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SEISMIC ANALYSIS OF MULTISTOREY RC BUILDINGS CONSIDERING SSI EFFECTS

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ABSTRACT

Structural designers commonly follow the practice of considering the soil as hard beneath the foundations during design. Thus, ignore the effect of soil-structure interaction to earthquake shaking even though the structures are built on varying soils. 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 and structures. Therefore, the effect of soil structure interaction should be considered in the design of multistorey buildings located in the earthquake prone areas. The prime importance in this paper is to understand the behaviour of RC 2D frames designed for seismic load combinations given in the code IS 1893 (Part 1) : 2002 by performing static and dynamic analyses. The investigation is carried out on ten storey buildings supported on hard and medium soil located in seismic zone III. The performance based seismic evaluation is carried out by non linear static pushover analysis as per the guidelines mentioned in FEMA 440. User-defined nonlinear hinge properties are assigned for beams and columns based on the moment-curvature relationships. Similarly load-deformation curve is used to assign hinge properties for strut. 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 building models. The investigation concludes that the base shear and global stiffness decrease with decrease in soil stiffness. Natural time period lengthens, lateral displacement, and storey drift increases. Safety ratio varies inversely with the stiffness of soil. Most of the 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

Response of structure depends on the properties of soil, structure, and the nature of the excitation. The process in which, the response of the soil influences the motion of the structure and vice versa, is referred to as soil-structure interaction (SSI). Implementing soil-structure interaction effects enables the designer to assess true behaviour of the soil-structure system precisely under the influence of seismic motion. Present design practice for dynamic loading assumes the building to be fixed at their bases. Whereas, in reality supporting soil medium allows movement to some extent due to their natural ability to deform which decrease the overall lateral stiffness of the structural system resulting in the lengthening of natural periods [1].

The behaviour of the buildings during the earthquake depends on the type of soil on which it is supported and stiffness of infill, etc. Majority of the existing RC structures do not meet the current seismic requirements as they are primarily designed for gravity loads only. The ground motion induces the random motions in all directions, radiating from the epicenter. These ground motions cause structure to vibrate and induces inertia forces in them. The effect of stiffness of the masonry infill walls is very important parameter in resisting the earthquake. 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 [2].

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 soils 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. EXAMPLE OF THE BUILDING STUDIED

In this paper ten storeyed 2D RC frames are considered located in seismic zone III. The bottom storey height is 4.8 m and upper storey height is taken as 3.6 m [1]. 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 [2]. The building is modeled to represent all existing components that influence the mass, strength, stiffness, and deformability of the structure. Slab loads are applied on the beam. Masonry brick infill walls are modeled by considering equivalent diagonal strut. The material properties and thickness of struts are same as that of masonry wall. The effective width of strut is calculated as proposed by Smith and Hendry [3]. M (moment hinge), PM (axial force and moment hinge), V (Shear hinge), and P (axial force hinge) hinge properties as per FEMA 356 [4] are assigned at rigid ends of beam, column, and strut elements respectively. The behaviour of soil can be conveniently simulated by modeling the same with a set of linear elastic springs. Three translational and two rotational springs about the mutually perpendicular global axes are assigned as per the procedure mentioned in ATC-40 [5], to simulate the effect of soil-flexibility. The models considered for the study are as bare frame building supported on i) Hard soil and ii) Medium soil, open ground soft storey building supported on iii) Hard soil and iv) Medium soil. Models are designed for 1.2(DL+LL+EQ) and 1.2(DL+LL+RS) [2]. The material and soil properties considered in the present work are given in Table 1 and Table 2 respectively. The plan and elevation of the building considered for the study are shown in Fig. 1and Fig. 2

III. METHODOLOGY OF THE STUDY

Majority of the existing 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. Therefore, it is necessary to retrofit and strengthen them after evaluating their strength and performance. Consequently, non linear analyses are carried out with user defined hinges to evaluate the performance of existing buildings.

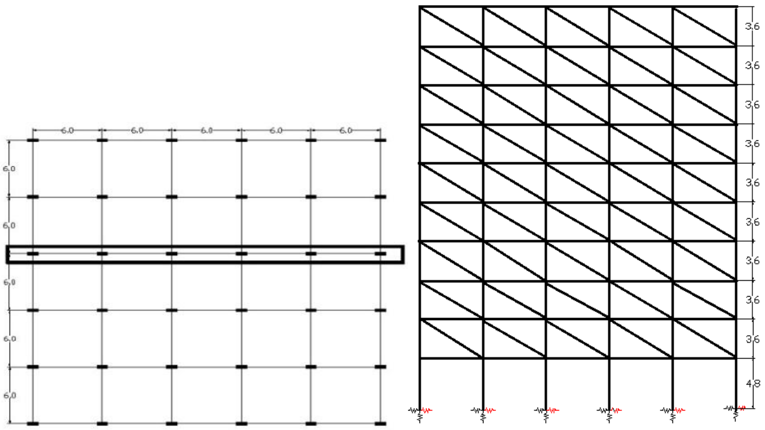

Fig. 1 Plan and elevation of soft storey building models

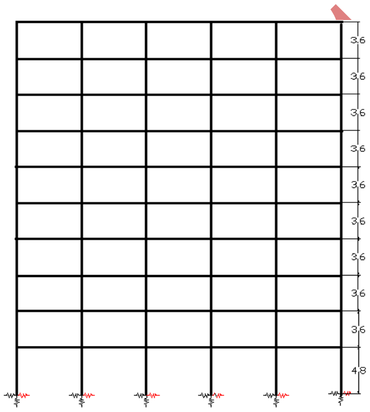

Fig. 2 Elevation of ten storeyed bare frame building models

Table 1. Material properties considered in the study [6]

Material Property	Values
Grade of concrete, Fck	25 Mpa
Grade of steel, Fy	415 Mpa
Modulus of Elasticity of brick wall	3285.9 Mpa
Modulus of Elasticity of steel, Es	20,0000 Mpa

Table 2. Soil properties [1]

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)
Medium	150	50000	0.45	17241.37
Hard	250	200000	0.45	68965.51

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 [7]. 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 (Moment) and V3 (Shear) hinges are assigned for beams, PM3 (Axial load with moment) hinges are assigned for columns and P (Axial load) hinges are assigned for struts The calculated moment-curvature values for beams (M3 and V3), columns (PM3), and load deformation curve values for struts (P) are given as input in SAP2000.

3.2 Pushover Analysis

Pushover analysis is one of the methods available to understand the behavior of structures subjected to earthquake forces. As the name implies, it is the process of pushing structure horizontally with a prescribed loading pattern incrementally until the structure reaches limit state. The static approximation consists of applying a vertical distribution of lateral loads to a model which captures the material non - linearity of an existing or previously designed structure, and monotonically increasing those loads until the peak response of the structure is obtained on a base shear vs roof displacement. Pushover analysis determines the behavior of a buildings, including the ultimate loads and the maximum inelastic deflections. At each step, the base shear and the roof displacement can be plotted to generate the pushover curve. In this paper the non-linear static pushover analysis is carried out as per FEMA 440 [8] guidelines. The models are pushed in a monotonically increasing order in a particular direction till the collapse of the structure. For this purpose, value of maximum displacement (4% of height of building [5]) at roof level and number of steps in which this displacement must be applied, are defined. The global response of structure at each displacement level is obtained in terms of the base shear, which is presented by pushover curve.

3.3 Element Description In SAP2000

Frame elements are modeled as line elements in SAP2000 having linearly elastic properties and nonlinear force-displacement characteristics. The force-deformation curve is shown in the Fig. 3.

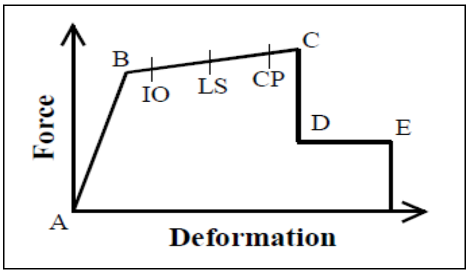

Fig 3. Force-Deformation for Pushover Hinge [9]

Point A corresponds to unloaded condition and point B represents yielding of the element. The ordinate at C corresponds to nominal strength and abscissa at C corresponds to the deformation at which significant strength degradation begins. The drop from C to D represents the initial failure of the element and resistance to lateral loads beyond point C is usually unreliable. The residual resistance from D to E allows the frame elements to sustain gravity loads [8]. Beyond point E, the maximum deformation capacity, gravity load can no longer be sustained .There are three types of hinge properties in SAP2000. They are default hinge properties, user-defined hinge properties and generated hinge properties. In this paper only user defined hinge properties are assigned to the frame elements.

IV. RESULTS AND DISCUSSIONS

4.1 Fundamental Natural Period

The changes in natural periods due to the effect of soil flexibility with respect to various parameters for hard and medium soil are compared. The comparison is made between ten storey bare and soft storey building models supported on hard and medium soils. The natural periods obtained for various building models by IS 1893 (Part 1) : 2002[2] code and analytical (SAP2000) are specified in Table 3.

It is observed that the fundamental natural period for ten storey bare frame structure is longer by 1.62 times compared to results obtained by codal procedure. Similarly shorter by 0.86 times is observed for the soft storey models. As the soil type changes from hard to medium natural period lengthens because of decrease in the stiffness of soil. The longer natural periods indicates the increase in the ductility.

Table 3. Codal and Analytical natural periods

Type of soil	Bare frame		Soft Storey	
	Codal	Analytical	Codal	Analytical
Hard	1.36	2.21	1.13	0.98
Medium	1.36	2.42	1.13	1.2

4.2 Base Shear

In the response spectrum method the design of base shear (Vb) is scaled to the base shear obtained from equivalent static method as per IS 1893 (Part 1) : 2002 as presented in Table 4 and Table 5. From the storey shear it is observed that there is underestimation of storey shear in bare frame as compared to the soft storey models. 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 for soft storey building models

Type of soil	$\bar{V}_b$ in kN	V_b in kN	Scale Factor
Hard	563.61	280.79	2.007
Medium	532.21	257.11	2.07

Table 5. Base shear for bare frame building models

Type of soil	$\bar{V}_b$ in kN	V_b in kN	Scale Factor
Hard	359.78	245.51	1.47
Medium	342.79	184.06	1.86

The base shear increases with increase in mass and stiffness of the soil. As the soil property changes from hard and medium the base shear decreases due to decrease in the stiffness of soil. For building models on hard and medium soil with bare frame, the base shear decreases by 1.56 and 1.55 times as compared to the soft storey building models on hard and medium soil by equivalent static method respectively. Similarly for soft storey building models supported on hard and medium soil base shear increased by 1.143 and 1.396 times as compared to bare frames by response spectrum method. The scale factor is found in the range 1.47 to 2.07. These results reveal that, as the stiffness of the soil decreases the strength in the buildings decreases thereby indicating a lesser amount of earthquake carrying capacity.

4.3 Lateral Displacements

The profile of lateral displacement along longitudinal direction by equivalent static and response spectrum method are shown Fig. 4.

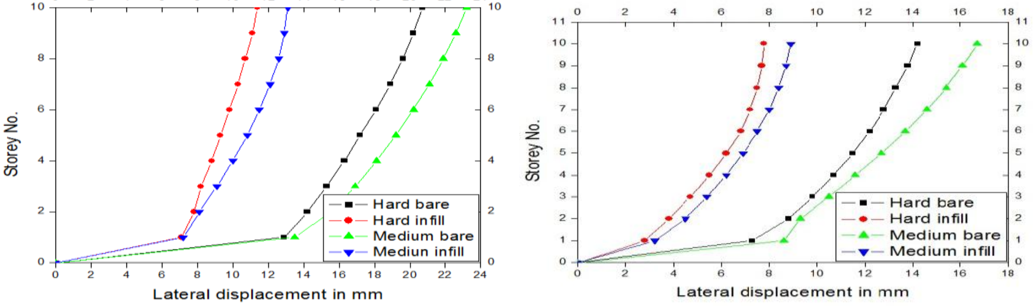

Fig 4. Lateral displacement in the longitudinal direction by ESM and RSM

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 less than the bare frame on medium soil. There is reduction in the lateral displacement by 10.77% and 12.97% for bare and soft storey building models on hard soil when compared to the models supported on medium soil by ESM respectively. Similarly 14.97% and 12.36% of decrement in lateral displacement are observed by RSM. The results indicate that higher flexibility in the building models supported on medium soil compared to hard soil.

4.4 Storey Drift

The profiles of storey drift for buildings along longitudinal direction by equivalent static method and response spectrum method are shown in Fig. 5.

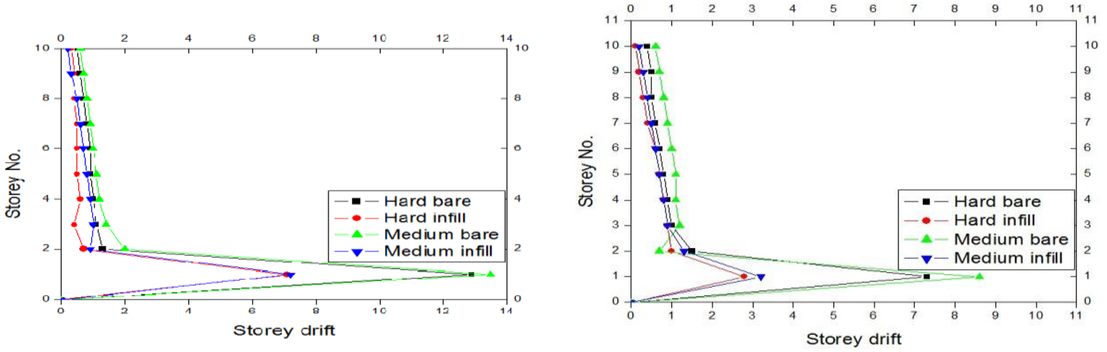

Fig 5. Storey drifts in the longitudinal direction by ESM and RSM

The storey drift of a building is a function of the stiffness. As per the clause 7.11.1 of IS 1893 (Part 1) : 2002 the storey drift should be within the 0.004 times the storey height [2]. Therefore, storey drift of the building decreases with the increase in the lateral stiffness. Thus, storey drift of the building models of bare and soft storey on hard soil is lesser than that of the building models on medium soil. For soft storey and bare frame building models on hard soil there is reduction in the storey drift by 1.20 and 0.667 times when compared to the bare and soft storey models supported on medium soil by equivalent static method respectively. Similarly 1.50 and 2.00 times decrement in storey drift are observed by the response spectrum method. The drift at the first storey is more compared to the upper storeys as first storey is designed without constructing infill walls resulting to soft storey. These static and linear results recommend that the civil engineering professionals should follow earthquake code procedures during design of multistorey buildings.

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 Table 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 MODELS BY ESM

Type of soil	**Hinge Status**	**Performance point**		**Location of hinges**					
		Base shear (kN)	**Displacement (mm)**	**A-B**	**B-IO**	**IO-LS**	**LS-CP**	**CP to E**	**TOTAL**
Hard	Yield	993.23	83.11	274	32	18	10	4	320
	Ultimate	1106.51	93.96	244	40	26	14	22	320
Medium	Yield	782.00	86.96	282	32	6	2	4	320
	Ultimate	979.35	99.01	253	31	10	12	24	320

Table 7. Performance point and location of hinges for soft storey building models 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 to E	TOTAL
Hard	Yield	1849.27	122.03	374	24	8	2	2	410
	Ultimate	2030.38	131.44	352	20	14	8	16	410
Medium	Yield	1684.94	124.49	378	26	4	1	1	410
	Ultimate	2070.81	133.087	360	20	8	5	17	410

Table 8. Performance point and location of hinges for bare frame building models 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 to E	TOTAL
Hard	Yield	1023.48	81.61	276	26	14	2	2	320
	Ultimate	1141.76	90.95	260	21	14	12	15	320
Medium	Yield	812.5	85.46	280	26	10	1	3	320
	Ultimate	1014.85	96.19	265	24	8	8	15	320

Table 9. Performance point and location of hinges for soft storey building models 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 to E	TOTAL
Hard	Yield	1879.42	120.38	380	24	2	1	3	410
	Ultimate	2065.53	128.18	366	8	10	10	16	410
Medium	Yield	1715.25	122.84	387	12	6	2	3	410
	Ultimate	2106.11	129.827	372	10	6	4	18	410

It is seen from Table 6 to Table 9 that there is an increment in base force at the ultimate state from bare to soft storey. The percentage increase in base shear for the bare and soft storey building models on hard soil is found to be 45.50% and 51.0% when compared to medium soil by equivalent static method. Similarly there is increment of 44.72% and 51.81% for the hard and medium soil by response spectrum method.

It is further observed that, The hinges are formed within the life safety range at the ultimate state is 93.125% and 92.5% for bare frame building models on hard and medium soil respectively. 96.08% and 95.86% for infill frame building models on hard and medium soils by equivalent static pushover analysis method. Similarly 95.89% and 95.62% for bare frame and 96.1% and 95.61% for infill frame building models on hard and medium soil by response spectrum method. The hinges are formed beyond the CP range at the ultimate state is 6.875% and 7.5% for bare frame building models on hard and medium soil respectively. 3.92% and 4.14% for infill frame building models on hard and medium soils by Equivalent static pushover analysis method. Similarly

4.11% and 4.38%, for bare frame and 3.9% and 4.39% for infill frames respectively by response spectrum pushover analysis method.

From the above discussions it can be concluded that as the soil property changes from hard to medium the yield and ultimate base shear decreases, this is due to the reduction in the stiffness of soil. The performances of the building bare frame and soft storey supported on hard and medium soil are within the life safety at the ultimate state for both equivalent and response spectrum 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)

Ductility ratio can be defined as the ratio collapse yield (CP) to the initial yield (IY) [10]. The ductility ratio (DR) results are presented in Table 10 and Table 11.

Table 10. Ductility ratio by equivalent static pushover analysis

Type of soil	Bare frame			Soft storey		
	CY	**IY**	**DR**	**CY**	**IY**	**DR**
Hard	93.96	86.11	1.13	131.44	122.03	1.08
Medium	99.01	86.96	1.14	133.09	124.49	1.07

Table 11. Ductility ratio by response spectrum pushover analysis

Type of soil	Bare frame			Soft storey		
	CY	**IY**	**DR**	**CY**	**IY**	**DR**
Hard	1141.76	336.1	3.4	2065.53	507.56	4.07
Medium	1014.85	359.78	2.82	2106.11	563.61	3.74

It is seen from the Table 10 and Table 11 that ductility ratio of the building models evaluated by the equivalent static pushover method are within the target value equal to 3. DR in remaining models are nearer to target value. These results also reveal that as the soil property changes from hard to medium the DR increases nearer or slightly more than the target value. 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 the structure is safer [11]. The safety ratio values are given in Table 12 and Table 13.

TABLE 12. SAFETY RATIO BY EQUIVALENT STATIC PUSHOVER ANALYSIS

Type of soil	Bare frame			Soft storey		
	Base Shear	**Base Force**	**SR**	**Base Shear**	**Base Force**	**SR**
Hard	1106.51	336.1	3.29	2030.38	507.56	4.00
Medium	979.35	359.78	2.72	2070.81	563.61	3.67

Table 13. Safety ratio by response spectrum pushover analysis

Type of soil	Bare frame			Soft Storey		
	Base Shear	**Base Force**	**SR**	**Base Shear**	**Base Force**	**SR**
Hard	1141.76	245.51	4.65	2065.53	232.28	8.89
Medium	1014.85	165.27	6.14	2106.11	257.11	8.19

It is observed that for bare frame building models on hard and medium soil by response spectrum pushover analysis method that there is increase in the safety ratio results by 1.413 and 2.257 times compared to equivalent static pushover analysis. The safety ratio for the soft storey building models on hard and medium soil by response spectrum pushover analysis is 2.222 and 2.231 times higher when compared to the soft storey models by equivalent static method.

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. From the above results it can be concluded that 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 [11]. 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 results are tabulated in Table 14 and Table 15.

Table 14. Global stiffness by equivalent static pushover analysis

Type of soil	Bare frame			Soft storey		
	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
Medium	979.35	99.01	10.55	2070.81	133.09	16.11

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	15.56
Medium	1014.85	96.19	9.89	2106.11	129.83	15.44

It is seen from Tables 14 and Table 15 for bare frame building models on hard soil as per response spectrum pushover analysis method that there is decrease in global stiffness by 1.065 times when compared with equivalent static pushover analysis. Similarly, the decrement of 1.066 times is observed for bare frame building models on medium soil. The GS of soft storey building models on hard soil by equivalent static method is found to be 1.042 times higher when compared to the soft storey models supported on hard soil by response spectrum pushover analysis. Similarly, the 1.04 times increment is observed for medium soil.

The global stiffness decreases with stiffness of the soil. It can be concluded the buildings are stiffer on hard soil compared to buildings on medium soil. These results reveal that, multistoreyed RC multistoreyed buildings designed considering earthquake load combinations prescribed in earthquake codes are stiffer to sustain earthquakes.

V. CONCLUSIONS

Based on the material properties, building considered, and analysis procedures the following conclusions are drawn,

1. The fundamental natural period of the building vary inversely with stiffness of the soil. The fundamental natural period lengthens as the soil property changes from hard to medium. Fundamental natural period empirical formula specified in IS: 1893 (Part 1)- 2002 code may be revised.

2. Stiffness of masonry infill walls must be considered during design of RC frame buildings to capture true behavior.

3. The soil property has influence on the base shear of the buildings, as the soil property changes from hard to medium the base shear decreases due to decrease in the soil stiffness.

3. The lateral displacement of the building increases as the soil property changes from hard to medium type soil. The flexibility of soil directly affects the lateral displacement of the building

4. The models considered in this paper are safer, ductile, stiffer, and more than 90% of hinges are developed within life safety level by non linear pushover analyses.

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