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Pushover Analysis of R.C.C. Building Including 3D Soil Structure Interaction

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Abstract: The paper explores the seismic vulnerability parameters of Jorhat Engineering College taking into consideration the effects of the flexibility of supporting soil foundation system. The building is analysed using non-linear static Pushover analysis procedure. The structure is surveyed and 2D drawings detailing the plan and elevation of the building, consisting of 13 structural units, are made using Autodesk AutoCAD. The building is modelled and analysed in SAP 2000®. Infill wall loads are included and bare-frame study is done for the units. Soil flexibility is considered. The soil type of the location considered for analysis is Type II (Medium or Stiff soils) as per IS 1893:2016. The flexible base units are modelled by assigning springs to the column bases, the stiffness of which are calculated by the Gazeta's equations as per ATC-40. Translational and rotational degrees of freedom are considered for X, Y and Z axes. Both linear and non-linear analyses are performed on all the units for both longitudinal and transverse direction loadings. Plastic hinge properties are assigned to the members as per FEMA-356, to identify the critical members which have exceeded their capacities. The Displacement-Coefficient Method given by FEMA-356:2000 is employed to find the Target Displacement for the Pushover analysis. Results of the analyses show variation in the performance of the buildings with flexible base foundations.

Keywords: Flexible base foundations, Gazeta's equations, Pushover analysis, Displacement Controlled Method, Pushover Capacity Curves.

1. Introduction

Deformation and movement of foundations can significantly affect the seismic response and performance of structures during earthquakes. The response parameters are dependent upon the properties of structural and geotechnical components like the foundation stiffness, foundation strength and the prevailing soil type. The soil-structure interaction refers to the effects of the flexibility of supporting soil foundation system on the response of the structure.

During earthquakes, the soil stratum below the foundation alters the earthquake loading and varies the lateral forces acting on the structure. This in turn influences the response and performance of the building. The conventional analyses methods which assume the structures to be fixed at the base are more conservative in this regard and will not generate accurate results as compared to flexible base analysis methods. Thus, the influence of the soil type on the performance of a structure and the

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variation of response compared to the fixed base analysis is significant and must not be ignored.

This paper presents the results of an investigation aimed at evaluating the seismic performance of Jorhat Engineering College Old Building on flexible soil using non-linear static Pushover analysis procedure. The evaluation of the 59 years old building is done considering both the fixed base foundations and flexible base foundations (considering the type of soil) for both longitudinal and transverse direction loadings.

2. Building Considered

The building considered for the study is the Jorhat Engineering College Old Building of Assam, India, established in 1960 (Pic: 2.1). It is one of the most important Government Engineering Colleges of North-East India. Constructed before the 1960's, the building confirms to IS 456: 1957. The evaluation of the seismic performance is necessitated by the unreliable earlier design considerations & timely upgradation of the building codes and to ascertain if the building has adequate capacity to resist the seismic demands imposed on it for the present earthquake considerations. Initial survey work was done using measuring tape and levelling staff. A detailed drawing of the plan and elevation of the building is prepared using Autodesk AutoCAD, showing the different units that are to be modelled (Fig. 1.1). A total of 13 units are modelled independently due to the presence of expansion joints between them.

Pic.2.1: Jorhat Engineering College Old Building Bird's view.

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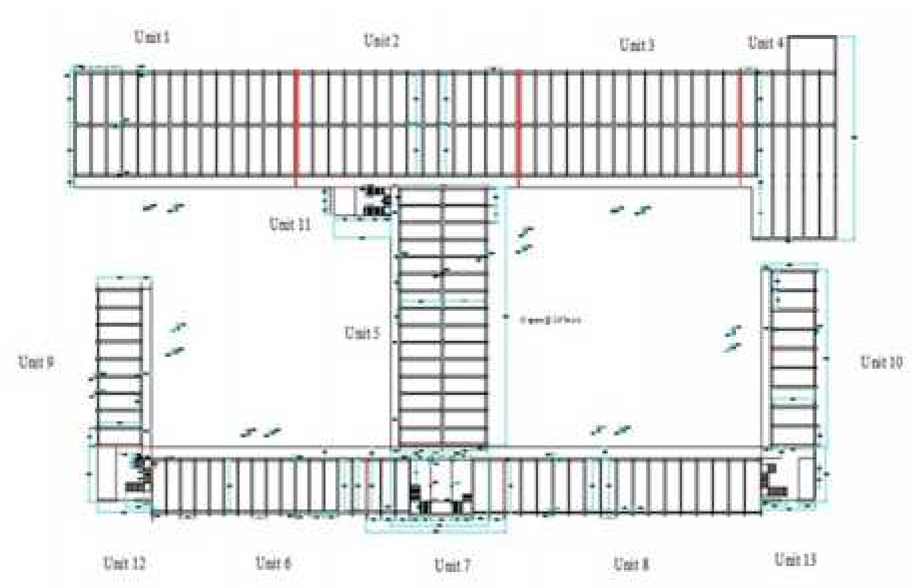

Fig.2.1: Autodesk AutoCAD drawing showing all the units that were modelled.

3. Structural Modelling

3.1 Modelling Data

The modelling data for all the units have been collected by initial survey works. The data for Unit 1 and Unit 7 are shown in Table 3.1 and Table 3.2.

Table 3.1: Modelling data of Unit 1 and Unit 7.

Unit No.	Columns (dimensions in mm)	Beams (dimensions in mm)	Slab Thickness (in mm)	Plan area (in sq.m)
Unit 1, (14 spans @ 3.35m c/c)	Column 1 : 350 × 870 mm Column 2 : 640 × 640 mm Column 3: 450 × 450 mm	Beam 1 (along Y axis) : 350 × 870 mm Beam 2 (along X axis): 380 × 970 mm	150 mm	47.25 × 20.76
Unit 7	Column 1 : 350 × 870 mm Column 2 : 420 × 420 mm Circular column 1: 0.5m (rad.) Circular column 2: 0.22m (rad)	Beam 1 (along Y axis) : 350 × 850 mm Beam 2 (along X axis): 350 × 850 mm	150 mm	29.79 × 12.14

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Table 3.2: Modelling data for the Unit 7 staircase.

Unit No.	Columns (dimensions in mm)	Treads	Plan area (sq.m)	Landing area (sq.m)
Unit 7	Column 1 : 270 × 350 mm Column 2 : 420 × 420 mm Circular column 1: 0.22 m (radius) Circular Column 2: 0.5 m (radius) Outer Column: 350 × 870 mm	1st flight : 13 no's 2nd flight: 7 no's. 3rd flight: 6 no's 4th flight: 5 no's	13 × 3.61	1st: 1.5 × 2 2nd:1.5 × 2

Column 1 refers to outer columns, Column 2 refers to intermediate columns, and Column 3 refers to interior columns. The floor to floor height of the ground floor is 4.48 m and that of the first floor is 4.14 m. Dead loads and Imposed loads are applied as per IS 875: Part 1: 1987 and IS 875: Part 2: 1987 respectively. The study is conducted for bare frames. The infill walls have not been modelled. However, the infill load is included in the analysis.

3.2 Material Specification

The grade of concrete used for the construction is found out from the Rebound Hammer test confirming to IS 13311 (Part 2): 1992 and is found to be of M20 Grade for all the units. The grade of steel is assumed to be Fe250 (Mild steel) which was normally used during the time of the construction.

3.3 Loads Applied

Dead Load: Element self-weight and mass is considered by SAP 2000®.
Infill wall loads: Floor 1: 24.192kN/m; Floor 2: 22.356kN/m; Balcony wall: 5.4kN/m
Imposed Load: Floor: 3kN/m^2; Roof: 1.5kN/m^2; Staircase: 5kN/m^2
Lateral load pattern:

- Base shear calculated as per IS: 1893 (Part 1): 2002. Applied for linear analysis.
- Response Spectrum/ Design Spectrum as per IS 1893 (Part 1): 2002 for Non-linear analysis.

4 Soil Type Considered

The type of soil considered is Soil Type II: Medium or Stiff Soils as per IS 1893 (Part 1): 2016. The soil structure interaction may not be considered in the seismic analysis of structures supported on rock or rock like material i.e. Soil type I. However, the soil present in the site is not hard soil which makes it important to include soil flexibility for the seismic analysis.

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The same soil can also be classified as per ATC-40 and ASCE 41-13 as Soil Class D i.e. S_D; stiff soil type as given by Clause 2.4.1.6.1 of ASCE 41-13 and Table 10-7 of ATC-40 (Vol. 1). The properties of the soil class are shown in Table 4.1

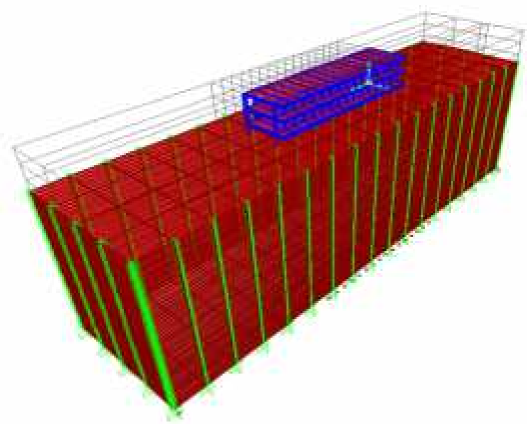
Table 4.1: Soil Classification of stiff soil (S_D) as per ATC-40

Soil Type	S_D
Classification	SW/SP/SM/SC/GM/GC
SPT N-value	$15 \leq N \leq 50$
Angle of Shearing Resistance	$33° \leq \phi \leq 40°$
Unit Weight	16 kN/m^3 to 20kN/m^3
Shear Wave Velocity	182.88 m/sec to 365.76m/sec
Undrained Shear Strength	47.8 kN/m^2 to 95.76kN/m^2

Softer and weaker soils are more likely to influence seismic response. Structures with periods ranging between 0.3 to 1 seconds are more sensitive than others to foundation effects. Soil-Structure Interaction may modify the seismic demands on a building. It can not only reduce or increase spectral accelerations and seismic forces, but also increase lateral displacements and secondary forces caused by P-Δ effects.

5 Foundation Modelling

Initial foundation modelling was done considering the structure along with the soil strata (Fig. 5.1 (a)). But due to the inherent limitation of SAP2000® in assigning the interaction between the structure and the soil, better and alternative methods were employed (Sarkar et al. (2014)). In the present study, springs (Uncoupled Component Model as suggested by ATC-40) are assigned to the column bases of all the structural unit models and their stiffnesses are calculated as per Gazeta's equation given in ATC-40; Vol. 1 (Table 10-2, 10-3). The supports no more behave like a fixed base and have translational and rotational degrees of freedom due to the flexibility of the soil. Spring assignments as per ATC-40 are shown in Fig. 5.1 (b).



a)

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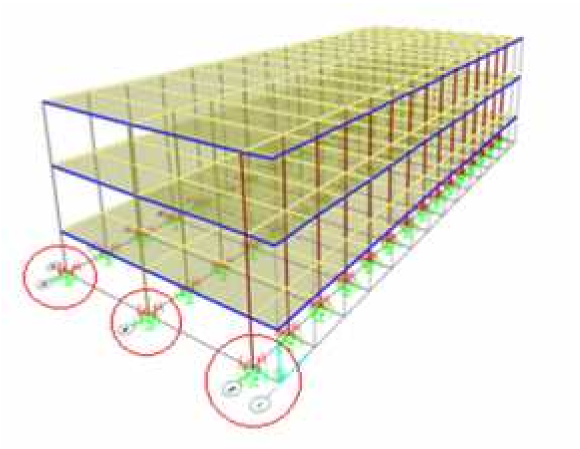

b)

Fig. 5.1: a) Initial foundation soil modelling done considering the soil stratum and **b)** Uncoupled Component Model as suggested by ATC-40, assigning springs to the column bases.

5.1 Bearing Stiffness Parameters (Gazeta's Equations)

The bearing stiffness parameters are determined from Gazeta's (1991) equations as suggested in ATC-40. (The Code is also suggested by IITK-GSDMA, in their commentary for Sixth Revision of IS 1893-Part 1: 2002).

The basic steps for determining the stiffness properties of shallow bearing geotechnical components are as follows:

1) Determine the uncoupled total surface stiffnesses K_i, 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 stiffnesses K_i for the effects of the depth of bearing by multiplying by the embedment factors, e_i, to generate uncoupled total stiffness.

The surface stiffnesses and stiffness embedment factors for shallow footings considered as rigid plate on a semi infinite homogenous Elastic Half Space are calculated from Gazeta's equations; 1991, (ATC-40), Table: 10-2 and Table 10-3 respectively.

Once the stiffnesses are calculated, their values are assigned to the springs at the column bases to mimic the soil characteristics and its flexibility. Values are assigned for translation in x, y and z direction ($k_{x,}$ k_y and $k_{z)}$ and rotation in x and y directions ($k_{\Theta x}$ and $k_{\Theta y}$).

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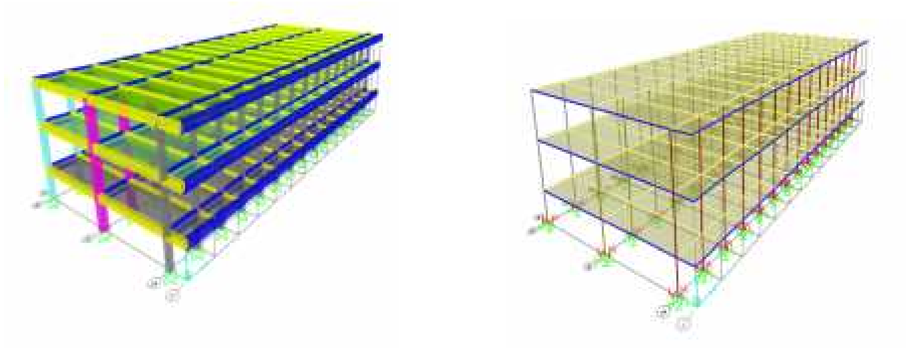
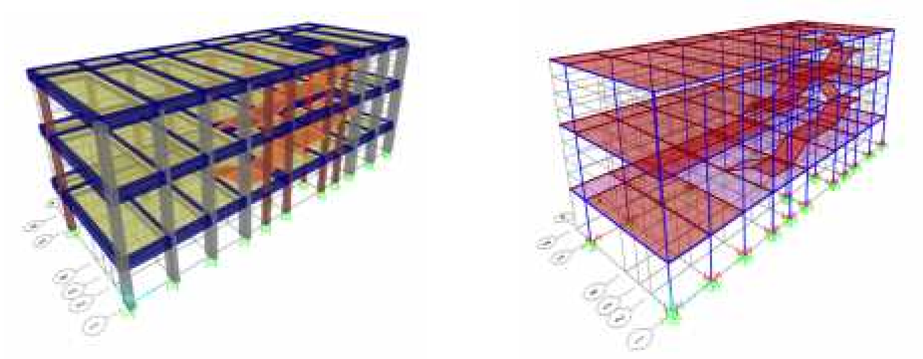
6 Structural Unit Models (Fixed and Flexible Base Foundations)



a) b)

Fig 6.1: Unit 1 modelled with Fixed and Flexible base Foundations: a) Fixed Base Model and b) Flexible Base Model (springs are assigned).



a) b)

Fig 6.2: Unit 7 modelled with Fixed and Flexible base Foundations: a) Fixed Base Model and b) Flexible Base Model (springs are assigned).

Similarly, all the structural units are modelled with fixed and flexible base foundations and are analysed for both longitudinal and transverse directional loadings.

7 Results and Discussion

7.1 Pushover Capacity Curves

The Pushover Capacity curves show how the building will behave before collapsing during an earthquake. For all the units with both flexible and fixed base foundations the curves show similar features. These are initially linear but start to deviate from linearity once the beams and columns undergo inelastic actions. When the buildings

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are pushed well into the inelastic range, the curves become linear again but with a smaller slope.

Considering the soil type and characteristics, it shows that the units with flexible base foundations can undergo greater displacements for the same yielding point. The ultimate collapse point for structures with flexible bases is also more than that of the structures with fixed base foundations.

The Pushover Capacity curves for two units namely Unit 1 and Unit 7 for both fixed and flexible base foundations for longitudinal axis loading are shown in Fig. 7.1 and Fig. 7.2 respectively.

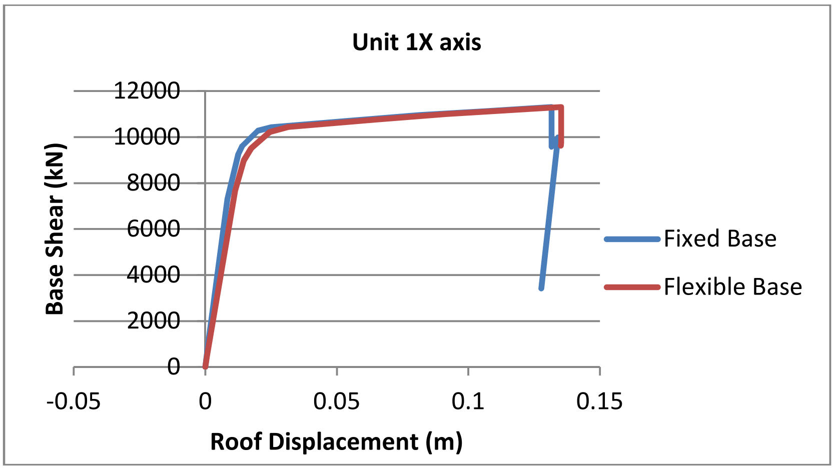

Fig 7.1: Pushover Capacity curves for Fixed and Flexible base foundations for Unit 1 for X axis loading.

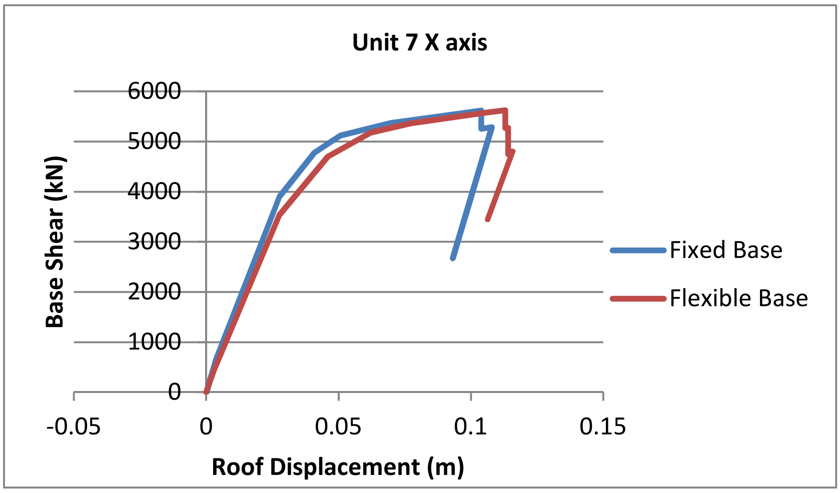

Fig 7.2: Pushover Capacity curves for Fixed and Flexible base foundations for Unit 7, for X axis loading.

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7.2 Hinge Details

The target displacements are calculated for all the units with fixed and flexible base foundations for both longitudinal and transverse axis loadings as per FEMA-356:2000.

The units are then pushed to their respective Target Displacements to monitor the different stages of Hinge Formation, their location and the failure mechanism. Three important performance levels are Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The numbers of hinges in different stages of formations for the units are tabulated in Table 7.1.

Table 7.1: Hinge Details of the structural units with flexible base foundations at their respective Target Displacements.

Unit No.	Pushover Direction	Target Displacement (mm)	No. of Hinges in different stages of formation in the post-elastic range			
			A-B	**B-IO**	**IO-LS**	**LS-CP**
1	Push X	52.80	-	73	67	0
	Push Y	68.92	-	80	57	0
2	Push X	52.80	-	73	67	0
	Push Y	68.92	-	80	57	0
3	Push X	52.80	-	73	67	0
	Push Y	68.92	-	80	57	0
4	Push X	74.45	-	45	39	0
	Push Y	70.34	-	35	49	0
5	Push X	67.47	-	79	48	0
	Push Y	50.96	-	45	89	0
6	Push X	71.72	-	48	48	0
	Push Y	68.91	-	79	35	0
7	Push X	54.14	-	42	35	0
	Push Y	71.72	-	43	25	0
8	Push X	73.21	-	58	46	0
	Push Y	71.72	-	25	68	0
9	Push X	95.79	-	18	42	0
	Push Y	98.99	-	21	38	0
10	Push X	85.18	-	16	44	0
	Push Y	88.42	-	21	48	0
11	Push X	42.66	-	23	6	0
	Push Y	65.42	-	16	8	0
12	Push X	68.92	-	20	11	0
	Push Y	80.38	-	22	11	0
13	Push X	68.92	-	23	2	0
	Push Y	82.46	-	14	8	0

7.3 Pounding

Pounding is the phenomenon of collision or hammering between adjacent buildings or different parts of the same building during strong earthquake motion when the two buildings oscillate towards each other.

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The Indian seismic code IS: 1893(Part 1): 2016 recommends that the separation between two adjacent units or buildings shall be at a distance equal to

$$\Delta_{separation} = (R_1 \Delta_1 + R_2 \Delta_2) \quad (7.1)$$

where R_1 and Δ_1 are response reduction factor and storey displacements corresponding to unit 1 & R_2 and Δ_2 are response reduction factor and storey displacements corresponding to unit 2. The likelihood of pounding between the flexible base units is tabulated in Table 7.2.

Table 7.2: Likelihood of occurrence of pounding between units with flexible base foundations.

Pounding Between Unit no.	Δ_1(mm)	Δ_2(mm)	IS 1893: 2016, specification for separation (mm)	Separation measured between the units (mm)	Occurrence of Pounding
1,2	13.32	13.32	79.92	110	NO
2,3	13.32	13.32	79.92	115	NO
3,4	13.32	14.40	83.16	115	NO
2,5	17.34	12.95	90.87	70	YES
2,11	17.34	21.5	116.52	50	YES
5,11	16.60	11.50	84.30	75	YES
5,7	12.95	17.25	90.60	80	YES
6,7	19.46	12.60	96.18	80	YES
7,8	12.60	21.59	102.57	80	YES
6,12	19.46	22.91	127.11	80	YES
12,9	27.98	17.97	137.85	80	YES
8,13	21.59	20.99	127.74	70	YES
13,10	20.12	15.42	106.62	60	YES

7.4 Fundamental Period

The fundamental period is an inherent property of a structure and is the shortest natural frequency or the longest time period of vibration for the first mode. The periods observed for the structural unit models with fixed and flexible bases are tabulated in Table 7.3.

Table 7.3: Fundamental period (seconds) observed for structural units with fixed base and flexible base foundation.

Unit No.	Fundamental Period (seconds)	
	Fixed Base	Flexible Base
Unit 1	0.47	0.50
Unit 2	0.47	0.50
Unit 3	0.47	0.50
Unit 4	0.53	0.56
Unit 5	0.46	0.49
Unit 6	0.52	0.55
Unit 7	0.47	0.51

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Unit 8	0.54	0.57
Unit 9	0.76	0.77
Unit 10	0.65	0.68
Unit 11	0.46	0.48
Unit 12	0.58	0.62
Unit 13	0.62	0.64

7.5 Lateral Displacements

The lateral displacements are found out for the applied earthquake motion for units with fixed base and flexible base foundations against both longitudinal and transverse axis loadings. The lateral displacements are tabulated in Table 7.4.

Table 7.4: Lateral displacements (mm) observed for units with fixed base and flexible base foundations for X-axis loading and Y-axis loading.

Unit No.	Lateral Displacement for X Axis Loading (mm)		Lateral Displacement for Y Axis Loading (mm)	
	Fixed Base	Flexible Base	Fixed Base	Flexible Base
Unit 1	11.48	13.32	15.37	17.34
Unit 2	11.48	13.32	15.37	17.34
Unit 3	11.48	13.32	15.37	17.34
Unit 4	13.08	14.40	16.42	18.29
Unit 5	14.81	16.60	10.99	12.95
Unit 6	18.01	19.46	14.99	17.95
Unit 7	9.92	12.60	14.47	17.25
Unit 8	20.45	21.59	19.41	21.68
Unit 9	25.59	26.95	16.64	17.97
Unit 10	23.30	24.99	14.87	15.42
Unit 11	9.22	11.5	17.37	21.5
Unit 12	18.66	22.91	25.99	27.98
Unit 13	19.85	20.99	16.33	20.12

10. Conclusion

The analysis of the 59 years old JEC building was done with an aim to evaluate its seismic performance for the present earthquake considerations. The analyses conclude that:

- Considering the soil type, the demand displacement likely to be faced were more for units with flexible base foundations. More displacements will hence lead to greater loss of stiffness of members and the structure as a whole.
- From the number of hinges in different stages of formation, it can also be seen that greater number of hinges in both the IO and LS levels are formed in case of flexible bases.

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- The fundamental periods for the units with flexible base foundation were also observed to be longer than their fixed base counterparts. This means greater spectral accelerations and variation in the performance of the structure, which is any case must not be neglected.
- The probability of occurrence of pounding is more for units with flexible base foundations on account of increased lateral displacements for the applied earthquake motion.
- This age old public building satisfies the life safety (LS) performance objective for the present earthquake considerations with likely pounding between all the units except 1 and 2, 2 and 3 & 3and 4. The stages of hinges formed in all the units for their respective target displacements were under the LS Performance Objective.

The inclusion of soil type and its characteristics in the seismic evaluation shows that there is much variation in the response of the structure and its performance under earthquake loading. The fixed base analyses results though are admissible but are not accurate which can be seen in the results of this study.

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