Study of Earth Quake Response of Plan-Irregular Structure, Considering soil Variability across different Seismic regions, using CYPE Software

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Abstract : This study investigates the seismic performance of irregular trapezoidal buildings founded on soft soil, focusing on the complex design issues that emerge from combined influences such as variations in seismic zones and the nonlinear behavior of soil during earthquakes. The analysis indicates that the irregular shape results in non-uniform stiffness and mass distribution, which in turn leads to torsional responses and greater seismic loads. Findings show the structure's vulnerability to lateral displacement, story drift, and alterations in stiffness when subjected to dynamic forces. The research highlights the necessity of adopting structure-specific design approaches to improve the earthquake resistance of irregular buildings resting on soft ground in highly seismic regions.

I. INTRODUCTION

The principles of seismic design are predicated on the concept of regularity. Buildings with symmetrical plans and a uniform distribution of mass and stiffness exhibit a more predictable and uniform response to lateral loads, such as those generated during an earthquake. This predictability ensures a direct and smooth flow of inertia forces from the upper stories to the foundation, which is a key virtue of earthquake-resistant design. The regular configuration provides inherent redundancy and direct load paths, which minimize stress concentrations and tensional effects. In stark contrast, irregular buildings, including those with a trapezoidal plan, are defined by discontinuities in mass, stiffness, or geometry. These discontinuities result in complex and often unpredictable dynamic responses, leading to stress concentrations, amplified displacements, and significant torsional effects. The trapezoidal plan is not a single irregularity but rather a geometric precursor that initiates a cascade of compounding seismic vulnerabilities. The non-orthogonal alignment of its sides directly creates a nonparallel system irregularity, as vertical lateral force-resisting elements are not parallel to the main orthogonal axes. This geometrical feature makes it inherently difficult to achieve a symmetrical distribution of mass and stiffness, leading to a significant eccentricity between the center of mass (CM) and the center of rigidity (CR). This eccentricity is the root cause of torsion amplification and floor rotation, which, in turn, imposes high stress concentrations, especially at the acute-angled corners of the trapezoid.

Building codes do not specifically identify a "Trapezoidal plan" as a structural irregularity. Instead, these guidelines concentrate on the seismic performance issues that such layouts can trigger, notably torsion irregularity and the presence of re-entrant corners. This part shows how various international codes define and address the irregularities resulting from such forms,outlining the criteria and penalties applied when these specific behavioral challenges occur.

Need of the study

The purpose of analyzing anomalous trapezoidal structures with CYPE is to understand how they behave under seismic loads and compare their results. Key objectives include evaluating structural responses to seismic forces, identifying irregularities in mass or stiffness that affect seismic performance, and refining design methods to improve resistance and minimize displacement. The study also explores how soil-structure interaction influences the overall seismic response, especially for flexible buildings on soft soils where seismic demands may be amplified or reduced.

1.1 Seismic Zone Classification

Regions across the world are divided into Earthquake zones based on how prone they are to earthquakes, and the likely intensity of those events. This categorization supports urban planning decisions, the creation of safety regulations for structures, and the preparation of disaster management strategies:

- **Zone II (Minimal Hazard):** These areas experience very few and weak tremors, mostly registering less than magnitude 4.9 on the Richter scale.
- **Zone III (Moderate Hazard):** Earthquake occurrences here are more likely, and typical magnitudes range between 5 and 6.
- **Zone IV (High Hazard):** These locations are exposed to more frequent and stronger tremors, with earthquake magnitudes moving between 6 and 6.9.
- **Zone V (Severe Hazard):** This category covers the most vulnerable areas, with earthquakes potentially exceeding magnitude 7 these regions require especially stringent building safety norms and emergency protocols.

Different countries implement seismic mapping, dividing their territory into zones to understand where significant earthquake damage is likely to occur. For instance, the Pacific Ring of Fire is renowned for intense seismic activity. Systematic zoning helps foster safer infrastructure and more effective risk management in locations most exposed to earthquakes.

1.2 Classification of soil based on seismic Activity

In seismic engineering, soils are generally classified as hard, medium, or soft based on their stiffness, strength, and resistance to deformation.

- **Hard Soil:** Hard soils are typically composed of rock or very dense materials like gravel and stiff clay. These soils have high shear wave velocities (above approximately 800 m/s) and high bearing capacity. During seismic shaking, hard soils transmit seismic waves with minimal amplification, resulting in reduced ground motion and displacement.
- **Medium Soil**: Medium soils include dense to medium dense sands, gravels, and stiff to medium stiff clays. Their shear wave velocities range roughly between 360 and 800 m/s. These soils show moderate seismic wave amplification, with longer shaking durations compared to hard soils. Buildings on medium soils may experience increased lateral movement and some resonance effects depending on their natural vibration periods.
- **Soft Soil:** Soft soils consist of loose sands, silts, soft clays, and other recently deposited materials. The velocities at which shearwaves travel through them are are typically less than 180–200 m/s, and they have low un-drained shear strength. Soft soils strongly amplify seismic waves, increasing ground shaking intensity, and are prone to large deformations and potential liquefaction during strong motions.

Table-1.1 : Seismic Behavior of structure

Soil	Motional Shear Velocity	Seismic Behavior	Construction Implication
Soft	>=800 m/s	Low Amplification, Minimal Risk	Preferred for foundation ; Low seismic risk
Medium	360-800 m/s	Moderate Amplification , Longer Time Period	Moderate Seismic risk of Earth deformation and its resonance
Hard	<=180-200 m/s	High Amplification, Long Shaking	High Seismic Risk Requires special design and mitigation

II. RESEARCH METHODOLOGY

The seismic action analysis can be carried out by applying one of the following analysis methods:

- Modal spectral analysis method (dynamic)
- Equivalent lateral force static method (static)

The constraints for using each method are determined by particular structural characteristics of the building, including its resistance system, dynamic behavior, and the consistency of its shape in the plan or elevation.

In sections 6.4.3, 7.6 and 7.7 of the IS 1893-(Part 1):2016 code, the following conditions are specified:

6.4.3 Effects of design earthquake loads applied on structures can be considered in two ways, namely:

- Equivalent static method
- Dynamic analysis method

The equivalent static analysis approach can be adopted for assessing regular buildings where the estimated fundamental natural period Ta is less than 0.4 seconds.7.6

7.6 Equivalent Static Analysis

This procedure is suitable for use in the evaluation of regular buildings having heights not greater than 15 meters and located in Seismic Zone II.

7.7 Dynamic Analysis

Approach Dynamic analysis shall be employed to determine the design lateral seismic forces for all categories of buildings, except for those classified as regular and having a height below 15 meters within Seismic Zone II.

Dynamic-analysis in structural engineering is a technique used to determine the maximum intraction of a structure under dynamic loads like earthquakes by employing a design response spectrum. This approach evaluates peak lateral forces and displacements by relating the building's inherent natural frequencies and damping properties to a spectral curve, which is derived from seismic data. It identifies the most critical responses for each vibration mode separately and then combines these modal results to calculate the total maximum forces and moments. This process enables engineers to design safer and more efficient structures by accurately capturing the seismic demands acting on the building.

3.1 General principal and design criteria followed for Analysis as per IS 1983(Part-1)-2016

The properties of seismic ground shaking—such as its strength, length, rate of occurrence, and overall nature—at a particular location are influenced by the earthquake's magnitude, its point of origin, distance from the epicenter, the route taken by the seismic waves, and the underlying soil layers where the structure is built. The unpredictable nature of earthquake-induced ground movements, which lead to structural vibrations, can be broken down into three axes. Typically, the main axis of ground shaking is horizontal.

Vertical vibrations caused by earthquakes can play a key role in assessing the overall stability of buildings, particularly for (a) those with expansive open areas, and (b) designs where stability is a primary consideration. Vertical ground movements can reduce the effective gravitational load, which may harm elements like prestressed horizontal components, cantilevered parts, and gravity-based structures. As a result, particular focus should be given to the impacts of vertical shaking on prestressed or overhanging beams, supports, and floor slabs.

- **The Response of a Structure to Ground Vibrations:** A building's reaction to seismic activity is shaped by (a) the kind of base it has; (b) the building materials used; and (c) the dimensions, building method, and time span of movements, along with specific traits. This guideline outlines. Earthquake design loads for buildings placed on stable rock or soil types that avoid issues like settling, soil liquefaction, or slippage from weakened strength during tremors.

- **Actual Forces That Appear on Structures During Earthquakes:** The real forces experienced by buildings in an earthquake exceed those outlined in design standards. The ability to deform without breaking, stemming from non-elastic material responses combined with suitable planning and precise construction details, plus extra robustness from built-in safety margins beyond the basic design strength, are all factored in for structures exceeding the design thresholds. The approach to earthquake-resistant design in this standard depends on non-elastic responses in buildings. However, the highest level of deformability that can be achieved in structures is capped.

- **Soil-Structure Interaction:** Soil-structure interaction describes the influence of the flexible soil-foundation system on a building's behavior. This factor may be excluded from seismic evaluations of buildings founded on solid rock or rock-like materials at shallow depths.

- **Equipment and Other Systems**: Equipment and additional systems mounted at various levels of a building will experience varying movements at their attachment points. In such scenarios, it may be essential to determine floor response spectra for designing the equipment and its supports. For further information.

III. MODELING AND ANALYSIS

Modeling a G+8 building with a trapezoidal floor plan in CYPE software involves utilizing several advanced features and following a specific workflow, especially due to the irregularity of the shape. CYPECAD is well-suited for the analysis and design of multi-storey structures with unconventional geometries, efficiently managing the complexities associated with non-rectangular floor plans in reinforced concrete or steel construction.

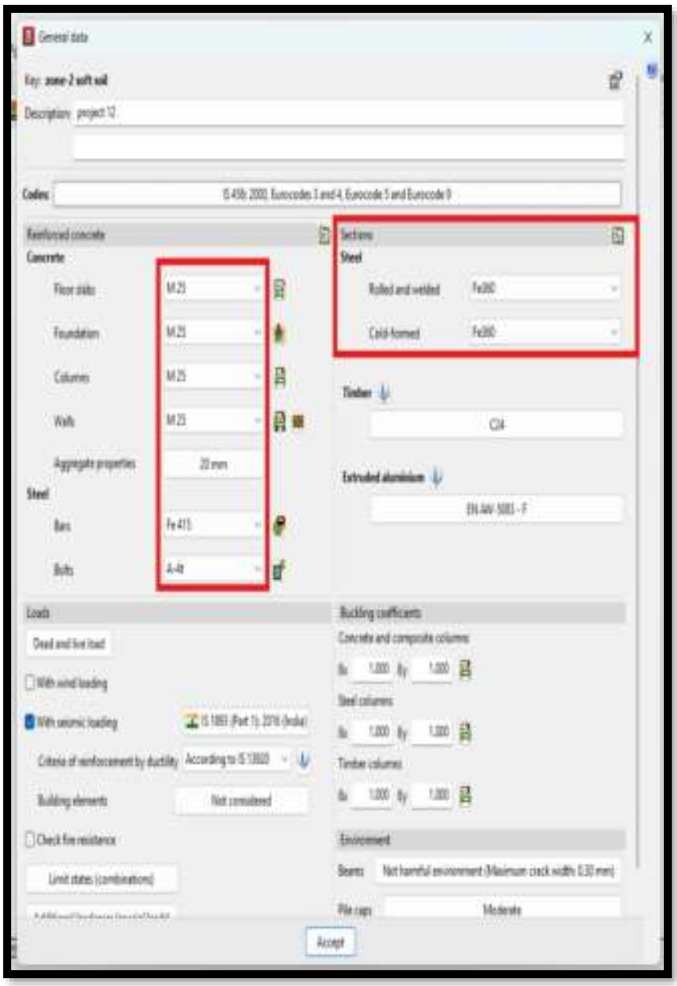
3.1 Project Setup

A new project was created in CYPE by selecting the appropriate design standards, materials, and storey height parameters. The orientation of the site and building was defined to accurately seismic impacts on the structure, taking into account the irregular geometry.

Key: zone-2 soft soil
Description: project 12
Codes: IS 456: 2000, Eurocodes 3 and 4, Eurocode 5 and Eurocode 9

Code selection
Concrete: IS 456: 2000 (India)
Cold formed steel: Eurocodes 3 and 4 (EU)
Rolled steel: Eurocodes 3 and 4 (EU)
Timber: Eurocode 5 (EU)
Aluminium: Eurocode 9
Reinforced concrete block wall: NTCRC (Mexico)
Composite slabs: Eurocode 4

☑ With seismic loading: IS 1893 (Part 1): 2016 (India)
Criteria of reinforcement by ductility: According to IS 13920
Building elements: Not considered
Beams: Not harmful environment (Maximum crack width: 0.30 mm)
Pile caps: Moderate



Key: zone-2 soft soil
Description: project 12
Codes: IS 456: 2000, Eurocodes 3 and 4, Eurocode 5 and Eurocode 9

Concrete
Floor slabs: M25
Foundation: M25
Columns: M25
Walls: M25
Aggregate properties: 20 mm

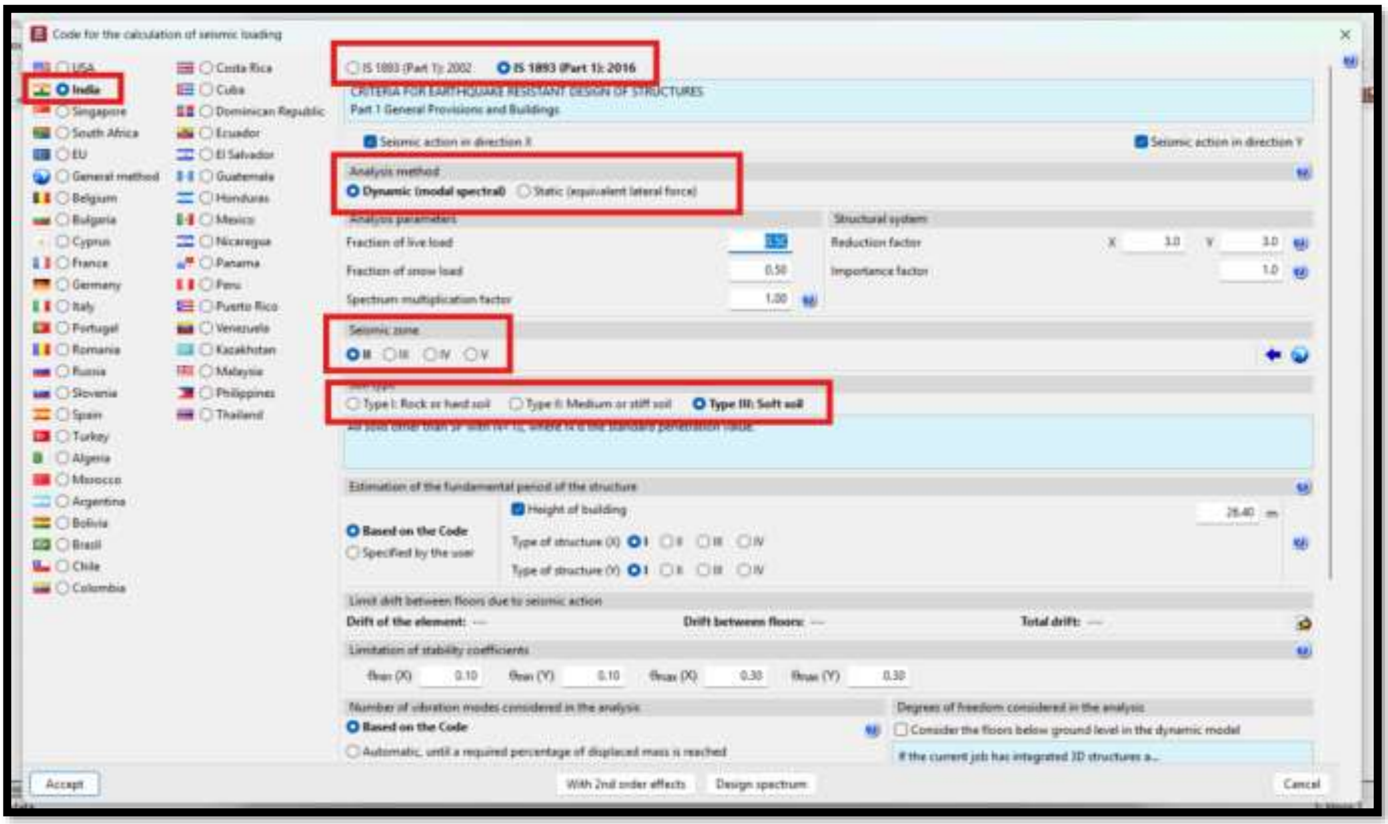
Steel
Bars: Fe415
Bolts: 4.6

Sections — Steel
Rolled and welded: Fe360
Cold-formed: Fe360
Timber: C24
Extruded aluminium: EN AW-5083-F

☑ With seismic loading: IS 1893 (Part 1): 2016 (India)
Criteria of reinforcement by ductility: According to IS 13920
Building elements: Not considered
Beams: Not harmful environment (Maximum crack width: 0.30 mm)
Pile caps: Moderate

Fig 3.1.1: Selection of Code for Concrete

Fig 3.1.2: Selection of Concrete Properties



Code for the calculation of seismic loading
● India
○ IS 1893 (Part 1): 2002 ● IS 1893 (Part 1): 2016
CRITERIA FOR EARTHQUAKE RESISTANT DESIGN OF STRUCTURES
Part 1 General Provisions and Buildings
☑ Seismic action in direction X ☑ Seismic action in direction Y
Analysis method: ● Dynamic (modal spectral) ○ Static (equivalent lateral force)
Fraction of live load: 0.50
Fraction of snow load: 0.50
Spectrum multiplication factor: 1.00
Reduction factor: X 3.0 Y 3.0
Importance factor: 1.0
Seismic zone: ● II ○ III ○ IV ○ V
Soil type: ○ Type I: Rock or hard soil ○ Type II: Medium or stiff soil ● Type III: Soft soil
Estimation of the fundamental period of the structure: ● Based on the Code ○ Specified by the user
☑ Height of building: 26.40 m
Type of structure (X): ● I ○ II ○ III ○ IV
Type of structure (Y): ● I ○ II ○ III ○ IV
Limitation of stability coefficients: 0.10, 0.10, 0.30, 0.30
Number of vibration modes considered in the analysis: ● Based on the Code ○ Automatic, until a required percentage of displaced mass is reached
Degrees of freedom considered in the analysis: ☐ Consider the floors below ground level in the dynamic model

Fig 3.1.3: Selection of IS seismic Codes and Parameters

3.2 Modeling of Structural Elements

Columns and walls were positioned In alignment with architectural and structural requirements oo guarantee efficient load distribution throughout the irregular floors. Beams were created along the non-orthogonal edges inherent to the trapezoidal shape, using coordinate snapping and angular controls for accuracy. Floor slabs were defined as polygons and subdivided into finite elements to enable detailed structural analysis.

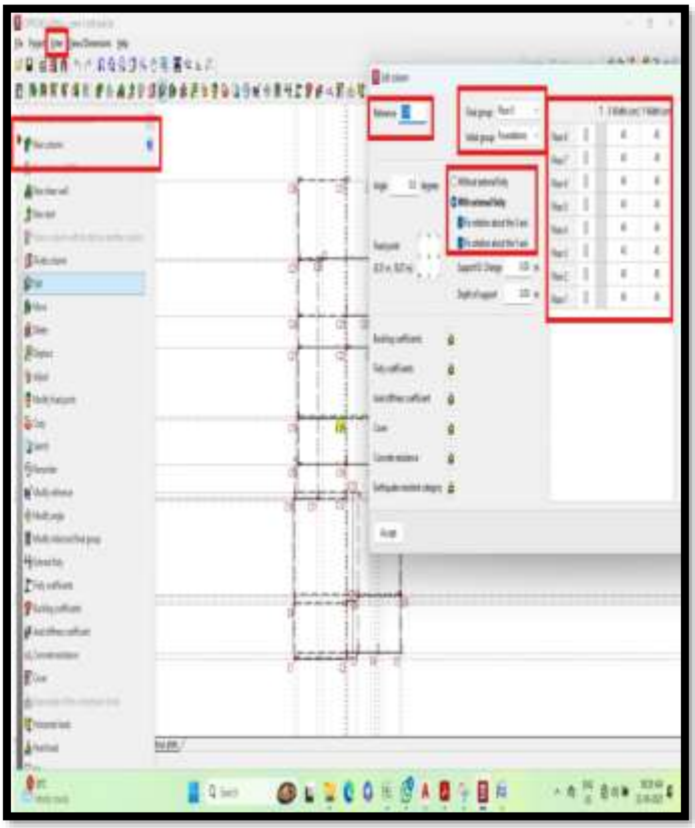


Fig 3.2.1: Selection of column dimensions and its orientation

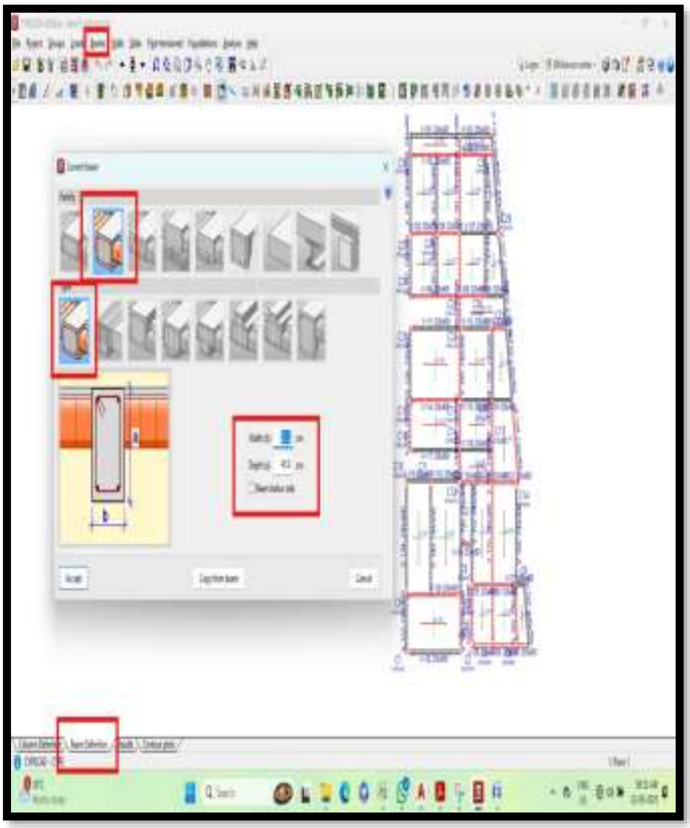


Fig 3.2.2: Selection of type of footing

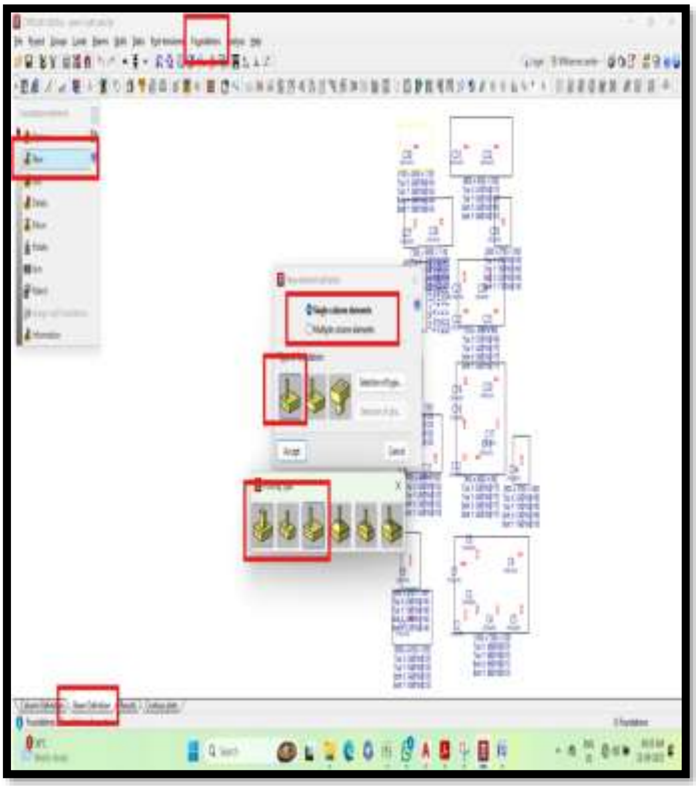


Fig 3.2.3: Selection of type of footing

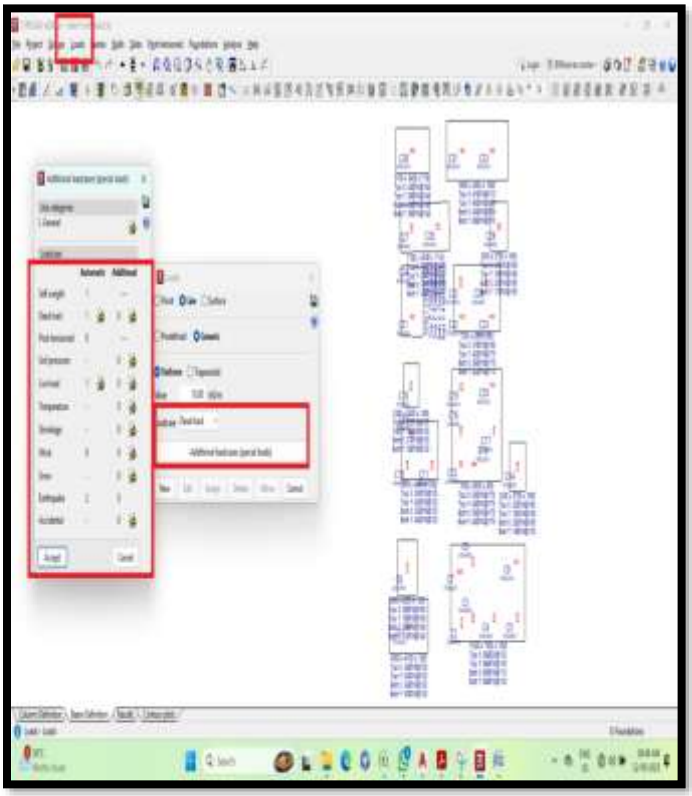


Fig 3.2.4: Loads applied on each floor

Table-3.1 : Types of Model Considered for analysis

Sl. No	Model Code	Seismic Zone	Type of Soil
1.	M-1	II	Hard
2.	M-2	II	Medium
3.	M-3	II	Soft
4.	M-4	III	Hard
5.	M-5	III	Medium
6.	M-6	III	Soft
7.	M-7	IV	Hard
8.	M-8	IV	Medium
9.	M-9	IV	Soft
10.	M-10	V	Hard
11.	M-11	V	Medium
12.	M-12	V	Soft

IV. RESULTS AND DISCUSSION

The result of structural analysis in CYPE was mainly focused and finding column displacement , Base Shear and Story Drift

Story Drift : Story drift measures how much one floor of a building shifts sideways compared to the floor directly below it, typically as a result of lateral forces such as wind or earthquakes.

Column Displacement : Column displacement refers to the movement or shift of a vertical support member Displaced from its initial location due to influence of applied forces such as gravity, wind, seismic events, or other loads.

Base Shear: Base shear is the total lateral force exerted at the base of a structure, primarily caused by horizontal loads such as those generated during an earthquake or strong winds. It represents the maximum force that the foundation and lower structural elements must resist to maintain overall stability and prevent structural failure.

4.1 Comparison Base Shear between the soil type Within the Zones

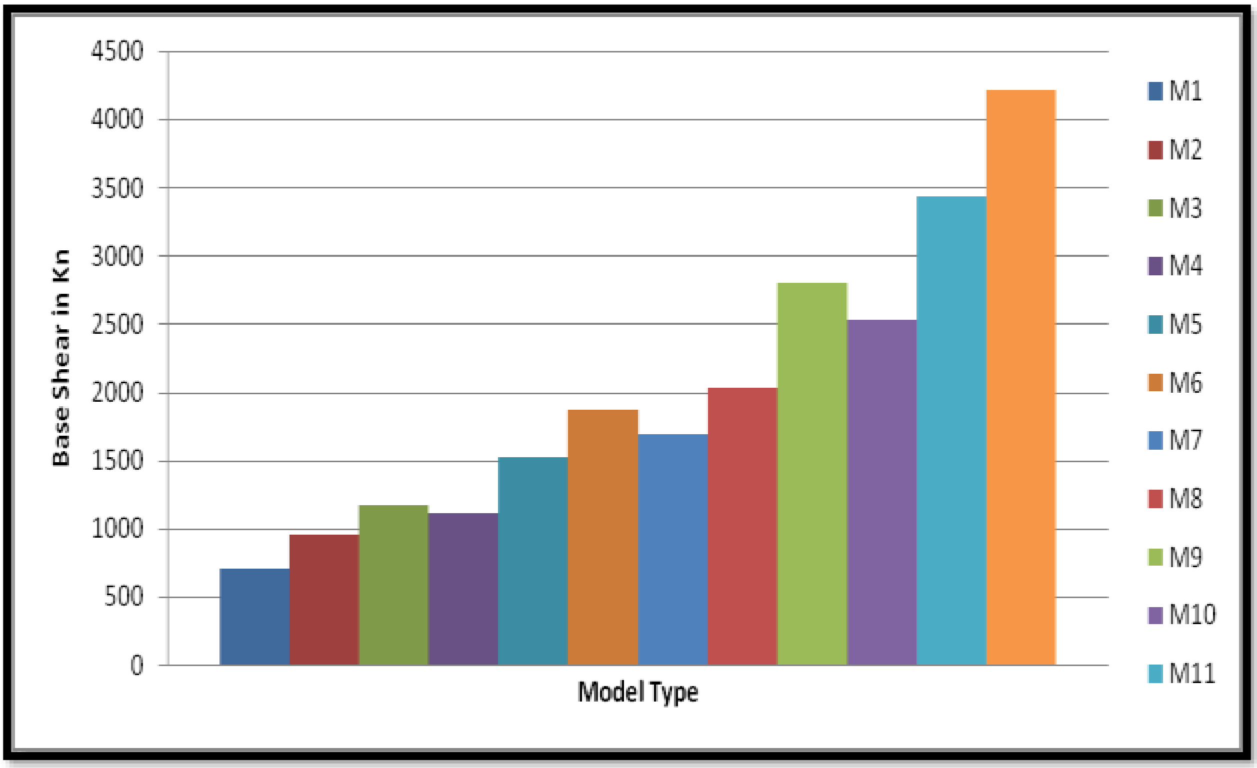
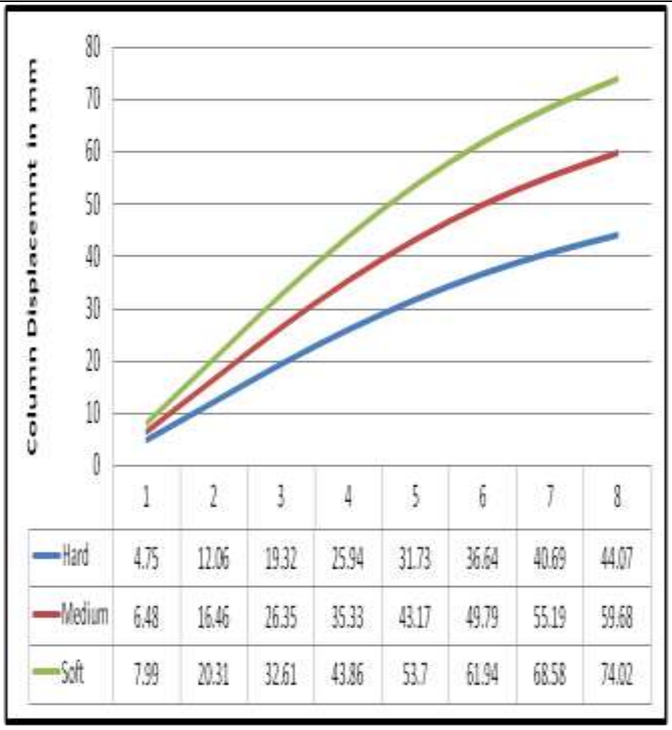


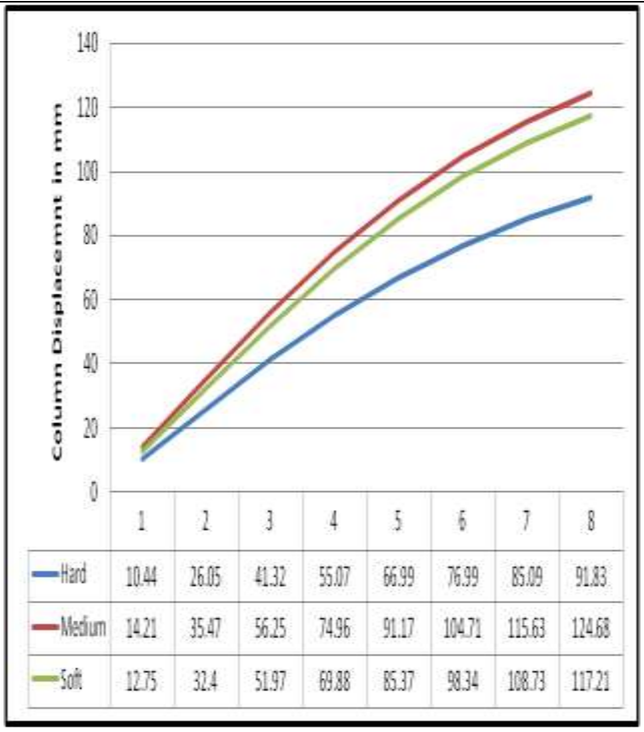
Fig 4.1.1:Graph Showing Base Shear for different Models

4.2 Comparison Column Displacement Between the Soil Type Within The Zones



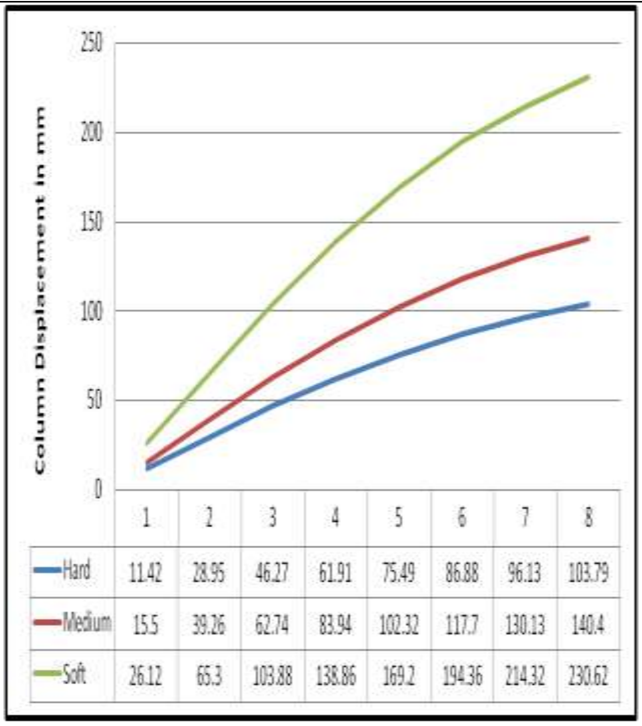
	1	2	3	4	5	6	7	8
Hard	4.75	12.06	19.32	25.94	31.73	36.64	40.69	44.07
Medium	6.48	16.46	26.35	35.33	43.17	49.79	55.19	59.68
Soft	7.99	20.31	32.61	43.86	53.7	61.94	68.58	74.02

Fig 4.2.1: Graph Showing Column Displacement in Models M-1, M-2, M-3



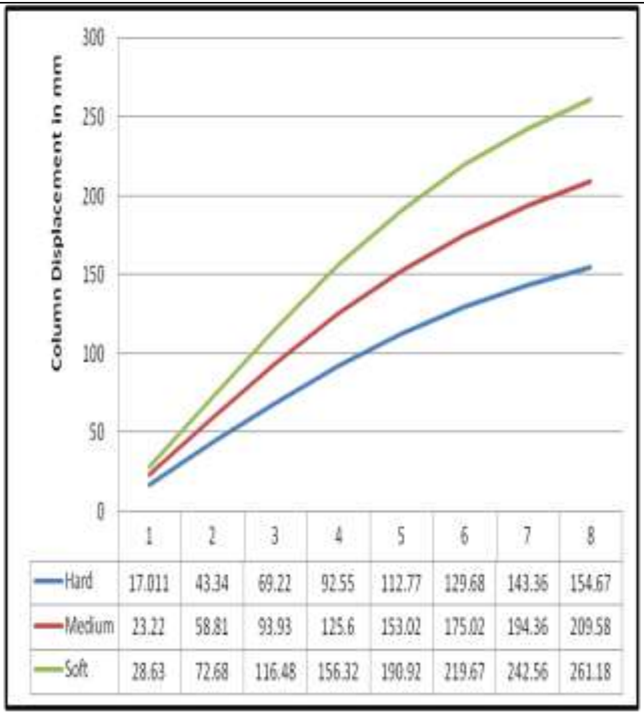
	1	2	3	4	5	6	7	8
Hard	10.44	26.05	41.32	55.07	66.99	76.99	85.09	91.83
Medium	14.21	35.47	56.25	74.96	91.17	104.71	115.63	124.68
Soft	12.75	32.4	51.97	69.88	85.37	98.34	108.73	117.21

Fig 4.2.2: Graph Showing Column Displacement in Models M-4, M-5, M-6



	1	2	3	4	5	6	7	8
Hard	11.42	28.95	46.27	61.91	75.49	86.88	96.13	103.79
Medium	15.5	39.26	62.74	83.94	102.32	117.7	130.13	140.4
Soft	26.12	65.3	103.88	138.86	169.2	194.36	214.32	230.62

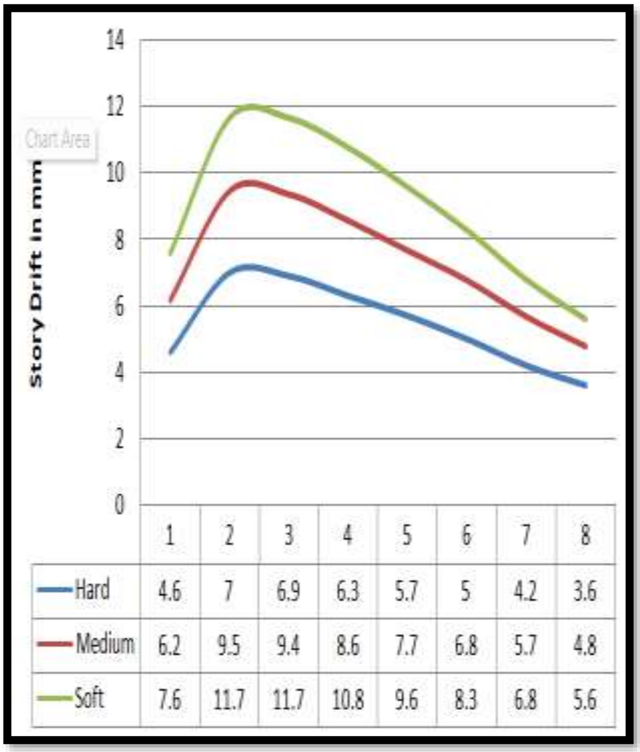
Fig 4.2.3: Graph Showing Column Displacement in Models M-7, M-8, M-9



	1	2	3	4	5	6	7	8
Hard	17.011	43.34	69.22	92.55	112.77	129.68	143.36	154.67
Medium	23.22	58.81	93.93	125.6	153.02	175.02	194.36	209.58
Soft	28.63	72.68	116.48	156.32	190.92	219.67	242.56	261.18

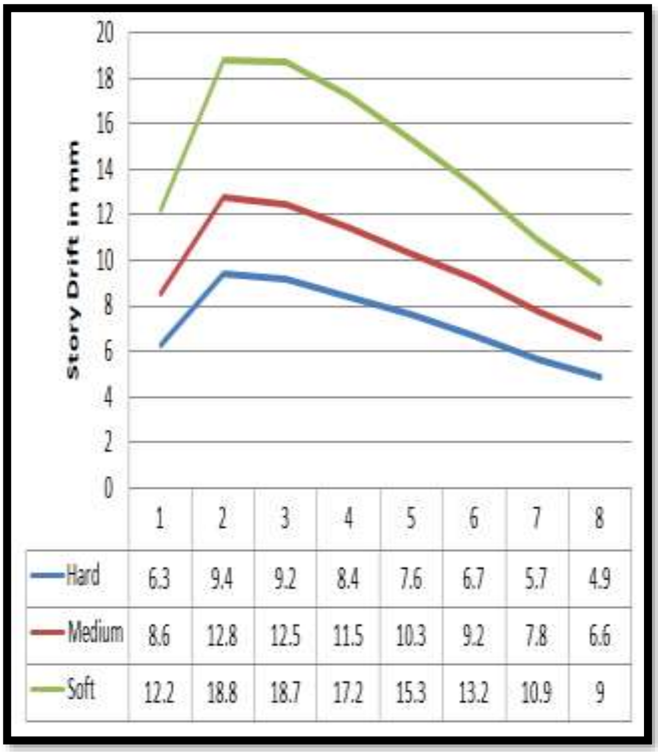
Fig 4.2.4: Graph Showing Column Displacement in Models M-10, M-11, M-12

4.3 Comparison Story Drift Between the Soil Type Within the Zones



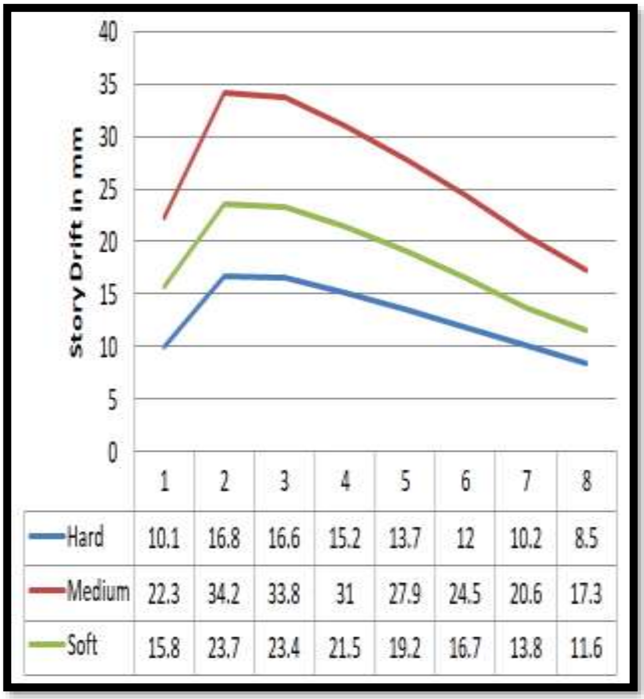
	1	2	3	4	5	6	7	8
Hard	4.6	7	6.9	6.3	5.7	5	4.2	3.6
Medium	6.2	9.5	9.4	8.6	7.7	6.8	5.7	4.8
Soft	7.6	11.7	11.7	10.8	9.6	8.3	6.8	5.6

Fig 4.3.1: Graph Showing Story Drift in Models M-1, M-2, M-3



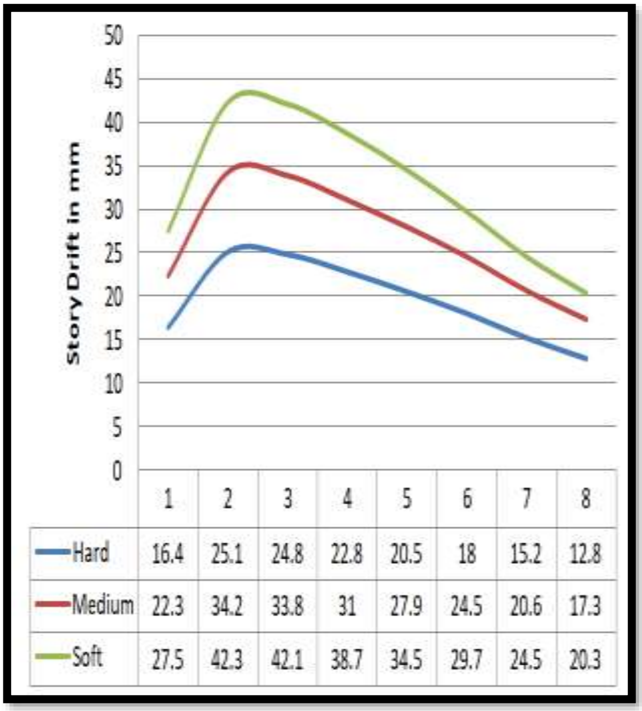
	1	2	3	4	5	6	7	8
Hard	6.3	9.4	9.2	8.4	7.6	6.7	5.7	4.9
Medium	8.6	12.8	12.5	11.5	10.3	9.2	7.8	6.6
Soft	12.2	18.8	18.7	17.2	15.3	13.2	10.9	9

Fig 4.3.2: Graph Showing Story Drift in Models M-4, M-5, M-6



	1	2	3	4	5	6	7	8
Hard	10.1	16.8	16.6	15.2	13.7	12	10.2	8.5
Medium	22.3	34.2	33.8	31	27.9	24.5	20.6	17.3
Soft	15.8	23.7	23.4	21.5	19.2	16.7	13.8	11.6

Fig 4.3.3 : Graph Showing Story Drift in Models M-7, M-8, M-9



	1	2	3	4	5	6	7	8
Hard	16.4	25.1	24.8	22.8	20.5	18	15.2	12.8
Medium	22.3	34.2	33.8	31	27.9	24.5	20.6	17.3
Soft	27.5	42.3	42.1	38.7	34.5	29.7	24.5	20.3

Fig 4.3.4: Graph Showing Story Drift in Models M-10, M-11, M-12

4.4 Comparative Discussion Of Results

Column Displacement: Seismic zone and soil type greatly affect displacement. Model M-1 (Zone II, hard soil) shows the least top-story displacement of 44.07 mm due to high stiffness and low seismic activity. Model M-12 (Zone V, soft soil) has the maximum displacement of 261.18 mm, nearly six times higher, caused by soft soil amplification. Displacement is higher along the Y-axis than the X-axis.

Base Shear: Both seismic intensity and soil condition influence base shear. The lowest value occurs in M-1 (701.08 kN), while the highest is in M-12 (4219.21 kN). Soft soil increases shear by around 67%, and higher seismic zones multiply lateral forces, demanding stronger reinforcement and soil improvement.

Story Drift

- M-1, M-4, M-7, M-10: Lowest drift (~25 mm), showing good stiffness.
- M-2, M-5, M-8, M-11: Moderate drift (~34 mm), needing extra bracing.
- M-3, M-6, M-9, M-12: Highest drift (~42 mm), exceeding limits and needing structural strengthening

4.5 Conclusion

Structural Performance: The best seismic response is observed in Zone II on hard soil (M-1) with minimal displacement, base shear, and drift. The weakest performance occurs in Zone V on soft soil (M-12), where displacement reaches 261.18 mm, base shear 4219.21 kN, and drifts exceed permissible limits. Structural stability is therefore strongly governed by seismic intensity and soil stiffness.

Structural Irregularities: The trapezoidal model shows irregular stiffness and uneven vertical displacement, especially in soft soil conditions. Excessive drifts at intermediate floors, notably the 2nd and 3rd levels, highlight potential weak zones that require design adjustments for uniform stiffness and balanced mass distribution.

Design Enhancements: In high-seismic, soft soil environments, improved measures such as shear walls, bracing systems, and damping devices are recommended. Increasing stiffness and optimizing the design help control displacement and drift while addressing weak points inherent to trapezoidal geometry.

Soil-Structure Interaction: Soft soils amplify seismic vibrations, causing higher displacements, drifts, and base shear compared to hard soils. Medium soils show moderate amplification, offering intermediate performance between the two extremes. This confirms that soil flexibility directly intensifies seismic effects.

Seismic Demand: Evaluation Higher seismic zones and softer soils considerably raise structural demands. Buildings on soft soil in severe seismic regions experience much stronger forces than those on hard soil. Accounting for soil-structure interaction is thus vital to avoid underestimating seismic risks, especially in flexible systems like trapezoidal frames.

The evaluation demonstrates that structural response to earthquakes is greatly affected by both the type of underlying soil and the level of seismic activity. Buildings supported by firm ground in less active zones perform considerably better, showing lower displacements, base shear, and story drifts. In contrast, those on softer soils exposed to more intense seismic forces suffer from significantly higher structural demands and may surpass safe limits. For dependable performance, incorporating reinforcement measures and thoroughly considering the interaction between soil and structure are crucial steps in seismic design.

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