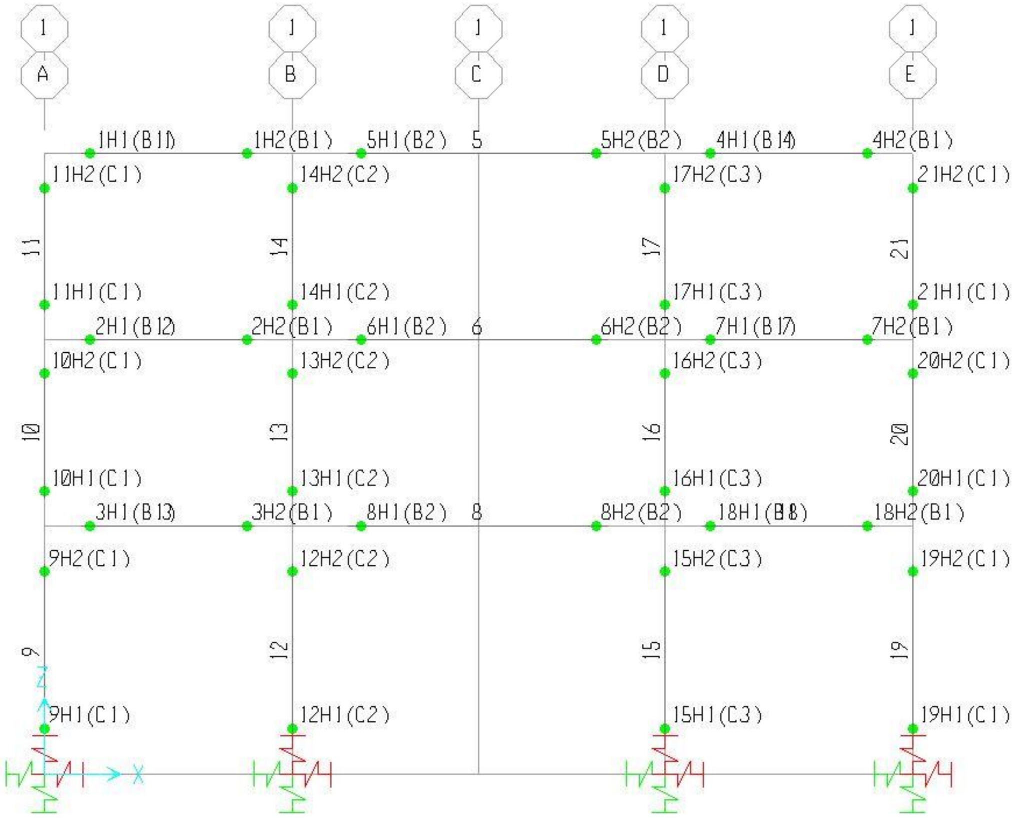

Figure 2. Finite element model of superstructure considering SSI with plastic hinge assignments at member ends

Once the pushover analysis are completed by employing finite element software package, the effects of soil classes and foundation geometry are evaluated by comparing values of target displacements, story drifts and plastic hinge mechanisms forms obtained from both considering rigid soil medium behavior and impedance function.

Target Displacements

Target displacement values are used to calculate the plastic hinge rotations which are needed to determine the performance level of a structure. Target displacement is the horizontal deflection value at the top of the given structure. Variation of target displacement demand of different foundation for each soil classes are given in Table 3. As the soil rigidity softens the displacement demand gets higher. In other words elastic deformation in the structure can change into a plastic deformation when impedance functions are employed in the analysis. Ignoring soil-structure interaction behavior for soil class C and D is not very sound. Maximum difference between rigid case and soil-structure interaction case is calculated 19.04%.

Table 3. Variation of displacement demand for soil classes

Foundation Dimensions (m)	Displacement Demand for Soil Classes (m)								
	Class C			Class D			Class E		
	Rigid	Imp. Func.	Variation (%)	Rigid	Imp. Func.	Variation (%)	Rigid	Imp. Func.	Variation (%)
2.0x0.5	0.079	0.079	0	0.139	0.143	2.8	0.189	0.225	19.04
2.0x1.0	0.079	0.079	0	0.139	0.141	1.4	0.189	0.214	13.22
2.0x2.0	0.079	0.079	0	0.139	0.141	1.4	0.189	0.206	9.0

However; this difference is calculated between 19%-9% for different foundation geometry under conditions described for soil class E.

Story Drifts

Story drift value, the difference in horizontal deflection at the top and bottom of a story, can be used to determine the performance level of a structure. In ASCE41-06 there are story drift limits for each performance level of the structures. For Immediate Occupancy performance level 2%, for the Life Safety performance level 3%, for the Collapse Prevention performance level 5% story drift value are determined. Story drift value for each story level is plotted in Figure 3 Figure 4 and Figure 5 for each foundation geometry. In each plot effect of soil structure interaction is also considered. For soil class E it is possible to have different performance levels in an unconservative way for the same structure if impedance functions are not included in the analysis.

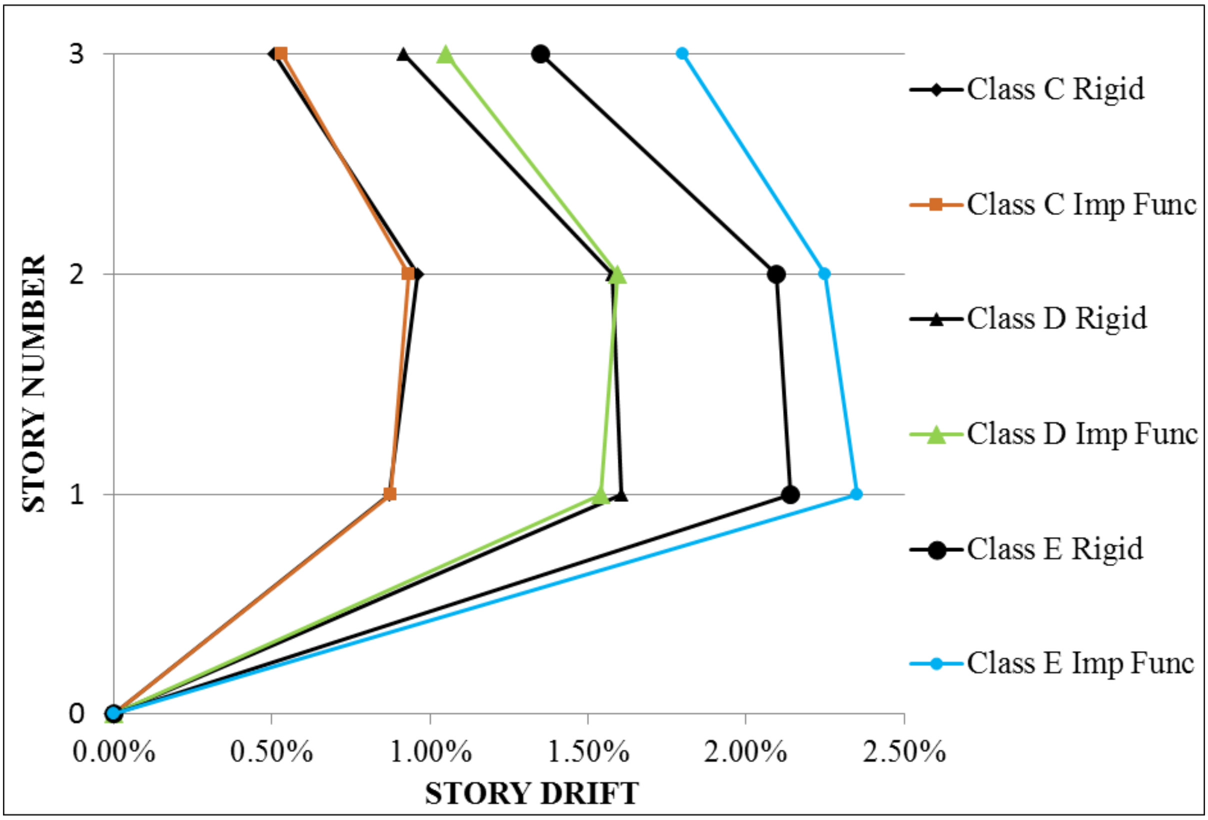

Figure 3. Variation of story drift for various soil classes in frame respectively with 2.0 x 2.0 m

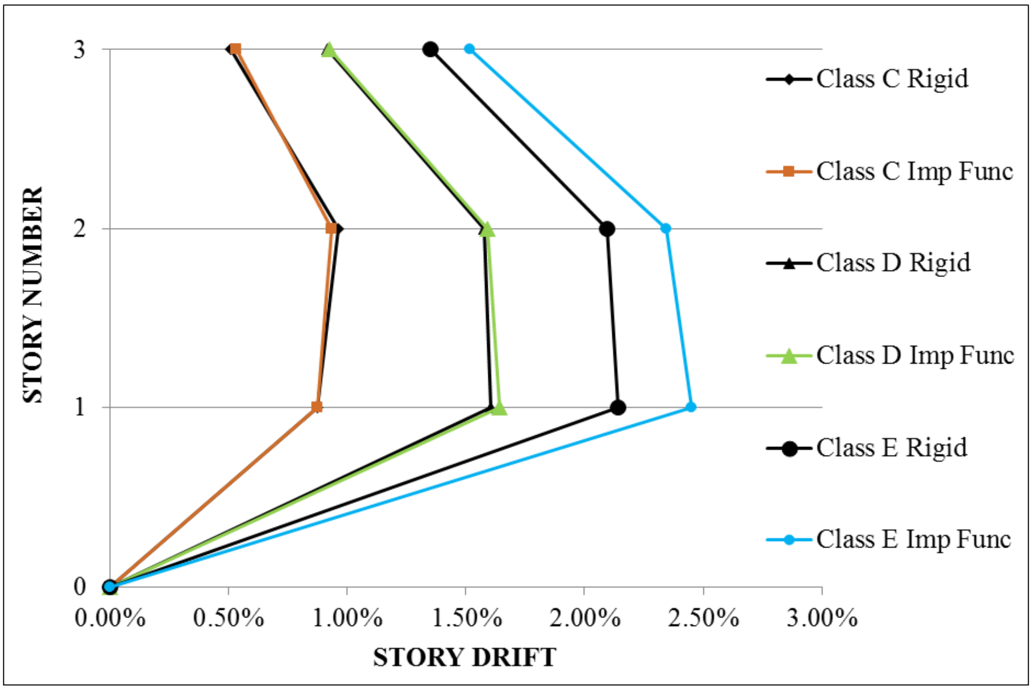

Figure 4. Variation of story drift for various soil classes in frame respectively with 2.0 x 1.0 m

The variation of story drifts gets more critical with increasing the aspect ratio between foundation dimensions.

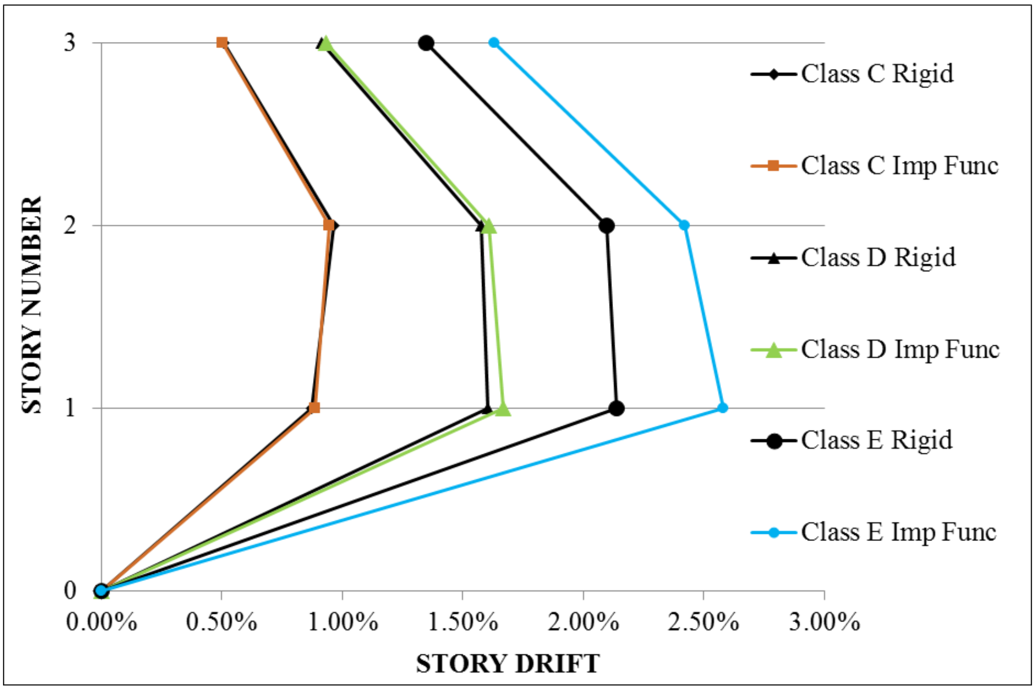

Figure 5. Variation of story drift for various soil classes in frame respectively with 2.0 x 0.5 m

Plastic Hinge Mechanisms

It is desired to have plastic mechanism at beam edges. Results showed that mechanism formation sequence could be changed when soil-structure interaction is considered. Moreover, a plastic hinge formed in a model with soft soil condition can disappear in a model with rigid soil condition. The results is plotted in Figure 6.

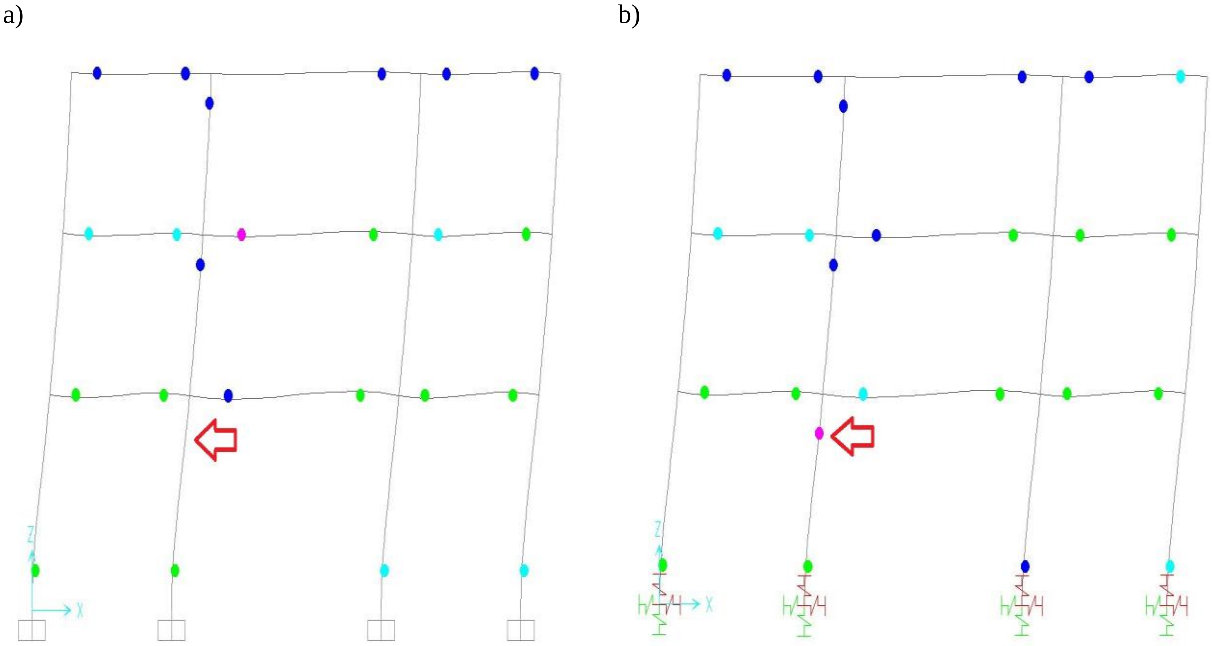

Figure 6. Variation of plastic hinge mechanism for various soil classes
a) Rigid soil condition b) Soil Class E – V_{shear} = 120 m/s

CONCLUSIONS

Including soil-structure interaction behavior in pushover analysis must be considered especially when soil class D&E are used. Neglecting such behavior can change performance level in unconservative way. According to the analysis results, the following conclusions can be summarized:

1-) The roof displacement and the displacement demand increase as the soil rigidity decreases when pushover analysis is used considering soil-structure interaction. The biggest difference between results when impedance functions are not ignored is obtained for in soil class E. Moreover, the differences also gets higher with the increase in the aspect ratio of foundation dimensions.

2-) The story drift, which also defines performance level in ASCE 41-06, reach critical limits when the aspect ratio of foundation dimension increase whereas the soil rigidity decrease.

3-) Plastic hinge rotation value gets higher as the roof displacement increase. Plastic hinge formation mechanism also changes especially in columns when soil structure interaction is considered.

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