

Performance Based Seismic Design of RC Building with Consideration Of Soil Structure Interaction

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Abstract – Current seismic procedure and codes do not fulfill the requirement of seismic resistant building. 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 structure. This paper presents the effect Soil Structure interaction on seismic performance of the structure is considered and designed the building for Life safety performance objective. Six storey building with and without considering soil-structure interaction (SSI). The RC building symmetric plan and total height 18 m, located in seismic zone v, shallow foundation is considered. These buildings are modeled, designed as per IS 456:2000 and analyzed using SAP2000 software under two different boundary conditions, namely fixed-base, and considering soil-structure interaction Nonlinear dynamic analysis with seven time history records are used for analysis with user defined hinge properties used in X-Y direction[10,11]. There are four types of model analysis and studies are done-(1) Fixed base model with no soil structure interaction (Model NSSI), (2) Rigid footing rest on hard soil with considering SSI (Model HSSI), (3) Rigid footing rest on medium Soil with considering SSI (Model MSSI), (4) Rigid footing rest on soft soil with considering SSI (Model SSSI). Performance analysis was carried out and results obtained using Soil structure interaction. A comparative study is done between HSSI, MSSI, SSSI models with fixed base model (NSSI). The average of seven peak responses of story drift ratio, storey shear and natural period is considered. After that design is carried out for desired performance objective. It was found that soil-structure interaction can alter the seismic performance of the building in terms of seismic force demands and deformations.

Keywords – Performance based seismic design, Soil structure interaction, Time History analysis, Natural Period, Storey shear, Storey drift ratio.

1. INTRODUCTION –

In last few years disaster due to earthquake gave the picture of failures of structures occurred even after building was design as per force based approach. It significantly shows inability to provide minimum performance of structure under design earthquake. The performance based seismic design (PBSD), evaluates how the buildings are likely to perform under a design earthquake. As compared to force-based approach, PBSD gives a methodology for assessment of the seismic performance of a building, ensuring life safety and minimize economic losses.

In last years the importance of Soil Structure Interaction (SSI) on earthquake response of structure has more appealing and intensive. The soil flexibility is the main problem for high rise structure when they constructed over soft or medium soil strata. The dynamic parameters (fundamental natural period, storey shear, storey drift etc) of the structure significantly altered due to soil flexibility. During an earthquake, seismic force demand and deformation characteristics of structure and soil components of the footing of building can alter or change more significantly.

Soil structure interaction is In an earthquake, seismic waves are propagated through the soil medium to a structure of. Many researcher and engineers have firstly deal with the development of different modeling procedures and give a simple solution to implementation of the SSI in performance based analysis.

The literature shows considerable research in PBSD and SSI. Some of correlated works are discussed below:

[Shehata E. et al]¹ The authors studied the effect of SSI on multistorey building rest on raft foundation and analyzed with three analysis method. The result shows that storey drift and fundamental period increased as soil spring stiffness decreases. Finally, they concluded that structure rest on soft soil and medium soil has more significant effect on seismic response than stiff soil.[I. Kraus & D. Džakić]²

The authors analyzed the structure with three different end conditions –Structure rest on -fixed base, Winkler springs and half space, they found storey drift and natural period much more for soft soil especially for Winkler springs model. [M.D.L. Millen et al]³ The authors mainly focused on the effects of SSI and carried out performance based design of building resting on flexible and rigid foundation. It has been observed that local deformation effect of SSI should be introduced into design procedure. [Hamid Reza et al]⁴ Study carried out on high rise building which is rest on soft soil strata wit time history analysis. It has been observed that performance level can be change. The lateral deformation significantly increases in no SSI, with SSI for elastic and, inelastic behavior of structure. [Yahiaoui Djarir & Kadid Abdelkrim]⁵ Study carried on low and high rise building with gap spring supported model and 3D Time history analysis is carried out. A Comparative study between vertical ground motions with SSI shows increases deformation demand and lowering seismic force demand. [Behzad Fatahi]⁶ Studied on 15 storey building was first analyzed with as per code procedure to optimize the sections of the building then time history analysis is carried out, a comparative study between fixed base model and SSI considered model indicates performance objective life safety changes from collapse. Also inter storey drift significantly increases for low shear wave velocity. [D chaudhari, G dhoot]⁷ The authors study PBSB with pushover analysis. Assumed that base is fixed. Result obtained shows the Performance based seismic design provides reliable methodology for seismic up-gradation, determine yielding of the components of a building, possible mode of failure.[D chaudhari , S More]⁸ Study has been carried out on six storey fixed base building with time history analysis. Result shows that Performance based seismic design with time history analysis provides reliable methodology for seismic up gradation, determine yielding of the components of a building, possible mode of failure more accurately than pushover analysis. From the literature, PBSB of building gave the fairly accurate performance of building but this analysis not so accurate. Because they 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 lateral natural periods. Such lengthening of lateral natural periods does considerably change the seismic response of building frames. So it is necessary to add the effects of SSI into the analysis to obtain more accurate performance of the structure. So the present work focused on analysis and performance based design with considering SSI.

2. IDIALIZATION OF METHODOLOGY

2.1 Performance Based Design -

Performance based seismic design is a procedure of designing new buildings or seismic up-gradation of existing buildings, which includes a specific intent to achieve defined performance objectives in future earthquakes.. Performance objectives are operational (O), immediate occupancy (IO), life safety (LS), collapse prevention (CP), as per FEMA356 in which Life safety is the major focus to reduce the threats to the life safety of the structure in Figure 1.



Figure - 1 Performance levels

In performance based design approach, performance levels are described in terms of displacement as damage is better correlated to displacements rather than forces. This is based on the idea that performance objectives can be related to the level of damage to the structure, which in term can be related to displacement and drift. Figure 2 shows the typical process of design is to be followed.

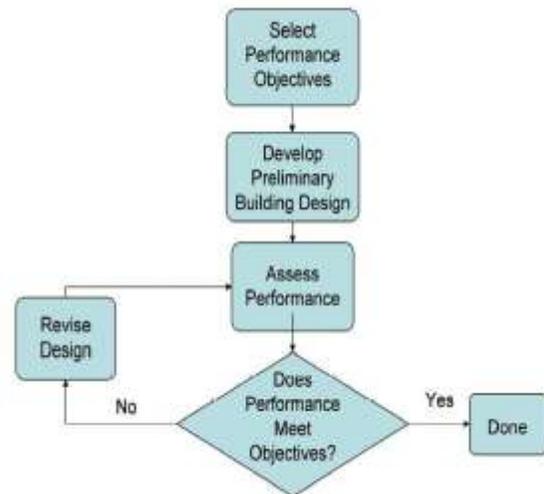


Figure 2 – Flow chart of performance based design

2.2 Soil-Structure Interaction –

Soil-Structure Interaction (SSI) is the considered effect of free response of structures caused by the flexibility of the foundation soils. The SSI can induce two distinct effects on the response of the structure, first, modification of the free field motion at the base of the structure, and second, the introduction of deformation from dynamic response of the structure into the supporting soil. The former is referred to as kinematic interaction, while the latter is known as inertial interaction.

There are two methods of implementing soil structure interaction. First is the direct method in which the soil structure and foundation is represented as a continuum and modeled together using finite element method. The ground motion is specified as free field motion and is applied at all boundaries. Second method is the substructure method in which soil material properties are used for incorporation of springs to represent the stiffness at the soil foundation interface. The general substructure method is suitable to complex structural idealizations, with the soil region idealized as a semi-infinite continuum or as a finite element system. For sites where essentially similar soils extend to large depths without a rigid boundary such as a soil rock interface. Sub-structure method is computationally more efficient than the direct method as most of the disadvantages of the direct method can be removed, if the substructure method is employed.

2.3 Proposed Work –

The present study on medium rise building is taken into consideration. Firstly building is modeled and preliminary analysis by using SAP2000 v19 and design carried out as per IS 456:2000. Then performance analysis is carried out by nonlinear dynamic analysis and designed the building for desire performance. In this study building is designed for Life safety and DBE (Design based earthquake)

2.3.1 Structural modeling and Analysis -

A ground plus Six storey RC frame building situated in zone V is taken for purpose of the study. It consists of 3 bays of 4m each in X-direction and 3 bays of 5m each in Y-direction. The total height of the building is 18 m. The building is designed and modeled as per IS 456: 2000. Subsequently the analysis and design has been carried out for a building with the symmetric geometry plan and elevation as shown in figure 3, resting on various soil types for shallow foundations in Zone V. Four types of foundation models viz. - (1) Fixed base model with No soil structure interaction (Model NSSI), (2) Hard soil base with considering SSI (Model HSSI), (3) Medium Soil base with considering SSI (Model MSSI), (4) Soft Soil base with considering SSI (Model SSSI). Performance

analysis is carried out and results are obtained using Soil structure interaction. Results of flexible base models (HSSI, MSSI, SSSI) are compared with the fixed base model (NSSI). Concrete frame elements are classified as beam and column frames. In the present study moment resistant frame is used Columns and beams are modeled using 3D frame elements. Slabs are as rigid diaphragms. The beam-column joints are assumed to be rigid. In SAP2000 V19 default hinge properties available as per the ASCE41, ATC-40 are assigned to the beam and column. Auto moment hinge M3 is assigned to beams; auto axial and moment hinges PM2M3 are assigned to columns.

2.3.1.1 Material Properties:

1. Concrete grade M 25
 2. Reinforcement steel grade Fe-415
- Properties of material are taken as per IS 456:2000

2.3.1.2 Section Properties:

Section properties for first trial are taken as per follow:
 Size of Beam = 230mm x 380mm
 Depth of Shallow footing = 1.5 m
 Thickness of Slab = 125mm

Table No 1 - Detail of column and footing sizes

Column Position	Column sizes	Footing sizes
Exterior Column	450x450	1.85 X 1.85 m
Interior Column	500x500	2.2 m X 2.2 m

2.3.1.3 Loading Considered

- i. Density of concrete = 25 KN/m³
- ii. Live Load = 4 KN/m²

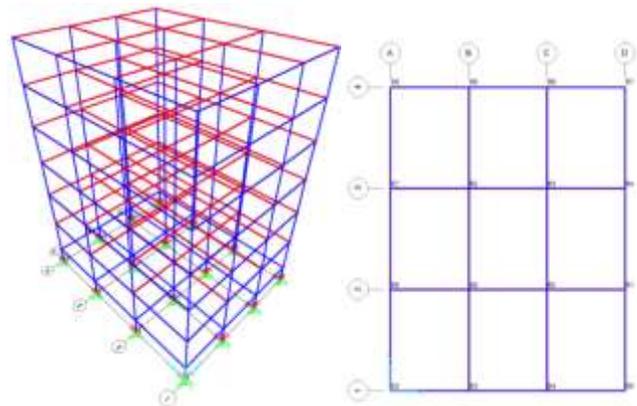


Figure 3 - SAP Model of proposed building supported on soil stiffness springs

2.3.1.4 Non Linear Dynamic Analysis -

Nonlinear dynamic analysis is the most comprehensive method for seismic analysis. The earthquake record in the form of acceleration time history is input at the base of the structure. The response of the structure is computed at each second for the entire duration of an earthquake. Selection and scaling of ground motion data from the PEER Database, all to match target response spectrum of soil type I defined according to IS 1893:2002. Those ground motions is modified and scaled on PEER web base tool by minimize MSE (Computed weighted mean squared error of record, and suite average, w.r.t target response spectrum). Using SAP2000 v19 computer aided code-based program the seven scaled ground motions were selected for conducting the analysis. Earthquake events used in present study are 1.Imperial Valley 02, 2.Kern County 3. Northern Calif03, 4. San Fernando, 5. Friuli- Italy-01, 6. Tabas-Iran, 7. Imperial Valley06. Acceleration ground motions for above earthquake shown in figure 4.

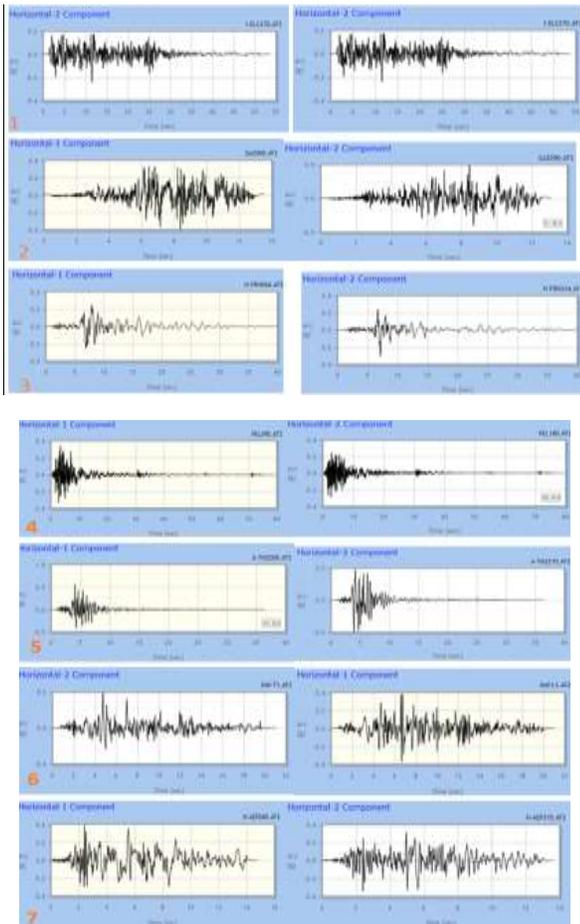


Figure 4 - Acceleration ground motion in X and Y direction for seven earthquake event respectively.

The average results of seven time history records is taken. Time history analysis carried out with previous nonlinear case stiffness and P-Δ effects are also incorporated in TH analysis and later on checked the performance level whether assumed desire performance objective is achieved or not if not then revised design. Load combinations are taken as per IS 1893:2002 and IS 456:2000

2.3.2 Soil Idealization -

In this present paper, substructure method is used for the implementation of SSI into analysis. The movement about three axes has been considered. Shallow isolated footing resting on varying soil types, three translational stiffness springs has been applied in two horizontal directions and one vertical direction i.e X-Y-Z direction respectively and similarly three rotational stiffness springs has been applied in X-Y-Z direction. To add SSI into the analysis, soil spring stiffness equations have been taken from FEMA356 (George Gazetas 1991). The Figure 5 shows the translational and rotational spring in X Y Z direction.

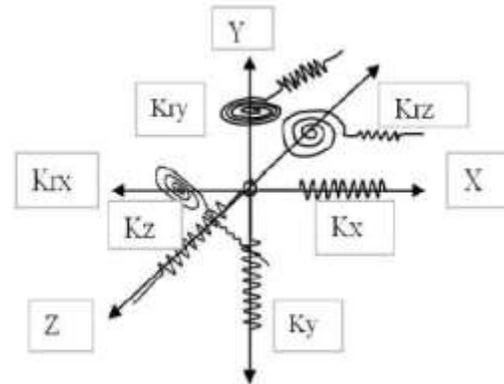


Figure 5 - Spring system at the foundation.

2.3.3 Soil classification and Properties :

Soil classification has taken into consideration the importance of local site effects as per IS code 1893 Part I-2002. The type of soil, mainly constituting the foundation is categorized into three type and parameters are considered from Jain and Murthy, IITK-GSDMA- EQ13 report.

Table 2 : Detail of soil parameter considered

Soil Type	Shear wave	SPT value	Mass Density(K)	Poisson Ratio	Shear Modulus(G)
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	velocity (m/s)		N/m ³		(KN/m ²)
Hard Soil	600	≥30	20	0.290	7.2 X 10 ⁶
Medium Soil	320	10 to 30	18	0.39	1.84 X 10 ⁶
Soft Soil	150	≤ 10	16	0.4	360 X 10 ³

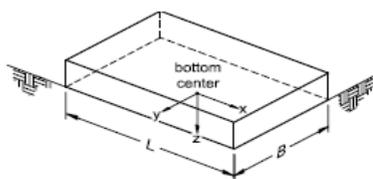
Figure 6 - Orientation of footing w.r.t axes.⁽¹¹⁾

Shear modulus (G) = Mass density X (Shear wave velocity)²

Table 3- Stiffness equations of foundation at surface⁽¹¹⁾

Degrees Of Freedom	Stiffness of foundation at Surface
Translational along x - axis	$K_x = \frac{GB}{2-\mu} \left[3.4 \left(\frac{L}{B} \right)^{0.65} + 1.2 \right]$
Translational along y - axis	$K_y = \frac{GB}{2-\mu} \left[3.4 \left(\frac{L}{B} \right)^{0.65} + 0.4 \frac{L}{B} + 0.8 \right]$
Translational along z - axis	$K_z = \frac{GB}{1-\mu} \left[1.55 \left(\frac{L}{B} \right)^{0.75} + 0.8 \right]$
Rocking about x - axis	$K_{xx} = \frac{GB^3}{1-\mu} \left[0.4 \left(\frac{L}{B} \right) + 0.1 \right]$
Rocking about y - axis	$K_{yy} = \frac{GB^3}{1-\mu} \left[0.47 \left(\frac{L}{B} \right)^{2.4} + 0.034 \right]$
Rocking about z - axis	$K_{zz} = GB^3 \left[0.53 \left(\frac{L}{B} \right)^{2.45} + 0.51 \right]$

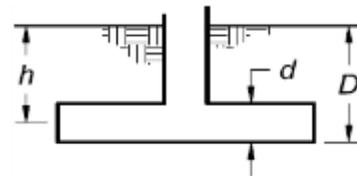
The above equations give stiffness of soil when the footing is at surface level. For embedment depth, correction factors have been used to get modified stiffness ($K_{emb} = \beta K_{sur}$)



Orient axes such that $L \geq B$

Table 4 -Correction factor equations⁽¹¹⁾

Degrees Of Freedom	Correction Factor for Embedment
Along x - axis	$\beta_x = \left(1 + 0.21 \sqrt{\frac{D}{B}} \right) \cdot \left[1 + 1.6 \left(\frac{hd(B+L)}{BL^2} \right)^{0.4} \right]$
Along y - axis	$\beta_y = \left(1 + 0.21 \sqrt{\frac{D}{B}} \right) \cdot \left[1 + 1.6 \left(\frac{hd(B+L)}{BL^2} \right)^{0.4} \right]$
Along z - axis	$\beta_z = \left[1 + \frac{1}{21} \frac{D}{B} \left(2 + 2.6 \frac{B}{L} \right) \right] \cdot \left[1 + 0.32 \left(\frac{d(B+L)}{BL} \right)^{2/3} \right]$
Rocking about x - axis	$\beta_{xx} = 1 + 2.5 \frac{d}{B} \left[1 + \frac{2d}{B} \left(\frac{d}{B} \right)^{-0.2} \sqrt{\frac{B}{L}} \right]$
Rocking about y - axis	$\beta_{yy} = 1 + 1.4 \left(\frac{d}{L} \right)^{0.6} \left[1.5 + 3.7 \left(\frac{d}{L} \right)^{1.9} \left(\frac{d}{B} \right)^{-0.6} \right]$
Rocking about z - axis	$\beta_{zz} = 1 + 2.6 \left(1 + \frac{B}{L} \right) \left(\frac{d}{B} \right)^{0.9}$



d = Height of effective sidewall contact (may be less than total foundation height)

h = Depth to centroid of effective sidewall contact.
For each degree of freedom, calculate $K_{emb} = \beta K_{sur}$

Figure 7 - Description and meaning of h, d, D for shallow footing.⁽¹¹⁾

3. Result and Discussion -

After the time history analysis comparative study is carried out for Inter story drift, storey shear, Fundamental natural period and design for life safety level for different model considered.

3.1 Inter story drift -

Inter story drift (ISD) limitation is given by IS 1893:2000. It should not greater than 0.4% of total height of the building. For present work considered building model results shows that ISD is within acceptable limit. The change in ISD for 6 storey building for different model considered in X and Y direction as shown in figure 8-9.. ISD for SSSI model is 45.6% and 40% more than NSSI model in X and Y direction respectively. Similarly, ISD for MSSSI and HSSI is increased by 38 %, 15.5 %, 11.80 % and 3.26 % more than NSSI model in X and Y direction respectively. ISD is more significant for 2,3,4 storey level. Result clearly shows that as soil stiffness decreases the ISD increase.

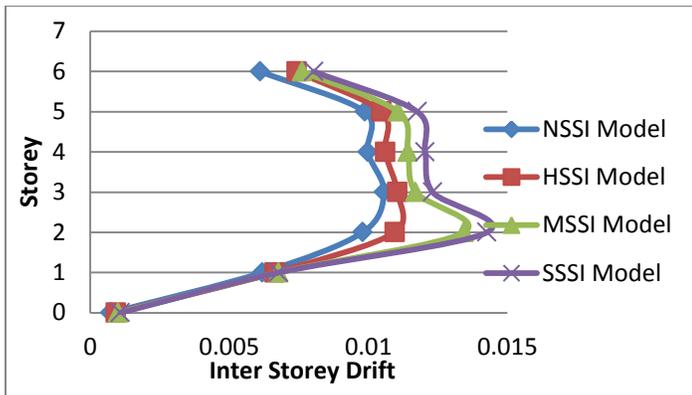


Figure 8 - Inter storey drift in x direction for all considered base models

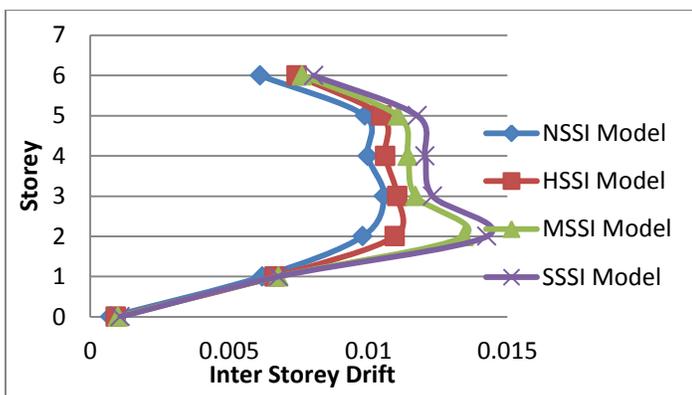


Figure 9 - Inter storey drift in Y direction for all considered base models.

3.2 Fundamental time period -

The fundamental time period depends on the stiffness of building load resisting system and height of the building. The inclusion of SSI into analysis leads to change in fundamental time period. From the figure 10 shows that inclusion SSI into analysis tends to increase fundamental time period by 1.30%,4.6% and 12% for HSSI model, MSSSI model, and SSSI model respectively. Increase in the fundamental time period is more significant for SSSI model.

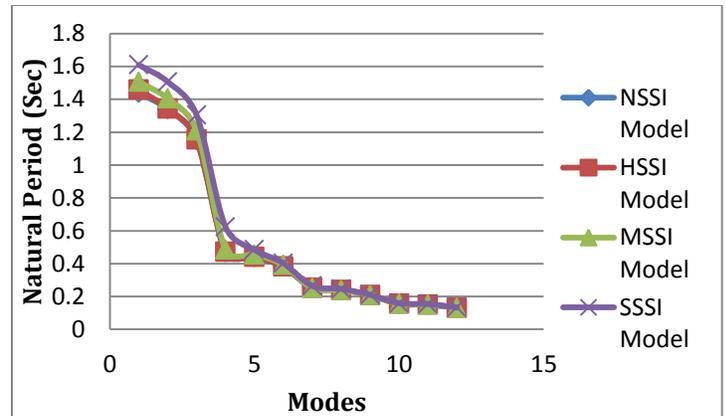


Figure 10 - Fundamental natural period for all considered base models

3.3 Storey shear -

This study has been carried out to understand the performance of building with the inclusion of SSI effect. The of response structure in the form of storey shear over the story levels of the building is carried out. The SSI incorporation effect on the storey shear for 6 storey building has been shown in below figure 11-1 in X and Y direction and compared result for NSSI model with SSI models. Results show that storey shear for SSSI model is more than MSSSI model, HSSI model, and NSSI model. Percentage decrease in storey shear w.r.t NSSI model is 9.46 %, 12.86 % and 16.21 % for HSSI model, MSSSI model, and SSSI model respectively. As the soil spring stiffness decreases the storey shear also decreases.

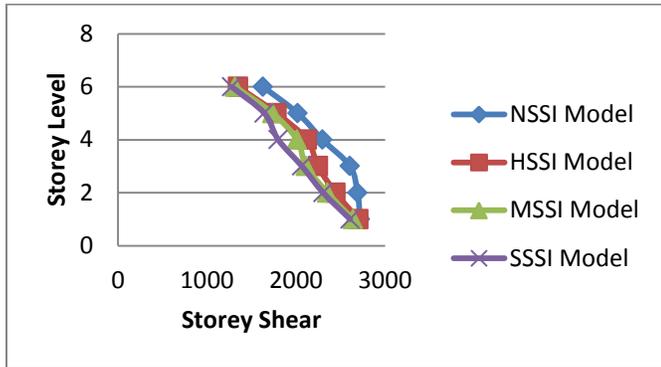


Figure 11 - Storey shear in X Direction for all considered base models

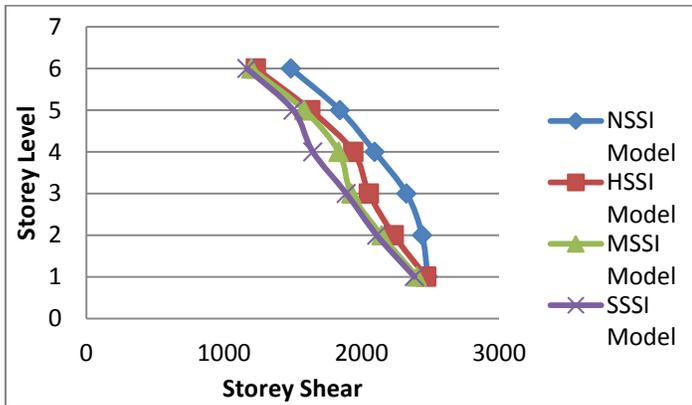


Figure 12 - Storey shear in Y Direction for all considered base models

3.4 Plastic Hinges Results :

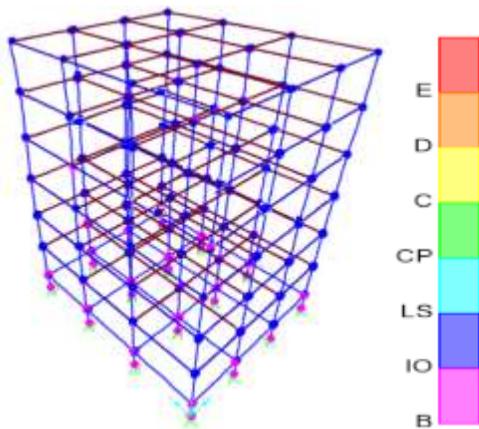


Figure 13 - Plastic hinges formation for fixed base model(NSSI)

Hinges shows the location of the weak point and failure modes while in seismic excitation are identified. The exact position of plastic hinges is forecast by using time history analysis for all ground motions with help of SAP2000 output as shown in Figure 13-14. Plastic hinges are generated in the column and beam shows blue color as per SAP2000 output the hinges are in life safety performance level. However, some hinges are in immediate occupancy level but no one hinge go beyond life safety level so desire life safety objective is to achieve for deigning of the building.

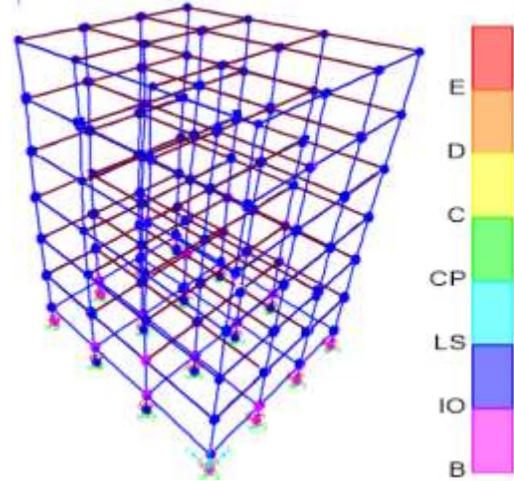


Figure 14 - Plastic hinges formation for Soft Soil base model(SSSI)

3.5 Performance based Seismic design -

After a number of trials of sections, the final life safety level design is arrived:

For Column:

Table No 5 - Reinforcement in column

Reinforcement in mm ² (NSSI model)					
Storey	Section	Sizes	CC	MC	OCMC
6	Column	400x400	1280	1280	1280
5	Column	400x400	1350	1650	2050
4	Column	400x400	1723	2535	2725
3	Column	400x400	2200	3620	3500
2	Column	400x400	2700	5150	4450
1	Column	450x450	4562	6200	5620
Average reinforcement			2303	3406	3272

Reinforcement in mm ² (HSSI model)					
Storey	Section	Sizes	CC	MC	OCMC
6	Column	400x400	1280	1280	1280
5	Column	400x400	1340	1600	2030
4	Column	400x400	1636	2508	2698

3	Column	400x400	1960	3250	3170
2	Column	400x400	2713	4690	4200
1	Column	450x450	4540	6000	5500
Average reinforcement			2245	3223	3146

Storey	Section		Steel
6	Beam	230x300	576(Top) 409(Bottom)
5	Beam	230x380	1010(Top) 871(Bottom)
4	Beam	230x380	1430(Top) 1275(Bottom)
3	Beam	230x380	1805(Top) 1640(Bottom)
2	Beam	250x380	2300(Top) 2040(Bottom)
1	Beam	250x380	2133(Top) 1950(Bottom)
Plinth	Beam	230x280	1500(Top) 1371(Bottom)

Reinforcement in beam for MSSSI model

Storey	Section		Steel
6	Beam	230x300	534(Top) 390(Bottom)
5	Beam	230x380	932(Top) 800(Bottom)
4	Beam	230x380	1330(Top) 1155(Bottom)
3	Beam	230x380	1750(Top) 1540(Bottom)
2	Beam	250x380	2242(Top) 1960(Bottom)
1	Beam	250x380	2120(Top) 2073(Bottom)
Plinth	Beam	230x280	1442(Top) 1281(Bottom)

Reinforcement in beam for SSSI model

Storey	Section		Steel
6	Beam	230x300	520(Top) 384(Bottom)
5	Beam	230x380	948(Top) 816(Bottom)
4	Beam	230x380	1330(Top) 1157(Bottom)
3	Beam	230x380	1722(Top) 1471(Bottom)
2	Beam	250x380	1972(Top) 1690(Bottom)
1	Beam	250x380	2100(Top) 1863(Bottom)
Plinth	Beam	230x280	1380(Top) 1228(Bottom)

Similarly, for the beam design, we observed that the top reinforcement percentage gradually decreases from SSI model to NSSI model (7.16%, 2.80%, 0.26% for SSSI model, MSSSI model, HSSI model, NSSI model respectively). Also, bottom reinforcement percentage gradually decreases from SSI model to NSSI model (11.17 %, 7.24 %, and 3.34 % for SSSI model). As seismic force demand decreases reinforcement area decrease.

Reinforcement in mm ² (MSSI model)					
Storey	Section	Sizes	CC	MC	OCMC
6	Column	400x400	1280	1280	1280
5	Column	400x400	1340	1600	2030
4	Column	400x400	1636	2508	2698
3	Column	400x400	1960	3475	3365
2	Column	400x400	2713	4690	4300
1	Column	450x450	4213	5506	5000
Average reinforcement			2190	3177	3113

Reinforcement in mm ² (SSSI model)					
Storey	Section	Sizes	CC	MC	OCMC
6	Column	400x400	1155	1155	1188
5	Column	400x400	1171	1462	1816
4	Column	400x400	1420	2440	2577
3	Column	400x400	1700	3250	3170
2	Column	400x400	2662	4930	4200
1	Column	450x450	3700	5090	4613
Average reinforcement			1968	3055	2928

From the design, we observed that the reinforcement percentage gradually decreases for NSSI model to SSSI model (11.57 %, 5.58 %, 4.1% for SSSI model, MSSSI model, HSSI model, respectively corresponding to NSSI model). As seismic force demand decreases, the reinforcement area also decreases.

For Beam-

Table No 6 – Reinforcement in the beam

Reinforcement in beam for for NSSI model			
Storey	Section	Sizes	Steel
6	Beam	230x300	530(Top) 400(Bottom)
5	Beam	230x380	985(Top) 855(Bottom)
4	Beam	230x380	1450(Top) 1284(Bottom)
3	Beam	230x380	1820(Top) 1655(Bottom)
2	Beam	250x380	2280(Top) 2110(Bottom)
1	Beam	250x380	2300(Top) 2200(Bottom)
Plinth	Beam	230x280	1543(Top) 1400(Bottom)
Reinforcement in beam for HSSI model			

4. Conclusion –

In this study, nonlinear dynamics analysis is used for analysis of G+6 building and design for Life safety performance level. The SSI with different soil strata has been incorporated and comparison is made with SSI and without SSI effect.

According to the results of an investigation conducted the following are the salient conclusions obtained from the present study:

1. The value obtained of natural period of RC building with a fixed base is less than flexible bases. It is also observed that natural period for the NSSI model and HSSI model is near about same. Such incremental natural period may considerably alter the response of buildings under seismic excitation.
2. The shear at each floor level is decreasing as soil stiffness decreases. Storey Shear at each storey level for the NSSI model is more than MSSI model and SSSI model but storey shear results for the NSSI model and HSSI model found to be near about same.
3. Inter Storey drift increases as soil stiffness decreases. Inter Storey drift increasing for lower storey i.e 2, 3, 4 levels. Second storey level shows maximum inter-storey drift.
4. It seen that the rebar area in beam and column member is decreased for SSSI model than the NSSI model.
5. It is observed that SSI effect was important for building erected on soft soil. However hard soil conditions its effect can be neglected.

In brief, the conventional inelastic design procedure excluding SSI is not adequate to guarantee the structural safety of RC building resting on medium soil and soft soil. As such in high seismic zones and for medium and soft soil strata, nonlinear dynamic analysis with soil structure interaction (SSI) shall be used.

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