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"Analyzing the Effect of Terrain Gradient on Seismic Response on SMRF Structures"

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Abstract -*This study presents a comprehensive seismic performance assessment of a G+12 Special Moment Resisting Frame (SMRF) structure located on sloping terrains, utilizing ETABS for structural analysis. The investigation encompasses four terrain slopes 0°, 20°, 45°, and 60° across three soil classifications: hard, medium, and soft, under seismic zones III and IV. Critical response parameters including story displacement, story drift, stiffness and strength irregularities, mass irregularity, torsional irregularity, diaphragm behavior (rigid vs. flexible), and mode shapes were evaluated to understand the influence of topographical and geotechnical variations on seismic behavior. The results show that increasing slope inclination and decreasing soil stiffness notably increase seismic demands. Structures situated on steeper slopes and softer soils exhibited greater lateral displacements, higher torsional irregularities, and more complex mode shapes, indicating a higher vulnerability to dynamic loading. Rigid diaphragm systems were found to enhance overall structural stability by reducing deformation and controlling inter-story drift. This study emphasizes the significant impact of slope geometry, soil flexibility, and diaphragm type on the seismic response of multistory structures. The findings reveal the limitations of traditional design assumptions based on flat ground and highlight the need for slope-adaptive structural strategies. Such approaches are essential for ensuring the safety and performance of structures in seismically active regions with irregular topography*

Key Words: Sloping ground, Soil Structure Interaction (SSI), Seismic analysis, Equivalent Static Method, Response Spectrum Analysis, Seismic Zones, Slope angel variation, Storey Drift, Storey Displacement, Stiffness Irregularity, Storey Shear, Mass Irregularity, Rigid & Flexible Diaphragm, Mode Shape, Torsional Irregularity, ETABS.

1. INTRODUCTION

Earthquakes are one of the most devastating natural hazards, capable of causing extensive damage to infrastructure, disrupting economies, and resulting in significant loss of life. Their unpredictable nature and the powerful forces they generate present substantial challenges for structural engineers, especially in regions with moderate to high seismic activity. As urban populations grow and available flat land becomes increasingly scarce, urban development has started to expand into hilly and mountainous areas. This trend has led to the construction of mid- to high-rise buildings on sloped terrains, introducing complex engineering challenges that go beyond those faced in traditional flatland construction.

Buildings located on sloping ground differ significantly in their behavior and design compared to those built on flat sites. The terrain requires stepped or terraced foundations, creating variations in elevation and support conditions across the base of the structure. This unevenness affects both the vertical load path and the distribution of stiffness throughout the building's footprint. Additionally, sloped terrain can lead to non-uniform mass distribution due to differences in story height, column length, and the overall shape of the building envelope. These irregularities can greatly impact the building's seismic response, resulting in complex interactions between lateral and torsional movements and increasing the likelihood of structural damage during earthquakes.

Seismic design codes typically identify certain structural irregularities—such as stiffness, strength, mass, and torsional irregularities—as critical factors that influence dynamic performance. These characteristics are often more pronounced in hillside buildings, making them particularly vulnerable to seismic activity. For example, one side of a structure, usually the uphill side, may behave more rigidly due to shorter columns, while the downhill side may exhibit greater flexibility because of longer unsupported column lengths. This asymmetry can result in non-uniform story drifts and concentrated internal forces, especially when subjected to lateral seismic loads. Additionally, soft or varying soil conditions on sloped terrain can worsen these effects, leading to differential settlements, amplification of ground motions, and increased base shear.

Besides geometric and geotechnical challenges, diaphragm behavior plays a crucial role in hillside construction. The assumption of rigid diaphragms, which is often valid for flat terrain, may not apply in irregular or staggered layouts. Flexible diaphragms can cause disproportionate load distribution among lateral force-resisting elements, further complicating the structural response.

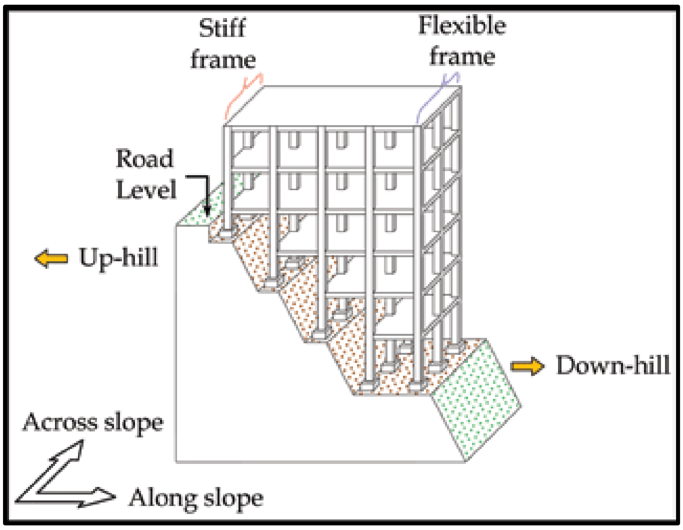


Figure 1. Building on sloping ground

To tackle these challenges, a more nuanced and site-responsive approach to structural analysis and design is necessary. Advanced computational tools, such as ETABS and other finite element-based platforms, enable detailed modeling of terrain-induced irregularities and soil-structure interactions. These tools facilitate accurate assessments of key seismic response parameters, including story displacements, inter-story drifts, base shear, mode shapes, and dynamic irregularities.

This study focuses on the seismic behavior of a G+12 Special Moment Resisting Frame (SMRF) structure built on varying slope angles and soil types, particularly in seismic zones III and IV. By examining how slope geometry, soil classification, and diaphragm behavior influence structural performance under seismic loading, the research aims to provide critical insights for engineers and designers. The objective is to emphasize the importance of slope-adaptive design methodologies that ensure both structural safety and compliance with codes, ultimately contributing to more resilient urban development in seismically sensitive and topographically challenging regions.

1.1. OBJECTIVES

1. To evaluate the effect of slope angle (0°, 20°, 45°, 60°) on the seismic response of G+12 SMRF structures, using ETABS software.
2. To assess key seismic response parameters, including storey displacement, storey drift, stiffness irregularity, and storey strength, in buildings constructed on sloping terrain.
3. To examine mass irregularity and torsional irregularity in sloped structures and their influence on overall dynamic behavior during seismic events.
4. To identify the building behaviour under different soil types and slope angles, and to observe how these variations affect the mode shape.
5. To investigate the role of diaphragm type (rigid vs flexible) in controlling lateral displacement and improving seismic stability
6. To compare the building behavior under different soil types (hard, medium, soft) and analyze how soil flexibility influences structural performance during seismic events.
7. To assess building performance in Seismic Zones III and IV and understand how increasing seismic intensity impacts structural behavior, especially in buildings with uneven terrain.

1.2. RESEARCH GAP

1. Absence of Terrain-Specific Design Guidelines in Seismic Codes.
2. Inadequate Integration of Soil-Structure-Terrain Interaction (SSTI).
3. Insufficient Focus on Mode Shape Variation Due to Slope-Induced Irregularities.
4. Limited Research on Seismic Behavior of Structures on Steep Slopes (45°–60°).
5. Neglect of Diaphragm Flexibility in Sloped Building Performance Analysis.

1.3. SCOPE OF WORK

This study investigates the impact of varying slope gradients (0°, 20°, 45°, and 60°) on geotechnical behavior across different seismic zones (Zone III and Zone IV) and soil types (I, II, and III), aiming to analyze the structural response and stability under diverse slope-soil-zone conditions.

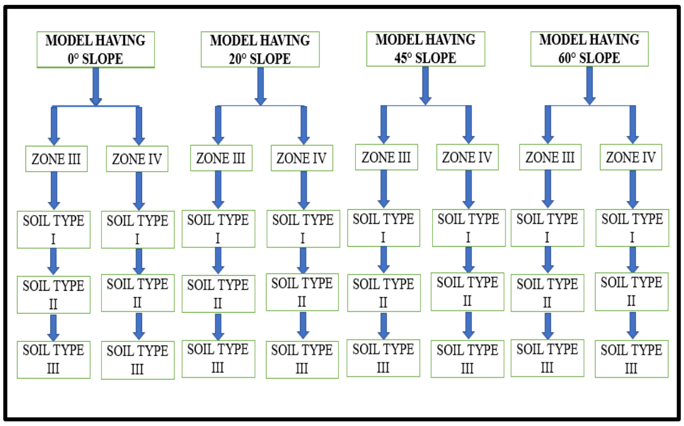


Figure 1.3.1. Scope of Work

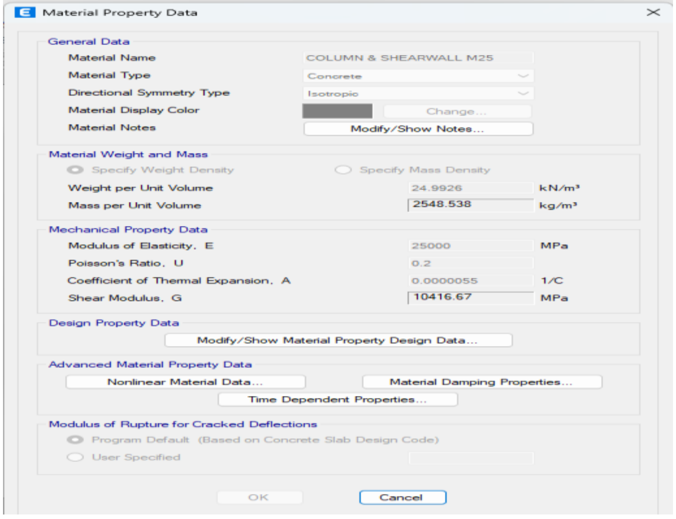
2. MODELLING

The analysis and design of a multistorey (G+12) Special Moment Resisting Frame (SMRF) building situated on sloping terrain are conducted utilizing ETABS software. In ETABS, the design and analysis of reinforced cement concrete (RCC) structures are carried out through five essential steps: Define, Draw, Assign, Analyze, and Design. This study evaluates the structural performance of the building across four different slope angles: 0°, 20°, 45°, and 60°, while considering three types of soil conditions: hard, medium, and soft. Furthermore, the building is examined under Seismic Zones III and IV in accordance with the guidelines outlined in IS 1893 (Part 1): 2016. A total of 24 models are created to combine variations in slope, soil type, and seismic zone, ensuring comprehensive data validation and a robust comparison of seismic responses. To facilitate effective analysis of these models, input parameters such as material properties, section dimensions, loading conditions, and boundary conditions are defined in accordance with the relevant Indian Standard codes (IS 456:2000, IS 875, and IS 1893).

DATA INPUT IN ETABS	
Height of Typical Storey	3m
Height of Ground Storey	3m
Length of the Building	15m
Width of the Building	13m
Height of the Building	39m
Number of Stories	13
Wall Thickness	230mm
Slab Thickness	150mm
Grade of Concrete	M25
Grade of Steel	Fe500
Support	Fixed
Column Size	300mm x 600mm
Beam Size	230mm x 450mm
Slope Angel	0°, 20°, 45°, and 60°
Location of Building	India
Live Load	At Typical Floor = 3 kN/m^2 At Terrace = 2 kN/m^2
Floor Finish	At Typical Floor = 2 kN/m^2 At Terrace = 2.5 kN/m^2
Density of Concrete	25 kN/m^3
Seismic Zone	Zone III, IV
Site Type	I,II, III
Importance Factor	1
Response Reduction	5
Damping Ratio	5%
Structure Class	C
Basic Wind Speed	47m/s
Risk Coefficient (k1)	1.00
Terrain Size Coefficient (k2)	2.00
Topography Factor (k3)	1.36
Wind Design Code	IS:875-2015 (Part-3)
RCC Design Code	IS:456-2000
Steel Design Code	IS:800-2007

Table 1. Data Input in Etabs

2.1. DEFINE


Material Property Data

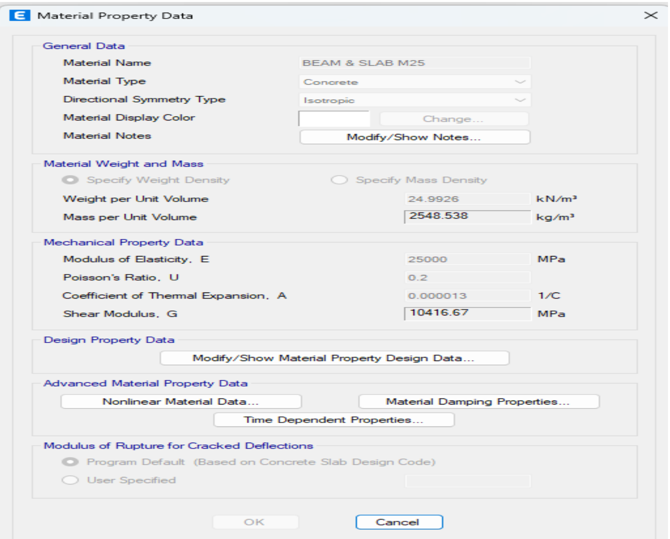
General Data
Material Name: COLUMN & SHEARWALL M25
Material Type: Concrete
Directional Symmetry Type: Isotropic

Material Weight and Mass
● Specify Weight Density ○ Specify Mass Density
Weight per Unit Volume: 24.9926 kN/m^3
Mass per Unit Volume: 2548.538 kg/m^3

Mechanical Property Data
Modulus of Elasticity, E: 25000 MPa
Poisson's Ratio, U: 0.2
Coefficient of Thermal Expansion, A: 0.0000055 1/C
Shear Modulus, G: 10416.67 MPa

Modulus of Rupture for Cracked Deflections
● Program Default (Based on Concrete Slab Design Code)
○ User Specified

Figure 2.1.1. Define Grade of Concrete for Column & Shear Wall


Material Property Data

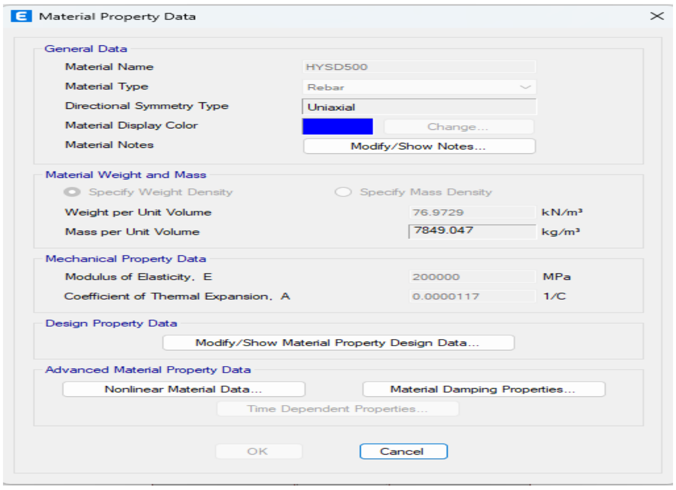
General Data
Material Name: BEAM & SLAB M25
Material Type: Concrete
Directional Symmetry Type: Isotropic

Material Weight and Mass
● Specify Weight Density ○ Specify Mass Density
Weight per Unit Volume: 24.9926 kN/m^3
Mass per Unit Volume: 2548.538 kg/m^3

Mechanical Property Data
Modulus of Elasticity, E: 25000 MPa
Poisson's Ratio, U: 0.2
Coefficient of Thermal Expansion, A: 0.000013 1/C
Shear Modulus, G: 10416.67 MPa

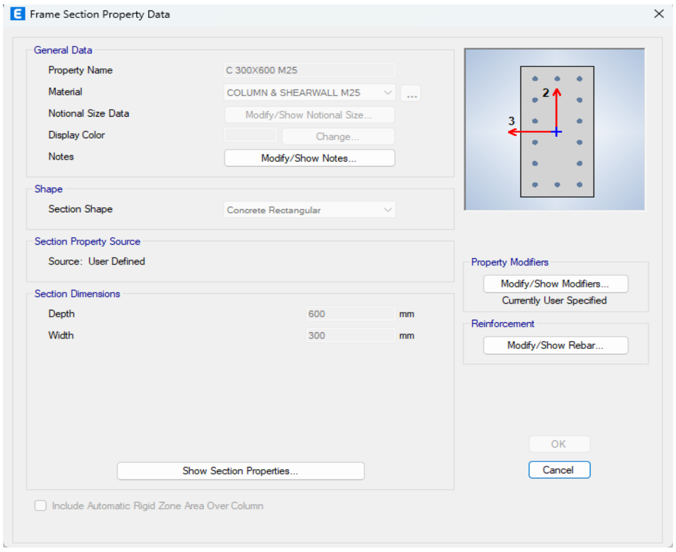
Modulus of Rupture for Cracked Deflections
● Program Default (Based on Concrete Slab Design Code)
○ User Specified

Figure 2.1.2. Define Grade of Concrete for Beam & Slab



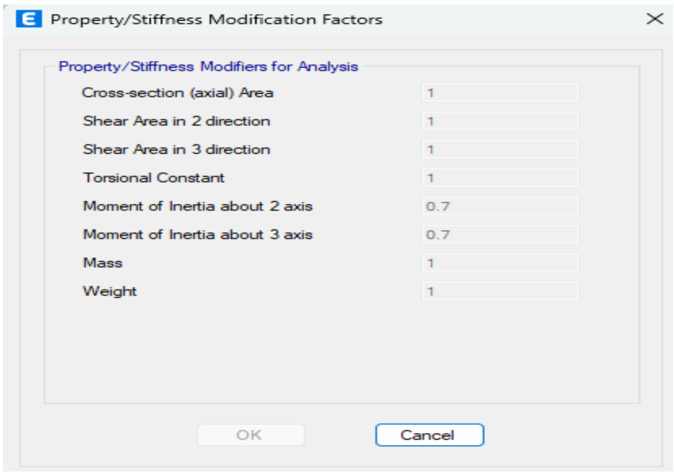
Material Name: HYSD500
Material Type: Rebar
Directional Symmetry Type: Uniaxial
Material Display Color: 🟦
● Specify Weight Density ○ Specify Mass Density
Weight per Unit Volume: 76.9729 kN/m³
Mass per Unit Volume: 7849.047 kg/m³
Modulus of Elasticity, E: 200000 MPa
Coefficient of Thermal Expansion, A: 0.0000117 1/C

Figure 2.1.3. Define Grade of Steel



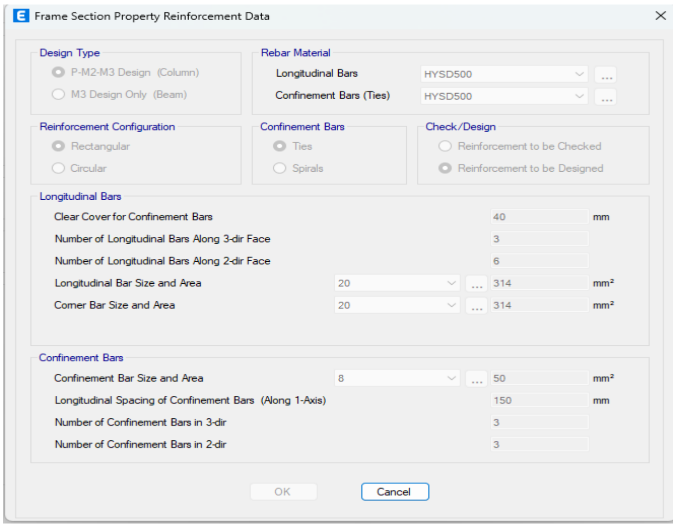
Property Name: C 300X600 M25
Material: COLUMN & SHEARWALL M25
Section Shape: Concrete Rectangular
Source: User Defined
Depth: 600 mm
Width: 300 mm
Property Modifiers: Currently User Specified
☐ Include Automatic Rigid Zone Area Over Column

Figure 2.1.4. Section Property of Column



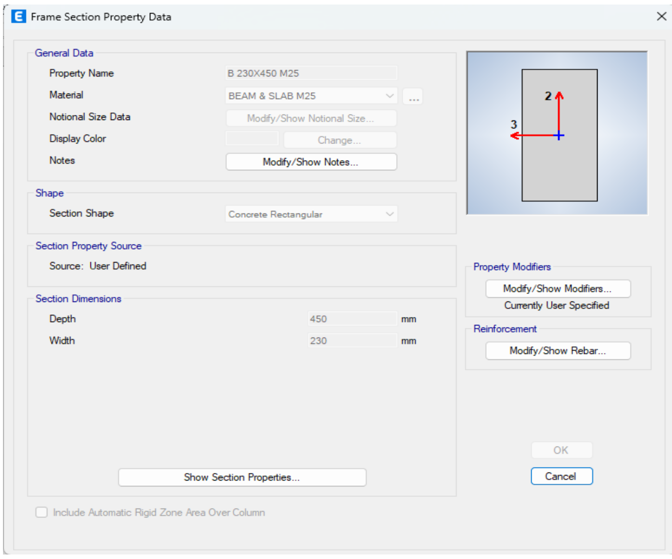
Cross-section (axial) Area: 1
Shear Area in 2 direction: 1
Shear Area in 3 direction: 1
Torsional Constant: 1
Moment of Inertia about 2 axis: 0.7
Moment of Inertia about 3 axis: 0.7
Mass: 1
Weight: 1

Figure 2.1.5. Modifiers of Column



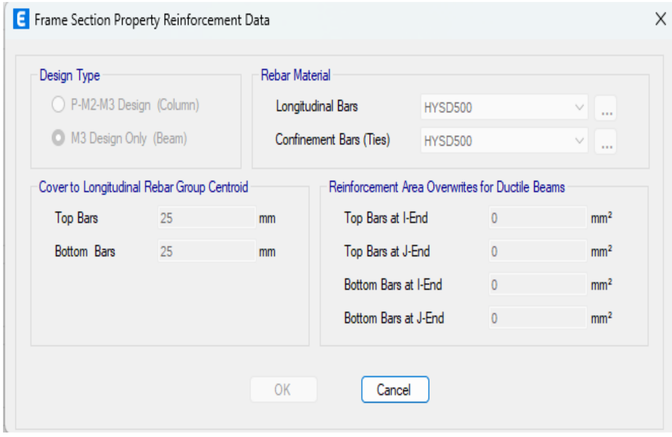
Design Type: ● P-M2-M3 Design (Column) ○ M3 Design Only (Beam)
Longitudinal Bars: HYSD500
Confinement Bars (Ties): HYSD500
Reinforcement Configuration: ● Rectangular ○ Circular
Confinement Bars: ● Ties ○ Spirals
Check/Design: ○ Reinforcement to be Checked ● Reinforcement to be Designed
Clear Cover for Confinement Bars: 40 mm
Number of Longitudinal Bars Along 3-dir Face: 3
Number of Longitudinal Bars Along 2-dir Face: 6
Longitudinal Bar Size and Area: 20 314 mm²
Corner Bar Size and Area: 20 314 mm²
Confinement Bar Size and Area: 8 50 mm²
Longitudinal Spacing of Confinement Bars (Along 1-Axis): 150 mm
Number of Confinement Bars in 3-dir: 3
Number of Confinement Bars in 2-dir: 3

Figure 2.1.6. Column Reinforcement Data



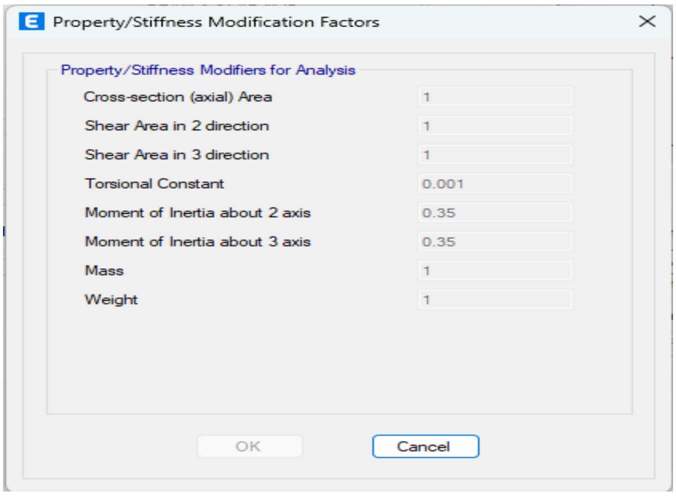
Property Name: B 230X450 M25
Material: BEAM & SLAB M25
Section Shape: Concrete Rectangular
Source: User Defined
Depth: 450 mm
Width: 230 mm
Property Modifiers: Currently User Specified
☐ Include Automatic Rigid Zone Area Over Column

Figure 2.1.7. Section Property of Beam



Design Type: ○ P-M2-M3 Design (Column) ● M3 Design Only (Beam)
Longitudinal Bars: HYSD500
Confinement Bars (Ties): HYSD500
Top Bars: 25 mm
Bottom Bars: 25 mm
Top Bars at I-End: 0 mm²
Top Bars at J-End: 0 mm²
Bottom Bars at I-End: 0 mm²
Bottom Bars at J-End: 0 mm²

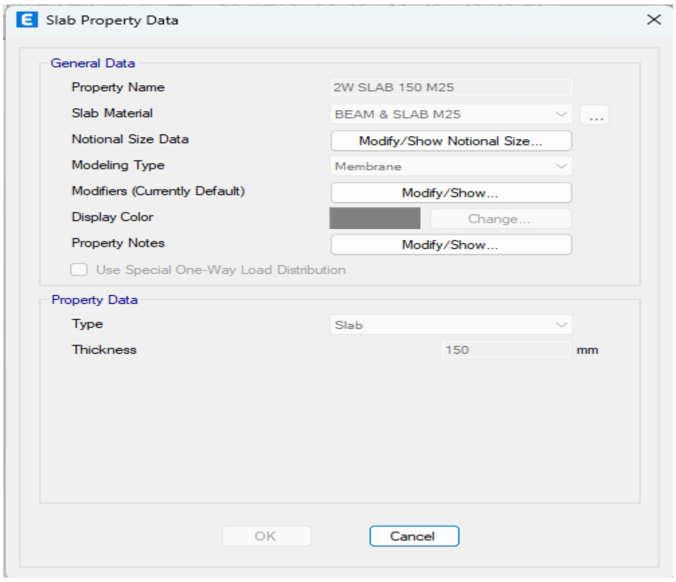
Figure 2.1.8. Beam Reinforcement Data



Property/Stiffness Modifiers for Analysis

Cross-section (axial) Area	1
Shear Area in 2 direction	1
Shear Area in 3 direction	1
Torsional Constant	0.001
Moment of Inertia about 2 axis	0.35
Moment of Inertia about 3 axis	0.35
Mass	1
Weight	1

Figure 2.1.9. Modifiers of Beams



General Data

Property Name	2W SLAB 150 M25
Slab Material	BEAM & SLAB M25
Notional Size Data	Modify/Show Notional Size...
Modeling Type	Membrane
Modifiers (Currently Default)	Modify/Show...
Display Color	
Property Notes	Modify/Show...

☐ Use Special One-Way Load Distribution

Property Data

Type	Slab
Thickness	150 mm

Figure 2.1.10. Section Property of Slab

2.2. Draw

We will create a total of 24 models of G+12 with different slope angles (0°, 20°, 45°, and 60°), different soil types (I, II, and III), and various seismic zones (Zone III and IV).

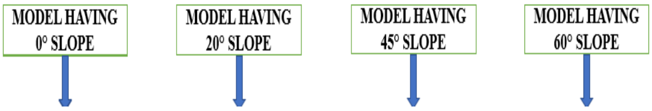


Figure 2.2.1. Types of Model

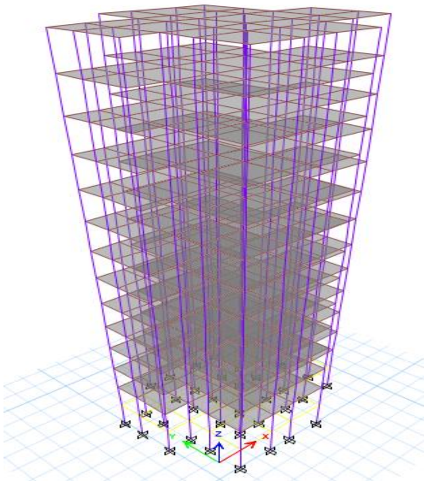


Figure 2.2.2. 3D-Model having 0° Slope

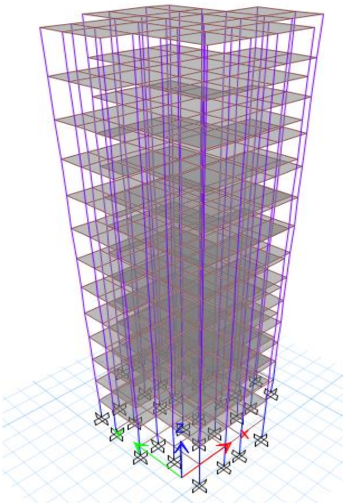


Figure 2.2.3. 3D-Model having 20° Slope

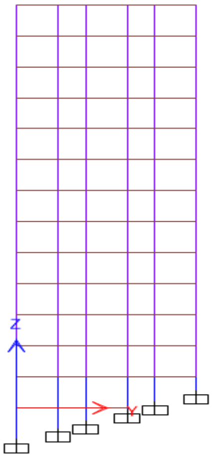


Figure 2.2.4. Elevation 20° Slope Model

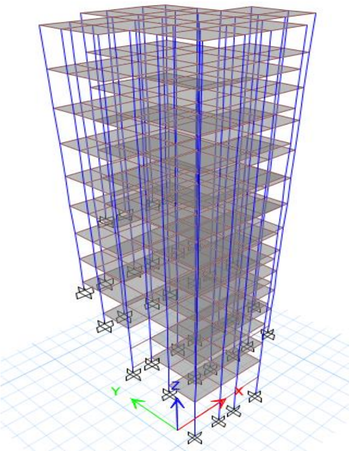


Figure 2.2.5. 3D-Model having 45° Slope

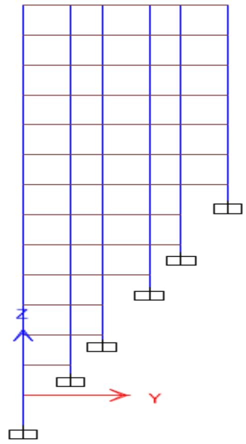


Figure 2.2.6. Elevation 45° Slope Model

2.3. ASSIGN

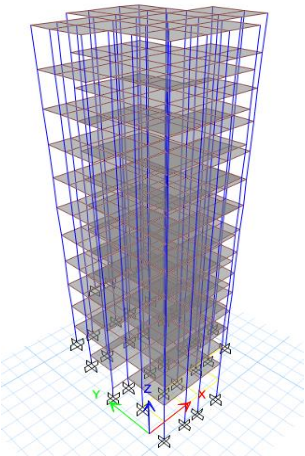


Figure 2.2.7. 3D-Model having 60° Slope

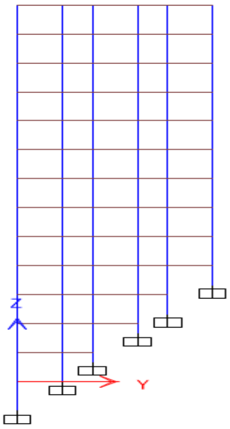


Figure 2.2.8. Elevation 60° Slope Model

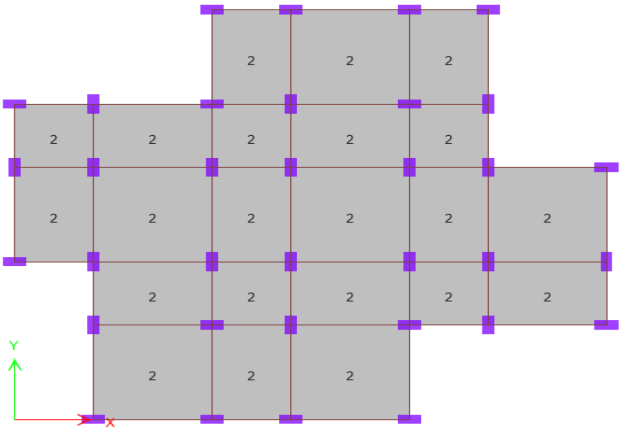


Figure 2.3.1. Assigning F.F. at Typical Floor

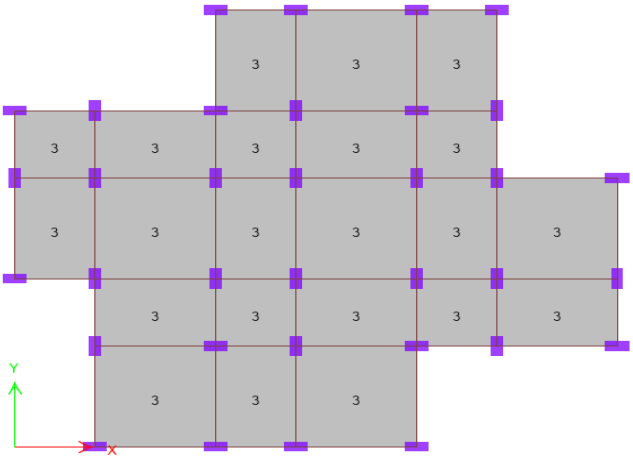


Figure 2.3.2. Assigning L.L at Typical Floor

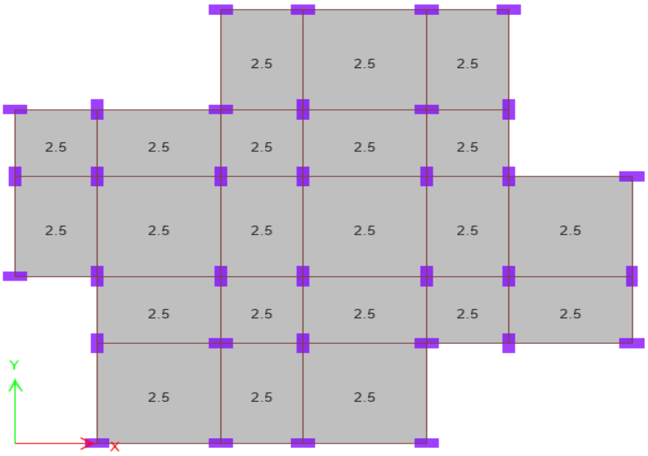


Figure 2.3.3. Assigning F.F. at Terrace level

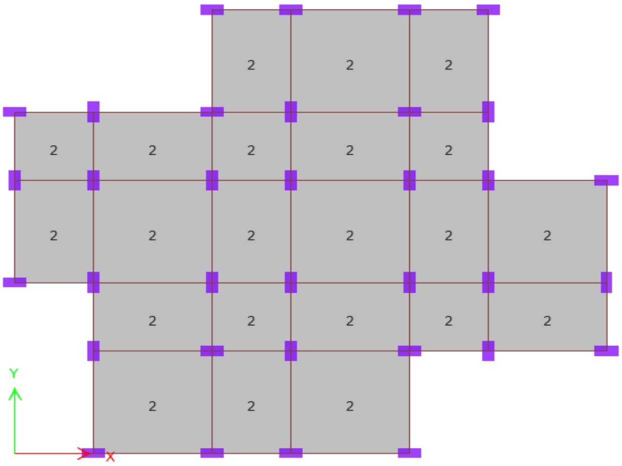


Figure 2.3.4. Assigning L.L. at Terrace level

2.4. ANALYZE

The structural analysis of Reinforced Cement Concrete (RCC) buildings subjected to seismic forces is typically conducted using two main approaches:

1. **Equivalent Static Method :**
   The Equivalent Static Method is a simplified procedure for estimating the seismic forces acting on a structure. In this method, lateral earthquake forces are assumed to act statically and are distributed along the height of the structure according to predefined code provisions. This approach assumes that the structure primarily responds in its fundamental mode and does not account for torsional or higher-mode effects.

   Due to its simplicity and ease of use, this method is commonly applied to low-rise, regular buildings where the structural behavior is relatively straightforward. However, it may not yield accurate results for structures with irregular geometries, significant heights, or mass/stiffness discontinuities.

2. **Dynamic Analysis Method :**
Dynamic analysis is a more sophisticated approach that considers the actual dynamic characteristics of the structure, including natural frequencies, mode shapes, and damping. This method is suitable for both regular and irregular buildings and is especially important for taller or more complex structures.

Dynamic analysis can be performed using one of the following techniques:

- **Response Spectrum Method:** This method utilizes a standard response spectrum curve to estimate the peak response of the structure based on its natural modes. It is a linear, modal-based approach widely used in design codes for seismic analysis due to its balance of accuracy and computational efficiency. In this study, the Response Spectrum Method has been adopted for analysis.
- ✓ **In the present study, the Response Spectrum Method has been adopted for the analysis.**
- **Time History Method:** This method involves applying actual ground motion records to the structure to evaluate its time-dependent response. It is the most detailed and computationally intensive form of dynamic analysis, capable of capturing nonlinear behavior and complex interactions.

3. OBSERVATION

After completing the modeling process and assigning the necessary structural properties in ETABS, the analysis phase was carried out to assess the behavior of the structure under seismic loading conditions. The following structural response parameters were closely observed:

- Storey Drift
- Storey Displacement
- Stiffness Irregularity
- Storey Strength
- Mass Irregularity
- Diaphragm (Flexible and Rigid)
- Mode Shapes
- Torsional Irregularity

These parameters were selected based on their significance in evaluating the structural performance and identifying potential irregularities that may influence the dynamic response of the building. The results have been systematically compiled and are presented in the form of graphs and tables for detailed interpretation.

3.1. STOREY DRIFT

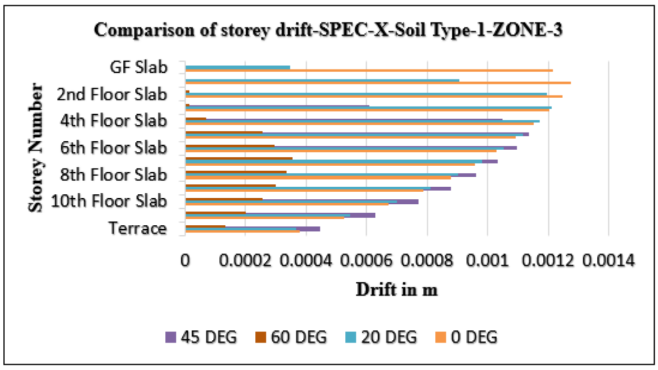


Figure 3.1.1. Comparison of storey drift-SPEC-X-Soil Type-1-Zone-3

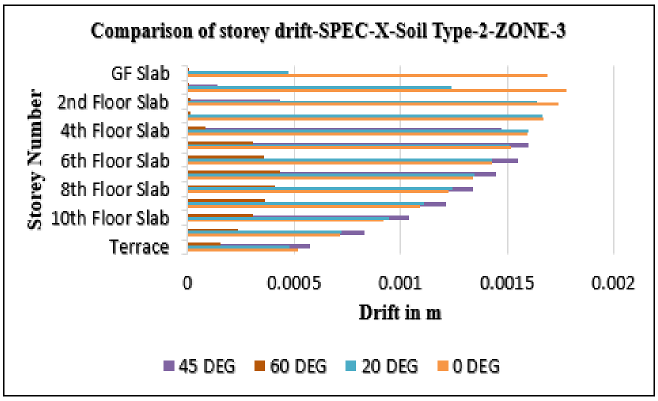


Figure 3.1.2. Comparison of storey drift-SPEC-X-Soil Type-2-Zone-3

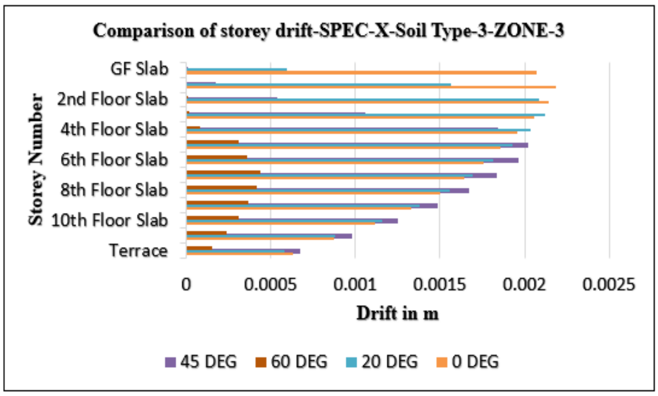


Figure 3.1.3. Comparison of storey drift-SPEC-X-Soil Type-3-Zone-3

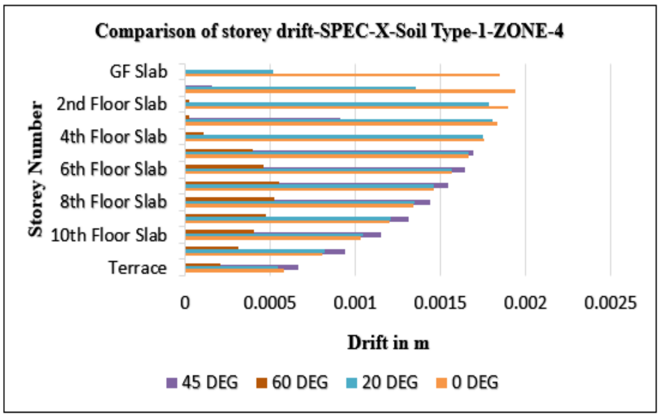


Figure 3.1.4. Comparison of storey drift-SPEC-X-Soil Type-1-Zone-4

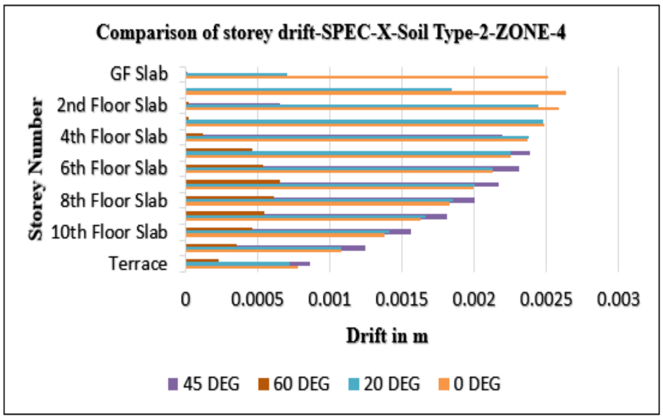


Figure 3.1.5. Comparison of storey drift-SPEC-X-Soil Type-2-Zone-4

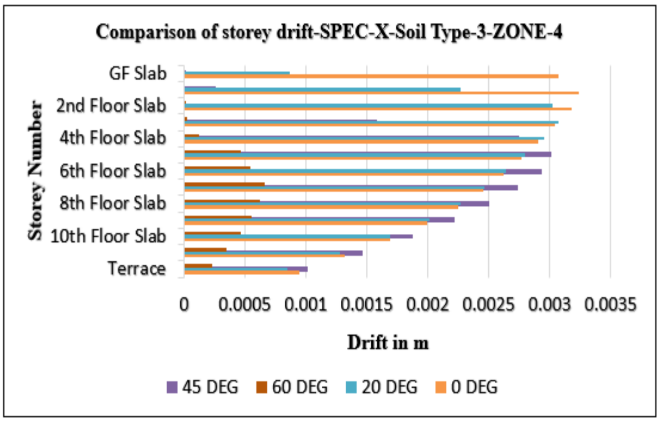


Figure 3.1.6. Comparison of storey drift-SPEC-X-Soil Type-3-Zone-4

3.2. STOREY DISPLACEMENT

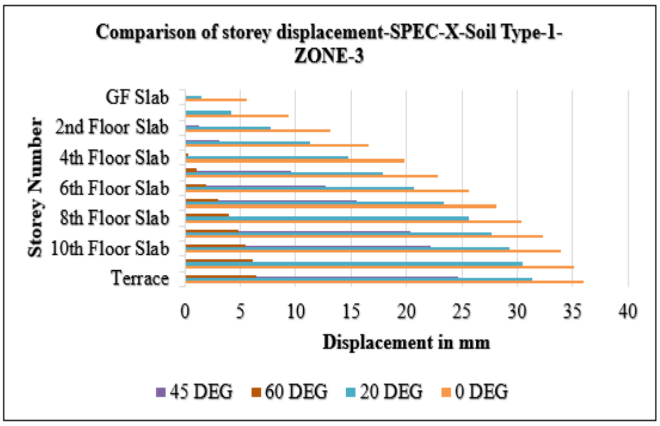


Figure 3.2.1. Comparison of storey displacement-SPEC-X-Soil Type-1-Zone-3

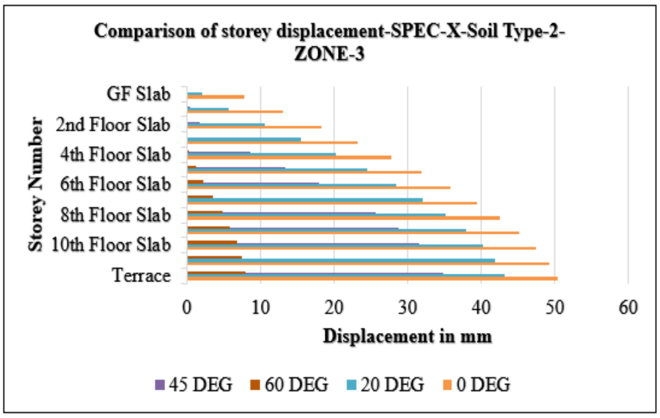


Figure 3.2.2. Comparison of storey displacement-SPEC-X-Soil Type-2-Zone-3

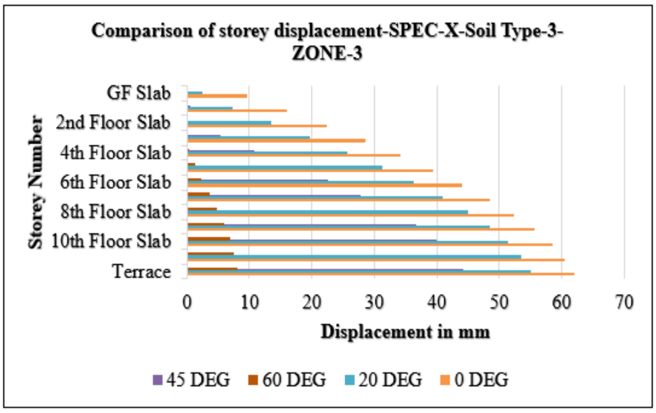


Figure 3.2.3. Comparison of storey displacement-SPEC-X-Soil Type-3-Zone-3

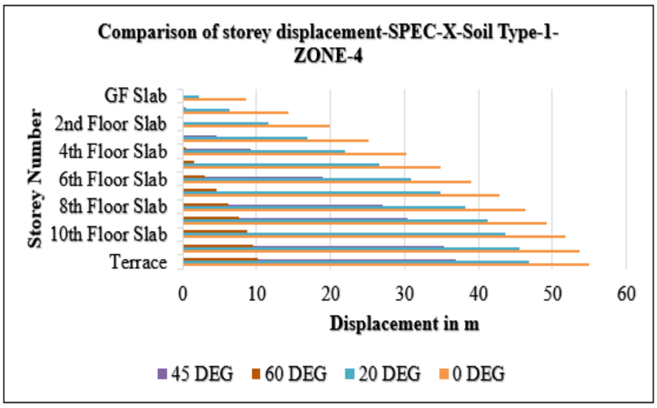


Figure 3.2.4. Comparison of storey displacement-SPEC-X-Soil Type-1-Zone-4

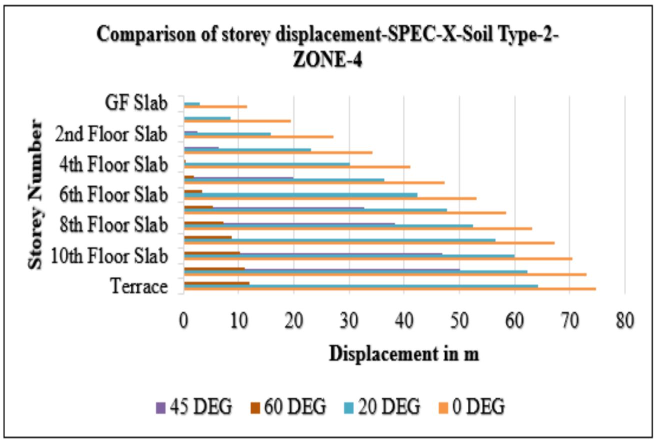


Figure 3.2.5. Comparison of storey displacement-SPEC-X-Soil Type-2-Zone-4

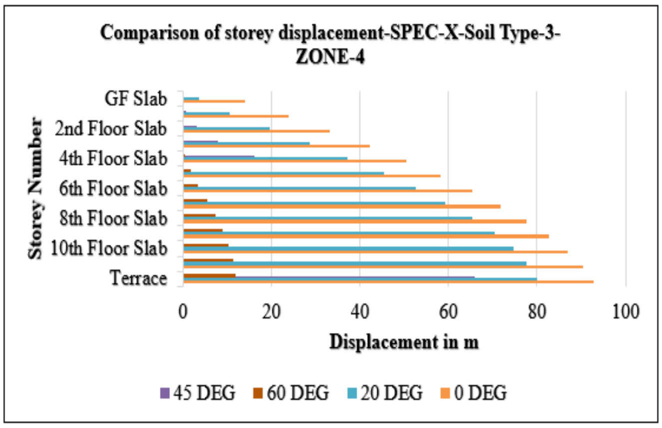


Figure 3.2.6. Comparison of storey displacement-SPEC-X-Soil Type-3-Zone-4

3.3. STIFFNESS IRREGULARITY

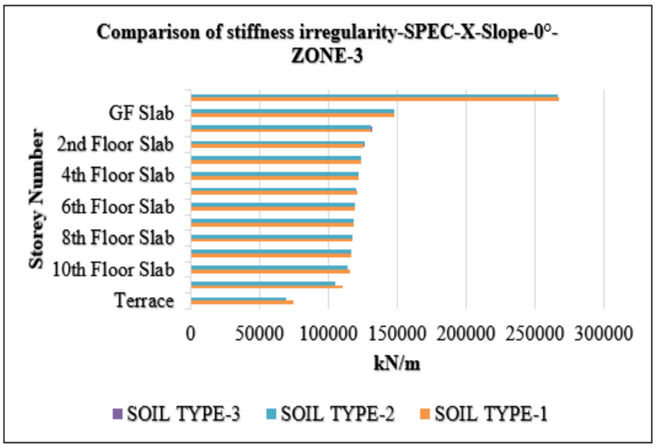


Figure 3.3.1. Comparison of stiffness irregularity-SPEC-X-Slope-0°-Zone-3

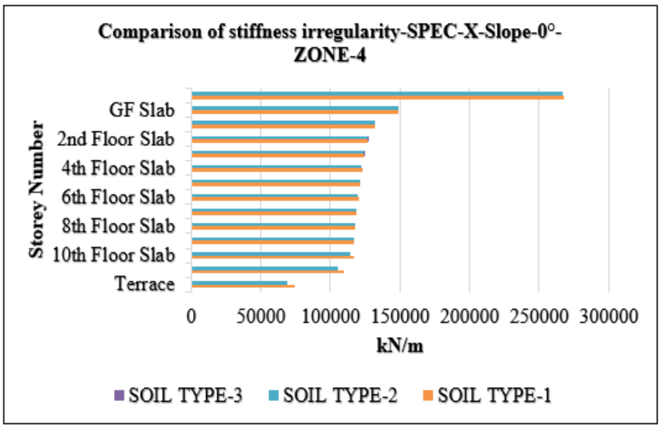


Figure 3.3.2. Comparison of stiffness irregularity-SPEC-X-Slope-0°-Zone-4

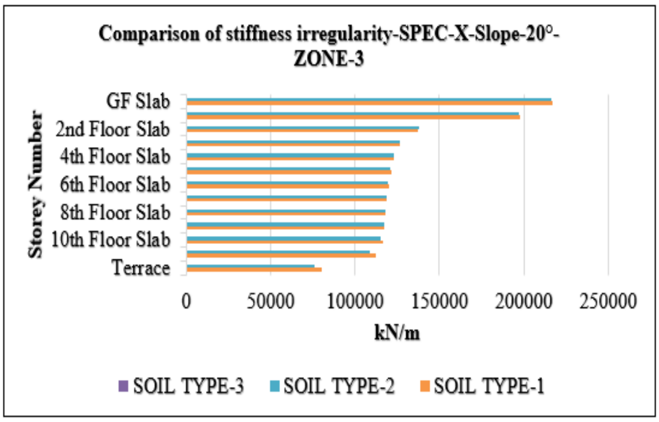


Figure 3.3.3. Comparison of stiffness irregularity-SPEC-X-Slope-20°-Zone-3

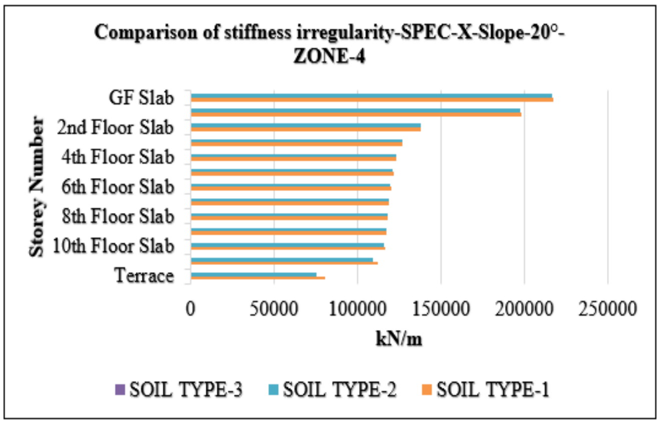


Figure 3.3.4. Comparison of stiffness irregularity-SPEC-X-Slope-20°-Zone-4

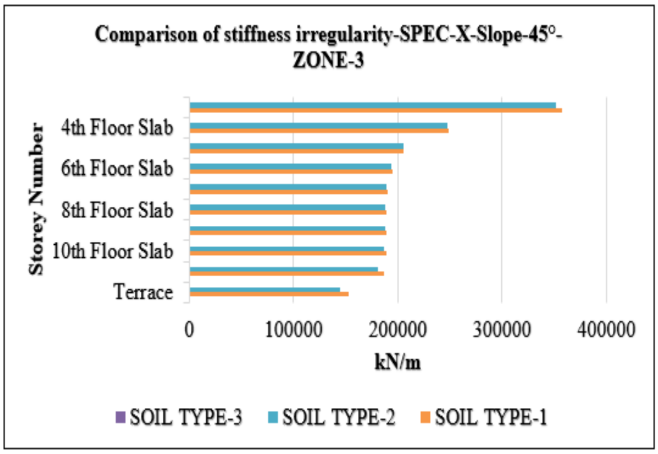


Figure 3.3.5. Comparison of stiffness irregularity-SPEC-X-Slope-45°-Zone-3

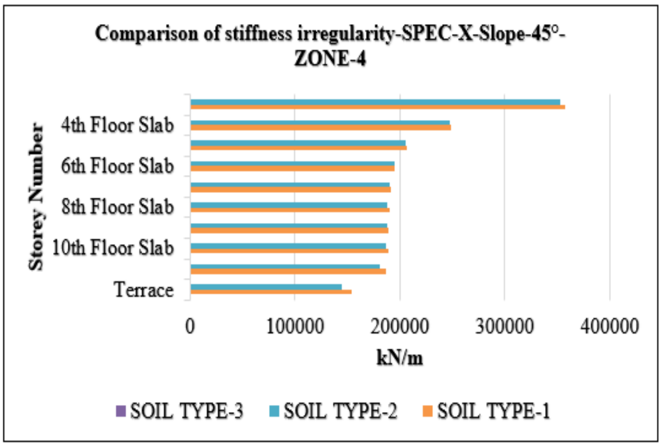


Figure 3.3.6. Comparison of stiffness irregularity-SPEC-X-Slope-45°-Zone-4

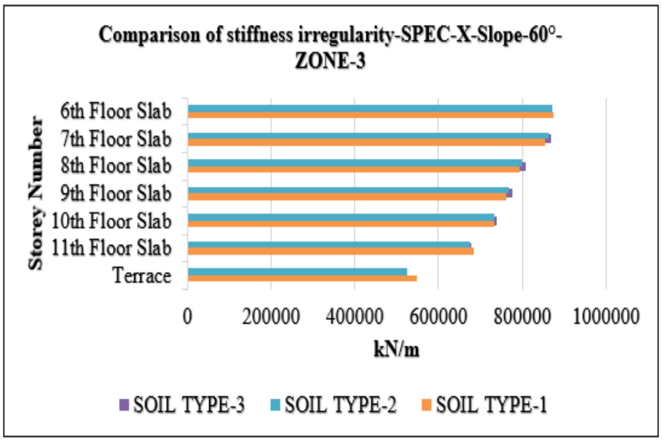


Figure 3.3.7. Comparison of stiffness irregularity-SPEC-X-Slope-60°-Zone-3

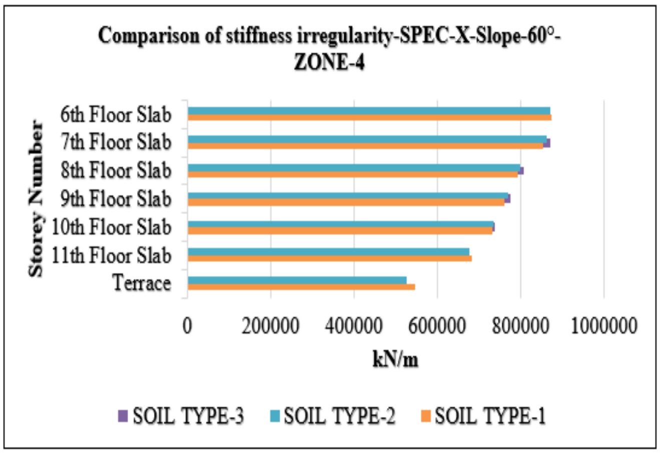


Figure 3.3.8. Comparison of stiffness irregularity-SPEC-X-Slope-60°-Zone-4

3.4. STOREY STRENGTH

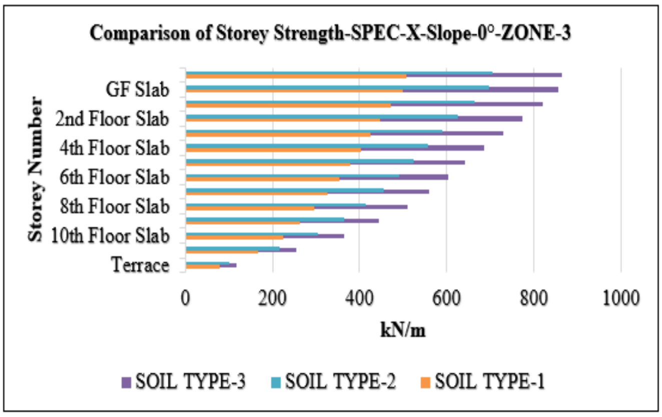


Figure 3.4.1. Comparison of storey strength-SPEC-X-Slope-0°-Zone-3

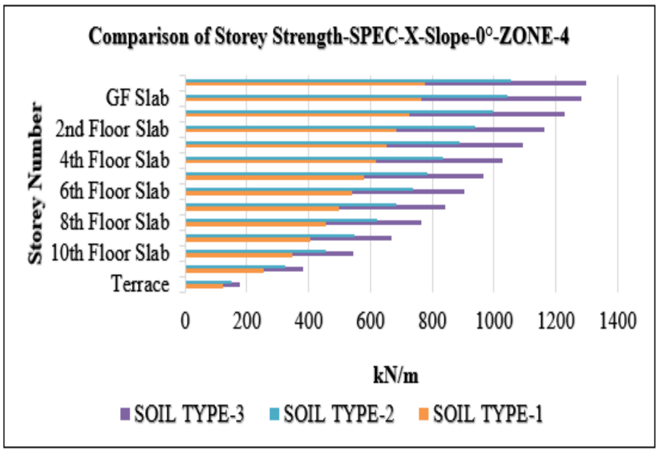


Figure 3.4.2. Comparison of storey strength-SPEC-X-Slope-0°-Zone-4

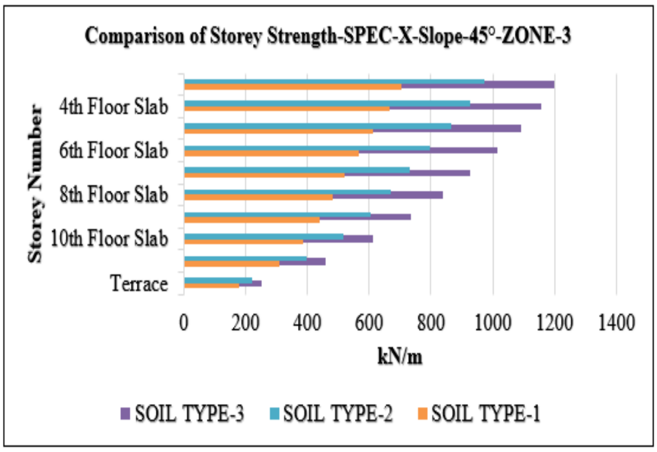


Figure 3.4.5. Comparison of storey strength-SPEC-X-Slope-45°-Zone-3

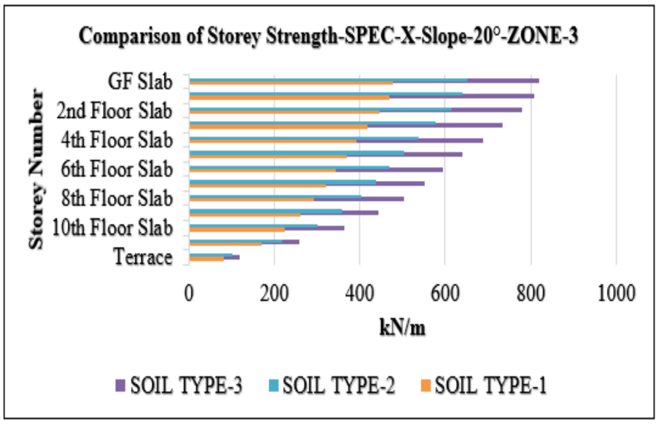


Figure 3.4.3. Comparison of storey strength-SPEC-X-Slope-20°-Zone-3

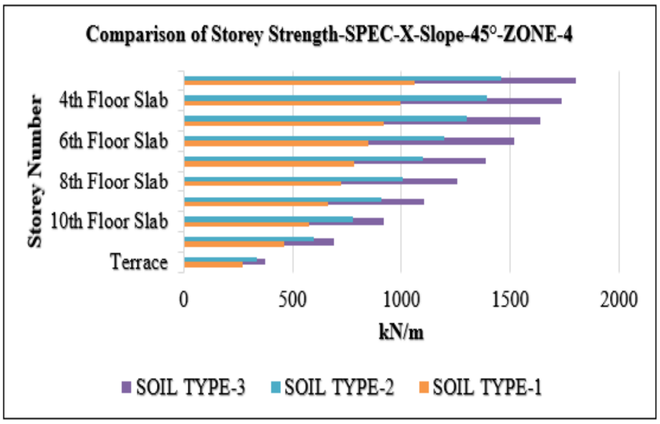


Figure 3.4.6. Comparison of storey strength-SPEC-X-Slope-45°-Zone-4

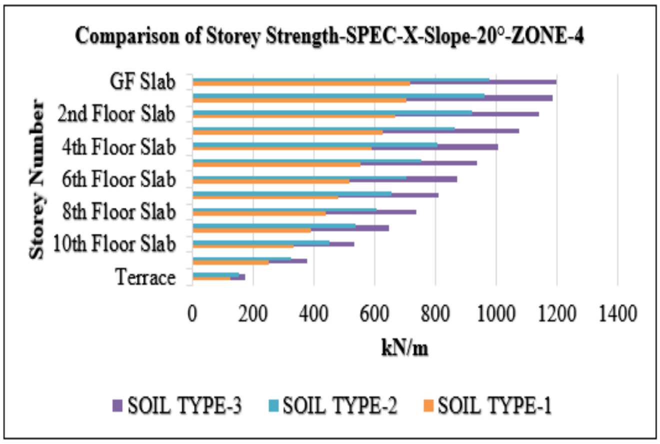


Figure 3.4.4. Comparison of storey strength-SPEC-X-Slope-20°-Zone-4

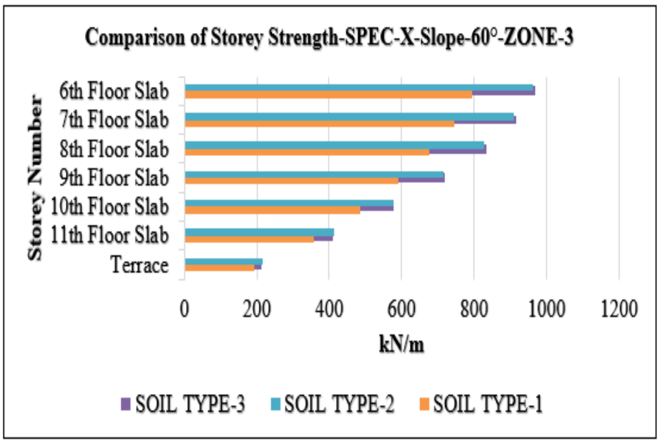


Figure 3.4.7. Comparison of storey strength-SPEC-X-Slope-60°-Zone-3

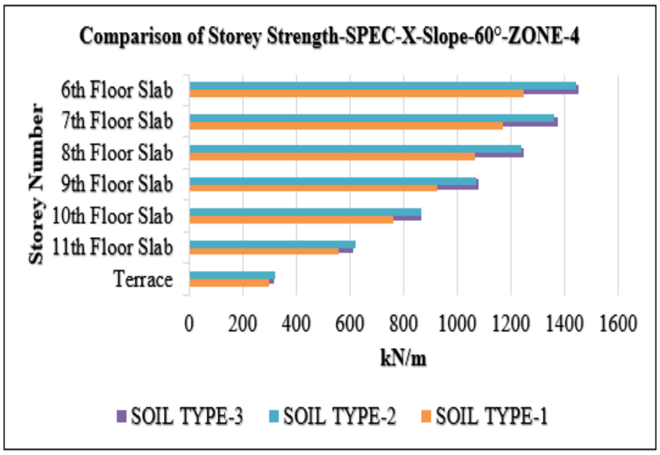


Figure 3.4.8. Comparison of storey strength-SPEC-X-Slope-60°-Zone-4

3.5. MASS IRREGULARITY

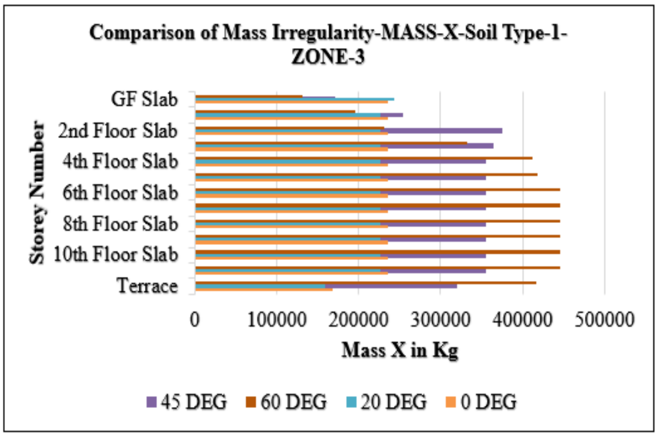


Figure 3.5.1. Comparison of mass irregularity-MASS-X-Soil Type-1-Zone-3

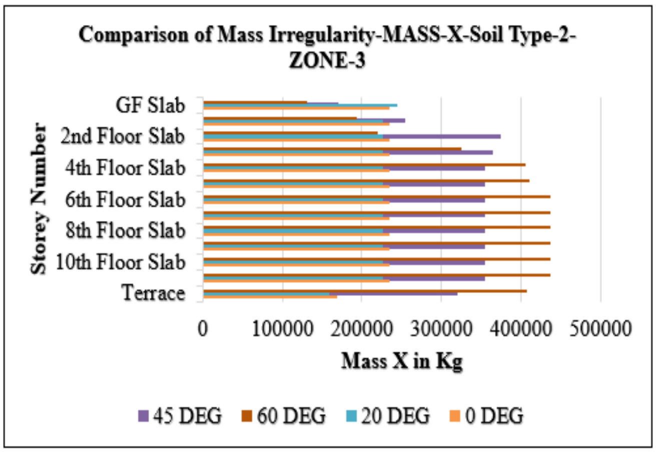


Figure 3.5.2. Comparison of mass irregularity-MASS-X-Soil Type-2-Zone-3

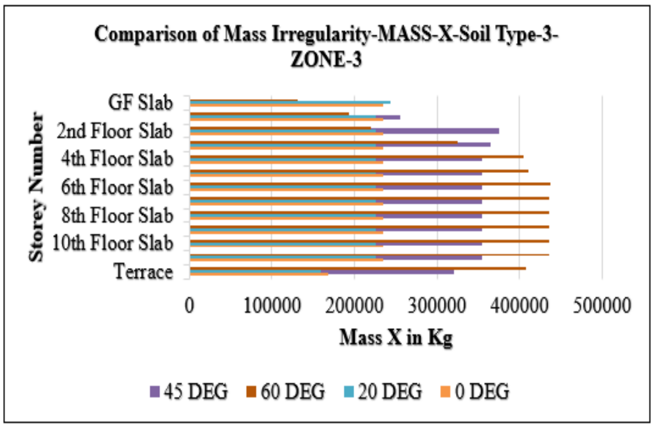


Figure 3.5.3. Comparison of mass irregularity-MASS-X-Soil Type-3-Zone-3

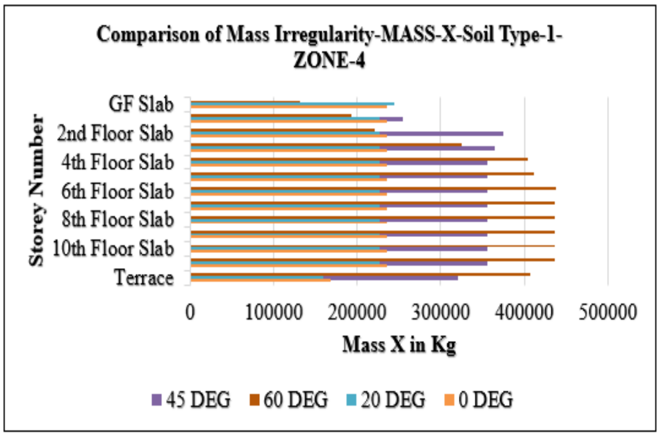


Figure 3.5.4. Comparison of mass irregularity-MASS-X-Soil Type-1-Zone-4

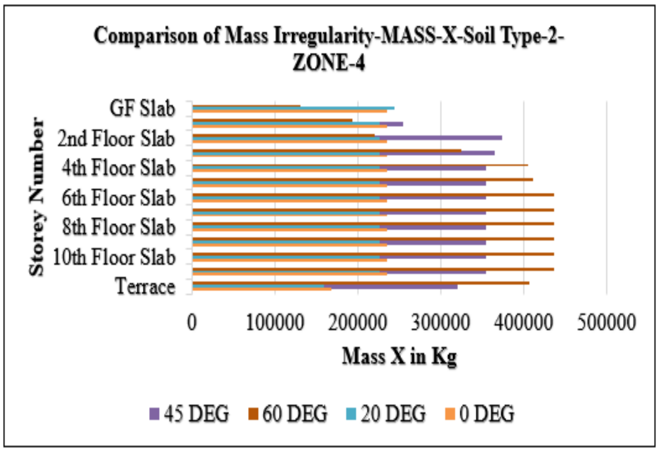


Figure 3.5.5. Comparison of mass irregularity-MASS-X-Soil Type-2-Zone-4

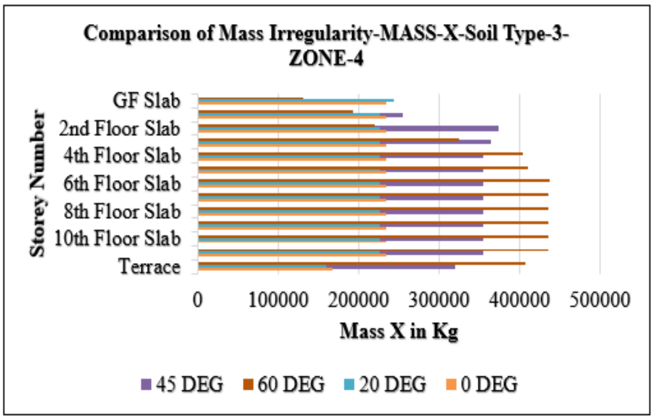


Figure 3.5.6. Comparison of mass irregularity-MASS-X-Soil Type-3-Zone-4

3.6. FLEXIBLE & RIGID DIAPHRAGM

Flexible & Rigid Diaphragm Check-SPEC-X-Soil Type-1-Zone-3 & 4									
Storey	Output Case	Ratio 0° Zone-3	Ratio 20° Zone-3	Ratio 45° Zone-3	Ratio 60° Zone-3	Ratio 0° Zone-4	Ratio 20° Zone-4	Ratio 45° Zone-4	Ratio 45° Zone-4
Terrace	SPEC-X	1.05	1.107	1.161	1.285	1.046	1.103	1.158	1.285
11th Floor Slab	SPEC-X	1.052	1.109	1.165	1.298	1.047	1.105	1.162	1.298
10th Floor Slab	SPEC-X	1.053	1.11	1.17	1.317	1.048	1.107	1.167	1.317
9th Floor Slab	SPEC-X	1.053	1.112	1.177	1.348	1.049	1.109	1.174	1.348
8th Floor Slab	SPEC-X	1.054	1.114	1.186	1.4	1.049	1.111	1.183	1.4
7th Floor Slab	SPEC-X	1.055	1.118	1.199	1.499	1.05	1.113	1.196	1.499
6th Floor Slab	SPEC-X	1.056	1.122	1.219	1.726	1.051	1.118	1.216	1.726
5th Floor Slab	SPEC-X	1.056	1.129	1.255	1.564	1.051	1.124	1.252	1.564
4th Floor Slab	SPEC-X	1.057	1.141	1.332	1.696	1.052	1.136	1.329	1.697
3rd Floor Slab	SPEC-X	1.058	1.16	1.544	1.6	1.053	1.155	1.543	1.6
2nd Floor Slab	SPEC-X	1.059	1.196	1.595	1.282	1.054	1.191	1.595	1.278
1st Floor Slab	SPEC-X	1.061	1.291	1.512	1.392	1.055	1.287	1.512	1.383
GF Floor Slab	SPEC-X	1.061	1.687	1.254	1.426	1.056	1.685	1.254	1.419

Figure 3.6.1. Comparison of flexible & rigid diaphragm-SPEC-X-Soil Type-1-Zone-3&4

Flexible & Rigid Diaphragm Check-SPEC-X-Soil Type-2-Zone-3 & 4									
Storey	Output Case	Ratio 0° Zone-3	Ratio 20° Zone-3	Ratio 45° Zone-3	Ratio 60° Zone-3	Ratio 0° Zone-4	Ratio 20° Zone-4	Ratio 45° Zone-4	Ratio 45° Zone-4
Terrace	SPEC-X	1.047	1.104	1.159	1.3	1.042	1.099	1.155	1.3
11th Floor Slab	SPEC-X	1.048	1.106	1.163	1.312	1.042	1.101	1.159	1.312
10th Floor Slab	SPEC-X	1.049	1.107	1.168	1.332	1.043	1.103	1.164	1.332
9th Floor Slab	SPEC-X	1.05	1.109	1.175	1.363	1.043	1.104	1.171	1.363
8th Floor Slab	SPEC-X	1.05	1.111	1.184	1.414	1.044	1.107	1.18	1.414
7th Floor Slab	SPEC-X	1.051	1.114	1.197	1.511	1.044	1.109	1.193	1.511
6th Floor Slab	SPEC-X	1.052	1.119	1.218	1.733	1.045	1.113	1.214	1.733
5th Floor Slab	SPEC-X	1.053	1.126	1.254	1.565	1.046	1.119	1.25	1.565
4th Floor Slab	SPEC-X	1.053	1.138	1.33	1.697	1.047	1.13	1.326	1.697
3rd Floor Slab	SPEC-X	1.054	1.156	1.542	1.607	1.048	1.149	1.54	1.607
2nd Floor Slab	SPEC-X	1.056	1.192	1.595	1.279	1.049	1.186	1.595	1.279
1st Floor Slab	SPEC-X	1.057	1.288	1.513	1.387	1.05	1.282	1.513	1.387
GF Floor Slab	SPEC-X	1.057	1.684	1.255	1.428	1.051	1.682	1.255	1.428

Figure 3.6.2. Comparison of flexible & rigid diaphragm-SPEC-X-Soil Type-2-Zone-3&4

Flexible & Rigid Diaphragm Check-SPEC-X-Soil Type-3-Zone-3 & 4									
Storey	Output Case	Ratio 0° Zone-3	Ratio 20° Zone-3	Ratio 45° Zone-3	Ratio 60° Zone-3	Ratio 0° Zone-4	Ratio 20° Zone-4	Ratio 45° Zone-4	Ratio 45° Zone-4
Terrace	SPEC-X	1.043	1.101	1.157	1.316	1.044	1.095	1.153	1.316
11th Floor Slab	SPEC-X	1.045	1.103	1.161	1.328	1.043	1.097	1.156	1.328
10th Floor Slab	SPEC-X	1.046	1.105	1.167	1.348	1.042	1.099	1.161	1.348
9th Floor Slab	SPEC-X	1.046	1.107	1.173	1.378	1.041	1.101	1.168	1.378
8th Floor Slab	SPEC-X	1.047	1.109	1.182	1.429	1.04	1.103	1.177	1.429
7th Floor Slab	SPEC-X	1.048	1.111	1.196	1.524	1.04	1.105	1.19	1.524
6th Floor Slab	SPEC-X	1.048	1.116	1.216	1.739	1.041	1.109	1.211	1.739
5th Floor Slab	SPEC-X	1.049	1.123	1.252	1.566	1.041	1.115	1.247	1.566
4th Floor Slab	SPEC-X	1.05	1.135	1.328	1.696	1.042	1.126	1.323	1.696
3rd Floor Slab	SPEC-X	1.051	1.154	1.539	1.611	1.043	1.145	1.536	1.611
2nd Floor Slab	SPEC-X	1.052	1.19	1.595	1.28	1.044	1.181	1.594	1.28
1st Floor Slab	SPEC-X	1.053	1.285	1.514	1.391	1.045	1.278	1.514	1.39
GF Floor Slab	SPEC-X	1.054	1.683	1.258	1.431	1.046	1.679	1.258	1.431

Figure 3.6.3. Comparison of flexible & rigid diaphragm-SPEC-X-Soil Type-3-Zone-3&4

3.7. MODE SHAPE

Mode Shape-Slope-0°-Soil Type-1-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	2.31	0.7864	0.0231	0.0028
2	2.255	0.0258	0.7449	0.0405
3	2.078	0.0002	0.0427	0.769
4	0.738	0.1009	0.0025	0.0008
5	0.719	0.003	0.0977	0.0044
6	0.667	0.0006	0.0055	0.0943
7	0.414	0.032	0.0005	0.0009
8	0.402	0.0009	0.0308	0.0019
9	0.377	0.0006	0.0023	0.0314
10	0.28	0.0158	0.0002	0.0005
11	0.272	0.0003	0.0153	0.001
12	0.255	0.0003	0.0011	0.0159

Figure 3.7.1. Mode Shape-Slope-0°-Soil Type-1-Zone-3

Mode Shape-Slope-0°-Soil Type-1-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	2.31	0.7857	0.0235	0.0032
2	2.255	0.0263	0.7464	0.0384
3	2.078	0.0003	0.0408	0.7708
4	0.738	0.1009	0.0025	0.0008
5	0.719	0.003	0.0978	0.0043
6	0.667	0.0006	0.0053	0.0944
7	0.414	0.032	0.0005	0.0009
8	0.402	0.0009	0.0308	0.0019
9	0.377	0.0006	0.0022	0.0314
10	0.28	0.0158	0.0002	0.0005
11	0.272	0.0003	0.0154	0.0009
12	0.255	0.0003	0.0011	0.0159

Figure 3.7.2. Mode Shape-Slope-0°-Soil Type-1-Zone-4

Mode Shape-Slope-0°-Soil Type-2-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	2.311	0.7852	0.0237	0.0035
2	2.254	0.0267	0.7477	0.0367
3	2.079	0.0005	0.0393	0.7722
4	0.738	0.1008	0.0025	0.0008
5	0.719	0.003	0.098	0.0042
6	0.667	0.0007	0.0051	0.0945
7	0.414	0.032	0.0005	0.0009
8	0.402	0.0009	0.0309	0.0018
9	0.377	0.0006	0.0022	0.0314
10	0.28	0.0158	0.0002	0.0005
11	0.272	0.0003	0.0154	0.0009
12	0.255	0.0003	0.001	0.0159

Figure 3.7.3. Mode Shape-Slope-0°-Soil Type-2-Zone-3

Mode Shape-Slope-0°-Soil Type-2-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	2.31	0.788	0.0223	0.0021
2	2.257	0.0244	0.7417	0.0452
3	2.077	0.0003	0.0468	0.7651
4	0.738	0.1011	0.0025	0.0007
5	0.719	0.0029	0.0973	0.0048
6	0.667	0.0005	0.0058	0.094
7	0.414	0.0321	0.0005	0.0008
8	0.402	0.0009	0.0306	0.002
9	0.376	0.0005	0.0024	0.0313
10	0.28	0.0158	0.0002	0.0005
11	0.272	0.0003	0.0153	0.001
12	0.254	0.0003	0.0011	0.0159

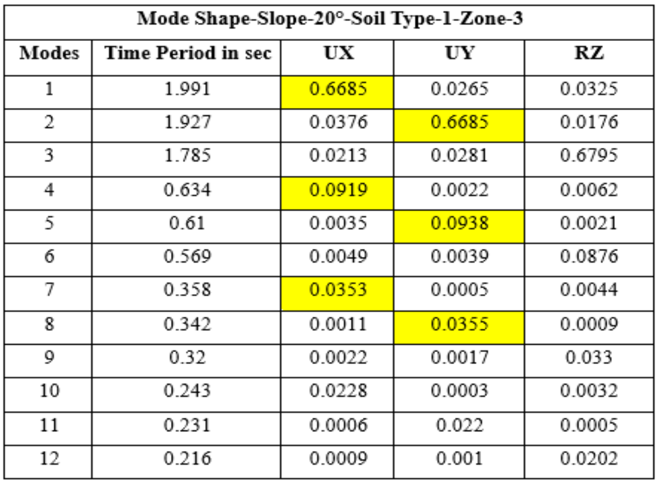
Figure 3.7.4. Mode Shape-Slope-0°-Soil Type-2-Zone-4

Mode Shape-Slope-0°-Soil Type-3-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	2.31	0.7864	0.0231	0.0028
2	2.255	0.0258	0.7449	0.0405
3	2.078	0.0002	0.0427	0.769
4	0.738	0.1009	0.0025	0.0008
5	0.719	0.003	0.0977	0.0044
6	0.667	0.0006	0.0055	0.0943
7	0.414	0.032	0.0005	0.0009
8	0.402	0.0009	0.0308	0.0019
9	0.377	0.0006	0.0023	0.0314
10	0.28	0.0158	0.0002	0.0005
11	0.272	0.0003	0.0153	0.001
12	0.255	0.0003	0.0011	0.0159

Figure 3.7.5. Mode Shape-Slope-0°-Soil Type-3-Zone-3

Mode Shape-Slope-0°-Soil Type-3-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	2.31	0.7902	0.0208	0.0013
2	2.258	0.0222	0.738	0.0513
3	2.076	0.0001	0.052	0.7598
4	0.738	0.1012	0.0024	0.0006
5	0.72	0.0029	0.0968	0.0052
6	0.667	0.0004	0.0063	0.0937
7	0.414	0.0321	0.0005	0.0008
8	0.402	0.0009	0.0305	0.0022
9	0.376	0.0005	0.0026	0.0312
10	0.28	0.0159	0.0002	0.0004
11	0.272	0.0004	0.0152	0.0011
12	0.254	0.0003	0.0012	0.0158

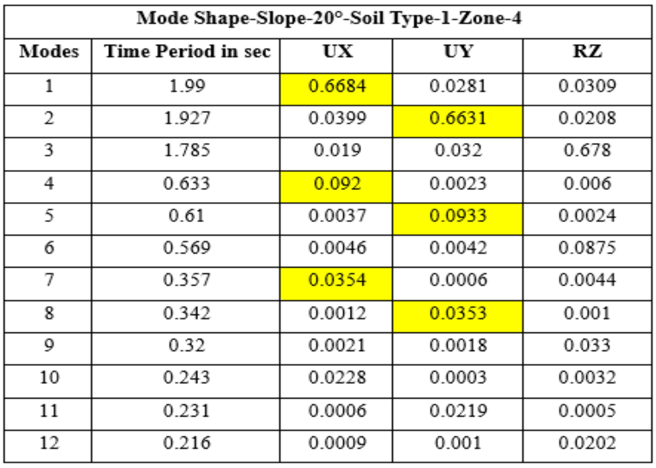
Figure 3.7.6. Mode Shape-Slope-0°-Soil Type-3-Zone-4



Mode Shape-Slope-20°-Soil Type-1-Zone-3

Modes	Time Period in sec	UX	UY	RZ
1	1.991	0.6685	0.0265	0.0325
2	1.927	0.0376	0.6685	0.0176
3	1.785	0.0213	0.0281	0.6795
4	0.634	0.0919	0.0022	0.0062
5	0.61	0.0035	0.0938	0.0021
6	0.569	0.0049	0.0039	0.0876
7	0.358	0.0353	0.0005	0.0044
8	0.342	0.0011	0.0355	0.0009
9	0.32	0.0022	0.0017	0.033
10	0.243	0.0228	0.0003	0.0032
11	0.231	0.0006	0.022	0.0005
12	0.216	0.0009	0.001	0.0202

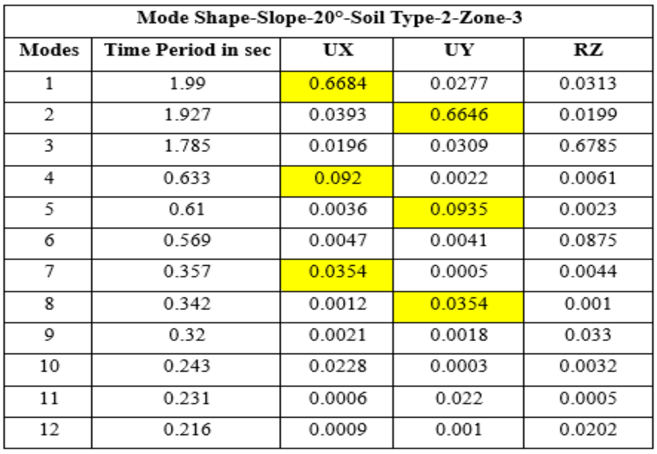
Figure 3.7.7. Mode Shape-Slope-20°-Soil Type-1-Zone-3



Mode Shape-Slope-20°-Soil Type-1-Zone-4

Modes	Time Period in sec	UX	UY	RZ
1	1.99	0.6684	0.0281	0.0309
2	1.927	0.0399	0.6631	0.0208
3	1.785	0.019	0.032	0.678
4	0.633	0.092	0.0023	0.006
5	0.61	0.0037	0.0933	0.0024
6	0.569	0.0046	0.0042	0.0875
7	0.357	0.0354	0.0006	0.0044
8	0.342	0.0012	0.0353	0.001
9	0.32	0.0021	0.0018	0.033
10	0.243	0.0228	0.0003	0.0032
11	0.231	0.0006	0.0219	0.0005
12	0.216	0.0009	0.001	0.0202

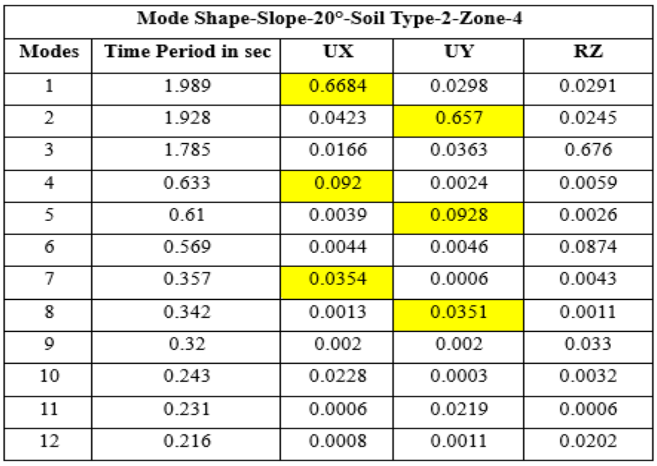
Figure 3.7.8. Mode Shape-Slope-20°-Soil Type-1-Zone-4



Mode Shape-Slope-20°-Soil Type-2-Zone-3

Modes	Time Period in sec	UX	UY	RZ
1	1.99	0.6684	0.0277	0.0313
2	1.927	0.0393	0.6646	0.0199
3	1.785	0.0196	0.0309	0.6785
4	0.633	0.092	0.0022	0.0061
5	0.61	0.0036	0.0935	0.0023
6	0.569	0.0047	0.0041	0.0875
7	0.357	0.0354	0.0005	0.0044
8	0.342	0.0012	0.0354	0.001
9	0.32	0.0021	0.0018	0.033
10	0.243	0.0228	0.0003	0.0032
11	0.231	0.0006	0.022	0.0005
12	0.216	0.0009	0.001	0.0202

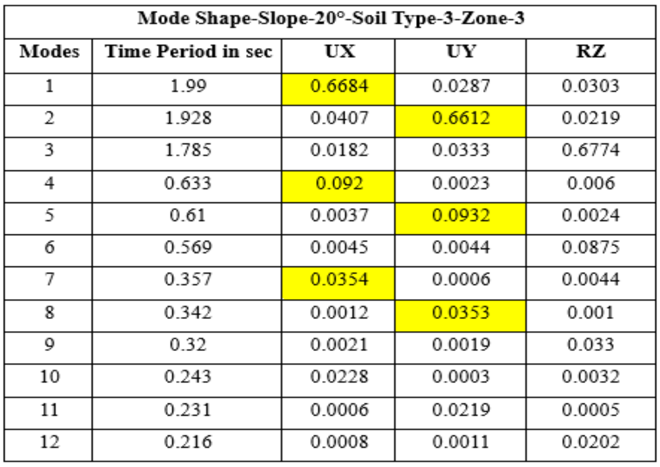
Figure 3.7.9. Mode Shape-Slope-20°- Soil Type-2-Zone-3



Mode Shape-Slope-20°-Soil Type-2-Zone-4

Modes	Time Period in sec	UX	UY	RZ
1	1.989	0.6684	0.0298	0.0291
2	1.928	0.0423	0.657	0.0245
3	1.785	0.0166	0.0363	0.676
4	0.633	0.092	0.0024	0.0059
5	0.61	0.0039	0.0928	0.0026
6	0.569	0.0044	0.0046	0.0874
7	0.357	0.0354	0.0006	0.0043
8	0.342	0.0013	0.0351	0.0011
9	0.32	0.002	0.002	0.033
10	0.243	0.0228	0.0003	0.0032
11	0.231	0.0006	0.0219	0.0006
12	0.216	0.0008	0.0011	0.0202

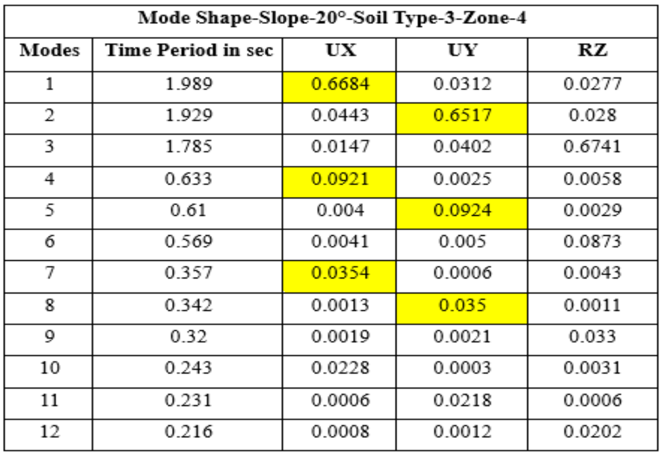
Figure 3.7.10. Mode Shape-Slope-20°-Soil Type-2-Zone-4



Mode Shape-Slope-20°-Soil Type-3-Zone-3

Modes	Time Period in sec	UX	UY	RZ
1	1.99	0.6684	0.0287	0.0303
2	1.928	0.0407	0.6612	0.0219
3	1.785	0.0182	0.0333	0.6774
4	0.633	0.092	0.0023	0.006
5	0.61	0.0037	0.0932	0.0024
6	0.569	0.0045	0.0044	0.0875
7	0.357	0.0354	0.0006	0.0044
8	0.342	0.0012	0.0353	0.001
9	0.32	0.0021	0.0019	0.033
10	0.243	0.0228	0.0003	0.0032
11	0.231	0.0006	0.0219	0.0005
12	0.216	0.0008	0.0011	0.0202

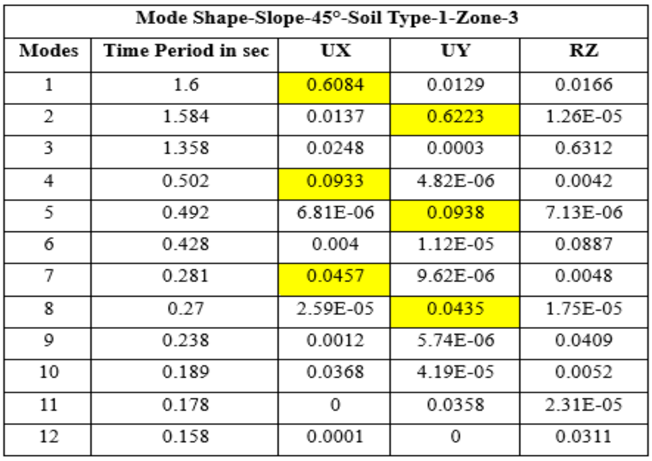
Figure 3.7.11. Mode Shape-Slope-20°-Soil Type-3-Zone-3



Mode Shape-Slope-20°-Soil Type-3-Zone-4

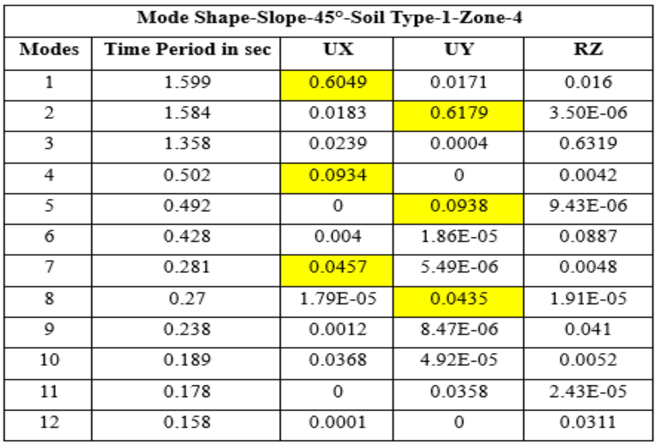
Modes	Time Period in sec	UX	UY	RZ
1	1.989	0.6684	0.0312	0.0277
2	1.929	0.0443	0.6517	0.028
3	1.785	0.0147	0.0402	0.6741
4	0.633	0.0921	0.0025	0.0058
5	0.61	0.004	0.0924	0.0029
6	0.569	0.0041	0.005	0.0873
7	0.357	0.0354	0.0006	0.0043
8	0.342	0.0013	0.035	0.0011
9	0.32	0.0019	0.0021	0.033
10	0.243	0.0228	0.0003	0.0031
11	0.231	0.0006	0.0218	0.0006
12	0.216	0.0008	0.0012	0.0202

Figure 3.7.12. Mode Shape-Slope-20°-Soil Type-3-Zone-4



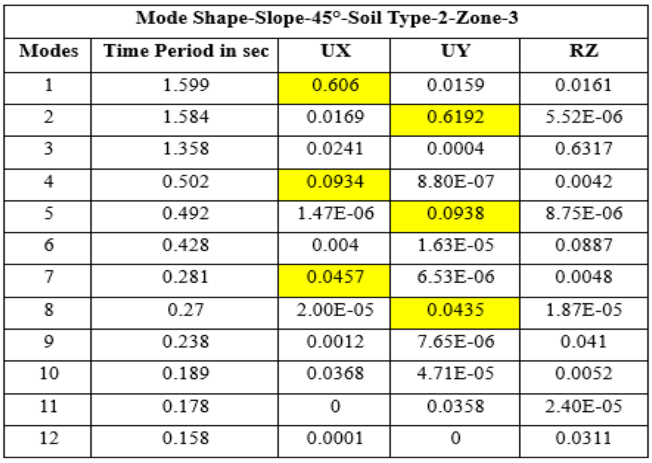
Mode Shape-Slope-45°-Soil Type-1-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	1.6	0.6084	0.0129	0.0166
2	1.584	0.0137	0.6223	1.26E-05
3	1.358	0.0248	0.0003	0.6312
4	0.502	0.0933	4.82E-06	0.0042
5	0.492	6.81E-06	0.0938	7.13E-06
6	0.428	0.004	1.12E-05	0.0887
7	0.281	0.0457	9.62E-06	0.0048
8	0.27	2.59E-05	0.0435	1.75E-05
9	0.238	0.0012	5.74E-06	0.0409
10	0.189	0.0368	4.19E-05	0.0052
11	0.178	0	0.0358	2.31E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.13. Mode Shape-Slope-45°-Soil Type-1-Zone-3



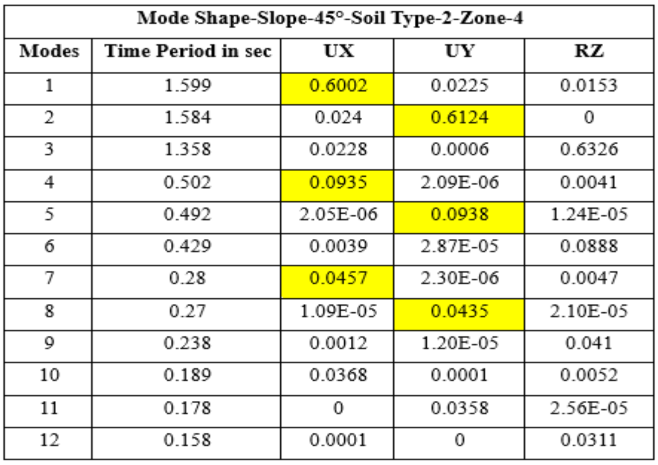
Mode Shape-Slope-45°-Soil Type-1-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	1.599	0.6049	0.0171	0.016
2	1.584	0.0183	0.6179	3.50E-06
3	1.358	0.0239	0.0004	0.6319
4	0.502	0.0934	0	0.0042
5	0.492	0	0.0938	9.43E-06
6	0.428	0.004	1.86E-05	0.0887
7	0.281	0.0457	5.49E-06	0.0048
8	0.27	1.79E-05	0.0435	1.91E-05
9	0.238	0.0012	8.47E-06	0.041
10	0.189	0.0368	4.92E-05	0.0052
11	0.178	0	0.0358	2.43E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.14. Mode Shape-Slope-45°-Soil Type-1-Zone-4



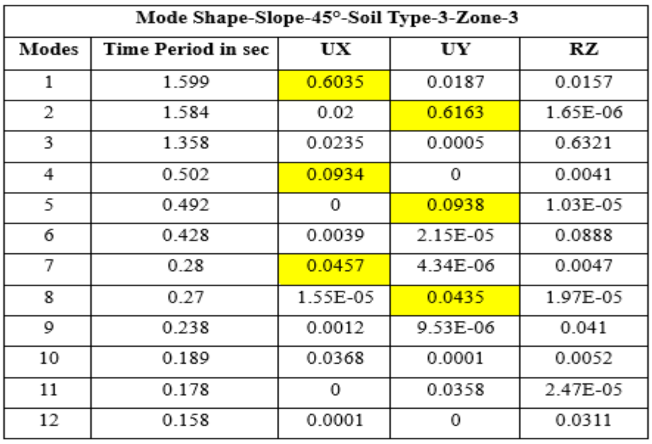
Mode Shape-Slope-45°-Soil Type-2-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	1.599	0.606	0.0159	0.0161
2	1.584	0.0169	0.6192	5.52E-06
3	1.358	0.0241	0.0004	0.6317
4	0.502	0.0934	8.80E-07	0.0042
5	0.492	1.47E-06	0.0938	8.75E-06
6	0.428	0.004	1.63E-05	0.0887
7	0.281	0.0457	6.53E-06	0.0048
8	0.27	2.00E-05	0.0435	1.87E-05
9	0.238	0.0012	7.65E-06	0.041
10	0.189	0.0368	4.71E-05	0.0052
11	0.178	0	0.0358	2.40E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.15. Mode Shape-Slope-45°-Soil Type-2-Zone-3



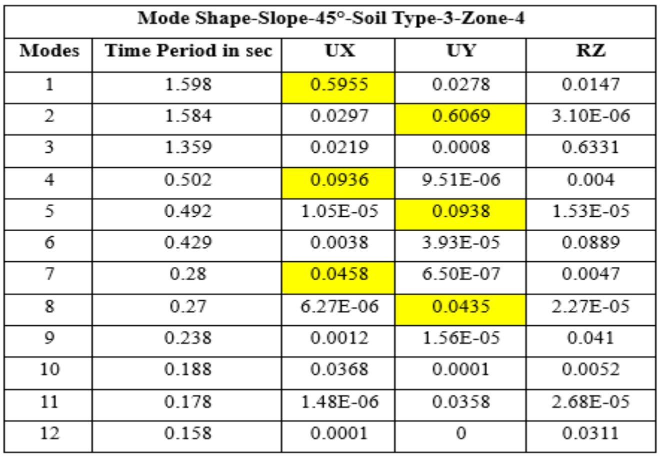
Mode Shape-Slope-45°-Soil Type-2-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	1.599	0.6002	0.0225	0.0153
2	1.584	0.024	0.6124	0
3	1.358	0.0228	0.0006	0.6326
4	0.502	0.0935	2.09E-06	0.0041
5	0.492	2.05E-06	0.0938	1.24E-05
6	0.429	0.0039	2.87E-05	0.0888
7	0.28	0.0457	2.30E-06	0.0047
8	0.27	1.09E-05	0.0435	2.10E-05
9	0.238	0.0012	1.20E-05	0.041
10	0.189	0.0368	0.0001	0.0052
11	0.178	0	0.0358	2.56E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.16. Mode Shape-Slope-45°-Soil Type-2-Zone-4



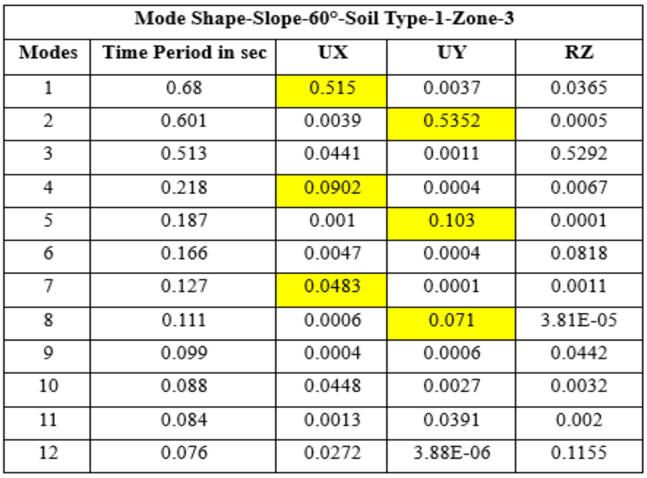
Mode Shape-Slope-45°-Soil Type-3-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	1.599	0.6035	0.0187	0.0157
2	1.584	0.02	0.6163	1.65E-06
3	1.358	0.0235	0.0005	0.6321
4	0.502	0.0934	0	0.0041
5	0.492	0	0.0938	1.03E-05
6	0.428	0.0039	2.15E-05	0.0888
7	0.28	0.0457	4.34E-06	0.0047
8	0.27	1.55E-05	0.0435	1.97E-05
9	0.238	0.0012	9.53E-06	0.041
10	0.189	0.0368	0.0001	0.0052
11	0.178	0	0.0358	2.47E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.17. Mode Shape-Slope-45°-Soil Type-3-Zone-3



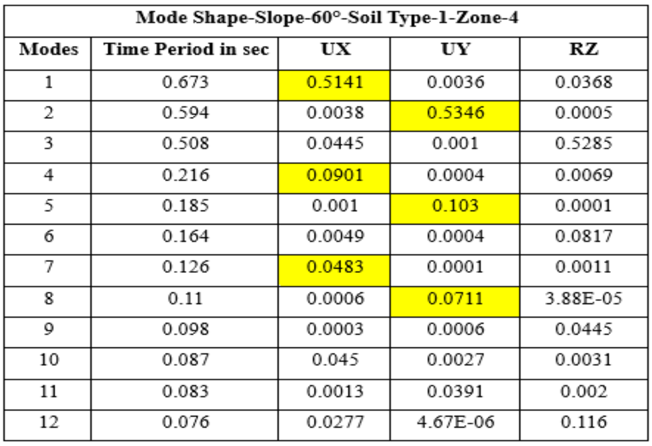
Mode Shape-Slope-45°-Soil Type-3-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	1.598	0.5955	0.0278	0.0147
2	1.584	0.0297	0.6069	3.10E-06
3	1.359	0.0219	0.0008	0.6331
4	0.502	0.0936	9.51E-06	0.004
5	0.492	1.05E-05	0.0938	1.53E-05
6	0.429	0.0038	3.93E-05	0.0889
7	0.28	0.0458	6.50E-07	0.0047
8	0.27	6.27E-06	0.0435	2.27E-05
9	0.238	0.0012	1.56E-05	0.041
10	0.188	0.0368	0.0001	0.0052
11	0.178	1.48E-06	0.0358	2.68E-05
12	0.158	0.0001	0	0.0311

Figure 3.7.18. Mode Shape-Slope-45°-Soil Type-3-Zone-4



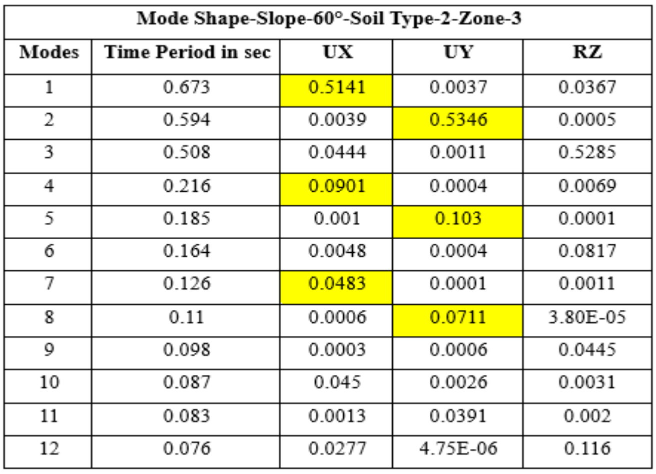
Mode Shape-Slope-60°-Soil Type-1-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	0.68	0.515	0.0037	0.0365
2	0.601	0.0039	0.5352	0.0005
3	0.513	0.0441	0.0011	0.5292
4	0.218	0.0902	0.0004	0.0067
5	0.187	0.001	0.103	0.0001
6	0.166	0.0047	0.0004	0.0818
7	0.127	0.0483	0.0001	0.0011
8	0.111	0.0006	0.071	3.81E-05
9	0.099	0.0004	0.0006	0.0442
10	0.088	0.0448	0.0027	0.0032
11	0.084	0.0013	0.0391	0.002
12	0.076	0.0272	3.88E-06	0.1155

Figure 3.7.19. Mode Shape-Slope-60°-Soil Type-1-Zone-3



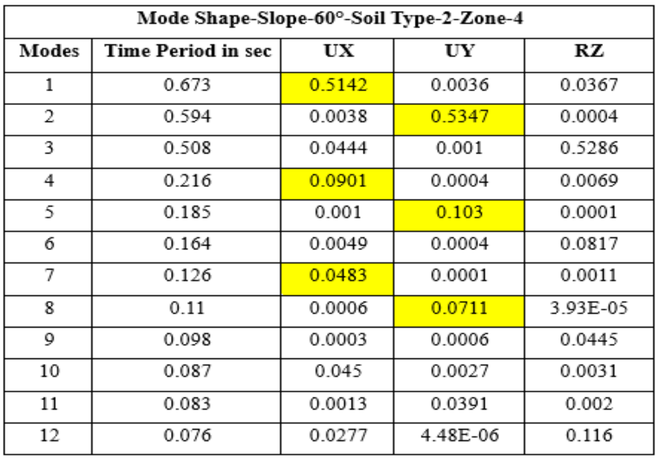
Mode Shape-Slope-60°-Soil Type-1-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	0.673	0.5141	0.0036	0.0368
2	0.594	0.0038	0.5346	0.0005
3	0.508	0.0445	0.001	0.5285
4	0.216	0.0901	0.0004	0.0069
5	0.185	0.001	0.103	0.0001
6	0.164	0.0049	0.0004	0.0817
7	0.126	0.0483	0.0001	0.0011
8	0.11	0.0006	0.0711	3.88E-05
9	0.098	0.0003	0.0006	0.0445
10	0.087	0.045	0.0027	0.0031
11	0.083	0.0013	0.0391	0.002
12	0.076	0.0277	4.67E-06	0.116

Figure 3.7.20. Mode Shape-Slope-60°-Soil Type-1-Zone-4



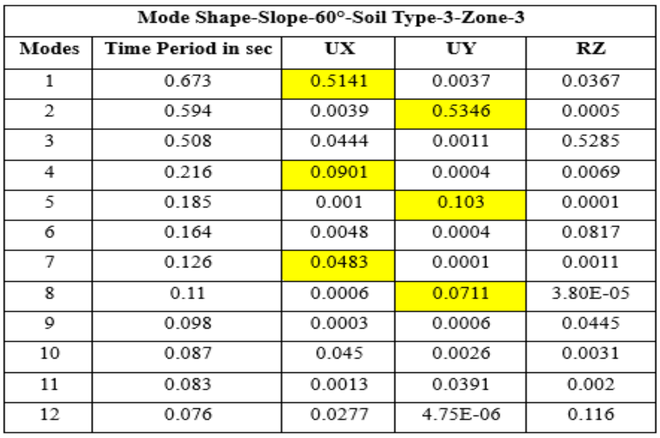
Mode Shape-Slope-60°-Soil Type-2-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	0.673	0.5141	0.0037	0.0367
2	0.594	0.0039	0.5346	0.0005
3	0.508	0.0444	0.0011	0.5285
4	0.216	0.0901	0.0004	0.0069
5	0.185	0.001	0.103	0.0001
6	0.164	0.0048	0.0004	0.0817
7	0.126	0.0483	0.0001	0.0011
8	0.11	0.0006	0.0711	3.80E-05
9	0.098	0.0003	0.0006	0.0445
10	0.087	0.045	0.0026	0.0031
11	0.083	0.0013	0.0391	0.002
12	0.076	0.0277	4.75E-06	0.116

Figure 3.7.21. Mode Shape-Slope-60°-Soil Type-2-Zone-3



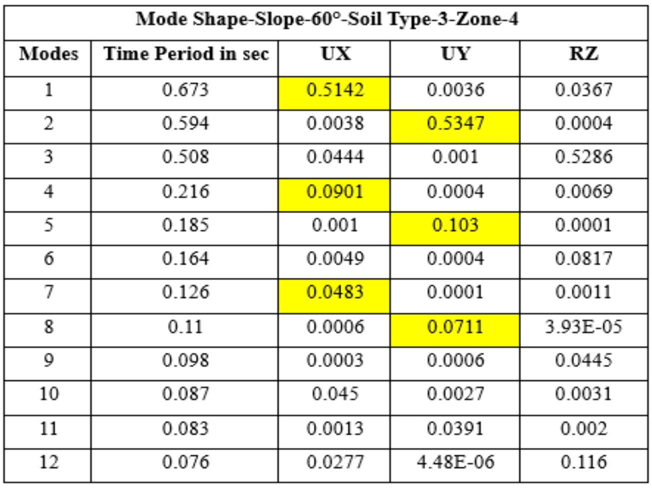
Mode Shape-Slope-60°-Soil Type-2-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	0.673	0.5142	0.0036	0.0367
2	0.594	0.0038	0.5347	0.0004
3	0.508	0.0444	0.001	0.5286
4	0.216	0.0901	0.0004	0.0069
5	0.185	0.001	0.103	0.0001
6	0.164	0.0049	0.0004	0.0817
7	0.126	0.0483	0.0001	0.0011
8	0.11	0.0006	0.0711	3.93E-05
9	0.098	0.0003	0.0006	0.0445
10	0.087	0.045	0.0027	0.0031
11	0.083	0.0013	0.0391	0.002
12	0.076	0.0277	4.48E-06	0.116

Figure 3.7.22. Mode Shape-Slope-60°-Soil Type-2-Zone-4



Mode Shape-Slope-60°-Soil Type-3-Zone-3				
Modes	Time Period in sec	UX	UY	RZ
1	0.673	0.5141	0.0037	0.0367
2	0.594	0.0039	0.5346	0.0005
3	0.508	0.0444	0.0011	0.5285
4	0.216	0.0901	0.0004	0.0069
5	0.185	0.001	0.103	0.0001
6	0.164	0.0048	0.0004	0.0817
7	0.126	0.0483	0.0001	0.0011
8	0.11	0.0006	0.0711	3.80E-05
9	0.098	0.0003	0.0006	0.0445
10	0.087	0.045	0.0026	0.0031
11	0.083	0.0013	0.0391	0.002
12	0.076	0.0277	4.75E-06	0.116

Figure 3.7.23. Mode Shape-Slope-60°-Soil Type-3-Zone-3



Mode Shape-Slope-60°-Soil Type-3-Zone-4				
Modes	Time Period in sec	UX	UY	RZ
1	0.673	0.5142	0.0036	0.0367
2	0.594	0.0038	0.5347	0.0004
3	0.508	0.0444	0.001	0.5286
4	0.216	0.0901	0.0004	0.0069
5	0.185	0.001	0.103	0.0001
6	0.164	0.0049	0.0004	0.0817
7	0.126	0.0483	0.0001	0.0011
8	0.11	0.0006	0.0711	3.93E-05
9	0.098	0.0003	0.0006	0.0445
10	0.087	0.045	0.0027	0.0031
11	0.083	0.0013	0.0391	0.002
12	0.076	0.0277	4.48E-06	0.116

Figure 3.7.24. Mode Shape-Slope-60°-Soil Type-3-Zone-4

3.8. TORSIONAL IRREGULARITY

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-1-Zone-3				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	34.923	25.856	17.822	3.544
Corner 2 (label-47)	34.923	25.856	17.822	3.544
Corner 3 (label-4)	36.043	31.394	24.664	6.374
Corner 4 (label-1)	36.043	31.394	24.664	6.374
Avg-X	35.483	28.625	21.243	4.959
Max/Avg.	1.02	1.10	1.16	1.285
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.1. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-1-Zone-3

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-2-Zone-3				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	49.297	35.737	25.318	4.258
Corner 2 (label-47)	49.297	35.737	25.318	4.258
Corner 3 (label-4)	50.37	43.107	34.909	7.905
Corner 4 (label-1)	50.37	43.107	34.909	7.905
Avg-X	49.8335	39.422	30.1135	6.0815
Max/Avg.	1.01	1.09	1.16	1.30
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.2. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-2-Zone-3

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-3-Zone-3				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	61.235	45.847	32.207	4.923
Corner 2 (label-47)	61.235	45.847	32.207	5.005
Corner 3 (label-4)	62.028	54.989	44.246	4.838
Corner 4 (label-1)	62.028	54.989	44.246	5.282
Avg-X	61.6315	50.418	38.2265	5.012
Max/Avg.	1.01	1.09	1.2	0.97
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.3. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-3-Zone-3

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-1-Zone-4				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	53.952	38.94	26.802	5.638
Corner 2 (label-47)	53.952	38.94	26.802	5.638
Corner 3 (label-4)	54.91	46.835	36.875	10.141
Corner 4 (label-1)	54.91	46.835	36.875	10.141
Avg-X	54.431	42.8875	31.8385	7.8895
Max/Avg.	1.01	1.09	1.16	1.29
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.4. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-1-Zone-4

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-2-Zone-4				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	74.638	53.906	38.113	6.386
Corner 2 (label-47)	74.638	53.906	38.113	6.386
Corner 3 (label-4)	74.828	64.178	52.124	11.857
Corner 4 (label-1)	74.828	64.178	52.124	11.857
Avg-X	74.733	59.043	45.1185	9.1215
Max/Avg.	1.00	1.09	1.16	1.3
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.5. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-2-Zone-4

Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-3-Zone-4				
	0°	20°	45°	60°
Load Case	SPEC-X	SPEC-X	SPEC-X	SPEC-X
Corner 1 (label-44)	92.922	67.711	48.523	6.247
Corner 2 (label-47)	92.922	67.711	48.523	6.247
Corner 3 (label-4)	91.965	79.902	65.989	12.007
Corner 4 (label-1)	91.965	79.902	65.989	12.007
Avg-X	92.4435	73.8065	57.256	9.127
Max/Avg.	0.99	1.08	1.15	1.3
Allowable	<1.4	<1.4	<1.4	<1.4
OK IF(Max/Avg.<1.4)	O.K.	O.K.	O.K.	O.K.

Figure 3.8.6. Torsional Irregularity-Terrace Level-SPEC-X-Soil Type-3-Zone-4

4. CONCLUSION

The observations from this study clearly show that terrain slope, soil type, and seismic zone intensity significantly affect the structural performance of buildings during seismic events. Among these factors, slope angle proved to be the most influential. This is mainly due to the vertical irregularities caused by varying column heights and staggered floor levels, which disrupt the uniform distribution of stiffness and mass. Consequently, structures on steeper slopes are more vulnerable to stiffness irregularities, torsional effects, and uneven load paths, all of which greatly influence the building's overall seismic response.

1. Analysis of the data indicates that in Zone III, with Soil Type-1, the maximum lateral drift 0.001273. In contrast, at slopes of 45° and 60°, there was a significant reduction in drift, with values decreasing to 0.000104 and 0.000001, respectively. This phenomenon can be attributed to the changes in slope angle, which result in a vertical irregularity in the building's structure. Specifically, columns situated on the downhill side experience increased height, while those on the uphill side remain shorter, leading to a non-uniform distribution of stiffness throughout the structure. This distribution can cause the lower storeys to exhibit greater flexibility, thereby increasing susceptibility to drift variations.

2. In the present case, however, the drift values decreased with steeper slopes. To enhance structural performance, particularly under complex mode shapes observed in steep slope configurations, it is crucial to bolster the lateral stiffness of the structure. This can be effectively accomplished by increasing the dimensions of columns and beams, especially in critical areas on the 45° and 60° slopes where structural configuration is associated with high flexibility. By reinforcing these members, we can mitigate inter-storey drift and improve overall stability, ensuring a more balanced distribution of stiffness throughout the building's elevation.

3. Additionally, the change in soil type greatly influences storey drift under seismic loading; as soil transitions from hard (Type I) to soft (Type III), drift values escalate. For instance, in Zone III at 0° slope, the drift in Soil Type I was 0.001273, which rose to 0.001779 in Soil Type II and 0.002186 in Soil Type III. Softer soils allow more ground movement, leading to greater lateral displacement and increased risk of non-structural damage and soft-storey failure. Similarly it happens in 20°, 45° & 60°.

4. The change in seismic zone significantly influences storey drift by increasing the seismic demand and design base shear. As the zone shifts from Zone III to Zone IV, higher lateral forces result in greater inter-storey displacements. At 0° slope, the maximum drift for Soil Type-1 increased from 0.001273 to 0.001938, for Soil Type-2 from 0.001779 to 0.002638, and for Soil Type-3 from 0.002186 to 0.003234. A similar trend was observed at 20°, 45°, and 60° slopes, confirming that drift consistently rises with increasing seismic intensity, regardless of slope or soil condition. While the impact of zone change is less severe than that of soil or slope, it remains a critical factor in seismic design.

5. The analysis shows that storey displacement decreases with increasing slope angle due to reduced building height and increased stiffness. For instance, in Zone III with Soil Type I, the maximum displacement at the terrace level was 36.043 mm at 0° slope, reducing to 31.394 mm at 20°, 24.664 mm at 45°, and 6.445 mm at 60°. Similarly, in Zone IV with Soil Type I, the maximum displacement at the terrace level was 54.91 mm at 0° slope, reducing to 46.835 mm at 20°, 36.875 mm at 45°, and 10.141 mm at 60°. While higher seismic zones lead to greater displacement overall, steeper slopes consistently reduce lateral movement.

6. Soil condition also plays a crucial role, soft soils allow more lateral movement. At 0° slope in Zone III, the terrace displacement increased from 36.043 mm (Soil I) to 50.37 mm (Soil II) and 62.028 mm (Soil III). Similarly at 0° slope in Zone IV, the terrace displacement increased from 54.91 mm (Soil I) to 74.828 mm (Soil II) and 92.922 mm (Soil III). Similarly it happens in 20°, 45°, and 60° slopes.

7. Additionally, increasing the seismic zone from Zone III to IV resulted in higher displacements across all soil types. For example, in Soil Type III at 0° slope, displacement rose from 62.028 mm in Zone III to 92.922 mm in Zone IV. Overall, the highest displacements were observed on flat terrain with soft soil in Zone IV, while the lowest occurred on steep slopes with hard soil in Zone III. This highlights the need for slope-adaptive structural design and soil-specific detailing to control lateral displacements under seismic loads.

8. The analysis reveals that stiffness irregularity is significantly influenced by slope angle, soil type, and seismic zone. As the slope increases, stiffness at the terrace level increases due to shorter column heights on the uphill side and greater lateral restraint. In Zone III with Soil Type I, stiffness rose from 74,433.74 kN/m at 0° slope to 80,538.24 kN/m at 20°, 153,422.64 kN/m at 45°, and peaked at 547,569.85 kN/m at 60°. A similar

trend was observed in Zone IV. However, when soil type changes from hard to soft, stiffness decreases due to reduced ground support. At 0° slope in Zone III, terrace-level stiffness dropped from 74,433.74 kN/m (Soil Type I) to 69,147.99 kN/m (Soil Type II) and further to 66,288.21 kN/m (Soil Type III). Seismic zone variation had a minor effect on stiffness. For example, at 45° slope with Soil Type I, stiffness increased slightly from 153,422.64 kN/m in Zone III to 153,486.11 kN/m in Zone IV. Overall, steeper slopes enhance stiffness, while softer soils reduce it, and zone changes have minimal influence. These findings highlight the importance of maintaining a balanced stiffness profile to prevent soft-storey effects and ensure seismic stability.

9. The analysis indicates that storey strength increases with slope angle, primarily due to longer column heights and greater force demands at the lower storeys. In Seismic Zone III with Soil Type I, the storey strength increased progressively from 79.41 kN at a 0° slope to 82.41 kN at 20°, 180.42 kN at 45°, and reached a peak of 192.08 kN at a 60° slope. A similar pattern was observed in Zone IV. However, the influence of soil type showed a contrasting trend: softer soils generally resulted in higher storey strength at the upper levels, despite offering lower resistance overall. For example, at a 0° slope in Zone III, the terrace level strength rose from 79.41 kN on Soil Type I to 100.55 kN on Soil Type II, and further to 116.92 kN on Soil Type III. Additionally, seismic zone classification had a noticeable impact on stiffness. At a 0° slope with Soil Type I, stiffness increased from 79.41 kN in Zone III to 121.89 kN in Zone IV.

10. The analysis indicates that mass irregularity increases notably with slope angle, primarily due to split-level configurations and the uneven distribution of structural mass across storeys. In Zone III with Soil Type I, the maximum mass at the 11th floor slab rose from 235,134.5 kg at 0° slope to 226,214.4 kg at 20°, then increased significantly to 355,273.7 kg at 45°, and peaked at 445,170.6 kg at 60°. This trend was similarly observed in Zone IV, confirming that steeper slopes contribute to greater mass concentration at upper levels, thereby heightening the potential for mass irregularity. However, changes in soil type and seismic zone had minimal impact on mass distribution, with values remaining relatively consistent across different soil conditions and zones. These findings emphasize the importance of considering slope-induced mass irregularity in seismic design, as it can influence torsional behavior and overall dynamic response.

11. The analysis reveals that diaphragm flexibility increases with slope angle and, particularly at the lower storeys. According to IS 1893:2016, a diaphragm is considered flexible if the in-plane deformation ratio exceeds 1.2. In Seismic Zone III with Soil Type I, this ratio at the ground floor slab increased from 1.061 at a 0° slope to 1.687 at 20°. Interestingly, at a 45° slope, the ratio decreased to 1.254 and further to 1.426 at 60°. This trend is attributed to the change in the starting level of the regular floor slabs beginning from the third floor at 45° and the sixth floor at 60° which resulted in higher flexibility ratios of 1.595 and 1.726, respectively, at those levels, thereby confirming flexible diaphragm behavior. A similar pattern was observed in Zone IV. Furthermore, diaphragm flexibility was found to decrease slightly with softer soils. For instance, at a 60° slope in Zone III, the flexibility ratio declined marginally from 1.061 (Soil Type I) to 1.056 (Soil Type III). A comparable decrease was noted with increasing seismic intensity; at a 60° slope with Soil Type I, the ratio reduced from 1.061 in Zone III to 1.056 in Zone IV.

12. Mode shape analysis shows that increasing slope angle reduces the fundamental time period, indicating greater stiffness dropping from 2.31 s at 0° to 0.68 s at 60° slope. The first two modes were dominated by translational displacements (UX, UY), while torsional effects (RZ) appeared in higher modes, especially on steeper slopes. Soil type had minimal impact on mode shape patterns, though softer soils showed slightly higher displacements. Seismic zone changes had negligible effect on mode shapes. The first three modes contributed significantly to mass participation, meeting IS 1893:2016 requirements.

13. Torsional irregularity tends to increase with slope angle due to asymmetrical geometry and non-uniform lateral stiffness, which intensifies eccentric lateral displacements. In Zone III with Soil Type-1, the edge-to-center displacement ratio rose from 1.02 at 0° to 1.285 at 60°, indicating growing torsional effects at steeper inclinations. However, when the soil type changes from hard (Type-1) to soft (Type-3), torsional irregularity slightly decreases. For instance, at 0° slope, the ratio reduced from 1.02 (Soil Type-1) to 1.01 (Soil Type-3), suggesting that increased soil flexibility helps distribute seismic forces more uniformly, reducing

torsional response. Despite variations, all models remained within the IS 1893:2016 allowable limit of 1.4, confirming torsional stability under the studied conditions.

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