Non-Linear Static Pushover Analysis of Plan Irregular Structure Incorporating Soil- Structure Interaction

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Abstract. This work studies the Nonlinear Static Pushover Analysis of an irregular block of Jorhat Engineering College old building situated in Seismic Zone-V with infill walls, using Soil-Structure Interaction. Infill walls are designed as per IS1893(Part-I):2016.

Sub-soil exploration is conducted and spring element representing soil-structure interaction is evaluated using standard literature.

Stiffness of the spring for the spring base structure is calculated as per ATC-40 guidelines. The stiffness values calculated using this code are along vertical, horizontal, and rotational directions. Modeling of the L Shape structure is done using SAP2000®. Analysis is done as per code considering different load combinations for both the fixed base and spring base conditions. A comparison is made between the fixed base model and a spring-based model in terms of Modal characteristics, Base shear and Top-story displacement and propagation of hinge formation.

Keywords: Soil- Structure Interaction, Fixed base, Spring base, Non-linear Static Pushover Analysis.

1 Introduction

Most of the structures are analysed considering as fixed-base. But in reality the structural behaviour is affected by flexibility of the soil. Inaccurate representation boundary condition in modeling leads to improper estimation of the design forces. Fixed-base can be replaced by springs representing the soil to address this issue to a larger extent. Stiffness of the soil-spring depends on the geotechnical parameters and dimension of the foundation. This can be estimated as per ATC-4O [1]guidelines. In this study, comparative seismic performance of two models of a Plan-Irregular Academic building is taken up for fixed base and spring base conditions. Static Pushover Analysis is used for this comparative analysis in SAP2000®.

2 Description of Frame Structure

The building under consideration is a Plan-Irregular block of Jorhat Engineering College.

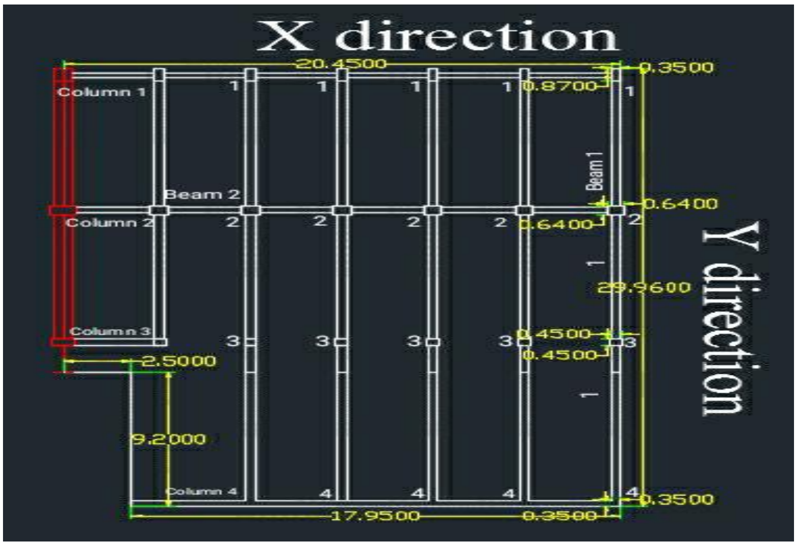

Fig. 1. Plan view of the model showing different sizes of beams and columns

Indian Seismic Code[5] defines plan irregularities for such L type building as in Fig. 2.

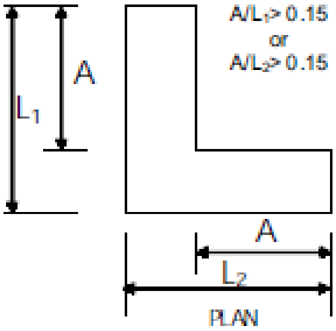

Fig. 2. Criterion for Plan Irregularity of L-type building[5]

As per Fig. 1, the ratio of outstands along Y-direction A/L_1 is 9.2/29.96 i.e 0.30>0.15.Thus, the classification of the structure as plan irregualar is valid.

The structure is modeled as a 3-D frame using SAP2000®. The element sizes are as follows:

Beam1 (along Y-axis):350mm×870mm
Beam2 (along X-axis):380mm×970mm
Column1:350×870mm

Column2:640×640mm
Column3:450×450mm
Column4:350×350mm
Slab thickness = 150mm
Plan area (sq m.) = 20.45m× 29.96m
Dead loads are calculated considering the unit weight of concrete as 25 kN/m^3.
Dead load =1×0.15×25=3.75 kN/m² [5]
Live load =1.5 kN/m²(for roof) & 3 kN/m²(for floors) [6]
Floor to floor height = 4.48 m(ground storey) and 4.14m(other floors)
Modulus of Elasticity(E_c) of concrete considering M20 concrete =5000$\sqrt{f_{ck}}$ =5000√20=22360.68 N/mm^2. [3]

Infill walls are modelled as equivalent concentric diagonal strut connected at the beam-column joints by pin joints.

3 Numerical Modelling

3.1 Modeling of strut

In this present study infill walls are designed as Equivalent Diagonal Strut Method as suggested in Indian Seismic Code[5]. The width of equivalent struts without openings are calculated as per the following relations-

$$\text{Width } (W_{eff}) = 0.175(\lambda_1 \times H)^{-0.4} \times w' \qquad (1)$$

$$\lambda_1 = \left[\frac{Em\ t\ \sin(2\theta)}{4Efe\ Icol\ hinf}\right]^{1/4} \qquad (2)$$

It may be noted here that the Indian seismic code[5] makes no distinction between walls, with and without opening. As such, when there is an opening in infill wall where no reduction of strut width is provided. Infill materials are considered for the calculations.

3.2 Models based on foundation condition

Two types of model are considered for the study-

a) Fixed-base
b) Spring base
c)

a) Fixed-base model

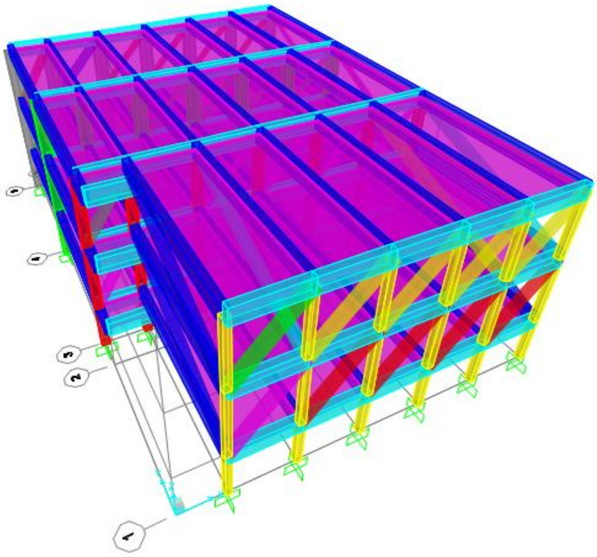

Fig. 3. 3D view of Fixed-base model with infill wall modelled as strut

b) Spring-base model

There are basically three mechanism related to soil failure. These are: axial, shear and rotation. Failure due to axial associated with punching of the soil. The second, shear failure is associated with the translation mechanism with the activation of a passive zone infront of the foundation and an active zone behind the foundation. The third mechanism is global rotation with active and passive zone around the foundation. [2]
Springs are provided at the base of the structure with calculated stiffness in order to accommodate these mechanisms. The stiffness of the spring is calculated as per ATC-40[1] guidelines along three directions i.e vertical, horizontal and rotation as shown in Table 1.

Table 1. Surface Stiffnesses for a Rigid Plate on a Semi-infinite Homogenous Elastic Half-Space[1]

Stiffness Parameters	Rigid Plate Stiffness at Surface, K_i
Horizontal Translation along X-axis, k_x	$kx = \frac{GL}{2-v}\left[2+2.5\left(\frac{B}{L}\right)^{0.85}\right] - \frac{GL}{0.75-v}\left[0.1\left(1-\frac{B}{L}\right)\right]$
Horizontal Translation along Y-axis, k_y	$ky = \frac{GL}{2-v}\left[2+2.5\left(\frac{B}{L}\right)^{0.85}\right]$
Vertical Translation along Z-axis, k_z	$kz = \frac{GL}{1-v}\left[0.73+1.54\left(\frac{B}{L}\right)^{0.75}\right]$

Rotation about X-axis $k_{\theta x}$	$k\theta x = \left(\frac{G}{1-\upsilon}\right)(Ixx)^{0.75}\left(\frac{L}{B}\right)^{0.25}\left(2.4+0.5\left(\frac{B}{L}\right)\right)$
Rotation about Y-axis $k_{\theta y}$	$K\theta y = \left(\frac{G}{1-\upsilon}\right)(Iyy)^{0.75}\left[3\left(\frac{L}{B}\right)^{0.15}\right]$

The basic steps followed for determining the stiffness properties of shallow bearing geotechnical components are as follows[1]:
1) Determine the uncoupled total surface stiffness Ki, of the foundation element by assuming it to be a rigid plate bearing at the surface of semi-infinite elastic half space.
2) Adjust the uncoupled total surface stiffness Ki for the effects of the depth of bearing by multiplying by the embedment factors, ie, to generate uncoupled total stiffness. The embedment factors are calculated as in Table 2.

Table 2. Stiffness Embedment Factors for a Rigid Plate on a Semi-infinite Homogenous Elastic Half-Space[1]

Stiffness Parameters	Embedment Factors, e_i
Horizontal Translation along X-axis, e_x	$ex = \left[1+0.15\left(\frac{2D}{L}\right)^{0.5}\right]\left\{1+0.52\left[\frac{\left(D-\frac{d}{2}\right)16(L+B)d}{LB^2}\right]^{0.4}\right\}$
Horizontal Translation along Y-axis, e_y	$ey = \left[1+0.15\left(\frac{2D}{B}\right)^{0.5}\right]\left\{1+0.52\left[\frac{\left(D-\frac{d}{2}\right)16(L+B)d}{BL^2}\right]^{0.4}\right\}$
Vertical Translation along Z-axis, e_z	$ez = \left[1+0.095\frac{D}{B}\left(1+1.3\left(\frac{B}{L}\right)\right)\right]\left[1+0.2\left(\frac{(2L+2B)d}{LB}\right)^{0.67}\right]$
Rotation about X-axis, $e_{\theta x}$	$e\Theta x = 1 + 2.52\frac{d}{B}\left(1+\frac{2d}{B}\left(\frac{d}{D}\right)^{-0.20}\left(\frac{B}{L}\right)^{0.5}\right.$
Rotation about Y-axis, $e_{\theta y}$	$e\Theta y = 1 + 0.92\left(\frac{2d}{L}\right)^{0.60}\left(1.5+\left(\frac{2d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right.$

In absence of exact design data(building being 60 years old) the bearing stiffnesses are calculated assuming the footing details as follows:
Thickness of the foundation (d) = 0.2 m
Total depth of foundation from ground level = 3m
Width of footing (B) = 3m
Length of footing (L) = 3m

Geotechnical site investigation is carried out for this study, by conducting the Standard Penetration Test (SPT) in a borehole to determine the SPT N value which is empirically related to many engineering properties. In the absence of the values of shear wave velocity, the N values are used to estimate the V_s through available correlation for all types of soil given in Eq.(3)[7]

$V_s= 89.31(N)^{0.358}$ (3)

Where, N= uncorrected SPT-N value; and V_s is in m/s. The shear wave velocity is ranges from 89.31 m/s to 261.01 m/s. As per Indian Seismic Code[5] , since the corrected N value less than 10 so the soil considered as soft soil (N<10).

Based on the classification of foundation soil as soft soil, other required values for calculation of Ki values are taken from standard literature as follows:

Poisson's ratio = 0.33[8]

Modulus of Elasticity, E = 61200 kN/m^2 [8]

Bulk unit weight of soil= 17 kN/m^3[Assumed]

Calculated stiffness

Shear modulus, $G = E/2(1+\upsilon)$

$= 6120/2(1+0.33)$

$=23007.51$ kN/m^2

Calculated values of Rigid Plate Stiffness at Surface, K_i

Horizontal Translation along X-axis, k_x = 185454.57 kN/m

Horizontal Translation along Y-axis, k_y = 185454.57 kN/m

Vertical Translation along Z-axis , k_z = 237476.95 kN/m

Rotation about X-axis, $k_{\Theta x}$ = 310.604×10^6 kNm/rad

Rotation about Y-axis, $k_{\Theta y}$ = 183.58×10^6 kNm/rad

Calculated values of embedment factors, e_i

Horizontal Translation along X-axis, e_x = 2.902 kN/m

Horizontal Translation along Y-axis, e_y = 2.902 kN/m

Vertical Translation along Z-axis, e_z = 2.726 kN/m

Rotation about X-axis, $e_{\Theta x}$ = 1.435 kNm/rad

Rotation about Y-axis, $e_{\Theta y}$ = 2.052 kNm/rad

Calculation of Total Embedded stiffness, K_{emb}

Translation along X axis, $K_{emb(x)} = 185454.57\times2.902 = 538189.16$ kN/m

Translation along Y axis, $K_{emb(y)} = 185454.57\times2.902 = 538189.16$ kN/m

Translation along Z axis, $K_{emb(z)} = 237476.95\times2.726 = 647362.16$ kN/m

Rotation along X axis, $K_{emb(\theta x)} = 310.604\times10^6\times1.435 = 445716740$ kNm/rad

Rotation along Y axis, $K_{emb(\theta y)} = 183.58\times10^6\times2.052 =376706160$ kNm/rad

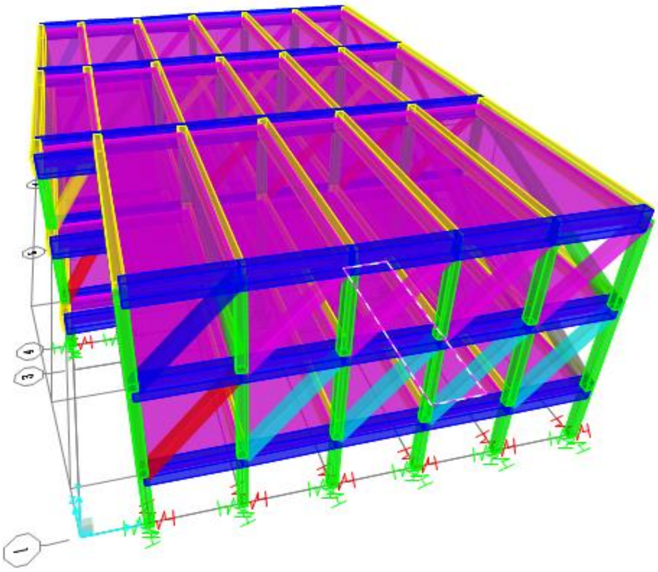

Fig. 4. 3D-view of spring base model with infill modelled as strut

4 Results and Discussion

4.1 Comparative Dynamic Properties of the two models

The time period for the two models under consideration are presented in Table 3.

Table 3. Dynamic properties

Nature of Mode	Time period	
	Fixed base	Flexible base
Translation along X-axis	0.44	0.65
Translation along Y-axis	0.41	0.58
Rotation about Z-axis	0.25	0.52

It is observed that time period for flexible base is longer compared to fixed base condition. Another significant observation here is that while the time periods for the third mode (thereby, the third natural frequency) of the fixed base model is far apart from the first two, the same is not true with the flexible based case. This implies that 3rd mode would contribute significantly for the flexible base case, in contradiction with that of fixed base case. This is a pointer towards taking soil flexibility into consideration for modeling of irregular building, where the torsional mode is significant contributor of response. It is also clear that equivalent static method is suitable for fixed base modeling only. Equivalent static method would not be appropriate for capturing the seismic behavior of the building where soil flexibility is considered, as the it takes into account of only first modal displacement(inverted triangular distribution of load). Again, the traditional pushover analysis may not be appropriate for model with soil flexibility at base. Modal pushover analysis would be a better choice as it considers not only the first mode, but all the significant modes.

4.2 Comparative Seismic Performance between the two models

Load conditions considered are as per IS1893(Part-I):2016 [5]and is represented in Table 4.

Table 4. Different load combinations.

Combinations	description
Combination 1	1.2(DL+LL-EQx)
Combination 2	1.2(DL+LL+EQx)
Combination 3	1.2(DL+LL-EQy)
Combination 4	1.2(DL+LL+EQy)
Combination 5	1.5(DL+EQx)
Combination 6	1.5(DL-EQx)
Combination 7	1.5(DL+EQy)
Combination 8	1.5(DL-EQy)

Pushover analysis is carried out for controlled displacement of 0.24m and formation of plastic hinges are observed.

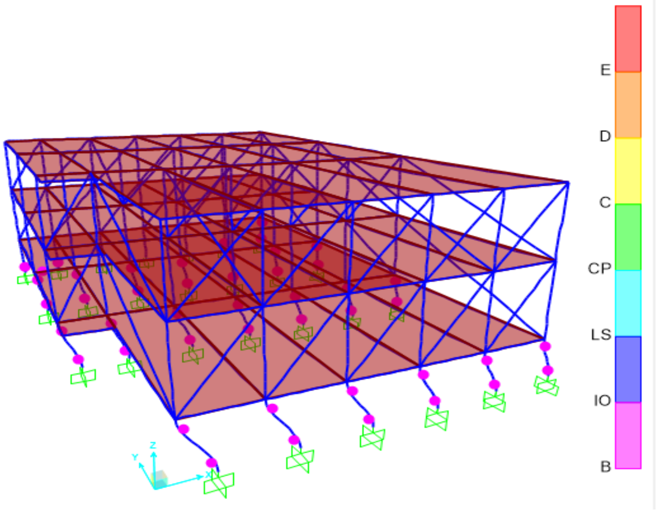

Fig. 5. Formation of plastic hinges in X-direction for Fixed base condition

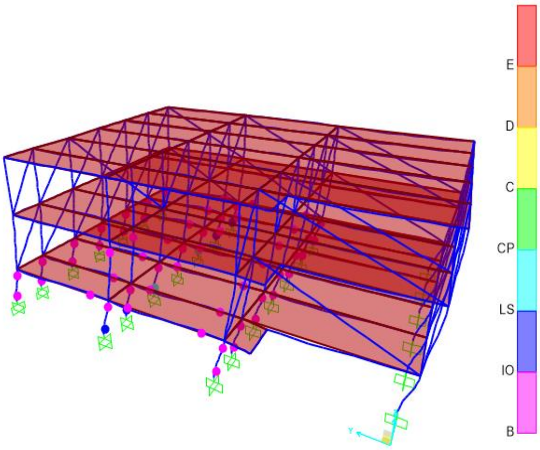

Fig. 6. Formation of plastic hinges in Y-direction for Fixed base condition

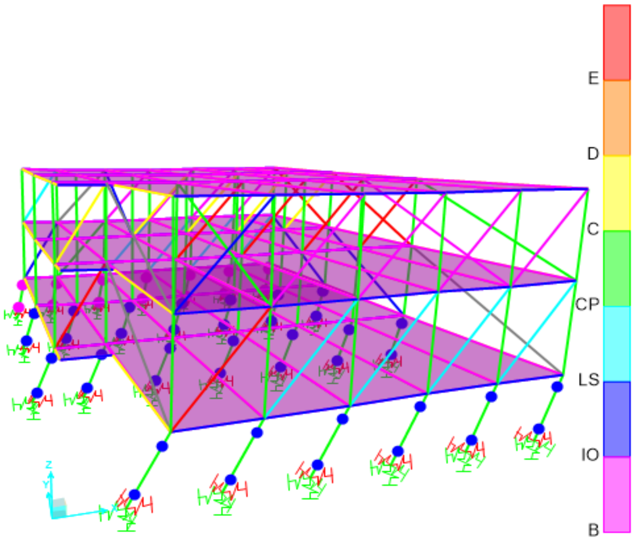

Fig. 7. Formation of plastic hinges in X-direction for Flexible base condition

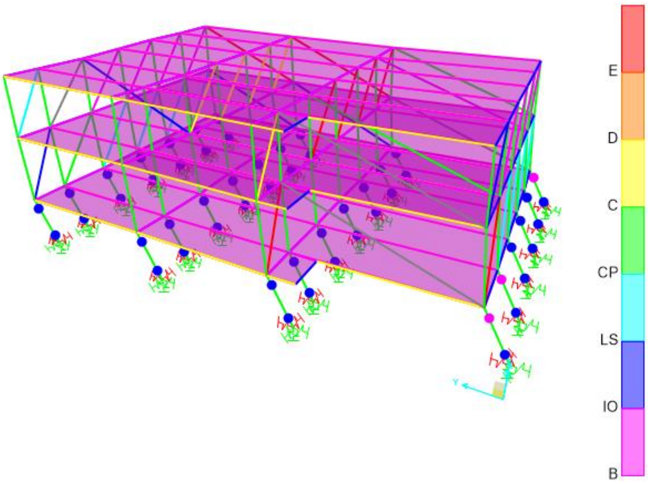

Fig. 8. Formation of plastic hinges in Y-direction for Flexible base condition

In the Figs (5-8) the colour codes for the plastic hinge is shown in terms of levels as shown in the Fig. 9. The range AB is elastic range, B to IO is the range of immediate occupancy ,IO to LS is the range of life safety and LS to CP is the range of collapse prevention

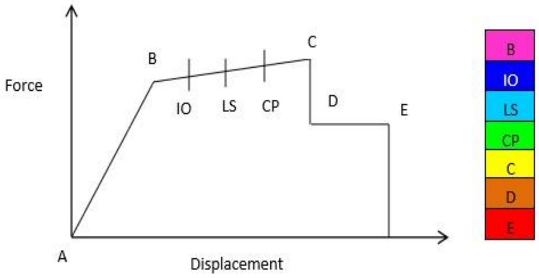

Fig. 9. Stages of plastic hinge

The plastic hinge formation starts with beam ends and base of the columns of lower stories, then propagates to upper stories and continues with the yielding of interior intermediate columns in the upper stories. Formation of plastic hinges gives an idea about the weakest structural member that can be strengthened in case the building needs to be retrofitted. In the present study, it is observed that the capacity of the building is sufficient to resist the demand imposed on it and the amount of damage in the building will be limited. However, it is clear from the Figs(5-8) that plastic hinges in case of the flexible base models are in the IO range whereas, those of the fixed base case are in the B level(lower level). It is thus concluded that, when soil flexibility effect is considered the building's seismic-vulnerability is more exposed in comparison with the case when soil-flexibility is not considered (fixed base condition). This presents a strong case for incorporating soil-flexibility in seismic analysis of buildings.

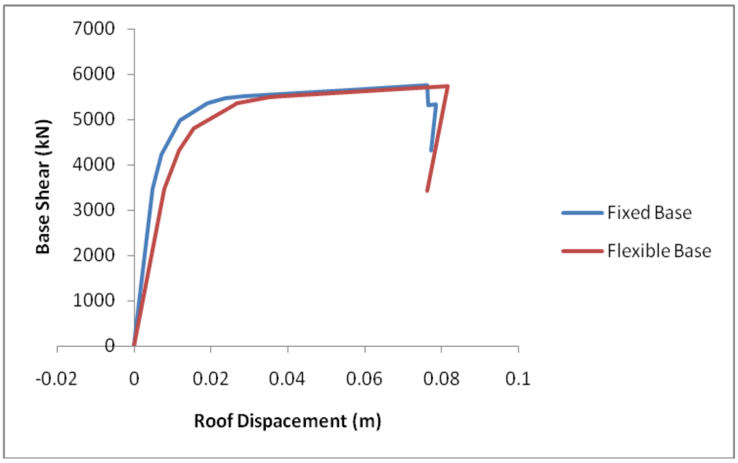

Fig. 10. Pushover capacity curve for fixed and flexible base foundation for X-axis loading

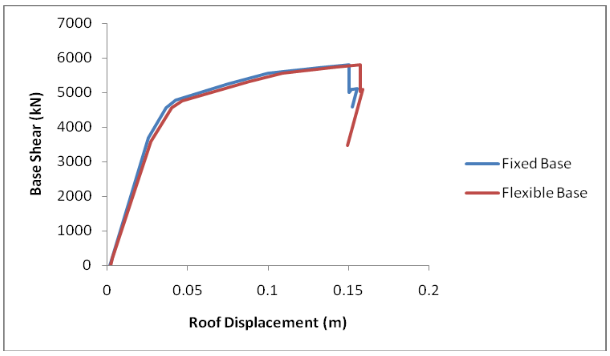

Fig. 11. Pushover capacity curve for fixed and flexible base foundation for Y-axis loading

Though the capacity curves(Fig. 10-11) show similar features for both fixed and flexible base conditions but it has been observed that the structure can undergo greater displacements for the same yielding point in case of flexible base. The ultimate collapse point for the structures with flexible base is more than that of the fixed base condition. This is again a more realistic representation of the state of the structure.

5. Conclusion

The present study emphasizes the necessity of accurate representation of the support condition for evaluation of seismic vulnerability of a structure. It is realized that the safety and serviceability aspects of the structure are downplayed in terms of deflection if the modeling is done with base as fixed, overlooking the soil flexibility effect. Further, it is realized that soil effect also changes the collapse progression in terms of development of plastic hinges. Representation of foundation soil is a prerequisite in simulating the exact nature of failure of a structure, and hence has immense significance in retrofitting of the structure.

References

1. ATC 40: Seismic evaluation and retrofit of concrete buildings, Applied Technology Council, Seismic Safety Commission, State of California, Volume 1, (1996).
2. Dange S., Kalurkar L.G.: Effect of soil structure interaction on the analysis and design of RC framed buildings. International Journal of Modern Engineering Research, IJMER, volumn 6, issue 5, May (2016).
3. IS 456 -Part I: Code of Design Reinforcement, Bureau of Indian Standards(2000).
4. IS 1893-Part I: Criteria for Earthquake Resistant Design of Structure, General Provisions and Buildings. Bureau of Indian Standard, New Delhi (2016).
5. IS:875 (Part1) :Code of practice for design loads for buildings and structures, Bureau of Indian standards, New Delhi (1897).
6. IS:875 (Part 2) :Code of practice for design loads for buildings and structures, Bureau of Indian standards, New Delhi (1897).
7. Maheswari R.U., Boominathan A., Dodagoudar G.R.: Use of Surface Waves in Statistical Correlations of Shear Wave Velocity and Penetration Resistance of Chennai Soils. Geotech Geol Eng , 28:119–137 (2010).
8. Raheem S.E.A., Mohamed M. A. and Tarek M.A.A.: Soil-Structure Interaction Effects On Seismic Response Of Multi-Story Buildings On Raft Foundation. Journal of Engineering Sciences Assiut University Faculty of Engineering, Research Gate, 17 August (2014).