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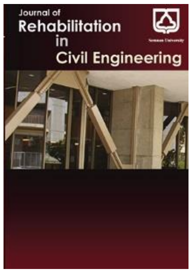

Evaluation of Seismic Vulnerability of Reinforced Concrete Buildings Adjacent to the Deep Excavations

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ABSTRACT

In this study, the effect of deep excavation on the seismic response of RC moment resisting building systems has been studied. Deep excavation can cause significant changes in the stress and strain levels of soil environment and also changes in the propagation of seismic waves. This leads to permanent displacements in the foundation system. In this study, three RC building systems, i.e. 5, 10, and, 15 stories, were modelled considering the nonlinear behaviour of soil and structural material as well as the soil-structure interaction effect. Nonlinear dynamic responses of buildings were evaluated before and after excavation and also with a rigid base (without soil modelling) under the seven earthquake records. Analysis results indicate an increase in seismic demands and responses in the vicinity of the excavation. So for 15-storey buildings near the excavation, 35% increase in the base shear, 70% increase in maximum drift, 26% increase in the story shear force, and a 30% increase in the maximum story acceleration was observed. As a result, considering the effect of excavation on the seismic response of RC building systems is inevitable.

1. Introduction

Rapid urban development is leading to more and more designs of deep excavation for construction of high-rise buildings and subways. In the process of deep excavation, significant changes occur in the stress and strain levels of the soil around the excavation site. The amount and distribution of ground motions for an excavation depends on soil property, excavation geometry (such as length, width, and depth), distance between excavation and the building, type of supporting system as well as construction methods. Since the soil is non-linear and contains inelastic material, deep excavation analysis will be a problem with the nature of soil-structure interaction. Deep excavation analysis process includes the simulation of soil behaviour, behavioural relationships of soil and structure, and the excavation process. Literature review in this regard confirmed the relative development of some simulation theories.

A study by Chungsik and Dongyeob[1] on deep excavation because of ground surface movement indicated that the general shape of a ground surface settlement profile is closely related to the source of the wall movement. Also, the unsupported span length has a significant influence on the magnitude and distribution of wall and ground movement characteristics. Maleki and Baei[2] reached the conclusion that the stiffness of the structure will draws the focus on the maximum horizontal displacement in the bottom area of wall excavation. Without considering structural stiffness, the maximum horizontal displacement will occur close to the ground surface. El-Sawwaf and Nazir[3] studied the effect of deep excavation-induced lateral soil movements on the behaviour of supported strip footing. The results indicated that soil reinforcement in granular soil under strip footing adjacent to deep excavation does not significantly decrease. The footing settlement, however, provides greater stability to the footing. Reinforcement is most effective when the footing is placed close to the excavation and the influence of the excavation on the footing behaviour may be neglected once footing is located at a distance of more than three times of footing width from the excavation. Hsieh et al. [4] studied the three-dimensional numerical analysis of deep excavations with cross walls. The study results indicated that the maximum lateral deflection at the position of the cross wall and the midpoint between two cross walls were predicted to have a reduction of 67 to 83% and 12 to 67% respectively compared to the condition where cross walls are absent. Abd El-Raheem[5] indicated that during earthquakes the maximum variation of building horizontal displacement after channel excavation increases by 18 to 24% which is a considerable value. For vertical displacement, an increase would be by 17 to 21% with respect to the model.

A study by Huang et al. [6] on deep excavations indicated that a significant lift of tunnel occurs when the tunnel is underlying the excavation and the influence of the excavation stretches sideward from the end of the excavation would be two times the excavation width. For both the road tunnel and subway tunnel the influence points are 1.5 times the excavation width away from the excavation axis. Castaldo and DeIulii[7]investigated the effects of deep excavation on the seismic vulnerability of existing framed structures. They reached this conclusion that after excavation ductility demand, Park and Ang index values would increase. Zahmatkesh and Choobbasti[8] studied wall deflections and ground surface settlements in deep excavations. The findings of the study indicated that when the depth of excavation was more than 60% wall length, use of support system in order to decrease ground surface settlement and wall deflection is most important. According to a numerical analysis by Dong et al. [9], wall deflection is such that increasing wall depth increases wall deflection and this pattern is adopted by field data. Viswanath et al. [10] showed when the distance between the bottom of excavation and tunnel axis is larger than 1.5D (D: tunnel diameter), the influence of tunnel structure on soil movement is negligible.

According to previous research, deep excavation can cause significant changes in the stress and strain levels of soil environment and also changes in the propagation of seismic waves. This consequently leads to permanent displacements in the foundation system. Therefore, considering the excavation effect on the structural seismic response is most important and effective. Accordingly, this study by emphasizing on RC buildings evaluates this subject.

2. Methodology

2.1. Soil-Structure Modelling

Three RC frames with 5, 10, and 15 storeysare used for structural modelling. The span and height of the frames are 5m and 3m respectively. In the modelling of linear and nonlinear behaviour of controlled members by deflection the lower-band strength and expected strength of material are used respectively. The distance between the buildings and excavation edge is 15m. Excavation characteristics are 15m depth, 15m length, and 10m width. The end of the excavation edge is assumed fixed. Properties of concrete, soil, and rebar have been presented in Table 1. Buildings in three scenarios of before excavation, after excavation, and fixed base foundation areanalysed. Soil-structure interaction effect is considered in the analysis.

The application of dynamic forces causes a dynamic interaction between the structure and soil. In the case of relatively soft soil and stiff structure, this effect would be more effective. When the dynamic forces of propagated waves reach to structure, it is excited because of wave motion in the soil. Owing to the relative motion between the structure and ground, structural displacement affects active soil displacement[11]. All regions in soil-structure interaction analysis are divided into two parts. The first part is named erratic area and includes the structural model and surrounding soil area. In this area soil behaviour is usually assumed to be linear. The second part is named regular area which extends from the first area to the infinity border. Since by getting away from the structure the stress domain is decreased the soil behaviour is assumed linear.

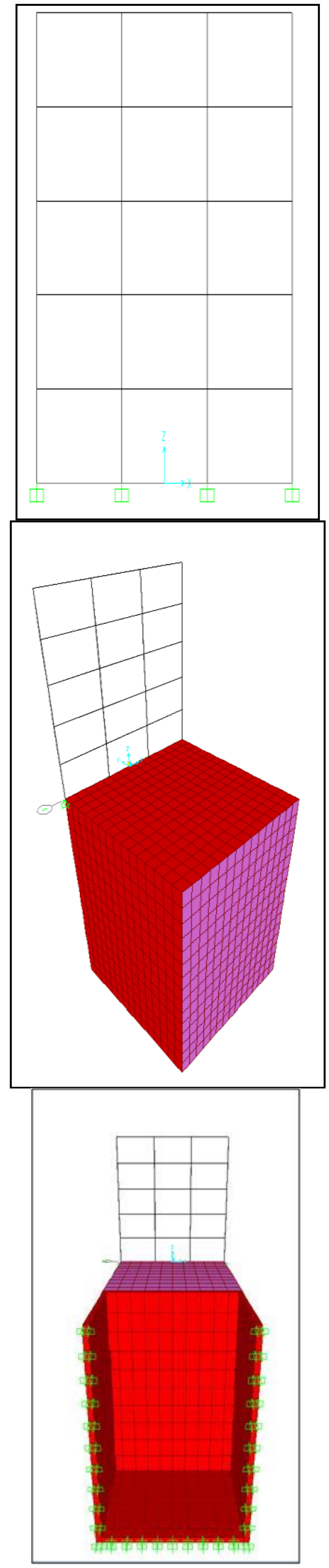

Figure 1. Model of 5-story building before and after excavation and with rigid base (no SSI)

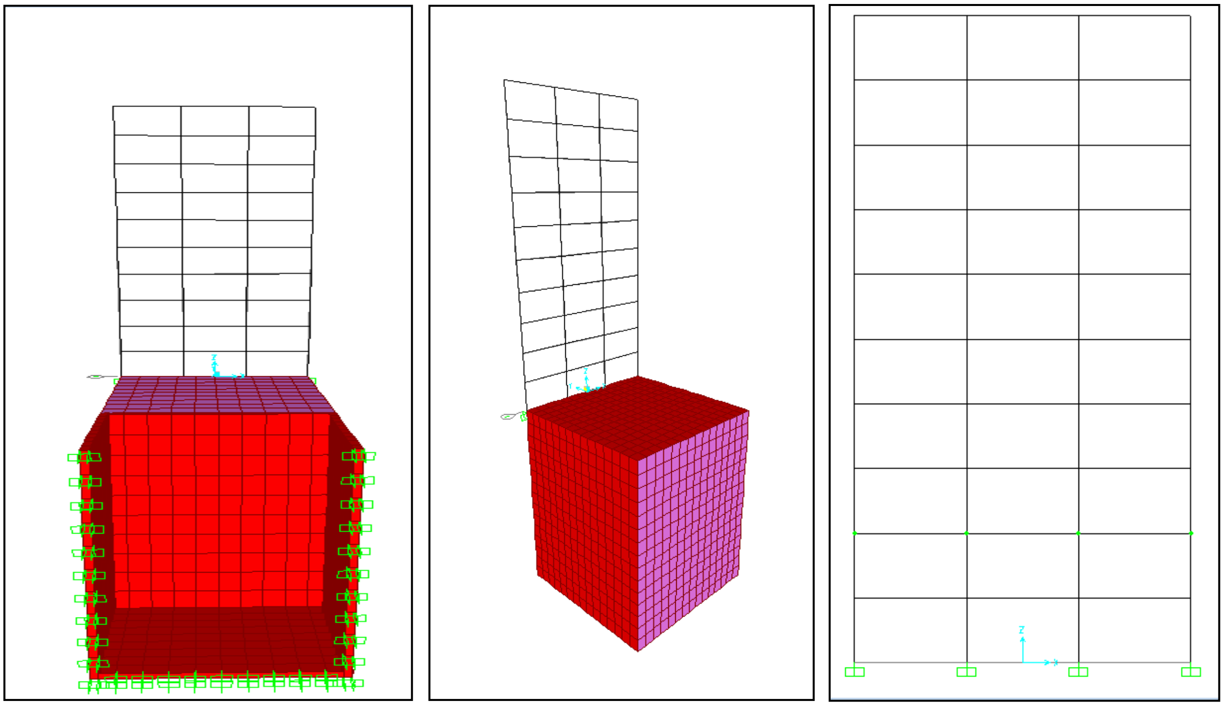

Figure 2. Model of 10-story building before and after excavation and with rigid base (no SSI)

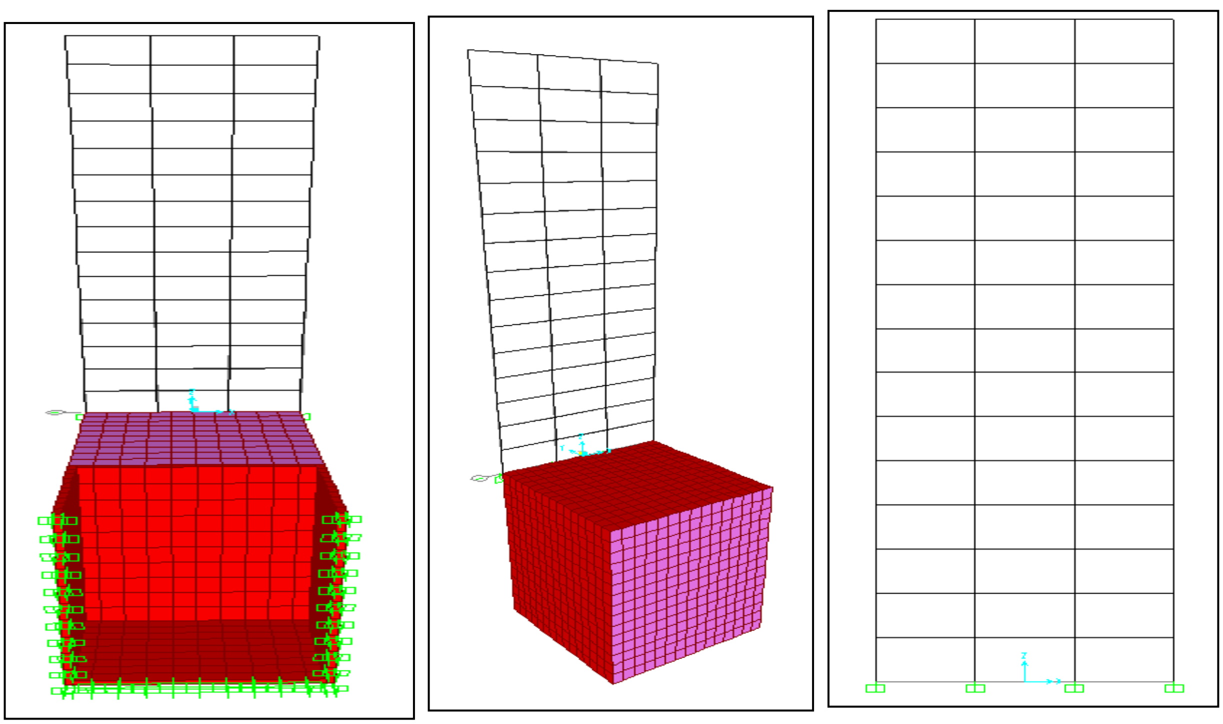

Figure 3. Model of 15-story building before and after excavation and with rigid base (no SSI)

Table 1. Material properties

Characteristics	Soil	Concrete	Steel
Module of elasticity (kg/m^2)	1.64×10^8	2.5×10^9	2×10^{10}
Weight per unit volume (kg/m^3)	1765.8	2500	7850
Poisson's ratio	0.28	0.15	0.3
Shear module (kg/m^2)	64062500	----	----
Strength (kg/cm^2)	----	f'_c =210	f_y =2350 f_u =3700 f_{y_e}=2580 f_{u_e}=4070

Automatic hinges properties are used for plastic hinges in the end of beams (M3) and columns (P-M3). Since the plastic hinges in SAP2000 programme[12]are defined as a lumped model, so the location of plastic hinges is approximated in 0.05L and 0.95L (L: length of beams and columns). The Type and property of plastic hinges are determined based on FEMA 356 [13]. Dead and live load in all storeys were $2000 kg/m$ and $500 kg/m$respectively. A rigid diaphragm based on the Iranian code of practice for seismic resistant design of buildings [14]is assigned to the nodes. By considering the nonlinear behaviour for soil, a four-node solid element is used for excavation modelling.

2.2. Selected Ground Motions

For nonlinear dynamic analysis seven near-fault records of earthquake ground motions are selected, as shown in Table 2. Wavelet analysis method, presented by Baker [15]is used for selecting pulse-like NF ground motions[16]. The moment magnitude of records ranged from 6.5 to 7.4 and all of them are associated with soil type C site classification.

Table 2. Near-fault ground motions used in this study

Earthquake	Year	Station	M_W	R_{rup} (km)	V_{s30} m/s (SP)	PGD (cm)	PGV (cm/s)	PGA (g)
Tabas,Iran	1978	Tabas	7.4	2.1	767 (I)	97	118	0.8
Imperial Valley	1979	EcMelol and	6.5	0.1	186 (III)	40	115	0.4
Loma Prieta	1989	Corralitos	6.9	3.9	462 (II)	14	45	0.5
Northridge	1664	Rinaldi	6.7	6.5	282 (III)	29	167	0.9
Kobe, Japan	1995	Takatori	6.9	1.5	256 (III)	45	170	0.7
Chi Chi, Taiwan	1999	Tcu052	7.6	0.7	579 (II)	215	169	0.4
Duzce,Turkey	1999	Duzce	7.2	6.6	276 (III)	47	62	0.4

WhereM_w is moment magnitude, PGA is peak ground acceleration, PGV is peak ground velocity, PGD is peak ground displacement,R_{rup} is closest distance to co-seismic rapture plane, V_{s30} is average shear-wave velocity of upper 30m of site, and SP is soil profile type according to the reference [14]. For scaling acceleration of earthquake records, the procedure proposed by the Iranian code of practice for seismic resistant design of buildings [14] is used. The mean response spectra for seven acceleration earthquake of records are shown in Figures 4 and 5.

3. Time history analysis and results

In this study, time history analysis has been done using time integration Hilbert-Hughes-Taylor method with α=0, β=0.25, γ=0.5. Dynamic nonlinear analysis includes three scenarios i.e. before excavation by considering soil-structure interaction (SSI), after excavation (EXC), and rigid base without considering soil-structure interaction (FIX). The scaling base of percent values is FIX state.

The maximum decrease and increase in base shear occurs after excavation. The values are 43.8% and 56.7% for 5-storey models. For 10-storey models no increase occurs, but the maximum decrease occurs before-excavation than after-excavation, i.e. 68.4%. In 15-storey buildings, maximum decrease is 17% before-excavation and the highest increase is 35.4% after-excavation. Base shear effective factors include 1) soil environment 2) ductility 3) total weight of the structure 4) fundamental period, and 5) structural stiffness. By considering the effective factors this variation can be explained (Figs 6 to 8).

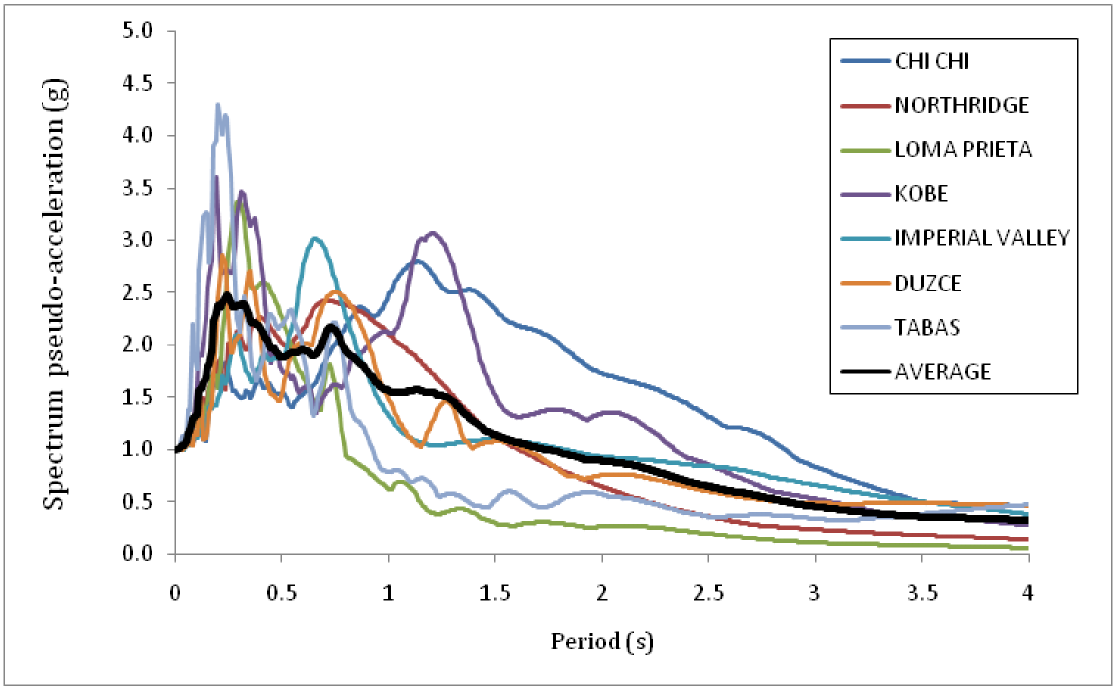

Figure 4. Pseudo-acceleration spectra for selected records for damping ratio = 5%

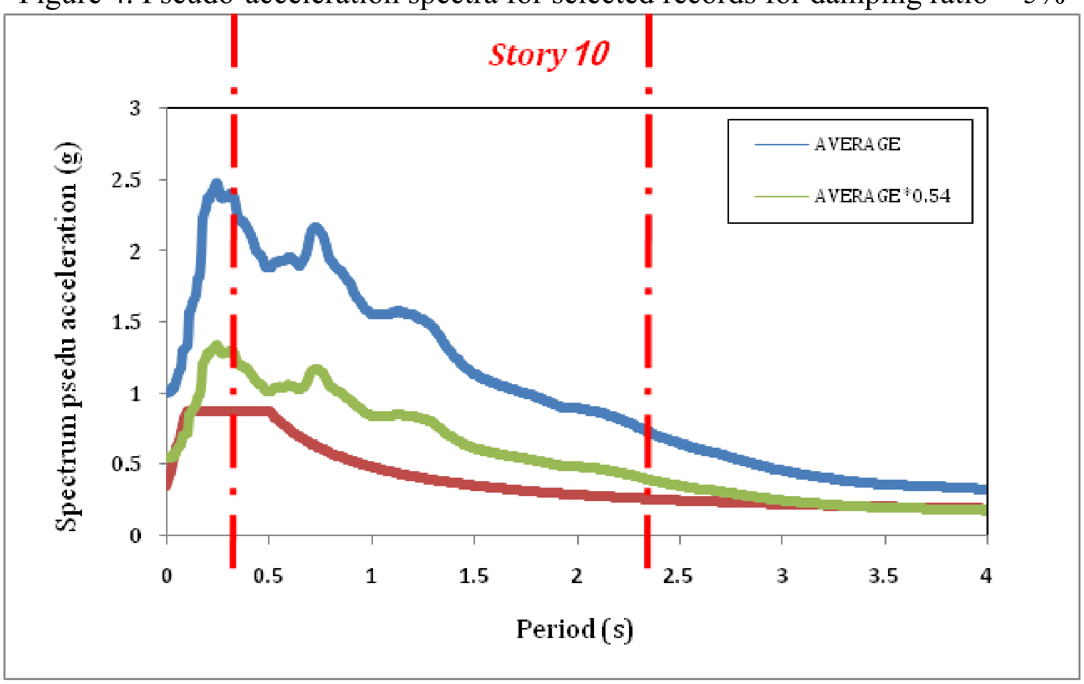

Figure 5. Mean response spectra of 10-story building in the range of 0.2T to 1.5T

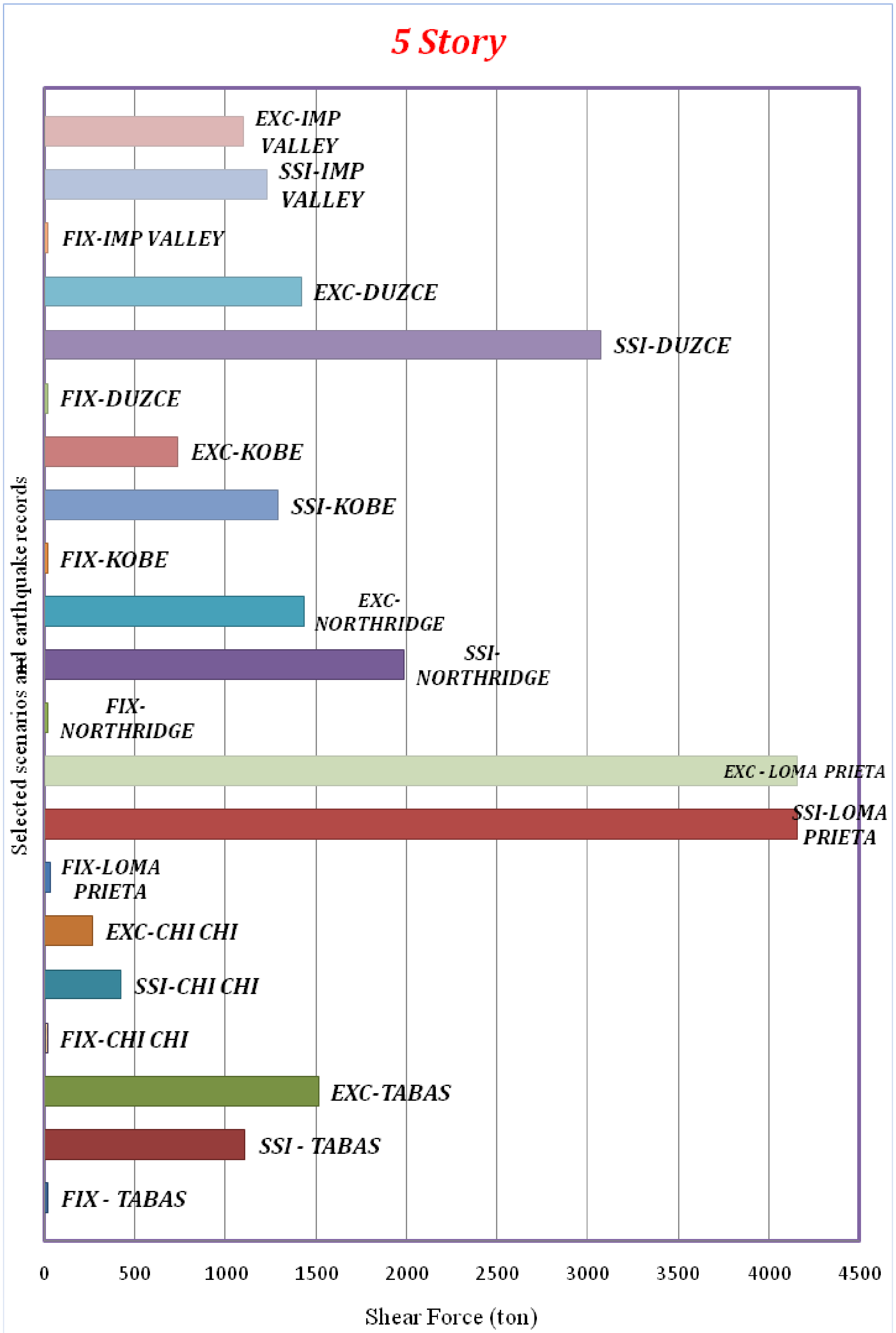

Figure 6. Results of base shear force in 5-story model

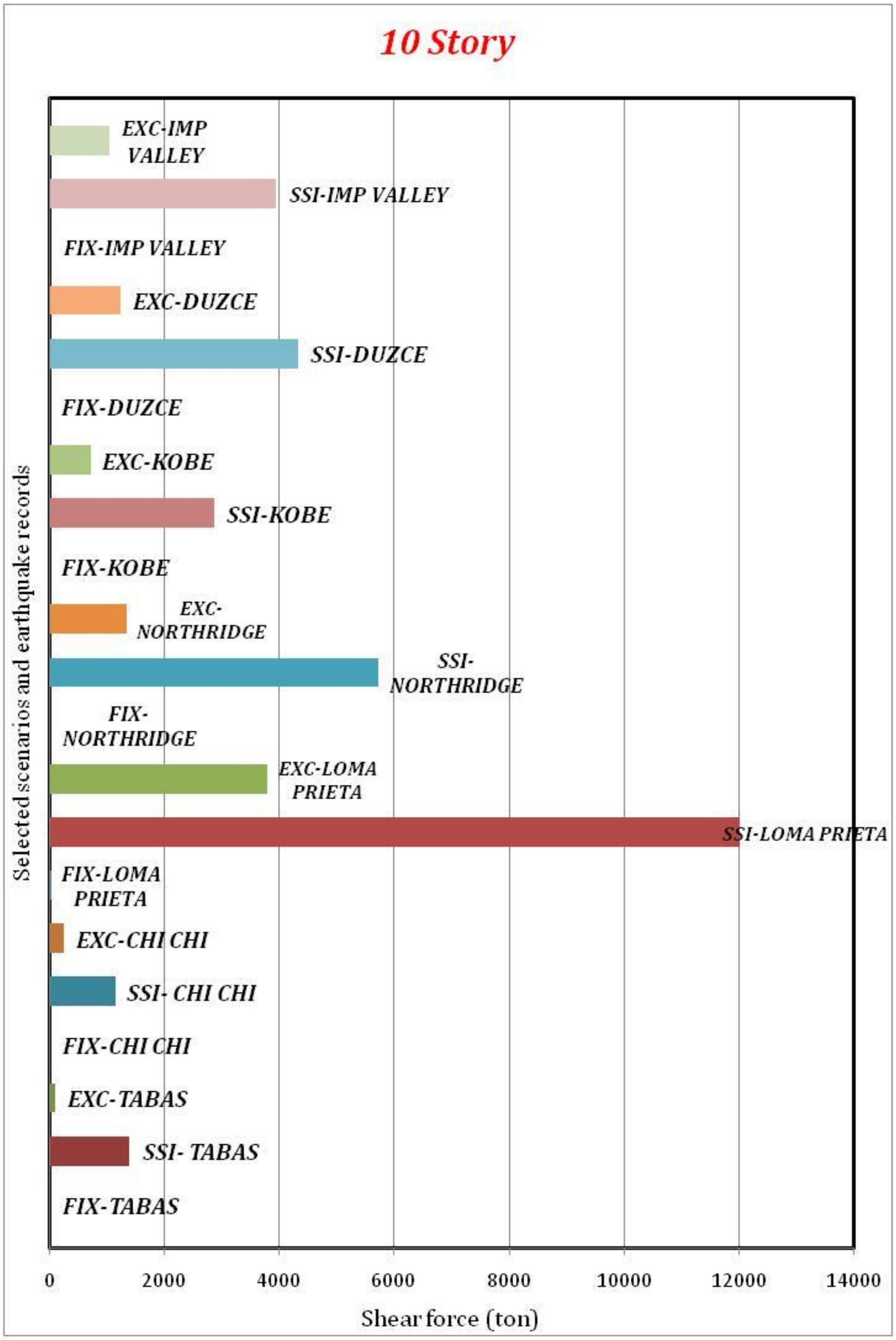

Figure 7. Results of base shear force in 10-story model

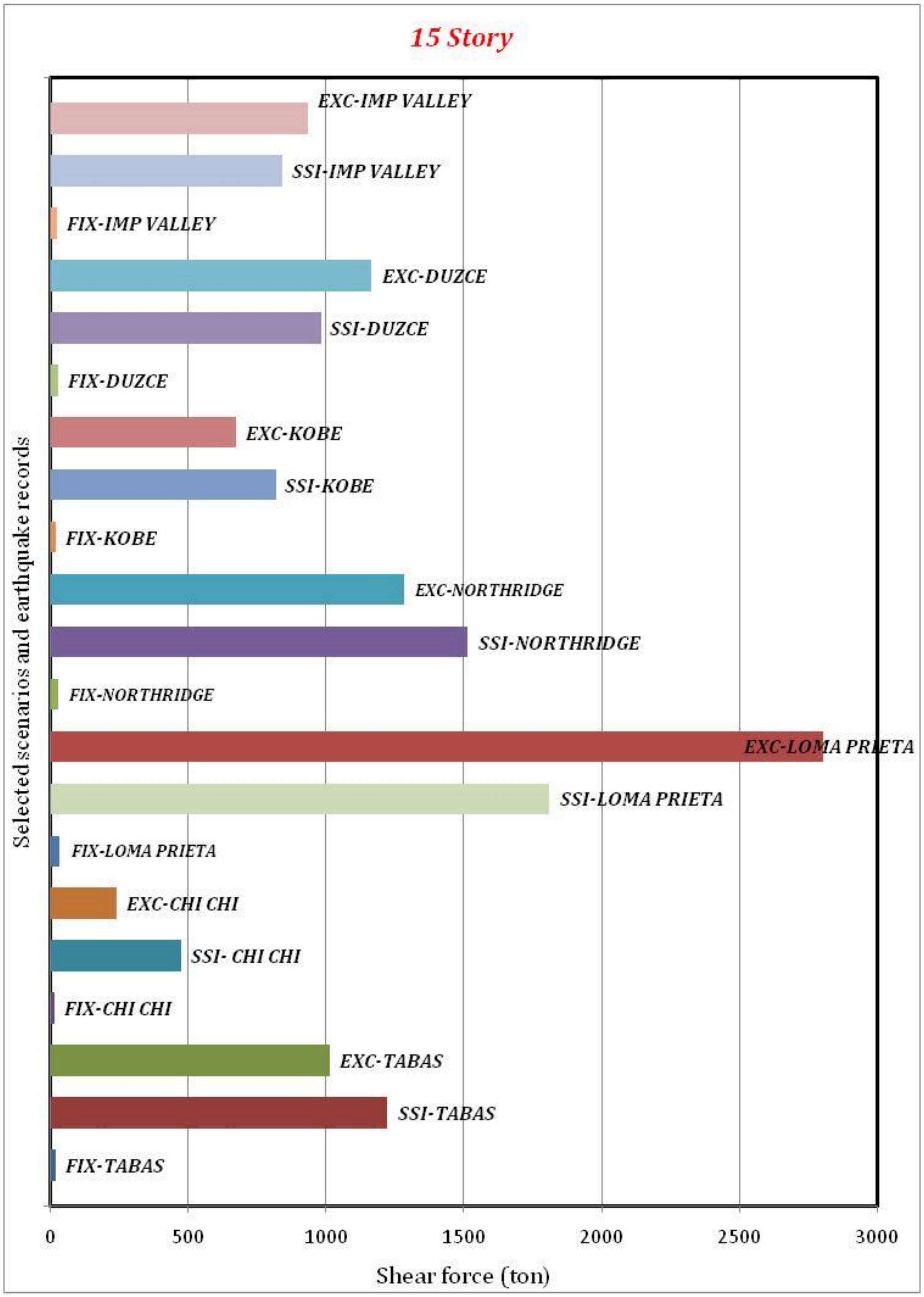

Figure 8. Results of base shear force in 15-story model

The maximum increase and decrease of beams shear force after-excavation than before-excavation in a 15-storey model are 26.11% and15.3% respectively. In this model, the maximum increase and decrease of shear force is related to the middle and end of beams. The beams of the 9th, 10th, and 11th floors have the highest increase and the beams of 15th floor have the highest decrease. The highest increase and decrease in 10-

storey models for after- and before excavation configurations are 3.16% and 18.9% respectively. The highest increase and decrease in before and after excavation configuration are 13.8% and 18.4% for the perimeter beams of 6th floor. The highest shear force decrease in fixed base and after-excavation configurations is related to the perimeter beams of 7th floors. Shear force changes rates in 5-storeymodels for all configurations is insignificant. The effective factors for the increase or decrease of shear force beams are 1) stiffness 2) ductility 3) beams bending strength. When stiffness, ductility, and bending strength increase, beams shear force decrease. These factors cause an increase in beams shear force, while the same factor on 10 floors models are inverse and the excavation is a factor for decreasing of beams shear force. Perimeter beams are always more vulnerable than middle beams.

3.1. Plastic hinges

In 15-story models, plastic hinges formation are more critical in after-excavation condition than before-excavation and fixed base configurations. The number of plastic hinges in the levels of B, IO, LS, C, E are respectively 366, 220, 20, 34in before-excavation status, 382, 207, 11, 34 in fixed base and 309, 170, 56, 83, 1 in after-excavation condition. In before- and after-excavation configuration the number of B, IO, LS, C, E points decrease by 15%, 25% and increase by 175%, 150%, and 100%, respectively.

In fixed base and after-excavation status, number of plastic hinges decreases by 20%, and 18% and increases by 400%, 150%, 100%. In 10-storey models plastic hinges formation are the same. The number of plastic hinges in the levels of B, IO, LS, C in before-excavation configuration are 189, 200, 8, 7, in fixed base configuration are 215, 196, 8, 8 and for after-excavation condition are 275, 151, 12, 11. In before and after excavation the number of B, IO, LS, C points respectively increase 45%, decrease 25%, 100%, 100%. In fixed base and after-excavation configuration the above amount increase 25% and decrease 25%, 100%, 100%. Plastic hinges formation in all5-story models isthe same and changing is negligible. The number of plastic hinges in the levels of B and IO in before-excavation configuration are 142, 94, fixed base are 141, 66 and after-excavation are 177, 96. In before and after excavation configuration, number of B, IO increase 20% and unchanged, in fixed base configuration increase 20% and 45% (Figs 9 to 11).

By difining a dimensionless parameter that the ratio of the maximum drift occur in the mensioned level to total height, it is determined that the results of 5-story models in before- and after excavation and fixed base configurations are unchanged. In 10-story models, there is no changing in the results but under the two earthquake records in after-excavation than before-excavation configuration,the maximum drift increase 30% and maximum changing in 4th floor occur and in fixed base and after-excavation configuration no change happened. The maximum drift of 15 story models in after-excavation configuration than before-excavation and fixed base configuration isshowed an increase of 70%. The highest changing occurs in the 6th floor and the changing increas by height reduction.

For investigating the maximum base shear effect, a dimensionless parameter is defined whichis the ratio of the maximum shear force occur in that height to total height[17]. According to the results in all configuration of 5 story models in first,second, and third span, no changing occur. On 10 story models in post-excavation than pre-excavation configuration in first span, maximum shear force decrease 41%, there is no changes in second span and in thirth span increase 62%. The shear force of first span in post-excavtion than fixed base configuration decrease 35%,second span is unchanged and third span decrease 33%. The change rates in 15 story models in post-excavation than pre-excavationincreased in the first span by 90%, in the second span by 200% and in the third span by 26%. In post-excavation than fixed base configuration the first span decreased by 5%, second span increased by 38% and third span decreased by 28%.

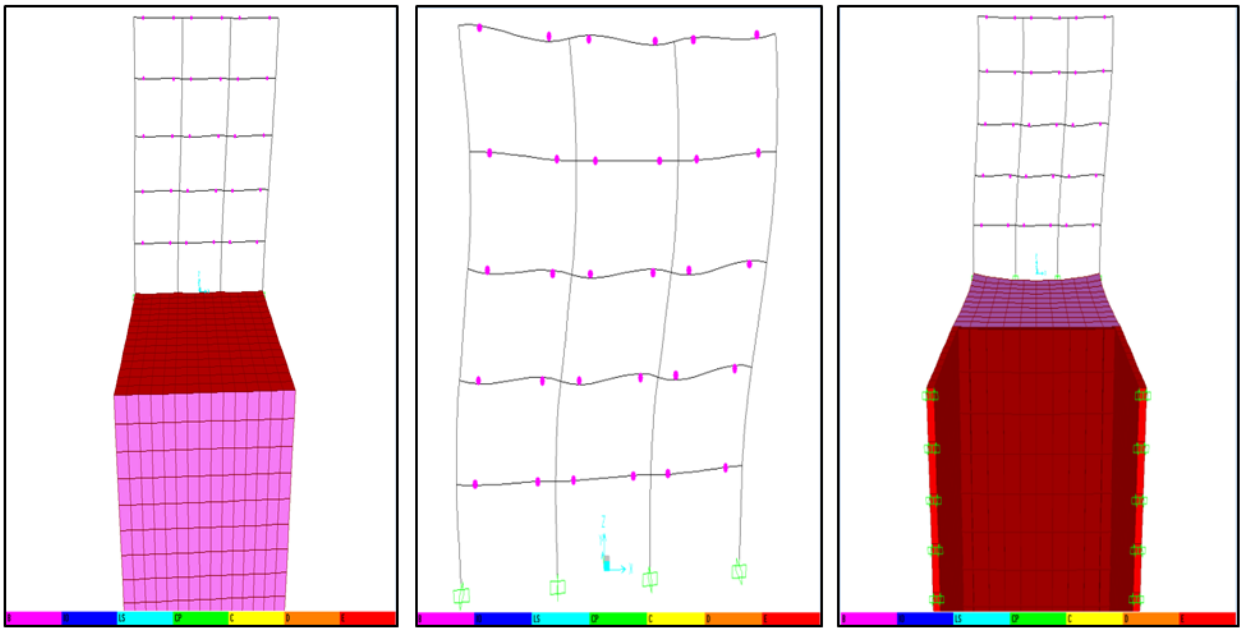

Figure9- Pattern of plastic hinges formation of 5-story models in three scenarios

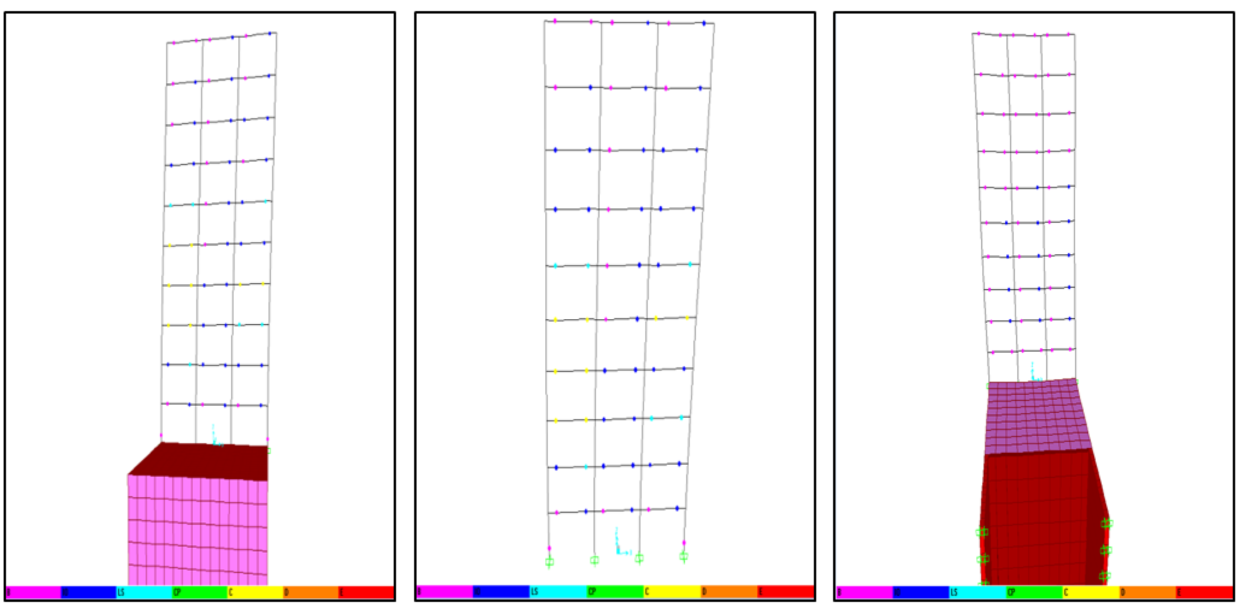

Figure10- Pattern of plastic hinges formation of 10-story models in three scenarios

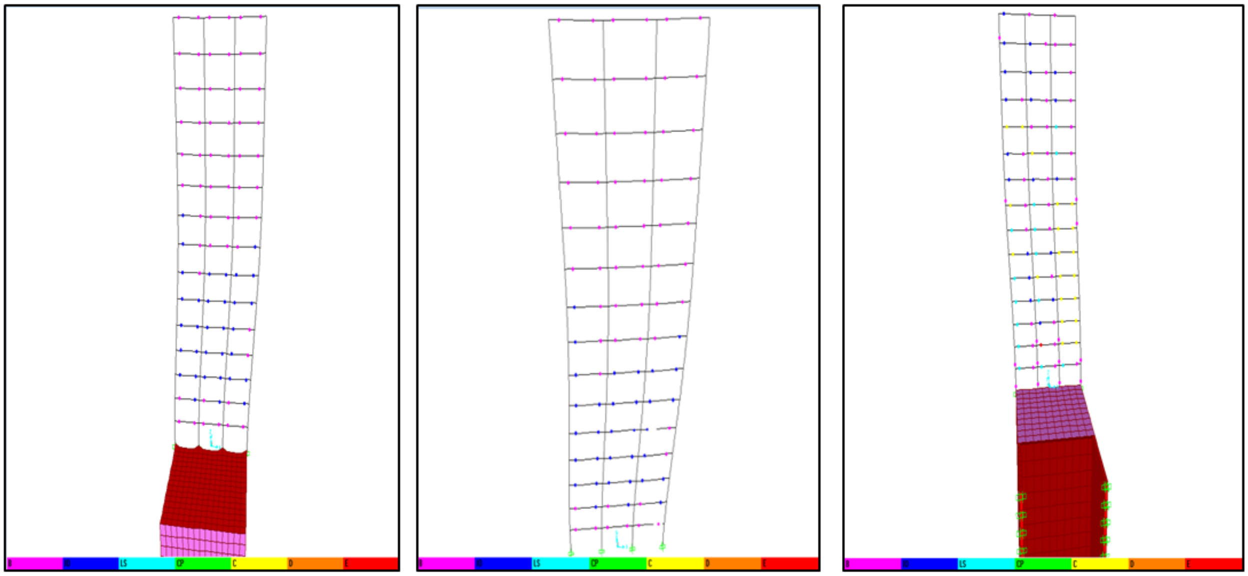

Figure11- Pattern of plastic hinges formation of 15-story models in three scenarios

In 5 and 10 story models, positive and negative maximum relative acceleration in three configurations are unchanged. The positive maximum relative acceleration in 15 story models in post-excavation than pre-excavation configuration increased by 30% and negative relative acceleration increased 85% (Figs 12 to 14). In post-excavation than fixed base configuration, the positive relative acceleration decreased by 10% and negative relative acceleration increased by 85%. The highest changing in 15 story model is related to 4^{th} and 15th floors, although in 5 and 10 story models did not happen changes except4^{th} and 10^{th} story in 10 story models and 5th story in 5 story models has greatest effect.

4. Conclusions

In this study, deep excavation effect on seismic response of reinforcement concrete buildings have been studied. It can be concluded that by considering soil type and excavation characteristics, excavation has the most effect on high-rise buildings than low-rise buildings.

1) The highest increase on base shear was 35.4% which was related to 15 story models.

2) The highest increase of period of 66% was related to 5 story models. The lowest increase was related to 15 story models. Low-rise buildings compared to high-rise buildings in after-excavation configuration had more period increase.

3) Storey acceleration was increased in after-excavation state rather than before-excavation and fixed base configuration.

4) Storey drifts in after-excavation configuration rather than before-excavation and fixed base configuration increase. The increase in 15 story models was more than 10- and 5-story models.

5) The maximum increase in columns axial force and beams shear force in after-excavation configuration of 15 story models was respectively 25.2% and 26.11%.

6) Plastic hinges formation in 15 story models in after-excavation was more than before-excavation and fixed base configuration, so that the structure has more tends to nonlinear behaviour and collapse mechanism.

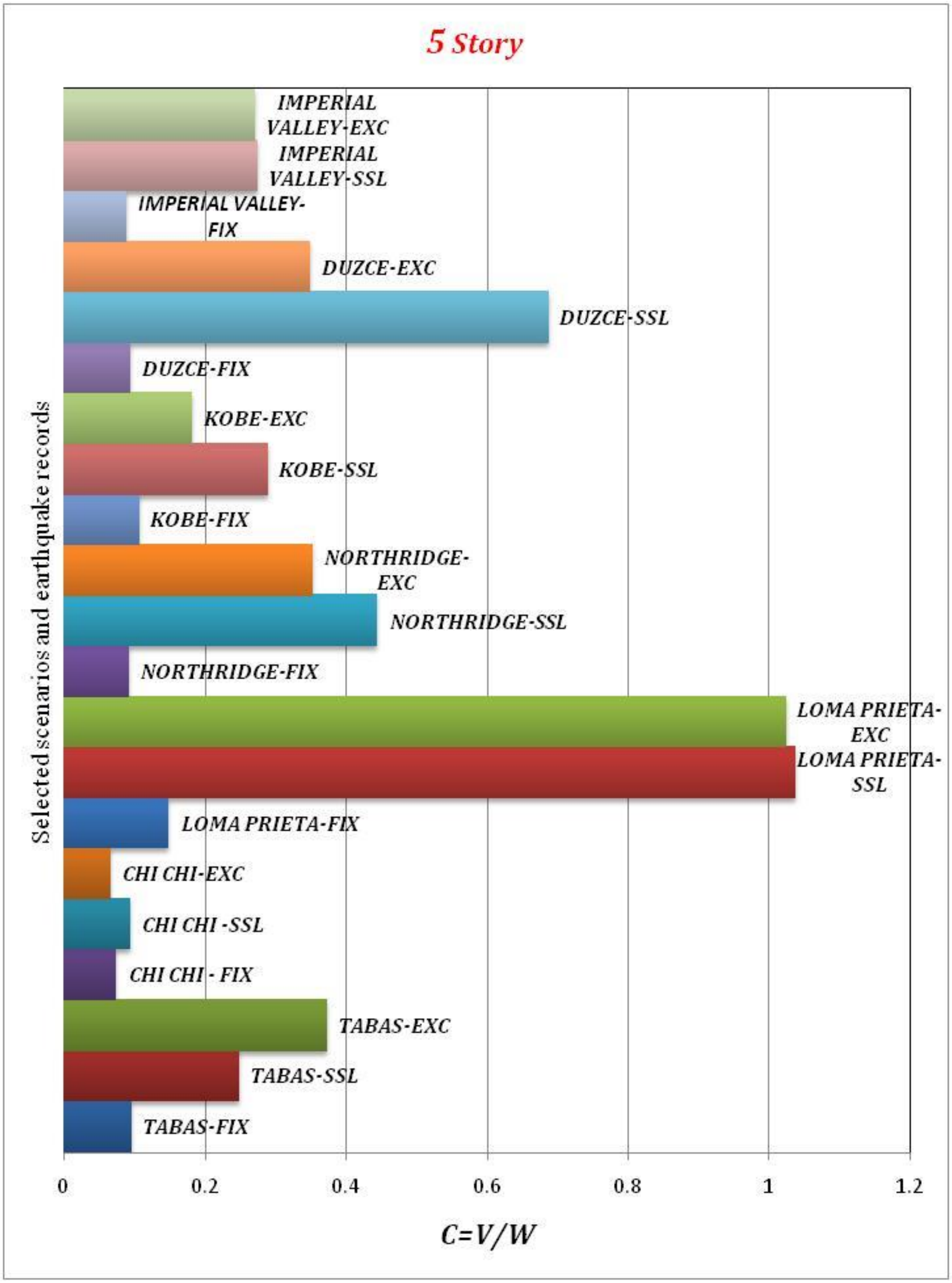

Figure12- Base shear coefficients of 5-story models

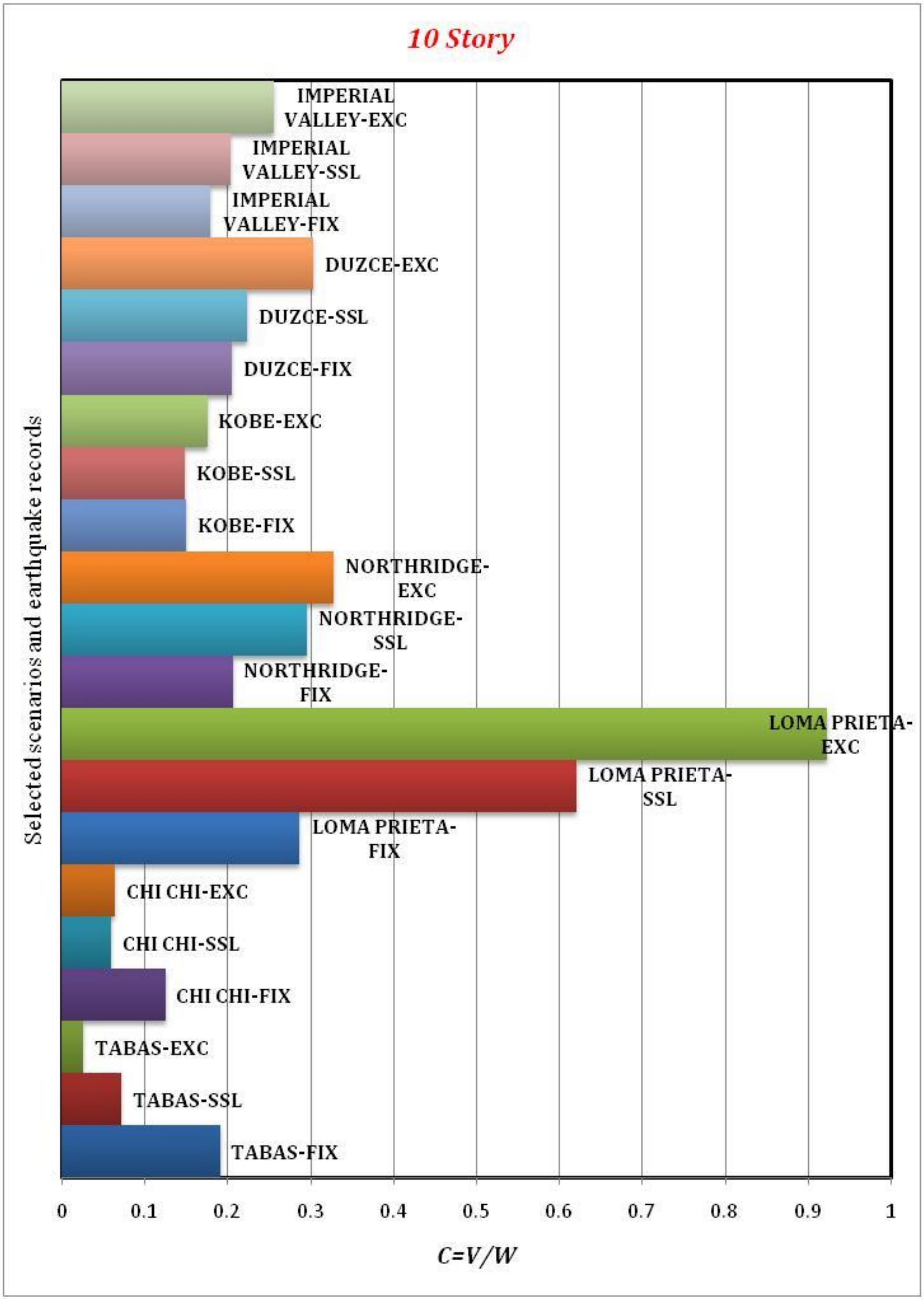

Figure13-Base shear coefficients of10-story models

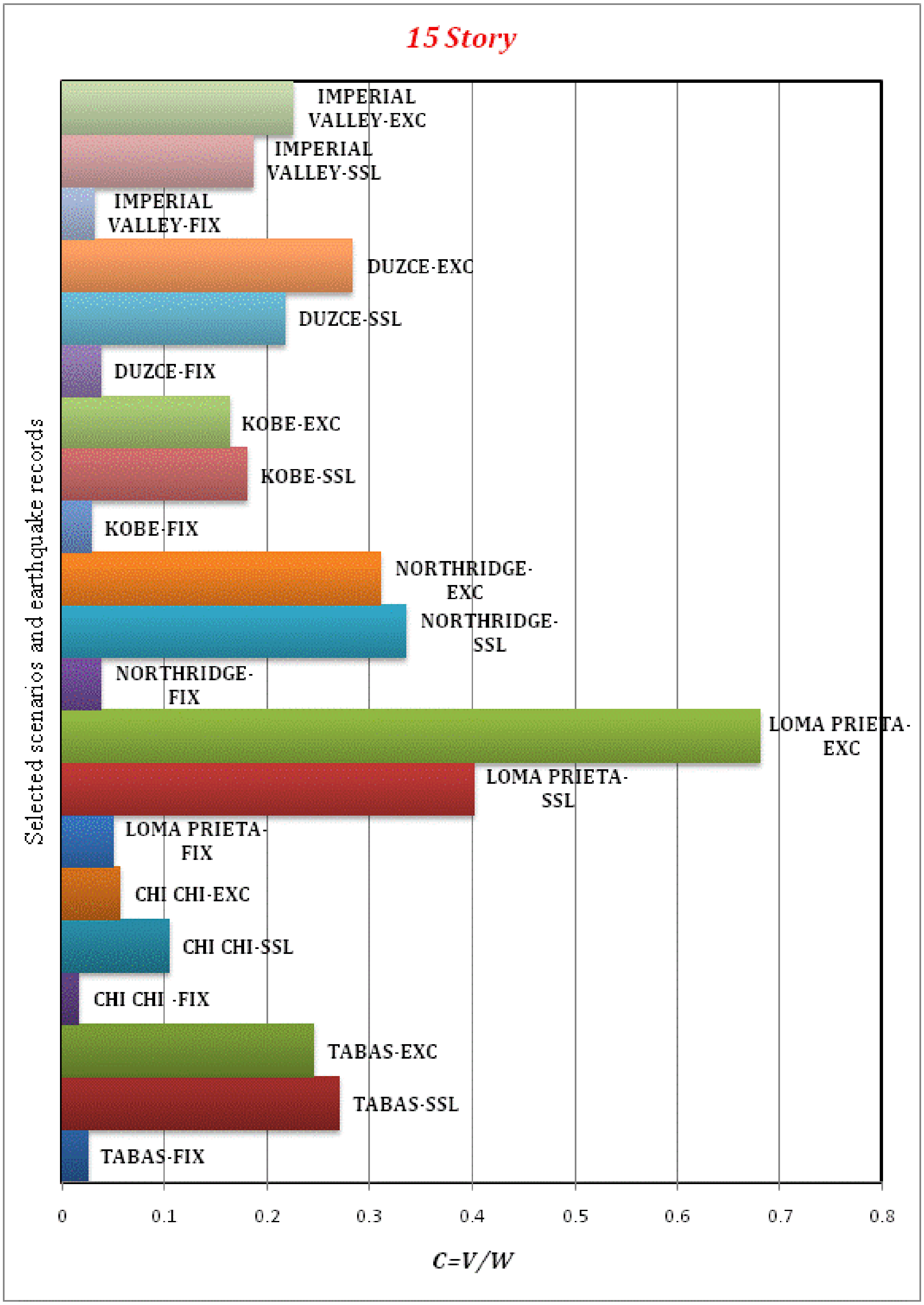

Figure14- Base shear coefficients of15-story models

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