NON-LINEAR STATIC ANALYSIS OF MOMENT RESISTING RC STRUCTURES OF VARIOUS GEOMETRY BY CONSIDERING SOIL STRUCTURE INTERACTION

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Abstract - *Pushover analysis, also known as nonlinear static analysis, is a widely used method for assessing the seismic performance of structures. This study applies pushover analysis to evaluate a G+10 multistoried building under different most sever seismic zone using ETABS21.2.0 software. The results evaluate the behavior of the structure in terms of the maximum displacement corresponding to the base shear. Additionally, the research examines the influence of Soil-Structure Interaction (SSI) on the seismic performance of the building, comparing models of various geometry with and without SSI considerations. The symmetric-plan reinforced concrete (RC) building is designed following IS 456:2000 guidelines and analyzed using ETABS21.2.0 software under two boundary conditions: fixed-base and nonlinear static pushover analysis accounting for soil-structure interaction.*

Key Words: RC frame, Soil Structure Interaction (SSI), Pushover analysis, Soil type, Support Conditions, Plastic Hinges, Performance Point.

1.INTRODUCTION

An effectively engineered structure must exhibit four key qualities: straight forward and organic design, strong lateral stability, ample stiffness, and sufficient ductility.

Buildings with a standard, straightforward configuration tend to sustain less damage in both design and elevation compared to those with irregular configurations. According to IS 1893-2016, a construction project is considered irregular when it lacks uniformity in configuration, mass distribution, or capacity-resistant elements. Such irregularities can disrupt the continuity of force flow and stress concentrations.

This study primarily aims to assess how a structure responds under various external influences. These influences include gust or wind pressure, vibrations, traffic movement, blasts, and seismic activity. Any design can be subjected to unpredictable loads, making structural configuration a critical factor in determining a building's overall performance. In the case of severe earthquakes, structural imbalance can result in excessive lateral loading, overwhelming the building's capacity and leading to significant damage

Soil-Structure Interaction (SSI) describes how a structure and its foundation soil influence each other under external forces, particularly lateral loads like earthquakes. The soil's flexibility affects displacement, stability, and internal forces, making this interaction crucial in soft or layered soil conditions.

Pushover Analysis is a nonlinear static approach of designed to find out a structure's behavior under lateral loading conditions. By gradually applying increasing loads, the analysis tracks deformation and the formation of plastic hinges, offering insights into structural behavior during seismic events.

Soil-Structure Interaction (SSI) refers to the process in which seismic activity affects both the underground soil and the structure above it, creating a mutual influence. As the ground moves, the structure's response alters the soil movement, leading to a dynamic relationship between the two. While SSI has a negligible impact on rigid soil and low-rise structures, it becomes a crucial factor in designs involving soft soil, high-rise buildings, roadways, heavy structures, nuclear power plants, and hydraulic systems.

This simplified approach may be suitable for certain structures and soil types, such as lightweight buildings on relatively firm ground. However, this assumption does not always hold. Ignoring SSI in structural analysis can negatively influence stability and lead to unsafe designs, affecting both the superstructure and the foundation.

2. LITERATUR REVIEW

Jonathan P. Stewart (1) Outlined approaches to assess the influence of inertial soil-structure interaction (SSI) on the seismic behavior of structures. Their approach builds on existing building code provisions, offering improvements by including the effects of foundation embedding, flexibility, and shape on site conditions and foundation impedance. Using data from buildings impacted by the 1994 Northridge earthquake, the authors demonstrated the accuracy of their methods in predicting SSI effects.

The study involved two primary analyses:

1. A simplified design approach to predict the period extension ratio and foundation damping coefficients for structures with surface (MV) or embedded (MV or MB) foundations.
2. A system identification method to determine the modal vibration parameters of structures with fixed and flexible bases using strong seismic motion data.

Uncertainties in applying MV and MB methods arise from factors such as impedance function evaluations, shear wave velocity profiling, and limitations in modeling embedded foundations—especially when basement walls are discontinuous. Features like oval-shaped foundations or flexible support for rigid shear walls also require careful consideration. Despite challenges with disturbances in seismic data and numerical inaccuracies, the parametric system identification process offers a reliable framework for evaluating modal vibration parameters, provided nonlinear structural responses are appropriately characterized.

Mathew et al. [2] conducted an analysis of a nine-story reinforced concrete (RC) building with an asymmetrical plan, located in seismic zone III, using SAP2000. Author has performed nonlinear static pushover analysis to understand the behavior of building resting on non-cohesive soil such as soft soil and rock under the impact of SSI. The properties for these soil types were defined according to ATC 40 standards. The study compared three scenarios: a fixed base without considering soil-structure interaction, a flexible base incorporating SSI into hard soil conditions, and a flexible base incorporating SSI in soft soil conditions. As per Richart and Lysmer model spring constant and corresponding displacement value for different soil strata were compared.

Ghandil and Behnamfar [3] explored the direct method of soil-structure interaction (SSI) analysis by performing dynamic non-linear time history analysis using earthquake records. They assessed structural responses under different soil behavior assumptions, including elasto-plastic, Mohr–Coulomb, equivalent linear, and a newly proposed modified equivalent linear approach. Their study examined six 3D steel buildings, ranging from 5 to 30 stories in height, all modeled using SAP2000 software. They evaluated maximum lateral story displacements and maximum story shear values for each building, both with and without SSI, to determine the impact of soil behavior on structural performance.

3. OBJECTIVES

1. To prepare the Etabs models and perform Nonlinear static push over analysis for various geometries of the building viz. viz. rectangular shape, L-shaped, C Shape, I Shape.
2. To evaluate the base shear and corresponding displacement of the structure.
3. To find out the performance point and corresponding shear force.
4. To compare seismic performance with and without consideration of the soil structure interaction process.
5. To find out the best shape of the building which shows good seismic performance with and without soil structure interactions.
6. To find and state the reason for the structure shows the poor behavior seismic performance.

4. METHODOLOGY & MODELING

Pushover Analysis is a nonlinear static approach used to evaluate a structure's behavior under lateral forces such as earthquakes. By incrementally applying lateral loads, the method identifies yielding points, the formation of plastic hinges, and the structure's response in the inelastic range, helping assess potential collapse mechanisms.

The capacity curve generated from this analysis plots base shear against roof displacement, illustrating how structural components yield and form plastic hinges while determining the structure's ultimate capacity. Integrating this with Soil-Structure Interaction (SSI) enhances the accuracy of seismic evaluations, leading to safer designs, particularly for high-rise RCC buildings in varying soil conditions. The core concept of Pushover Analysis is governed by the following equation.

$$[K]\cdot\{\Delta\}+\{P\}NL=\{F\}$$

Where:

- [K]: Tangent stiffness matrix (updated as structure yields)
- {Δ}: Displacement vector
- {P}NL: Nonlinear internal force vector (due to plasticity)
- {F}: Applied external lateral force vector

In this study, a seismic analysis is performed on a G+10 reinforced concrete moment-resisting building frame. The various geometry considered for the study viz. rectangular shape, L-shaped, C Shape, I Shape layout with square grid dimension, the total height considered of 30 m from ground level. The plinth level is considered at 3 m above the base, with each floor maintaining a uniform height of 3 m.

Four different support conditions are considered in the study:

1. Building with a infinite rigidity (Restraint against both rotation & translation in X, Y & Z direction)
2. Building on hard soil base condition.
3. Building on medium soil base condition
4. Building on soft soil base condition.

ETABS 21.2.0 is used to create & analyze a 3D model of a 10-story reinforced concrete (RC) structure. Beams and columns are represented as beam elements, each having six degrees of freedom at their nodes. The slab functions shell as a rigid diaphragm, distributing horizontal forces to the columns. Steel is modeled using bar elements, while concrete is represented as beam elements, with perfect bonding assumed between materials. The line elements incorporate material grades of M30 for concrete and Fe 500 for steel.

Table -1: RCC section properties of all structural members

COLUMNS	BEAMS	SLABS
C:700X700M-30	B:300X600-M30	S:125M-30

All the structures of various geometries are modeled and analyzed by considering the most severe earthquake zone i.e. zone V and zone factors consider Z=0.36. The response reduction factor considered for the analysis as R=5 by considering all the beams and columns as ductile. The soil type is considered type-I for fixed support condition and hard soil condition, soil type-II considered for medium soil condition, soil type III considered for medium soil condition. The earthquake static load cases viz. EQX in X direction & EQY in Y directions are assigned in modeled. The PushY in Y directions are assigned in modeled. The mass source has been defined as factor 1 for dead load and factor of 0.25 taken for the lived load since the live load assigns for the structure as 2 kn per sq.m. Also, the dead load considered as 1.5 kn per sq.m as floor finish. The static nonlinear gravity defined for the pushover analysis with full load condition. The hinges for the columns and beams are assigned at both the ends of the respective columns and beams at 100mm from ach end.

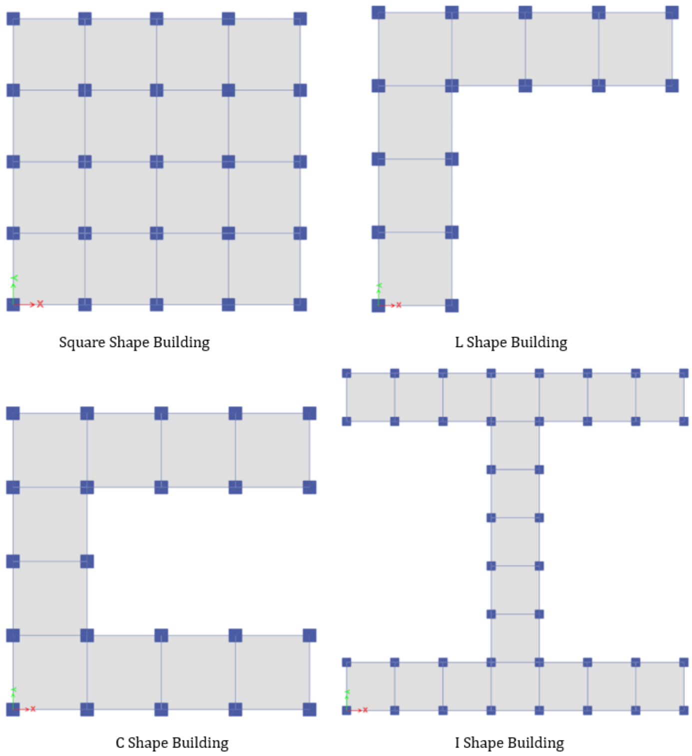


Fig -1: Plan view of ETABS Square, L, C & I Shape Building

The above snap shows the difference shape modeled In the Etabs software. The square building shows symmetry from all four sides of the building and the I shape building shows the symmetry about the horizontal as well as vertical axis of the plan. However, the L and C shape building shows the unsymmetric and shows one re-entrant corner in the L shape building whereas the C shape building shows the 2 re-entrant corner in the same building. The centroid of the building of every shape has different location in the plan which may further cause variation of the load distribution in the structure and provide the different structural behavior.

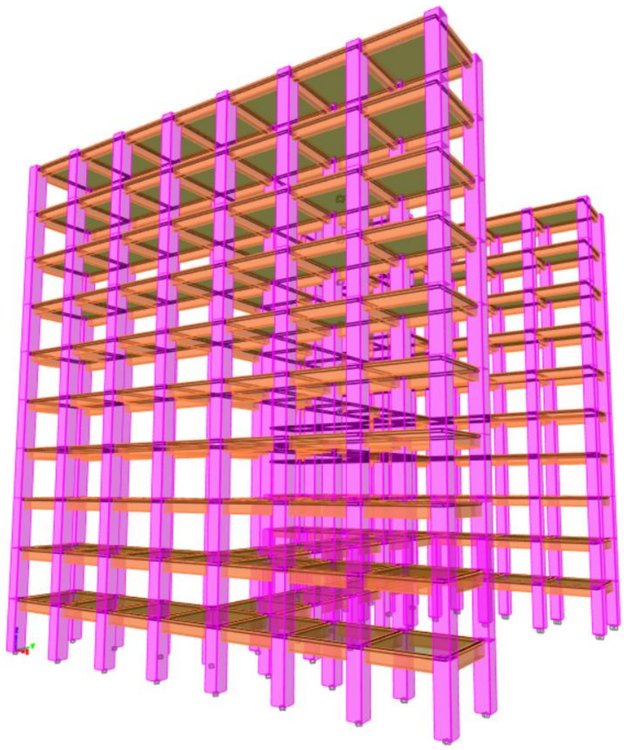


Fig -2: 3D Rendered view of ETABS Model with Fixed Base Support Condition.

In a fixed-base scenario, the coordinate points indicate the placement of columns according to the base layout of the structure. All these points are constrained in six degrees of freedom: three translational (ux, uy, uz) and three rotational (rx, ry, rz). This ensures that neither linear nor rotational displacements occur, maintaining complete stability.

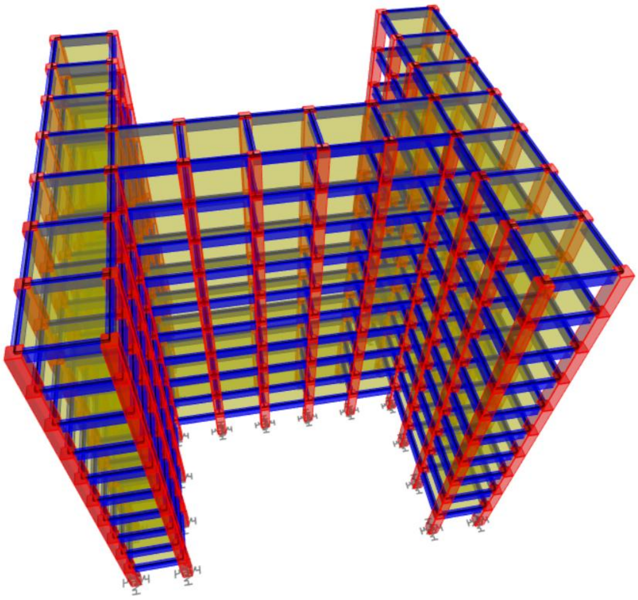


Fig -3: 3D Rendered view of ETABS Model with Different Soil Base Support Condition (Hard, Medium & Soft).

This involves modeling a building on a raft foundation to simulate the effects of Soil Structure Interaction (SSI) for various soil types-soft, medium, and hard. The process includes:

- Utilizing a building model with its foundation as depicted in Figure 3.
- Table 2 shows the properties of soil strata.
- Meshing the entire area using quad shell elements and applying a soil layer to capture the interaction between the foundation and the soil.

Such simulations are essential for analyzing how different soil conditions influence the stability and behavior of structures.

	Unit Weight (γ) kN/m³	Shear Modulus (G) kN/m²	Poisson's Ratio (ν)	Cohesion (c)	Friction Angle (ϕ')	Shear Wave Velocity (Vs) [m/s]	Modulus of Elasticity (kN/m²)
Fixed Condition	Infinitely Rigid						
Hard Soil	20	90000	0.42	75	40	500000	255600
Medium Soil	16	30000	0.46	48	27	250000	87600
Soft Soil	12	18000	0.48	35	21	140000	53280

Table -2: Soil Layer Properties

In this study, Linear static and Nonlinear Static (pushover Analysis) is performed to understand the behavior of the structure under different soil conditions. In this research the hinge formation pattern for this has been studied and based on that the behavior of hinges are as follows,

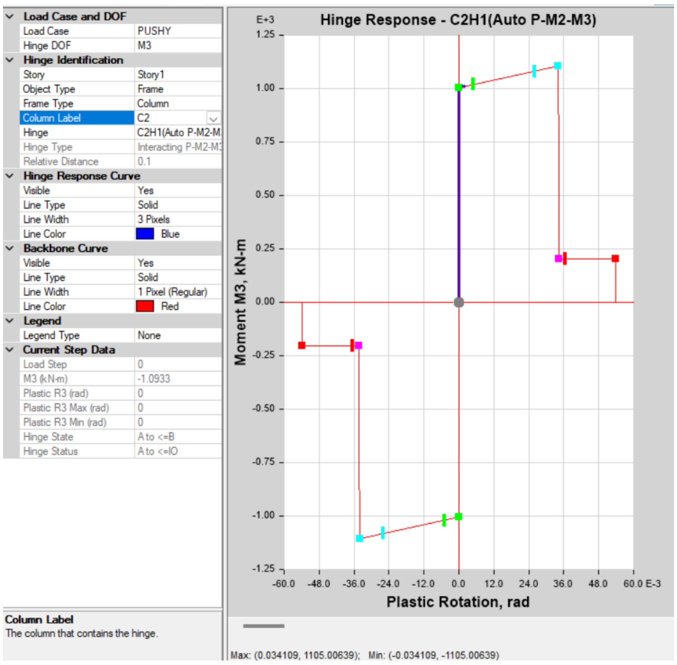


Fig -3: Shows Hinge formation details

The majority of hinges have formed within the IO-LS range, indicating minor structural damage and an insignificant risk to life. While some structural elements have experienced notable damage, they retain residual strength, ensuring a low however for the unsymmetrical building hinges in threat to occupants.

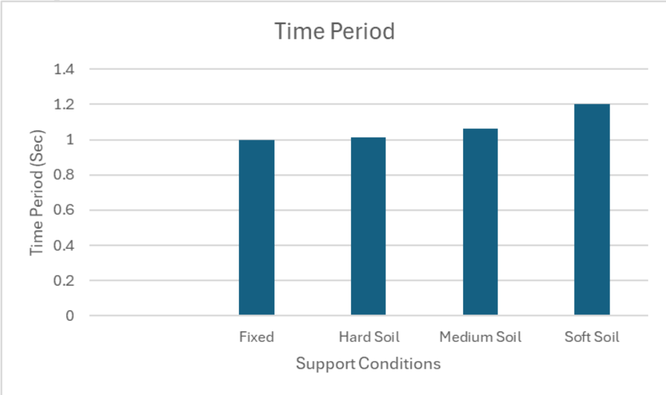


Chart-1: Chart shows comparison of time for various base support conditions

The above graph shows the impact of soil condition on the time period for structure, also it is noticed that, for soft soil condition's structure behaves more flexible compared to other soil strata. The same behavior was observed under the roof displacement criteria.
Below graph shows the relation between the displacement and base shear for fixed based condition, hard, medium and soft soil condition. Also, it is observed that displacement is maximum in case of soft soil compared to other soil strata, while the base shear is also found maximum in the same case.

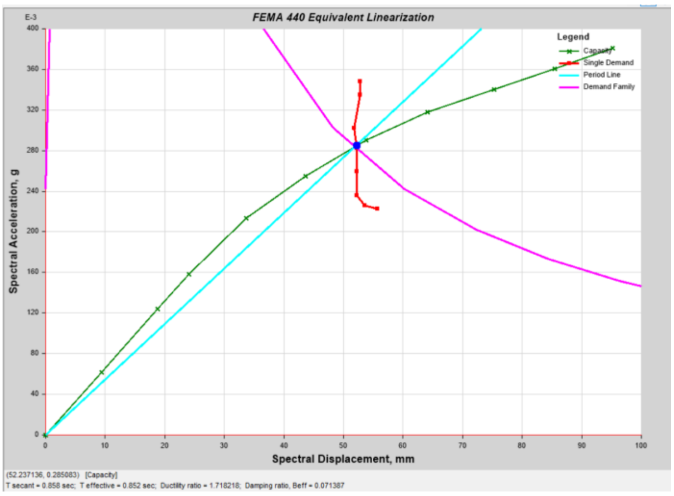
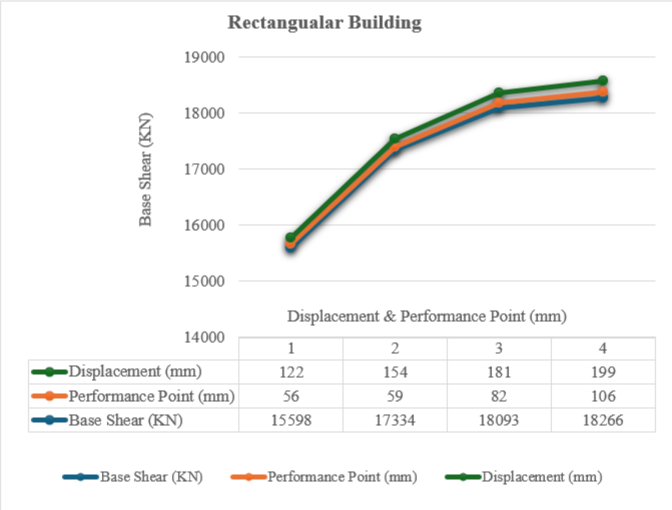


Fig -4: Shows Performance point location

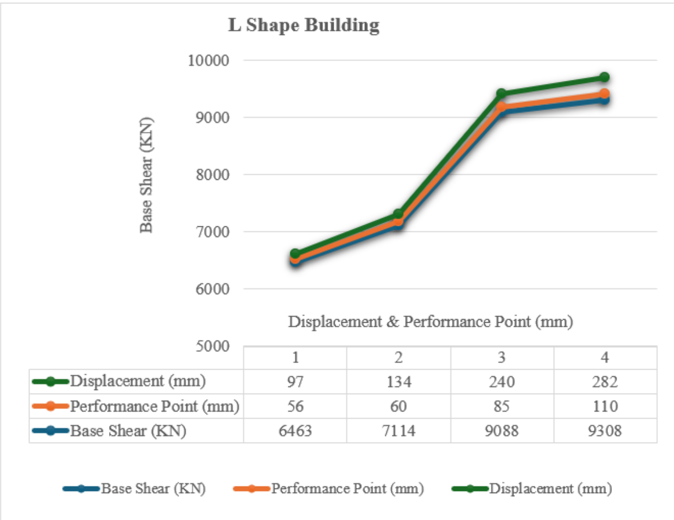
Stiffness of equivalent soil spring (KN/m)						
Base Condition	Horizontal (longitudinal direction)	Horizontal (lateral direction)	Vertical	Rocking (about the longitudinal)	Rocking (about the lateral)	Torsion
Fixed Base	Infinitely Rigid					
Hard soil	948418	948418	1303293	3535345	3657253	465553
Medium soil	324351	324351	466611	1265741	1309387	155184
Soft soil	197171	197171	290735	788654	815849	93111

Table -3: Shows Stiffness equivalent soil spring.



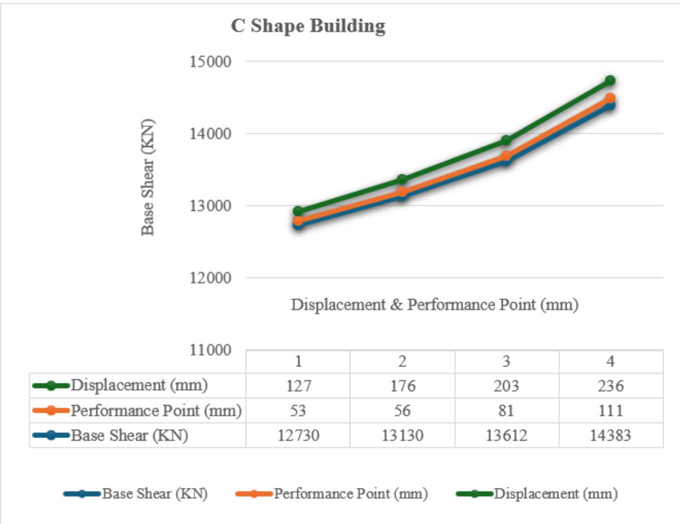
	1	2	3	4
Displacement (mm)	122	154	181	199
Performance Point (mm)	56	59	82	106
Base Shear (KN)	15598	17334	18093	18266

Chart 2: Chart shows the relation of base shear vs displacement & performance point for Rectangular Building.



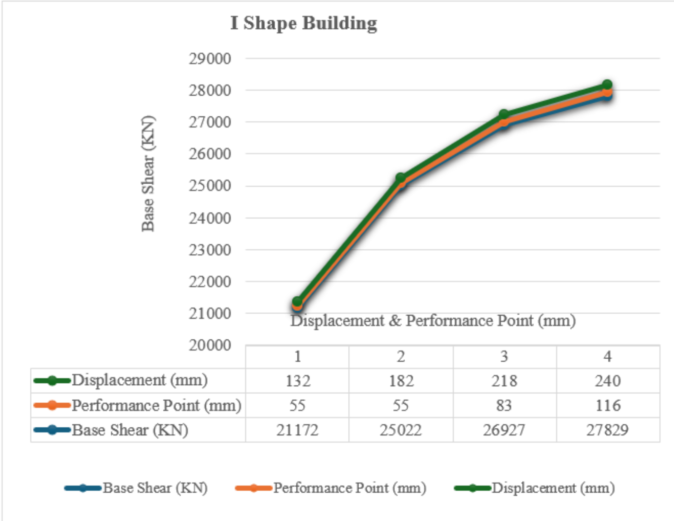
	1	2	3	4
Displacement (mm)	97	134	240	282
Performance Point (mm)	56	60	85	110
Base Shear (KN)	6463	7114	9088	9308

Chart 3: Chart shows the relation of base shear vs displacement & performance point for L Shape Building.



	1	2	3	4
Displacement (mm)	127	176	203	236
Performance Point (mm)	53	56	81	111
Base Shear (KN)	12730	13130	13612	14383

Chart 3: Chart shows the relation of base shear vs displacement & performance point for C Shape Building.



	1	2	3	4
Displacement (mm)	132	182	218	240
Performance Point (mm)	55	55	83	116
Base Shear (KN)	21172	25022	26927	27829

Chart 3: Chart shows the relation of base shear vs displacement & performance point for I Shape Building.

5. CONCLUSIONS

1. The percentage difference of displacement between hard soil and medium soil of square shape building & Symmetrical I shape building is 15%. Whereas for L shape building is 44%.
2. The percentage difference of displacement between medium soil and soft soil of square shape building & Symmetrical I shape building is 9%. Whereas for L shape building is 15%.
3. Hence from observation mentioned in point-1 & 2 of conclusion, it observes that there is large displacement occurs in unsymmetrical buildings as compared to symmetrical or square shape building.
4. In L Shape Building for Hard soil, Greater the moment of inertia leads more will be the stiffness of the structure and lesser will be the displacement hence even if the lesser value of base shear for L shape building causing the higher value of displacement is just because of the moment of inertia is lesser of L shape building as compared with other shape building viz Rectangular, C shape, I shape building .
5. In L shape building in hard soil, the value of the displacement is less as compare with the l shape building in Medium & soft soil even after moment of inertia of the L shape building is same in all condition of soil the stiffness of the structure is also depends on the Modulus of elasticity of the material since the value of modulus of elasticity for hard soil is greater than medium & soft soil hence the stiffness of the building in Hard soil is considerably more as compared with the stiffness of same L shape building in medium & soft soil.
6. Square shape and Symmetrical I shape building show good performance in such aggressive seismic zones as compared to C shape & L Shape buildings.
7. Soil-structure interaction (SSI) may contribute to an increase in seismic base shear and prolong the

natural period of building frames. This impact is more pronounced in soft soils due to their lower stiffness compared to harder soils.

8. In interaction analysis, the soil mass is assumed to be uniform and isotropic, capable of exhibiting both linear and nonlinear behavior.
9. Incorporating SSI results in increased roof displacement and story displacement.
10. Mass participation in the third mode reaches 77% for structures with fixed bases across hard, medium, and soft soil conditions.
11. Story drift is observed on the second floor of the structure in all considered soil conditions (fixed base, hard, medium, and soft). The maximum drift occurs at the second floor when the structure is situated on soft soil.
12. The highest base shear is recorded for the structure positioned on soft soil.

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BIOGRAPHIES

Pushkar Chavan has over 11 years of experience in civil and structural engineering. He specializes in analyzing and designing RCC structures for industries like data centers, healthcare, hospitality, and residential buildings. His role includes reviewing designs, tender specifications, and cost estimates, while coordinating with clients, site teams, and other disciplines to ensure smooth project execution.

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