NON-LINEAR STATIC ANALYSIS OF MULTISTOREY RC BUILDINGS CONSIDERING SOIL STRUCTURE INTERACTION

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ABSTRACT

Commonly designers consider the building to be fixed at their bases. Although structures are supported on soils, most of the designers do not consider the effect of soil structure interaction during earthquake. When a structure is subjected to an earthquake excitation, it interacts with the foundation and soil, and thus changes the motion of the ground. The supporting soil medium allows shaking of the whole ground. Structural system is influenced by the type of soil as well as the type of structure. The effect of soil structure interaction should be considered in the buildings which are located in the earthquake prone areas. The prime importance in this paper is to understand the behaviour of RC 2D frames subjected to seismic forces for varying soil conditions given in the code IS 1893 (Part 1): 2002. The investigation is carried out on G+9 storey buildings supported on hard and soft soil located in seismic zone III. Performance based seismic evaluation is carried out by non linear static pushover analysis as per the guidelines specified in FEMA 440. User-defined nonlinear hinge properties are assigned for beams and columns based on the moment-curvature relationships. Natural period, base shear, lateral displacement, storey drift, ductility ratio, safety ratio, global stiffness, and hinge status at performance point results are obtained and compared among the models. The investigation concludes that as the stiffness of soil decreases the base shear and global stiffness decreases. Natural period, lateral displacement, and storey drift increases. Safety ratio varies inversely with the stiffness of soil. Most of flexural hinges are found within the life safety range at the ultimate state.

Keywords: Soil Structure Interaction, Pushover Analysis, User Defined Hinge, Performance Levels, Ductility Ratio, Safety Ratio, Global Stiffness

I. INTRODUCTION

Majority of the existing reinforced concrete structures do not meet the current seismic requirements as they are primarily designed for gravity loads only. However, the behaviour of the buildings during the earthquake depends on type of soil on which it is supported, stiffness of infill etc. Earthquake causes the random motions in all directions, radiating from the epicentre. These ground motions cause structure to vibrate and induces inertia forces in them. Building supported on stiff soil can resist certain amount of lateral forces due to earthquake while the same building may not be able to resist the minor earthquake supported on soft soil. For the structure to perform better during the earthquakes, it must be analyzed and designed as per the Indian seismic code IS 1893 (Part 1): 2002 [1].

Several studies have been made on the effect of soil-structure interaction problems to obtain more realistic analysis. They have quantified the effect of interaction behaviour and established that there is redistribution of forces in the structure and soil mass. Hence, structures and their supporting soil should be considered as a single compatible unit. The interaction effects are found quite significant, particularly for the structures resting on highly compressible soils. The flexibility of soil mass causes the differential settlement and rotation of footings under the application of load. The relative stiffness of structure, foundation, and soil influence the interaction behaviour of structure-foundation-soil system.

II. DESCRIPTION OF STRUCTURES

2D frames building models with G+9 storeyed are considered in the present paper. These consist of beam–column RC frame buildings, located in seismic zone III and intended for office use. The bottom storey height is 4.8 m and upper storeys height is taken as 3.6 m for all buildings [2]. The buildings are kept symmetric to avoid torsional response under pure lateral forces.

In the seismic weight calculations, only 25% of the live load is considered [1]. The building is modeled to represent all existing components that influence the mass, strength, stiffness, and deformability of the structure. Slabs loads are applied on the beam. Masonry brick are modeled by considering equivalent diagonal strut. The material properties and thickness of struts are same as that of masonry wall and the effective width of strut is calculated as proposed by Smith and Hendry [3], M (moment), PM (axial force and moment), V (Shear) and P (axial force) user defined hinge properties as per FEMA 356 [4] are assigned at rigid ends of beam, column, and strut elements respectively. The models considered for the study are building supported on (i) hard soil and has no walls in the first storey and unreinforced brick masonry wall in the upper storeys and building is modeled as bare frame. However the masses of walls are included. (ii) soft soil and has no walls in the first storey and unreinforced brick masonry wall in the upper storeys and building is modeled as bare frame. However the masses of walls are included. (iii) hard soil and has no walls in the first storey and unreinforced brick masonry wall in the upper storeys. However stiffness and mass of walls are included and building is modeled as soft storey. (iv) Soft soil and has no walls in the first storey and unreinforced brick masonry wall in the upper storeys. However stiffness and mass of walls are included and building is modeled as soft storey. The material and soil properties considered in the present paper are specified in Table 1 and 2 respectively. The plan and elevation of the buildings considered are shown in Fig 1 and 2.

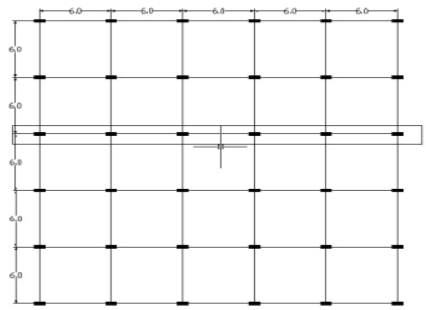

Fig 1. Plan of the building

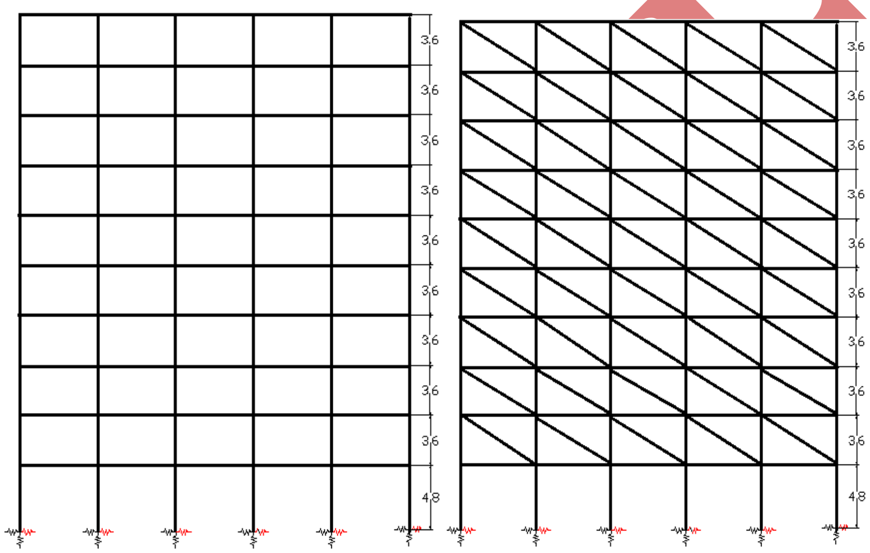

Fig 2. Elevation of ten storeyed brick infill and bare frame buildings with spring supports

Table 1. Material considered in the study [5]

Material Properties	Values
Grade of concrete, F_{ck}	25 Mpa
Grade of steel, F_y	415 Mpa
Modulus of Elasticity of brick wall	3285.9 Mpa
Modulus of Elasticity of steel, E_s	20,0000 Mpa

Table 2. Soil properties [2]

Type of soil	S.B.C of soil (kN/m^2)	Young's modulus (kN/m^2)	Poisson's ratio	Shear modulus (kN/m^2)
Soft	120	15000	0.45	5172.41
Hard	250	200000	0.45	68965.51

III. METHODOLOGY

The majority of the existing RC multistorey buildings in our country are still under threat, because buildings are not designed as per seismic codes, wrong construction practice and lack of knowledge for earthquake resistant design. It is very uneconomical to demolish and reconstruct them as per code provisions. It is a wiser to retrofit and strengthen them after evaluating their strength and performance. Therefore, it is necessary to use non linear analysis to evaluate the performance of existing buildings. Non linear static pushover analysis is carried out with user defined hinges.

3.1 User Defined Hinges

Moment-curvature relationships are predicted in order to define the user-defined plastic hinge properties. The moment curvature relationships are developed as per IS: 456 – 2000[6]. The definition of user-defined hinge properties requires moment–curvature analysis of each element. For the problem defined, building deformation is assumed to take place only due to moment under the action of laterally applied earthquake loads. Thus user-defined M3 hinges were assigned at rigid ends where flexural yielding is assumed to occur. Moment-curvature relationships are developed for beams, columns in SAP2000 to represent the flexural characteristics of plastic hinges at the ends.

3.2. Pushover Analysis

Pushover analysis is a static non-linear procedure in which the magnitude of the lateral load is incrementally increased maintaining a predefined distribution pattern along the height of the building. With the increase in the magnitude of loads, weak links and failure modes of the building can be found. Pushover analysis can determine the behaviour of a building, including the ultimate load and the maximum inelastic deflection. At each step, the base shear and the roof displacement can be plotted to generate the pushover curve for the structure. Pushover analysis as per FEMA 440 [7] guide lines is adopted. The models are pushed in a monotonically increasing order in a particular direction till the collapse of the structure. 4% of height of building [8] as maximum displacement is taken at roof level and the same is defined in to several steps. The global response of structure at each displacement level is obtained in terms of the base shear, which is presented by pushover curve. The peak of this curve represents the maximum base shear i.e., maximum load carrying capacity of the structure. The initial stiffness of the structure is obtained from the tangent at pushover curve at the load level of 10% that of the ultimate load and the maximum roof displacement of the structure is taken that deflection beyond which the collapse of structure takes place [4].

IV. RESULTS AND DISCUSSIONS

4.1 Fundamental Natural Period

4.1.1 Effect Of Soil Structure Interaction

The change in natural periods due to the effect of soil flexibility with respect to various parameters such as types of soil ranging from hard and soft are compared. The comparison is made between ten storey bare and soft storey building models supported on hard and soft soils. The natural periods obtained for various building models by IS: 1893 (Part 1) - 2002 [1] code and analytical (SAP2000) are specified in Table 3.

Table 3. Fundamental natural period for ten storeyed building models

Type of soil	Bare frame		Soft Storey	
	Codal	Analytical	Codal	Analytical
Hard	1.36	2.21	1.13	0.98
Soft	1.36	2.61	1.13	1.49

It is observed that the fundamental natural period for ten storey bare frame structure is longer by 15.32% as compared to codal values. Similarly an increment of 34.22% is found for the soft storey models. As the soil changes from hard to soft, natural periods are longer as a result of decrease in the stiffness of soil.

4.2. Base Shear

In the response spectrum method the design base shear (V_b) is scaled to the base shear obtained from equivalent static method $\overline{V_b}$ as per IS 1893 (Part 1): 2002 shown in Table 4 and 5. From the storey shear results it is observed that there is underestimation of storey shear in bare frame as compared to the soft storey. This is because of higher natural time period and stiffness of infill wall being considered in the soft storey building models.

Table 4. Base shear and scaling factor for soft storey building models

Type of soil	$\overline{V_b}$ in kN	V_b in kN	Scale factor
Hard	563.61	280.79	2.007
Soft	507.53	232.27	2.19

Table 5. Base shear and scaling factor for bare frame building models

Type of soil	$\overline{V_b}$ in kN	V_b in kN	Scale factor
Hard	359.78	245.51	1.47
Soft	336.10	165.27	2.03

The base shear increases with increase in mass and stiffness of the soil. As the soil property changes from hard to soft the base shear decreases due to decrease in the stiffness of soil. For building models on hard soil with bare frame, there is decrement in the base shear values by 36.17%, and 33.78 % as compared to the brick infill frame building models on soft soil by equivalent static method. Similarly 12.67% and 28.85% increment in base shear for hard and soft soil are observed by response spectrum method. The scale factor is found in the range 1.47 to 2.19.

4.3 Lateral Displacements

4.3.1 Effect of soil structure interaction

The profile of lateral displacements along longitudinal direction for equivalent static and response spectrum method are shown in Fig 3.

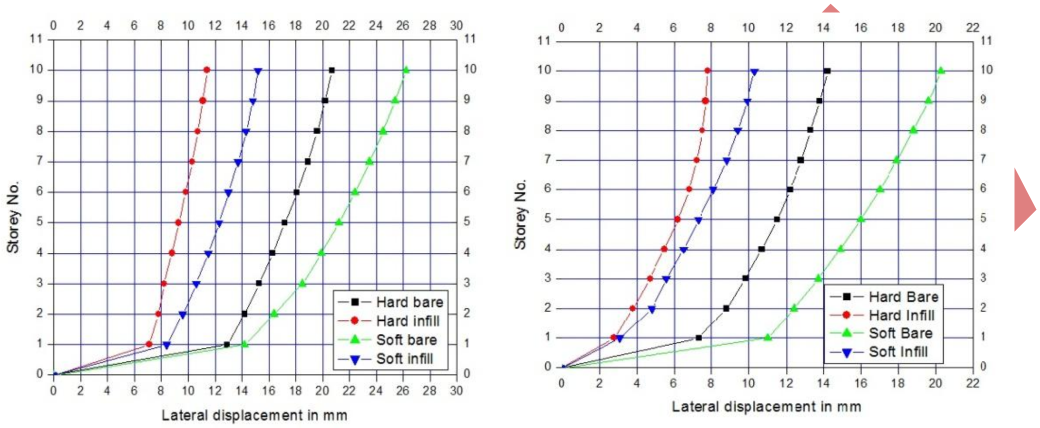

Fig 3. Lateral displacement in the longitudinal direction by ESM and RSM

The lateral displacement of a building is a function of the stiffness, thus lateral displacement of the building decreases with the increase in the lateral stiffness. Therefore, the displacement of the building models of soft storey on hard soil is lesser than the bare frame on soft soil. There is reduction in the lateral displacement by 21% and 25% for bare and soft storey building models on hard soil when compared to the models supported on soft soil by ESM respectively. Similarly 30.04% and 24.27% of decrement in lateral displacement are observed by the RSM.

4.4 Storey Drift

The profiles of storey drift for buildings along longitudinal direction by equivalent static and response spectrum method are shown in Fig 4.

The storey drift of a building is a function of the stiffness. Therefore, storey drift of the building decreases with the increase in the lateral stiffness. Thus, the storey drift of the building models of bare and soft storey on hard soil is lesser than that of the building models on soft soil. For soft and bare frame building models on hard soil there is reduction in the storey drift by 37.5% and 25% when compared to the bare and soft storey models supported on soft soil by equivalent static method. Similarly 42.85% and 75% of decrement in storey drift are observed by the response spectrum method.

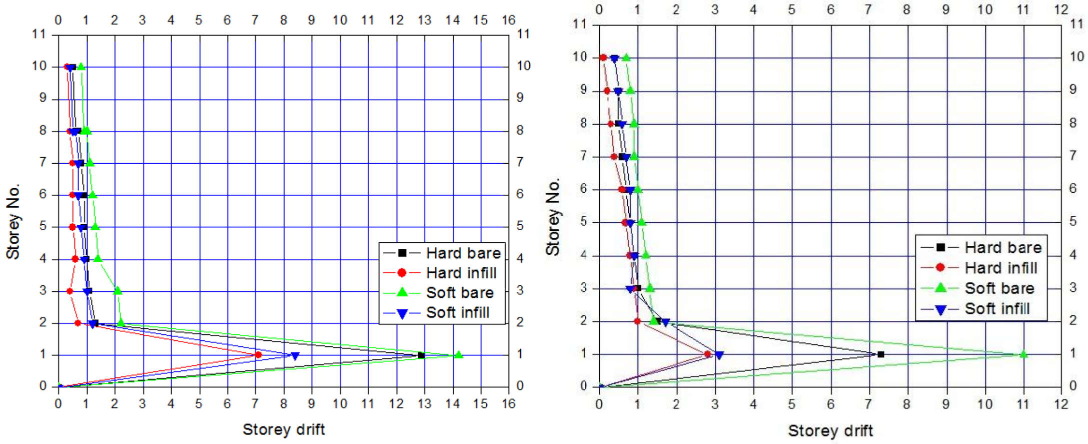

Fig 4. Storey drifts in the longitudinal direction by ESM and RSM

4.5 Performance Evaluation of Building Models

Performance based seismic evaluation of building models are carried out by non linear static pushover analysis (i.e. Equivalent static pushover analysis and Response spectrum pushover analysis). User defined hinges are assigned for building models along the longitudinal direction.

4.5.1 Performance point and location of hinges

The base force, displacement, and the location of the hinges at the performance point, for various performance levels along longitudinal direction for all building models are presented in the Table 6 to 9. In most of the buildings, flexural plastic hinges are formed in the first storey because of open ground storey. The plastic hinges are formed in the beams and columns.

Table 6. Performance point and location of hinges for bare frame building along longitudinal direction by ESM

Type of soil	No of stoteys	Performance point		Location of hinges								
		Base shear (kN)	Displacement (mm)	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E	TOTAL
Hard	Yield	993.23	83.11	274	32	18	10	1	1	1	1	320
	Ultimate	1106.51	93.96	244	40	26	14	6	8	8	0	320
Soft	Yield	550.54	89.69	286	30	6	2	1	1	0	0	320
	Ultimate	704.67	106.48	258	24	14	12	8	8	10	0	320

Table 7. Performance point and location of hinges for soft storey building along longitudinal direction by ESM

Type of soil	No of stoteys	Performance point		Location of hinges								
		Base shear (kN)	Displacement (mm)	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E	TOTAL
Hard	Yield	1849.27	122.03	374	24	8	2	1	1	0	0	410
	Ultimate	2030.38	131.44	352	20	14	8	4	8	4	0	410
Soft	Yield	1240.79	126.88	381	18	4	2	2	1	2	0	410
	Ultimate	1690.31	137.36	366	14	10	2	6	8	4	0	410

Table 8. Performance point and location of hinges for bare frame building along longitudinal direction by RSM

Type of soil	No of stoteys	Performance point		Location of hinges								
		Base shear (kN)	Displacement (mm)	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E	TOTAL
Hard	Yield	1023.48	81.61	276	26	14	2	1	1	0	0	320
	Ultimate	1141.76	90.95	264	21	12	10	4	5	4	0	320
Soft	Yield	581.29	88.19	286	22	6	2	2	1	1	0	320
	Ultimate	740.42	100.39	271	11	12	10	6	7	3	0	320

Table 9. Performance point and location of hinges for soft storey frame building along longitudinal direction by RSM

Type of soil	No of stoteys	Performance point		Location of hinges								
		Base shear (kN)	Displacement (mm)	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E	TOTAL
Hard	Yield	1879.423	120.38	380	24	2	1	2	1	0	0	410
	Ultimate	2065.532	128.18	366	8	10	10	4	6	6	0	410
Soft	Yield	1271.249	125.23	390	8	3	6	1	1	1	0	410
	Ultimate	1725.769	134.11	380	8	2	0	8	4	8	0	410

It is seen in Tables 6 to 9 that there is an increment in base force at the ultimate state for both bare and soft storey frames. The percentage increase in base shear for the bare and soft storey building models on hard soil is found 45.50% and 58.31% when compared to the building models on soft soil by equivalent static pushover analysis method. Similarly there is increment of 44.72% and 57.09% for the hard and soft soil by response spectrum pushover analysis method.

It is further observed that, The hinges are formed within the life safety range at the ultimate state is 93.125% and 91.875% for bare frame building models on hard and soft soil respectively. 96.08% and 95.13% for infill frame building models on hard and soft soils by equivalent static pushover analysis method. Similarly 95.89% and 95%, for bare frame and 96.1% and 95.13% for infill frames by response spectrum pushover analysis method. The hinges are formed beyond the CP range at the ultimate state is 6.875% and 8.125% for bare frame building models on hard and soft soil respectively. 3.92% and 4.87% for infill frame building models on hard and soft soils by equivalent static pushover analysis method. Similarly 4.11% and 5%, for bare frame and 3.9% and 4.87% for infill frames by response spectrum pushover analysis method.

From the above discussions it can be concluded that as the soil property changes from hard to soft, the yield and ultimate base shear decreases, this is due to the reduction in the stiffness of soil. The performances of the bare frame and soft storey building supported on hard and soft soil are within the life safety at the ultimate state for both equivalent and response spectrum pushover method. Few collapse hinges are formed in bottom storey columns of soft storey models and the may be same are retrofitted to enhance the performance of buildings.

4.6 Ductility Ratio (DR)

The ability of the structure or its component, or the material used to offer resistance in the inelastic domain of response is described by the term ductility. This is important for an earthquake resisting system because if the structure is incapable of behaving in ductile fashion then it should be designed for higher seismic forces. The ductility ratio (DR) values are given in Table 10 and 11

Ductility factor μ is the ratio of total imposed displacement Δ at any instant to that at the onset of yields Δ_y i.e. $\mu = \Delta/\Delta_y > 1$ [9].

Table 10. Ductility ratio by equivalent static pushover

Type of soil	Bare frame			Soft storey		
	CY	IY	DR	CY	IY	DR
Hard	93.96	83.11	1.13	131.44	122.03	1.08
Soft	106.48	89.69	1.19	137.36	126.88	1.08

Table 11. Ductility ratio by response spectrum pushover

Type of soil	Bare frame			Soft storey		
	CY	IY	DR	CY	IY	DR
Hard	1141.76	336.10	3.40	2065.53	507.56	4.07
Soft	1014.85	359.78	2.82	2106.11	563.61	3.74

For bare frame building models on hard soil as per response spectrum pushover analysis method there is increment in ductility ratio by 66.76% when compared with equivalent static pushover analysis. Similarly the increment of 57.80% is observed for bare frame building models on soft soil. The percentage variation for soft storey building models on hard soil by response spectrum pushover analysis is 73.46% more when compared to the soft storey models supported on hard soil by equivalent static method. Similarly the percentage increment for soft soil is found to be 71.12%. It is concluded from the results that the buildings are more ductile as evaluated by RSM compared to ESM.

4.7 Safety Ratio (SR)

The ratio of base shear force at performance point to the base shear by equivalent static method is called safety ratio. If the safety ratio is equal to one then the structure is safe, if it is less than one than the structure is unsafe and if ratio is more than one then the structure is safer [10]. The safety ratio values are given in Table 12 and 13

Table 12. Safety ratio by equivalent static pushover analysis

Type of soil	Bare frame			Brick Infill		
	Base Shear	Base Force	SR	Base Shear	Base Force	SR
Hard	1106.51	336.10	3.29	2030.38	507.56	4.00
Soft	740.42	359.78	2.06	1725.77	563.61	3.06

Table 13. Safety ratio by response spectrum pushover analysis

Type of soil	Bare frame			Brick Wall		
	Base Shear	Base Force	SR	Base Shear	Base Force	SR
Hard	1141.76	245.51	4.65	2065.53	232.28	8.89
Soft	740.42	184.06	4.02	1725.77	280.79	6.15

It is observed for bare frame building models on hard soil as per response spectrum pushover analysis method that there is increase in safety ratio by 29.24% when compared with equivalent static pushover analysis. Similarly the increment of 48.75% is observed for bare frame building models on soft soil. The percentage increment soft storey building models on hard soil by response spectrum pushover analysis is 55.00% when compared to the soft storey models supported on hard soil by equivalent static method. Similarly the percentage increment for soft soil is found to be 50.24%.

The safety ratio is directly proportional to the stiffness of the building models. As the safety ratio values are greater than one, the building models are safer. The soft storey buildings are safer than the bare frame buildings.

4.8 Global Stiffness (GS)

The ratio of base shear to the displacement at performance point is called as global stiffness [10]. In present study the stiffness parameter is studied in order to understand the behavior of the building in terms of strength due to applied earthquake load. The global stiffness values are shown in Table 14 and 15

Table 14. Global stiffness by equivalent static pushover analysis

Type of soil	Bare frame			Brick Infill		
	BF at PF	Displacement at PF	GS	BF at PF	Displacement at PF	GS
Hard	1106.51	93.96	12.55	2030.38	131.44	16.22
Soft	704.67	100.39	7.38	1725.77	134.11	12.87

Table 15. Global stiffness by response spectrum pushover analysis

Type of soil	Bare frame			Soft storey		
	BF at PF	Displacement at PF	GS	BF at PF	Displacement at PF	GS
Hard	1141.76	90.95	11.78	2065.53	128.18	15.26
Soft	740.42	106.48	6.62	1690.32	137.36	12.31

It is seen from Tables 14 and 15 for bare frame building models on hard soil as per response spectrum pushover analysis method that there is reduction in global stiffness by 6.13% when compared with equivalent static pushover analysis. Similarly, the decrement of 15.71% is observed for bare frame building models on soft soil. The increment for soft storey frame building models on hard soil by equivalent static method is found to be 5.92% when compared to the soft storey models supported on hard soil by response spectrum pushover analysis. Similarly, the percentage increase for soft soil is found to be 4.36%. The global stiffness decreases with stiffness of the soil. It can be concluded the buildings are stiffer on hard soil compared to buildings on soft soil.

V. CONCLUSIONS

Based on the building and soil parameters considered in this paper the following conclusions are drawn,

- The fundamental natural period of the building vary inversely with stiffness of the soil. There is increase in fundamental natural period as the soil property changes from hard to soft.
- The soil property has influence on the base shear of the buildings as the soil property changes from hard to soft the base shear decreases due to decrease in the soil stiffness.
- The lateral displacement of the building increases as the soil property changes from hard to soft soil. The flexibility of soil directly affects the lateral displacement of the building.
- The storey drift is inversely proportional to the stiffness of soil, as the stiffness of soil increases the storey drift decreases, the storey drift values are found within the limit for all building models.
- Few collapse hinges were developed in the columns of ground storey and the same can be retrofitted.
- Flexural hinges are found within the life safety range at the ultimate state.
- Soft storey buildings are more stiffer and safer compared to bare frame models as per global stiffness and safety ratio results.

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