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SEISMIC ANALYSIS OF BUILDING ON SLOPING GROUND WITH SHEAR WALL

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Abstract: Buildings constructed on hill slopes are highly asymmetrical, often irregular, and torsionally coupled, making them particularly vulnerable to severe damage during earthquake ground motion. A significant danger arises from the unequal height of columns and shear walls on the sloping surface, leading to increased stiffness in the structure's ground floor. This increased stiffness attracts more seismic forces, which can cause cracks and potential failure in the building. This study examines a 21-storey Reinforced Concrete (RC) framed building situated on sloping ground in Uttarakhand, India. The seismic response of this high-rise building is analysed using linear dynamic analysis (Response Spectrum Analysis).

This research addresses the unique challenges posed by sloping terrains by focusing on the seismic analysis of buildings incorporating shear walls with varying thickness throughout the structure's height in seismic zone IV. The slope angles considered in this analysis are 10˚, 15˚, 20˚ and 25˚ degrees. With the increase in the slope angle from 10˚ to 25˚, base shear, overturning moments, and displacement patterns change significantly, especially in the x-direction where higher base shear and overturning moments occur, while in the y-direction, displacement is greater due to uneven stiffness from varied column heights. Key parameters analysed include maximum Storey displacement, Storey shear, time period, Storey drift, stability checks against overturning moments, torsion, and mass irregularity. Modal time periods decrease with slope, storey drift remains within the permissible limits, and models satisfy the requirements for Torsion as per IS 1893 (Part 1)-2016. By addressing these critical factors, the study recommends the factors to be considered in the design and safety of buildings in seismic-prone areas with challenging topography.

Index Terms *- RC Building, Sloping Ground, Response Spectrum method, Shear Wall.*

I. INTRODUCTION

The Dehradun city, which is nestled in the high ground of the Himalayas in the northern state of Uttarakhand, India, is known for its diverse and rugged topography, with undulating hills and valleys. The city lies in a seismically active area, which positioned it in Seismic Zone IV, making it susceptible to frequent and significant seismic activity. Surrounding mountain ranges, including the Shivalik's and parts of the lower Himalayas, contribute to the region's complex geological structure. Much of Dehradun's landscape consists of sloping grounds, creating unique construction and infrastructure development challenges. In this area, constructing multi-storeyed Reinforced Concrete (RC) framed buildings on hill slopes is common. So, constructing buildings on such uneven terrain exhibits dynamic characteristics that are distinct from those on flat ground, as they often become irregular and asymmetrical along vertical axes, introducing additional difficulties for seismic design and structural stability.

Objectives

The objectives of this research are as follows:

- **To Evaluate Seismic Performance:** Assess the seismic response of multi-storeyed reinforced concrete (RC) framed buildings on sloping ground in Dehradun city in the state of Uttarakhand, India, using dynamic analysis methods (Response Spectrum analysis)
- **To Investigate Structural Behaviour:** Analyse the dynamic characteristics, including maximum Storey displacement, Storey shear, time period, Storey drift, torsion, and stability against overturning moments, of buildings with varying slope angles.

- **To Optimize Shear Wall Design:** Investigate the impact of shear wall thickness variations along building height on structural stiffness, seismic resilience, and potential failure modes due to irregular ground profiles.
- **To Provide Design Recommendations:** Develop practical design recommendations and strategies for constructing earthquake-resistant buildings on sloping terrains in seismic-prone regions, aiming to enhance structural safety and resilience in sloping regions of the country.

II. LITERATURE REVIEW

Anjeet Singh Chauhan and Rajiv Banerjee [1] have considered a G+10 RCC Step back building having each Storey of height 3.6m with a horizontal angle of inclination 20°, 30°, 40º, and 45° in seismic zone V by Response Spectrum method for the purpose of commercial of people during a disaster with two of the top Storey to be used for setup of machinery equipment which induces as Mass irregularity and ground to top of the Storey at the edge of the planned building used as an opening for the purpose of natural lighting and stair which induces as Diaphragm irregularity.

The analysis and modeling of the Step back building is carried out by ETABS software as per IS 1893 (Part 1): 2016. This study examines the seismic performance of four models of a G+10 step back building on sloping ground, each with distinct structural irregularities. Model-1, the baseline with no added irregularities, serves as a reference, showing moderate increases in base shear, Storey displacement, and drift as the slope angle rises, with higher base shear values than Model-4. Model 2 incorporates mass irregularity, making certain floors significantly heavier and increasing seismic forces due to added weight. This model exhibits the highest mode period, displacement, and drift, particularly on a 45° slope, indicating it is highly susceptible to seismic forces.

Model 3 includes diaphragm irregularity, where the horizontal floors are less rigid, allowing for reduced force distribution across the structure. Consequently, it shows the lowest base shear, displacement, and drift values, especially at a 20° slope, making it the least vulnerable to seismic forces. Model 4 has vertical geometric irregularity due to variable column heights, affecting its stiffness distribution. While Model-4 is generally stable and less responsive than Models 1 and 2, its performance remains slightly more resilient than Model-2's, reflecting a lower susceptibility to seismic impact on sloping ground.

B. G. Birajdar and S. S. Nalawade [2] have reported that from the seismic analyses conducted on 24 Reinforced Concrete (RC) buildings with three different configurations viz., 'Step Back', 'Step Back Setback', and 'Setback' buildings. A 3-D analysis, including torsional effects, was performed using the Response Spectrum method. The study focused on dynamic response properties, such as the fundamental time period, top Storey displacement, and base shear action induced in columns, to determine the suitability of each building configuration on sloping ground.

They found that 'Step Back Setback' buildings are the most suitable for construction on sloping ground. At the same time, in step-back buildings and 'step-back setback' buildings, the columns at the ground level, which are shorter and stiffer, are the worst affected, and special attention should be given to design and detailing.

C. B. Nayak and Snehal Uttekar [3] have studied G+8 Storey RCC building with ground slopes varying from 15˚, 30˚, 45˚, and 60˚. The modelling and the analysis of the building were done using the structural analysis tool SAP-2000 by Response Spectrum method to study the effect of unequal column height on the ground floor and the effect of infill walls during the earthquake.

They found that the base shear decreases with increasing slope angle for both configurations 'step back' and 'step back setback' with and without infill wall by Equivalent Static Method, but the base shear increases with increasing slope angle for both with and without infill wall for 15˚, 30˚, 45˚ respectively, but it decreases for 60˚ slope angle by Response Spectrum Method.
Similarly, they found that, in both methods, as the slope angle increases, the top Storey displacement reduces, and among all the configurations, the 'step-back setback' building has less displacement compared to the other configuration.

G Suresh and Dr. E Arunakanthi [4] have considered the three-dimensional space frame analysis for two different configurations of 'step back'' frame and step back-setback' frame ranging from 8 to 10 Storey resting on the sloping ground of 27 degrees and plain ground under the action of seismic load by using ETABS software, at the same time considering the bracing system for 'step back' building configuration. The dynamic response of these buildings is presented in terms of base shear, fundamental time period, and displacement and compared within the considered configurations.

They concluded that 'step-back' frames without bracings produce higher base shear than 'step-back-set back' frames, and the 'step-back' building frames without bracing give higher values of time periods and top Storey displacement compared to 'step-back-setback' frames. Also, the 'step-back' frames without bracing are not desirable on the sloping ground because their performance during seismic excitation is affected worse than other configurations; similarly, as the number of storeys increases, time periods and top Storey displacement also increase. As a result, the 'step-back' frames with bracing give less displacement than 'step-back' frames without bracing and 'step back-set back' frames.

Mohammad Umar Farooque Patel [5] has considered a 3D analytical model of eight storeyed building which consists of 5 bays in both directions with symmetric and asymmetric building configuration and analysed using the structural analysis tool ETABS to study the effect of unequal column height in ground Storey of a bare frame, and building with shear wall on the sloping ground, at the same time considering the effect of shear wall with the different position at center and at the corner during earthquake in seismic zone III.

The seismic analysis has been carried out using the linear static and dynamic methods and evaluated by the pushover analysis. As a result, they concluded that the performance of the building on the sloping ground brings into the picture an increased vulnerability of the structure with the presence of the column hinges at the base level and beam hinges at each Storey level at the performance point.

Similarly, they concluded that the building with shear walls at the centre and at the corner had 41.4% and 61.5%, respectively less displacement, and based on Response Spectrum analysis, the building had 23.6%, 38.1% less displacement compared to the bare frame model on sloping ground, which leads to the conclusion that the structure resting on terrain or sloping ground has higher

displacement and the availability of the shear wall reduces the lateral displacement considerably, and the pushover analysis found out that the spectral displacement of the buildings on hill slopes have 114%-179% higher than building model on the plain ground in the longitudinal direction and at the same time the plastic hinge formation is more in bare frame model.

Mohammad Baqi and Arif [6] have reported that the Framed structures built on hill slopes exhibit significantly different structural behaviours than those on the plain ground due to their inherent asymmetry. This asymmetry attracts substantial shear forces and torsional moments, causing unequal force distribution because of varying column lengths. This study modelled and analysed two different configurations of hill buildings using the ETABS v 9.0 finite element software. These models were analysed using the Response Spectrum method. The dynamic parameters, such as shear forces at the foundation level, fundamental time periods, maximum top Storey displacements, Storey drifts, and Storey shear were examined and compared across the different building configurations.

They found that the performance of step-back and 'step-back setback' configurations differed significantly from each other and from buildings on flat ground. The empirical relations provided in IS 1893 (Part 1): 2002 (Clause 7.6) did not accurately depict time period values for buildings on slopes. Therefore, the equivalent static method is unsuitable for designing hill buildings; instead, Response Spectrum analysis of a three-dimensional model should be conducted to determine proper behaviour. The 'Step-back setback' configurations experienced fewer torsional moments and seismic forces compared to step-back buildings due to lower seismic weight, with a 45% reduction in base shear observed. Step-back buildings exhibited higher Storey drift and Storey shear, making them more vulnerable to earthquake forces. Consequently, 'step-back setback' buildings performed better under seismic loads.

III. METHODOLOGY

This paper presents a comprehensive dynamic analysis of a G+20 storeyed Reinforced Concrete (RC) building resting on sloping ground, by adopting the Response Spectrum Method. The building considered is located in Dehradun city of Uttarakhand, India, and it is analysed as per IS1893 (Part 1):2016 [7]. The building is modelled using a commercially available software package ETABS, which allows for detailed modelling and simulation of the building's response to seismic forces.

The building analysed in this study is characterized by a plan dimension of 23.6m ×26.95m and a total height of 71.1m. It is a high-rise structure with ground plus 20 storeys (G+20). The structure is designed with shear walls at the periphery and interior columns, providing a combination of rigidity and flexibility necessary for seismic resistance. The footing depth below the ground level is considered as 2.5m. The slope of the ground is 10˚, 15˚, 20˚ and 25˚. All the building frames are analysed considering seismic zone IV and the Bureau of Indian Standards IS 456-2000 [8], IS 875(Part-1) 1987 [9], IS 875(Part-2) 1987 [10], IS 875(Part-3) 2015 [11], IS 13920-2016 [12] and IS 16700-2023 [13].

IV. BUILDING DESCRIPTION

Structure type…… ……..: Symmetric regular Building(G+20)
Plan dimension……..: 23.6×26.9 m
Height of typical floor……. ……...: 3.1m
Height of the ground floor……... : 6 m
Beam size……..: 200×600 mm
Column size……. : 600×600 mm
Slab size: …… …….: 125 mm
Grade of concrete……..: M 30
Grade of steel……: Fe 500
Thickness of exterior wall…… : 230 mm
Thickness of interior wall……. : 150 mm
Partition wall type……..: AAC-Block
Unit weight of AAC-Block……. ..: 5.5-6.5 kN/m^3

4.1 Earthquake Details:

Seismic zone…… : Zone-IV
Soil type……..: Type-II, medium soil as per IS1893(Part-1)-2016, cl 6.4.2.1, Table 4
Zone factor……..: 0.16 (IS 1893(Part-1): 2016, cl 6.4.2, Table 2)
Importance factor……...: 1.2 (IS 1893(Part-1): 2016, cl 7.2.3, Table 8)
Response reduction factor…….: 4 (IS 1893(Part-1): 2016, cl 7.2.6, Table 9)

4.2 Wind Details:

Basic wind speed……..: 50 m/s
Terrain category……...: Category-4
Risk coefficient (K_1) ……....: 1
Terrain height factor (K_2) ……: 0.47
Topography factor(K_3) ……..: 1.15(10˚), 1.18297(15˚), 1.18(20˚), 1.18(25˚).
Important factor(K_4) ……: 1

4.3 Property Modifiers:

The following values for the moment of inertia are considered as the property modifier based on the IS16700-2023, Table 5 for the serviceability design.

Slabs: ……..: 0.35 I_g
Beams: ……...: 0.7 I_g
Columns: ……...: 0.9 I_g
Walls: ……: 0.9I_g

4.4 Loads and Load Combination

Live load on typical floor…….: 2 kN/m^2
Live load on the corridor: …….: 3 kN/m^2
Live load on the staircase: ……...: 3 kN/m^2
Live load on the terrace: ……..: 1.5 kN/m^2
Live load on parking floor……: 2.5 kN/m^2
Overhead water tank loads: ……..: 25 kN/m^2, 27 kN/m^2
Floor finish: ……..: 1.5 kN/m^2

The serviceability check is obtained for the following load combinations as per IS 1893 (Part-1):2016.

- *COMB1 = 1.5 (DL ± EQX)*
- *COMB2 = 1.5 (DL ± EQY)*
- *COMB3 = 1.5(DL ± Spec-X)*
- *COMB4 = 1.5 (DL ± Spec-Y)*
- *COMB5 = 0.9DL ± 1.5EQX*
- *COMB6 = 0.9DL ± 1.5EQY*
- *COMB7 = 0.9DL ± 1.5Spec-X*
- *COMB8 = 0.9DL ± 1.5Spec-Y*

Here, DL ≡ Dead load, Spec ≡ Dynamic Load, and EQ ≡ Earthquake Load

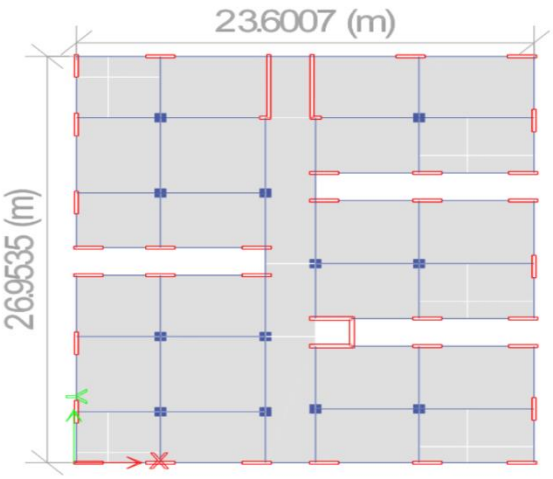

Fig 4.1: Plan of the building from ETABS

4.5 Shear Wall Detailing

The building is categorized into three groups based on the thickness of the shear walls, as detailed in Table 4.1, with specific thicknesses provided in Tables 4.2, 4.3, and 4.4. These shear walls are further classified into four types based on their function: W1 represents the periphery walls, W2 corresponds to the lift walls, and W3 and W4 are designated for the staircase walls.

Table 4.1: Building division based on shear wall

Division-1	Ground Floor to Storey-6	M30
Division-2	Storey-7 to Storey-13	M30
Division-3	Storey-14 to Storey-21	M30

Table 4.2: Division-1 wall schedule

Label	Size(mm)
W1	250×1500
W2	250×2182
W3	250×4191
W4	250×474

Table 4.3: Division-2 wall schedule

Label	Size(mm)
W1	225×1500
W2	250×2182
W3	225×4191
W4	225×474

Table 4.4: Division-3 wall schedule

Label	Size(mm)
W1	200×1500
W2	250×2182
W3	200×4191
W4	200×474

4.6 3-D Modelling of The Building:

In this study, four distinct structural models are created to analyze the behavior of buildings on sloping ground with angles of 10°, 15°, 20° and 25°. Each model is developed in ETABS, where the slope variations is carefully implemented to reflect realistic building conditions on inclined surfaces. The seismic analysis is carried out using the Response Spectrum method to evaluate the structural performance under seismic loads.

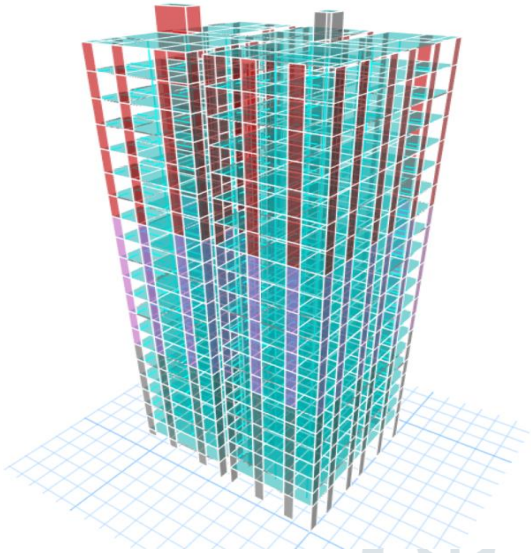

Fig 4.2 Building resting on 10˚ Slope (3-D view)

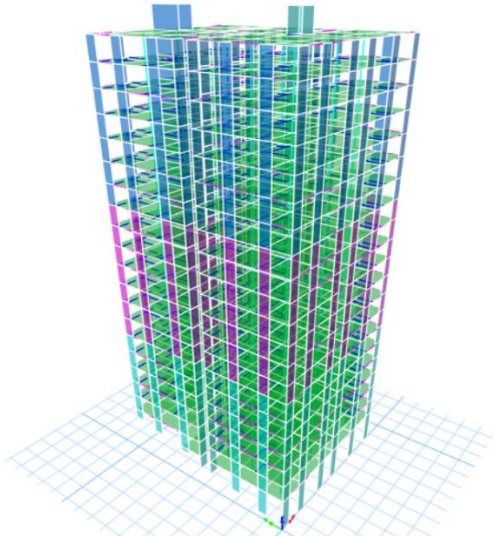

Fig 4.3 Building resting on 15˚ Slope (3-D view)

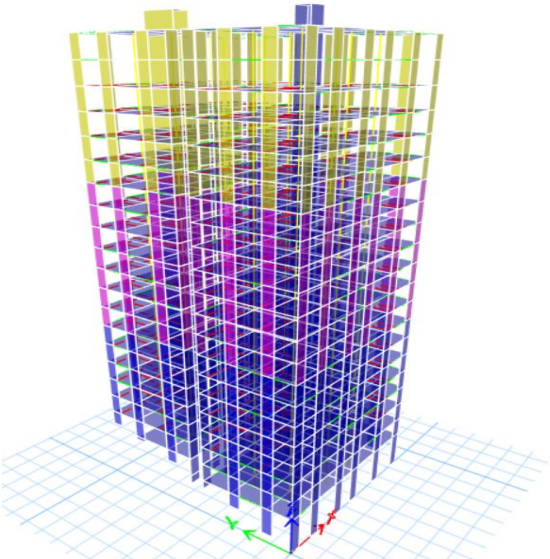

Fig 4.4 Building resting on 20˚ Slope (3-D view)

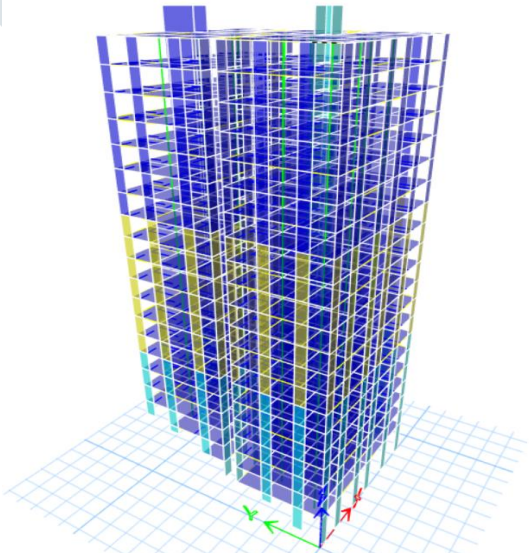

Fig 4.5 Building resting on 25˚ Slope (3-D view)

V. RESULTS and DISCUSSION

In this study, seismic analysis of buildings on sloping ground with shear walls is performed for slopes of 10°, 15°, 20°, and 25°, for a site in seismic zone IV. Buildings on sloping ground are inherently complex due to varying column heights on the uphill and downhill sides, leading to stiffness irregularities and torsional effects under seismic loads. To address these challenges, shear walls are incorporated as lateral load-resisting elements, and the behavior of the models is analysed under seismic loads. The building is subjected to earthquake forces independently in both along and across slope directions. The results are discussed in terms of key seismic parameters, including fundamental time period (FTP), lateral displacement, storey shear, torsional irregularity, mass irregularity and inter-storey drift, emphasizing the critical role of slope and shear wall configuration in ensuring the stability and seismic performance of hill buildings.

5.1 STOREY SHEAR: Storey shear at a given storey is the sum of all the lateral forces acting on that storey due to dynamic loads. It typically decreases as you move up the building, with the maximum at the base (base shear). Storey shear using the Response Spectrum method by considering the earthquake in both X and Y-directions is shown in Fig 5.1 (a) and (b).

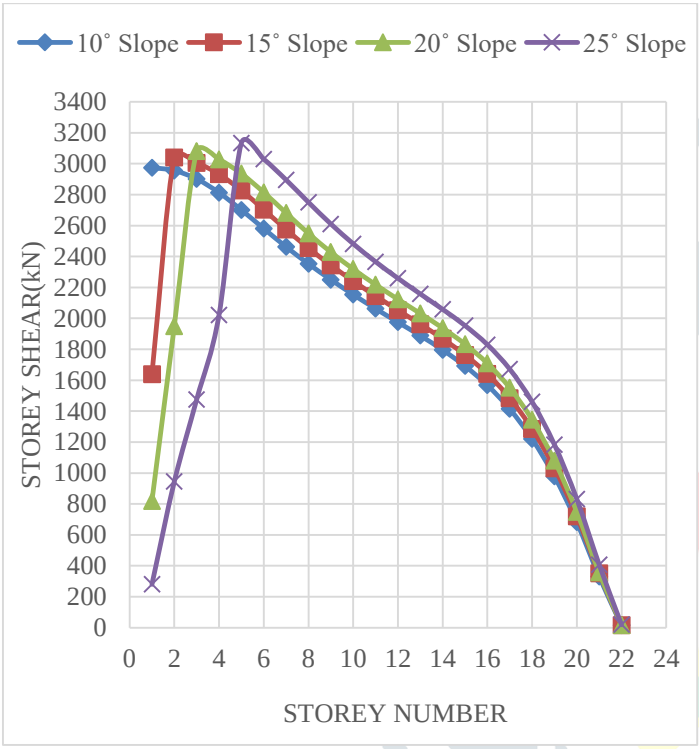

Fig 5.1(a) Variation of Storey Shear (Spec-X)

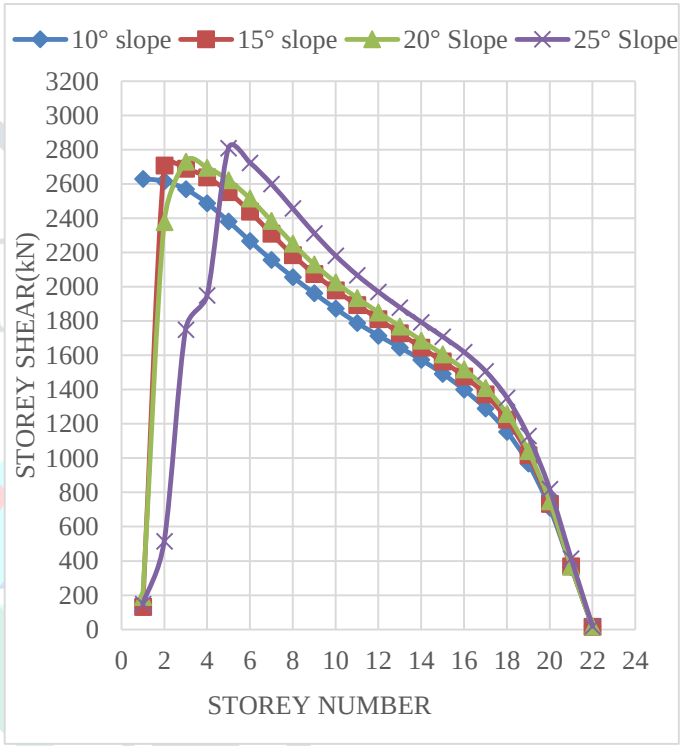

Fig 5.1(b) Variation of Storey Shear (Spec-Y)

If the angle of slope increases, the building's stiffness increases, as shown in Figs. 5.1(a) & (b), causing it to attract greater lateral forces. The maximum storey shear is observed at 25˚ slope with values of 3133.1123 kN in the X-direction and 2809.1491 kN in the Y-direction (sloping direction). The value of Storey shear is higher in the X-direction than sloping direction due to its consistency in stiffness, and the building moves more as a unit, which causes the greater seismic force to be resisted here.

5.2 STOREY DISPLACEMENT: It is the relative movement of a storey in a building compared to its original position during dynamic events like earthquake forces. Excessive movement can affect the usability of the building, causing discomfort to occupants and damaging partitions, facades, or finishes. The displacement of the building in the X and Y-directions is shown in Fig. 5.2(a) and (b).

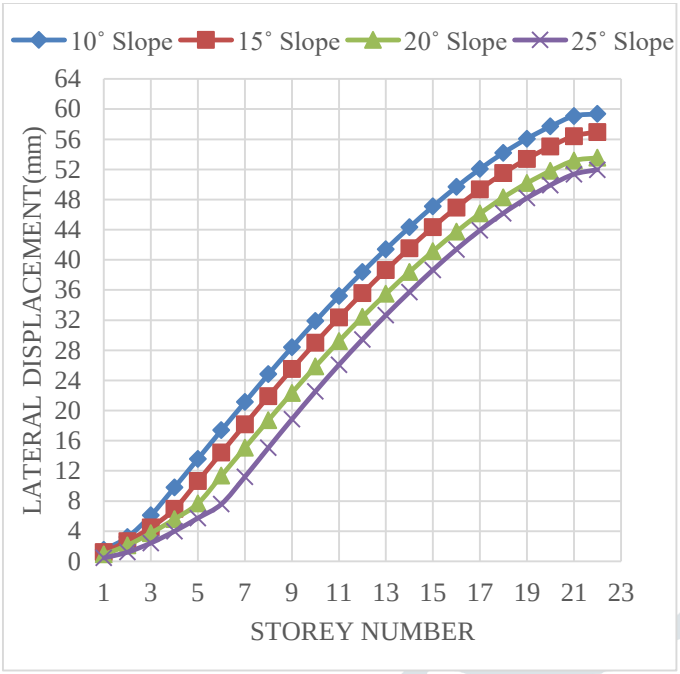

Fig 5.2(a) Storey Displacement Variation (Spec-X)

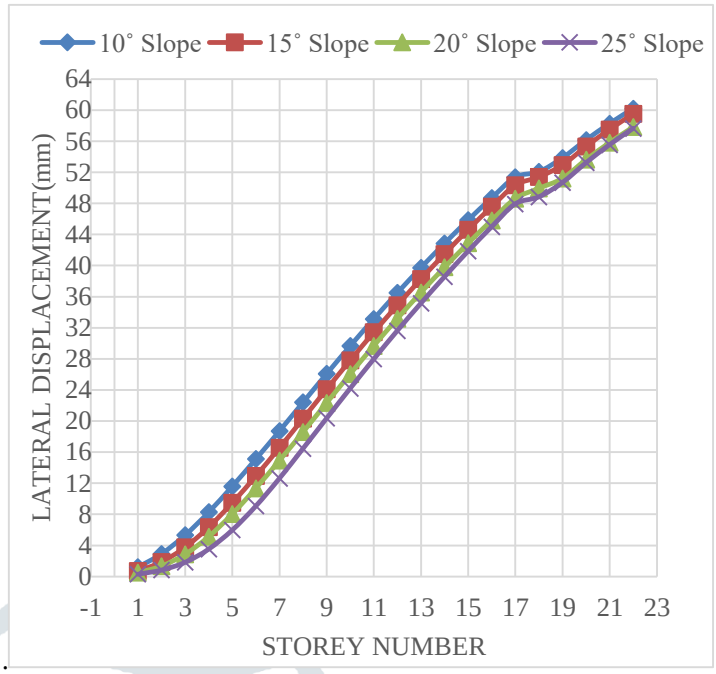

Fig 5.2(b) Storey Displacement Variation (Spec-Y)

Fig 5.2(a) and (b) show that as the slope of the building increases, the displacement values decrease. Maximum displacement value is observed at 10˚ sloping ground in the X-direction, i.e., 59.09 mm, and in the Y-direction, i.e., 58.279 mm. But based on Fig 5.2(b), the overall displacement in the Y-direction (sloping direction) is relatively higher than the X-direction because, in the Y-direction (sloping direction), the building has columns and walls of varying heights. The shorter columns and walls on the uphill side are stiffer, while the longer columns and walls on the downhill side are more flexible. This uneven stiffness distribution means that the structure is relatively less stiffer in the Y-direction (sloping direction) than in the X-direction, leading to higher lateral displacement.

5.3 STOREY DRIFT: Storey drift in a building structure is the horizontal displacement of one floor relative to the floor below, caused by lateral loads such as wind or earthquakes. The inter-storey drift due to earthquake loading is shown in Fig 5.3 (a) and (b).

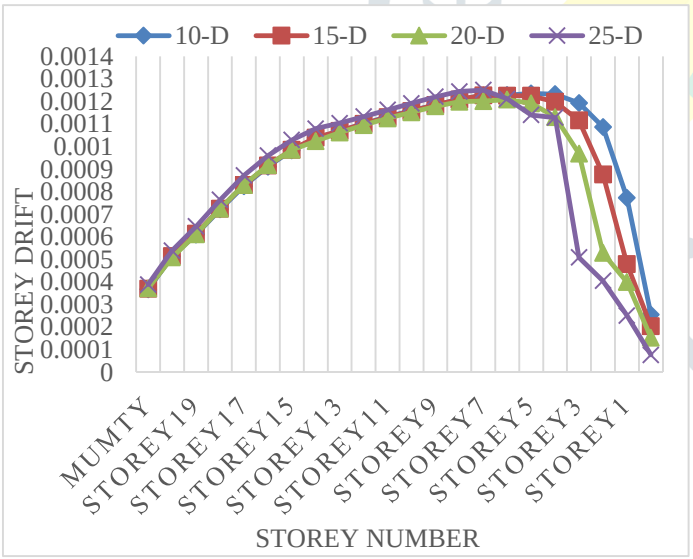

Fig 5.3(a) Storey Drift values (Spec-X)

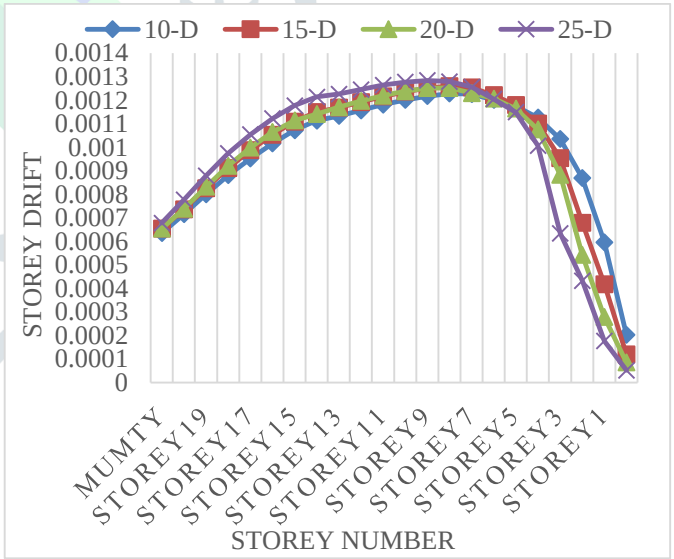

Fig 5.3(b) Storey Drift values (Spec-Y)

According to IS 1893 (Part-1)-2016 cl.7.11.1, the permissible Storey drift is limited to 0.004 times the Storey height, and according to the figures the maximum storey drift is at storey 9 i.e., 0.001284 due to Spec-Y at 25˚ slope, it is within the permissible limit.

5.4 MODAL TIME PERIOD:

The modal time period refers to the time it takes for the structure to complete one cycle of vibration in one of its natural modes. Each mode represents a specific way the structure can deform and oscillate when it responds to dynamic loading, which in this case the twelve modes of oscillation are shown in the Table 5.1.

Table 5.1 Modal Time Period of the Building

Mode No	Building on Sloping Terrain			
	10˚	15˚	20˚	25˚
1	2.476	2.361	2.251	2.113
2	2.184	2.094	1.986	1.87
3	1.799	1.751	1.686	1.565
4	0.739	0.702	0.674	0.629
5	0.678	0.647	0.618	0.578
6	0.571	0.555	0.538	0.499
7	0.386	0.367	0.351	0.324
8	0.356	0.339	0.325	0.304
9	0.311	0.303	0.295	0.276
10	0.252	0.241	0.238	0.236
11	0.239	0.238	0.228	0.216
12	0.225	0.222	0.219	0.21

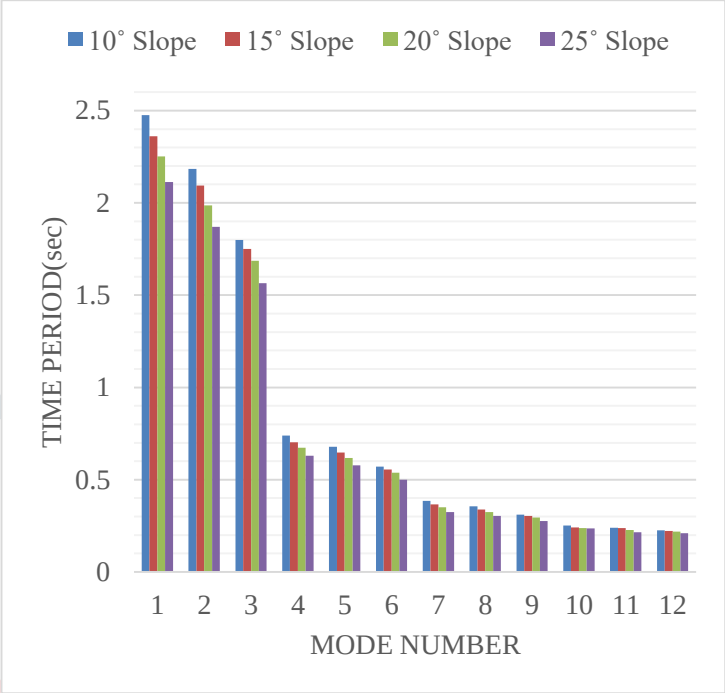

Fig 5.4 Modal Time Period due to Different Ground Slopes

Table 5.1 & Fig 5.4 indicate that as the slope of the terrain increases from 10˚, 15˚, 20˚ to 25˚, the time period values decrease.

- IS 16700-2023 Clause 5.5.2 indicates that the fundamental translational natural period in any of the two horizontal plan directions shall not exceed 8sec.
- IS 1893:2016 Clause 7.1 states that the fundamental lateral natural periods of the building in the two principal plan directions are away from each other by at least 10 percent of the larger value.
- IS 16700:2023 Clause 6.3.4 states that the fundamental period shall not exceed the value obtained from the approximate fundamental translational natural period of oscillation, which is determined as:

$T_a = 0.0644 \times H^{0.9}$
$= 0.0644 \times (71.1)^{0.9}$
$= 2.989$sec.

Table 5.1 shows that the maximum value of the time period is 2.476 sec, and in all the twelve modes of oscillation, the consecutive time periods are away from each other at least by 10% of the larger value.
As a result, it is concluded that the considered building structure modal time period shown in the Table 5.1 complies with all the codal provisions of IS 16700 (2023) and IS 1893 (Part 1) 2016 and is within the permissible limit.

5.5 OVERTURNING MOMENTS

Table 5.2 and Figure 5.5 illustrate the variation of overturning moments with the slope of the terrain. From the Fig.5.5, it can be observed that as the slope of the terrain increases from 10° to 25°, the overturning moments due to the earthquake also increase. The overturning moment is maximum at 25° slope in both the X and Y-directions, with the X-direction exhibiting a higher value compared to the Y-direction (sloping direction).

Table 5.2 Overturning Moment due to Spec-X and Spec-Y

Slope of Terrain	Spec-X (kN m)	Spec-Y (kN m)
10˚	119115.4	101456.1
15˚	124147.3	108168.3
20˚	130909.9	113600.6
25˚	139678.9	121834.6

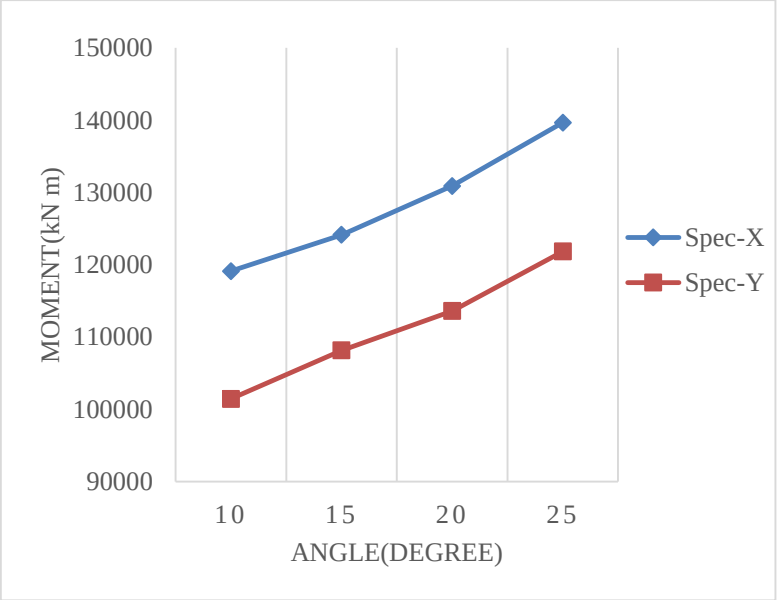

Fig 5.5 Overturning Moment due to Spec-X and Spec-Y

5.6 DISPLACEMENT CHECKS:

The building's total drift at the topmost usable floor due to earthquake loading for the X-direction and Y-direction (sloping direction) are depicted in Table 5.3.

Table 5.3 Total Drift Check at The Topmost Floor

No	Loading Type	Earthquake Base Shear (kN)		Max. Displacement(mm)		Storey Drift				Height	
		X	Y	X	Y	X		Y		71.1	m
1	Response Spectrum	3133.1123	2809.1491	59.09	58.279	0.001251	ok	0.001284	ok		
						story 7(25-D)		story 9(25-D)			
		Spec-x	Spec-y	Spec-x	Spec-y	Spec-x		Spec-y			
Displacement due to EQ < (H×1000)/250											
	284.4	mm	OK								

Based on IS 16700-2023, Clause 5.4.1, total drift at the topmost usable floor shall be limited to (H×1000)/250, in which the H is the total height of the structure, which is 71.1m for the building considered in this study.

5.7 STABILITY CHECK FOR OVERTURNING MOMENTS:

A stability check due to the overturning moment is an analysis performed to ensure that a structure remains stable under lateral loads. To ensure stability, the resisting moment must be greater than or at least equal to the overturning moment.

Table 5.4 Stability Check Due to Overturning Moment for 10˚ Sloping Ground

Moment Due to Spec-X	119115.4	kNm
Moment Due to Spec-Y	101456.1	kN m
Total Dead weight of the building		
	123572.4	kN
Lever arm (X-D)	11.6834	m
Lever arm (Y-D)	13.2903	m
Restoring Moments:	1. in x-direction = total dead weight of the building × lever arm in x-direction.	
	1443746	kNm
	2. in y-direction = total dead weight of the building × lever arm in y-direction.	
	1642314	kNm

F.O.S(Earthquake X-dir.) =	(0.9×restoring moment in x-dir.)/ (overturning moment due to spec x)		
	10.90851	OK	
F.O.S(Earthquake Y-dir.) =	(0.9×restoring moment in y-dir.)/ (overturning moment due to spec y)		
	14.5687	OK	

As per prevailing practices, the Factor of Safety (F.O.S) for earthquake loading in the specified direction should be greater than 1.4 to ensure the building's stability against overturning moments caused by seismic forces.

Table 5.5 Stability Check Due to Overturning Moments for 15˚ Sloping Ground

Moment Due to Spec-X	124147.3	kNm
Moment Due to Spec-Y	108168.3	kNm
Total Dead weight of the building		
	121854.5	kN
Lever arm (X-D)	11.6834	m
Lever arm (Y-D)	13.2903	m
Restoring Moments:	1. in x-direction = total dead weight of the building × lever arm in x-direction.	
	1423675	kNm
	2. in y-direction = total dead weight of the building × lever arm in y-direction.	
	1619483	kNm
F.O.S(Earthquake X-dir.) =	(0.9×restoring moment in x-dir.)/ (overturning moment due to spec x)	
	10.32087	OK
F.O.S(Earthquake Y-dir.) =	(0.9×restoring moment in y-dir.)/ (overturning moment due to spec y)	
	13.4747	OK

Table 5.6 Stability Check Due to Overturning Moments for 20˚ Sloping Ground

Moment Due to Spec-X	130909.9	kNm
Moment Due to Spec-Y	113600.6	kNm
Total Dead weight of the building		
	119981.6	kN
Lever arm (X-D)	11.6834	M
Lever arm (Y-D)	13.2903	M
Restoring Moments:	1. in x-direction = total dead weight of the building × lever arm in x-direction.	
	1401793	kNm
	2. in y-direction = total dead weight of the building × lever arm in y-direction.	
	1594592	kNm
F.O.S(Earthquake X-dir.) =	(0.9×restoring moment in x-dir.)/ (overturning moment due to spec x)	
	9.637265	OK
F.O.S(Earthquake Y-dir.) =	(0.9×restoring moment in y-dir.)/ (overturning moment due to spec y)	
	12.63314	OK

Table 5.7 Stability Check Due to Overturning Moments for 25˚ Slope

Moment Due to Spec-X	139678.9	kNm
Moment Due to Spec-Y	121834.6	kNm
Total Dead weight of the building		
	117486.2	kN
Lever arm (X-D)	11.6834	m
Lever arm (Y-D)	13.2903	m
Restoring Moments:	1. in x-direction = total dead weight of the building × lever arm in x-direction.	
	1372638	kNm
	2. in y-direction = total dead weight of the building × lever arm in y-direction.	
	1561426	kNm
F.O.S(Earthquake X-dir.) =	(0.9×restoring moment in x-dir.)/ (overturning moment due to spec x)	
	8.844387	OK
F.O.S(Earthquake Y-dir.) =	(0.9×restoring moment in y-dir.)/ (overturning moment due to spec y)	
	11.53436	OK

Tables 5.4, 5.5, 5.6 and 5.7 indicate that the factor of safety due to the earthquake loading in both X and Y-directions are within the limit, and also indicate that the building is stable against the overturning moment due to the earthquake forces.

5.8 TORSIONAL IRREGULARITY OF THE BUILDING:

The building displacement due to torsion at the four corners of the plan at top-storey of the building is shown in Table 5.8.

Table 5.8 Torsional irregularity of the building for 10˚ sloping ground

Load Case	Corner-1 (mm)	Corner-2 (mm)	Corner-3 (mm)	Corner-4 (mm)	Avg (mm)	Ratio= Max/Avg	Check
Spec-X	34.103	55.475	55.57	34.115	44.81575	1.24	<1.4---ok
Spec-Y	39.739	39.778	57.349	57.38	48.5615	1.18	<1.4---ok

In the Fig 5.6(a) and (b) the corners-1, 2, 3 and 4 of Table 5.8 are designated as C1, C2, C3 and C4 respectively.

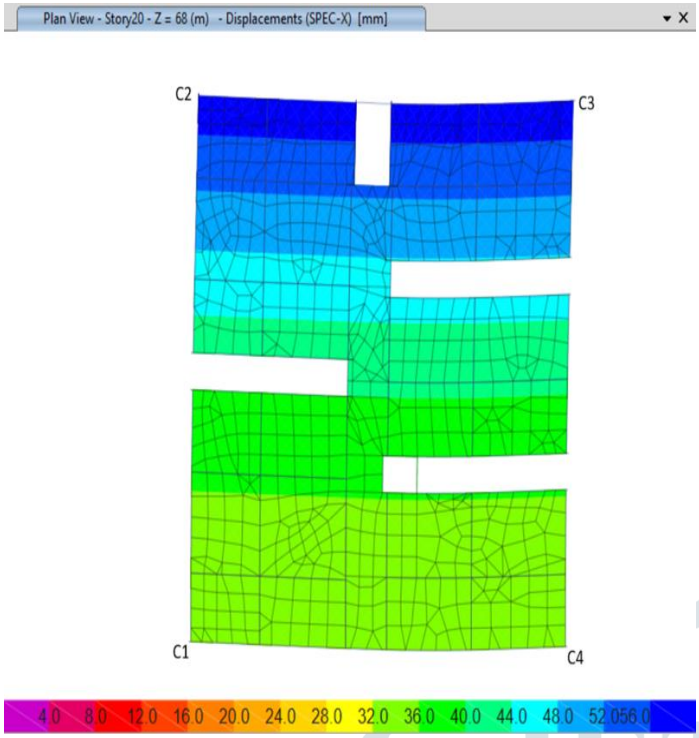

Fig 5.6(a) Torsional irregularity of the building due to Spec-X

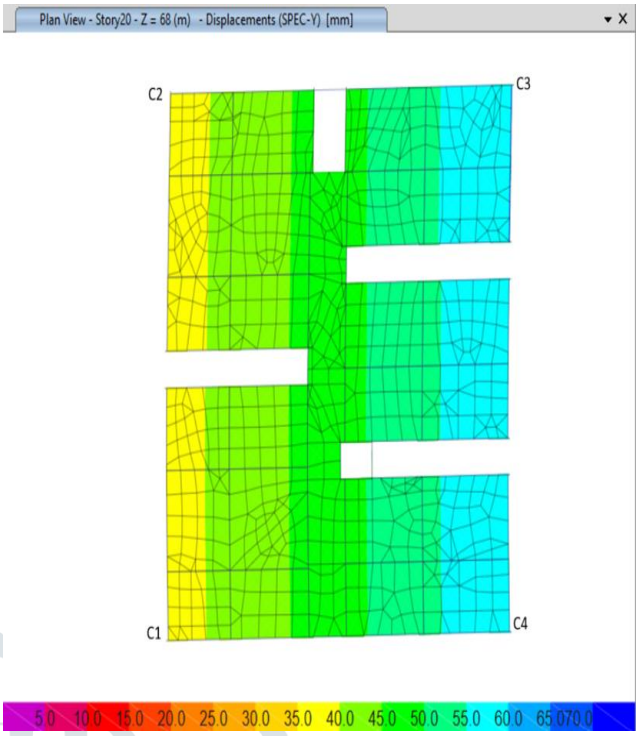

Fig 5.6(b) Torsional irregularity of the building due to Spec-Y

Based on the IS 1893 (Part-1):2016 clause 7.1, when the ratio of the maximum horizontal displacement of the four corners to its average displacement is in the range of 1.5 – 2.0, the building configuration shall be revised. However, if the ratio is smaller than 1.4, then the building configuration is stable against the torsional irregularity, and there is no need for the building configuration to be revised. Similarly, the following cases apply to the 15, 20, and 25-degree slopes.

Table 5.9 Torsional irregularity of the building for 15˚ sloping ground

Load Case	Corner-1 (mm)	Corner-2 (mm)	Corner-3 (mm)	Corner-4 (mm)	Avg-X(mm)	Ratio= Max/Avg	Check
Spec-X	33.476	53.121	53.206	33.5	43.32575	1.23	<1.4---ok
Spec-Y	39.298	39.201	57.213	56.612	48.081	1.19	<1.4---ok

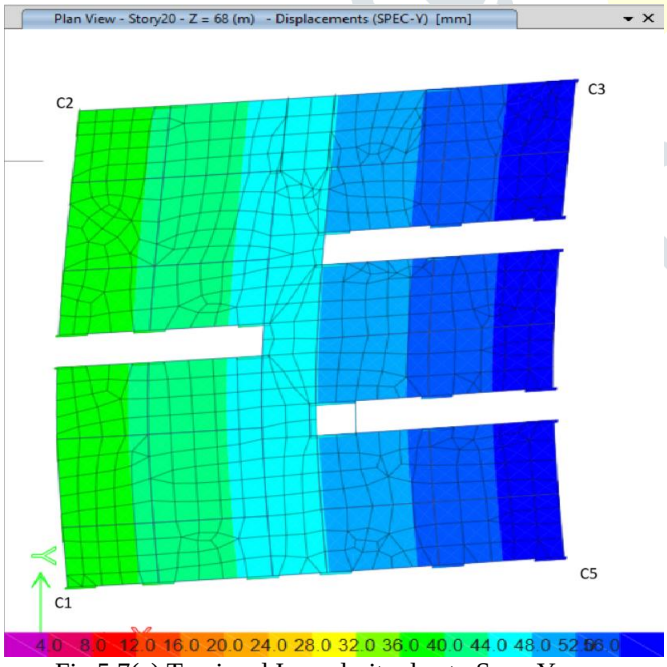

Fig 5.7(a) Torsional Irregularity due to Spec-Y

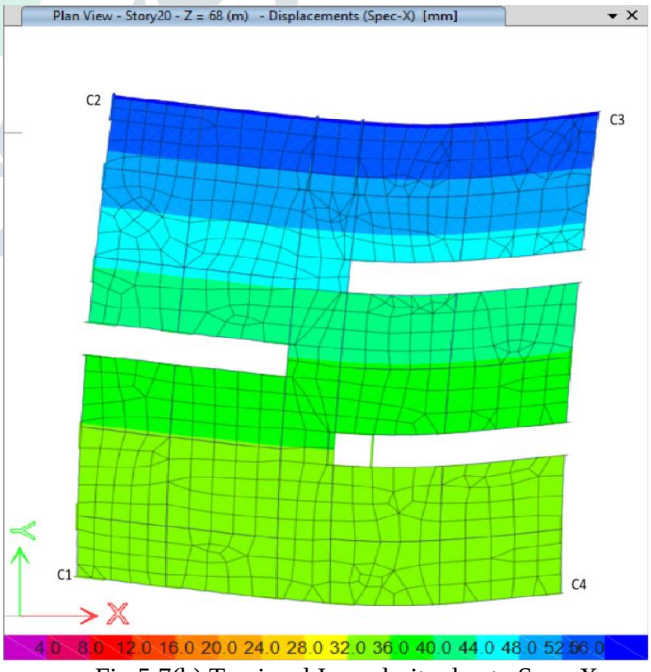

Fig 5.7(b) Torsional Irregularity due to Spec-X

Table 5.10 Torsional irregularity of the building for 20˚ sloping ground

Load Case	Corner-1 (mm)	Corner-2 (mm)	Corner-3 (mm)	Corner-4 (mm)	Avg-X(mm)	Ratio= Max/Avg	Check
Spec-X	32.685	50.323	50.397	32.583	41.497	1.21	<1.4---ok
Spec-Y	38.075	37.973	55.571	54.973	46.648	1.19	<1.4---ok

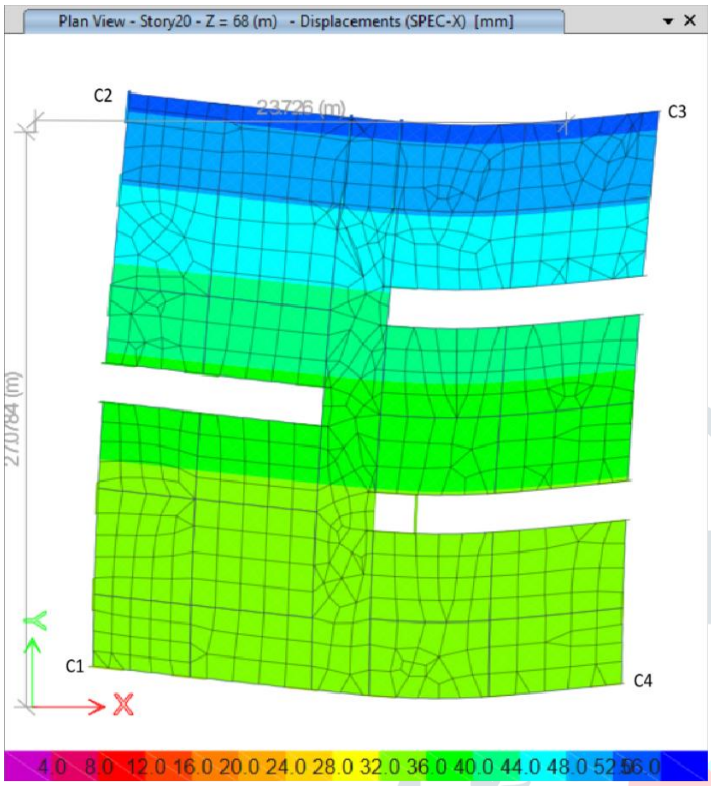

Fig 5.8(a) Torsional Irregularity due to Spec-X

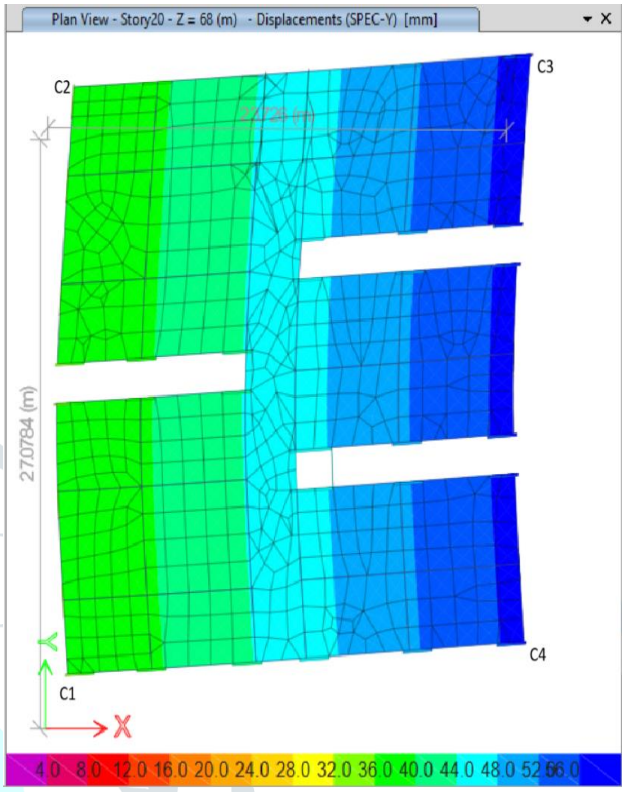

Fig 5.8(b) Torsional Irregularity due to Spec-Y

Table 5.11 Torsional irregularity of the building for 25˚ sloping ground

Load Case	Corner-1 (mm)	Corner-2 (mm)	Corner-3 (mm)	Corner-4 (mm)	Avg-X(mm)	Ratio= Max/Avg	Check
Spec-X	31.176	48.751	48.819	31.007	39.93825	1.22	<1.4---ok
Spec-Y	36.055	35.919	53.937	53.233	44.786	1.20	<1.4---ok

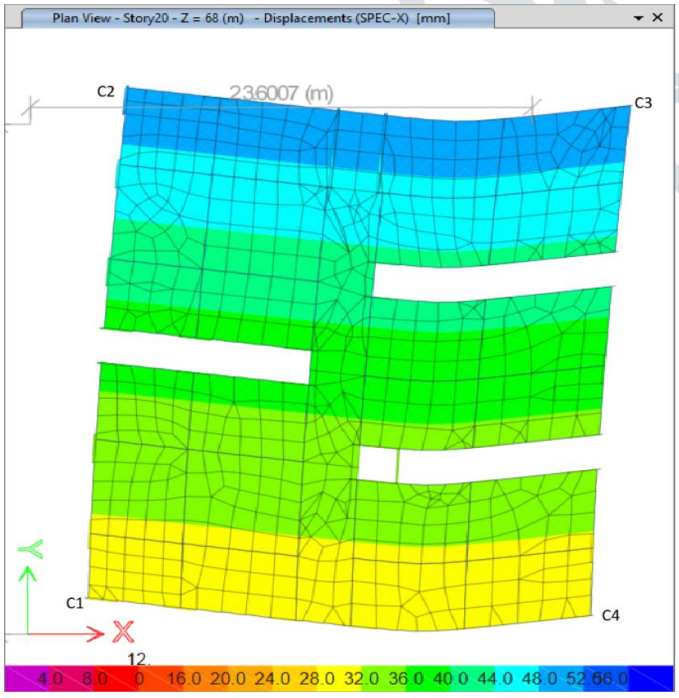

Fig 5.9(a) Torsional Irregularity due to Spec-X

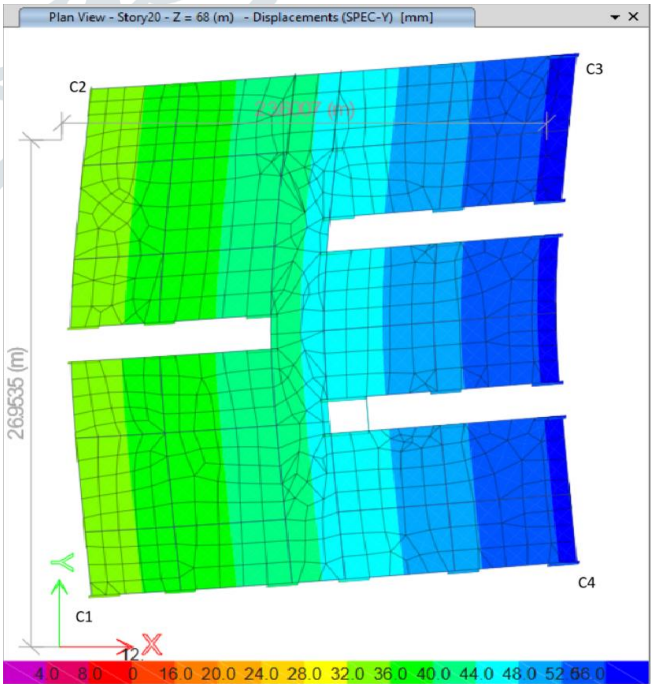

Fig 5.9(b) Torsional Irregularity due to Spec-Y

5.9 MODAL MASS PARTICIPATION RATIO CHECK:

This check ensures that the primary modes of vibration capture sufficient mass participation for an accurate prediction of structural behavior under dynamic loads. In dynamic analysis, each mode of vibration in a structure (e.g., the first mode, second mode) is associated with a certain amount of "mass participation." This mass effectively participates in the lateral motion induced by seismic forces.

Table 5.12 The modal mass participating ratio for 10˚ sloping ground

Modal Mass Participating Ratios					
Case	Mode	Period	UX	UY	UZ
Modal	1	2.476	0.0142	0.6437	0.0563
Modal	2	2.184	0.5856	0.0421	0.118
Modal	3	1.799	0.1506	0.0246	0.593
Modal	4	0.739	0.0102	0.0985	0.0164
Modal	5	0.678	0.0793	0.0253	0.0172
Modal	6	0.571	0.0343	0.0045	0.0773
Modal	7	0.386	0.0126	0.0176	0.014
Modal	8	0.356	0.0137	0.0308	0.0022
Modal	9	0.311	0.0147	0.0021	0.0237
Modal	10	0.252	0.0096	0.0041	0.0092
Modal	11	0.239	1.07E-05	3.68E-05	1.4E-05
Modal	12	0.225	0.0045	0.0238	0.0001

Table 5.13 The modal mass participating ratio for 15˚ sloping ground

Modal Mass Participating Ratios					
Case	Mode	Period	UX	UY	UZ
Modal	1	2.361	0.0123	0.6279	0.0582
Modal	2	2.094	0.5874	0.0386	0.112
Modal	3	1.751	0.1417	0.0267	0.5911
Modal	4	0.702	0.0103	0.0948	0.018
Modal	5	0.647	0.0787	0.0261	0.016
Modal	6	0.555	0.0338	0.0053	0.0775
Modal	7	0.367	0.0127	0.0161	0.0155
Modal	8	0.339	0.0138	0.0319	0.0016
Modal	9	0.303	0.0149	0.0029	0.0246
Modal	10	0.241	0.0074	0.003	0.0078
Modal	11	0.238	0.002	0.001	0.0024
Modal	12	0.222	0.0002	1.19E-05	3.72E-05

Table 5.14 The modal mass participating ratio for 20˚ sloping ground

Modal Mass Participating Ratios					
Case	Mode	Period	UX	UY	UZ
Modal	1	2.251	0.0062	0.6327	0.0547
Modal	2	1.986	0.606	0.026	0.0977
Modal	3	1.686	0.1212	0.0302	0.5999
Modal	4	0.674	0.0058	0.1012	0.0159
Modal	5	0.618	0.0851	0.018	0.0161
Modal	6	0.538	0.0306	0.0062	0.0795
Modal	7	0.351	0.0102	0.0194	0.0152
Modal	8	0.325	0.0171	0.0272	0.0018
Modal	9	0.295	0.0139	0.0038	0.0255
Modal	10	0.238	0.0003	0.0001	0.0001
Modal	11	0.228	0.0082	0.0043	0.0105
Modal	12	0.219	0.0007	0.0001	0.0002

Table 5.15 The modal mass participating ratio for 25˚ sloping ground

Modal Mass Participating Ratios					
Case	Mode	Period	UX	UY	UZ
Modal	1	2.113	0.0006	0.604	0.0667
Modal	2	1.87	0.6138	0.0136	0.0817
Modal	3	1.565	0.0944	0.0432	0.5746
Modal	4	0.629	0.0024	0.1008	0.0167
Modal	5	0.578	0.0923	0.0112	0.0133
Modal	6	0.499	0.0249	0.0102	0.082
Modal	7	0.324	0.0078	0.0221	0.0157
Modal	8	0.304	0.0231	0.0205	0.0013
Modal	9	0.276	0.0113	0.0077	0.0301
Modal	10	0.236	0.0003	0.0001	4.45E-05
Modal	11	0.216	0.0026	0.001	0.0027
Modal	12	0.21	0.0058	0.004	0.0097

Tables.5.12, 5.13, 5.14 and 5.15 show the modal mass participating ratios in X, Y and Z directions due to 10˚, 15˚, 20˚ and 25˚. Based on IS 1893(Part-1) 2016, Table 6, the building located in seismic zone-IV shall be ensured that the first three modes together contribute at least 65% mass participation factor in each principal plan direction, and the fundamental lateral natural periods of the building in the two principal plan directions are away from each other by at least 10% of the larger value.
The two provisions are accurate and valid in all the four cases, it can be concluded that there is no torsional irregularity due to mass.

VI. CONCLUSIONS:

The following conclusions can be made from the analysis:

1. The base shear is getting increased with the increase in the angle of the sloping ground, i.e., 10˚,15˚,20˚ and 25˚ respectively along both directions.
2. The base shear value in the X-direction is relatively higher compared to the Y-direction (sloping direction) because the building moves more as a unit due to its uniform and consistent stiffness distribution in this direction, causing greater seismic forces to be resisted here.
3. The lateral displacement of the structure decreases as the slope of the terrain increases from 10˚,15˚,20˚ and 25˚ respectively.
4. The lateral displacement values in the Y-direction (sloping direction) are higher than the X-direction lateral displacement because, in the Y-direction (sloping direction), the building has columns and walls of varying heights. The shorter columns and walls on the uphill side are stiffer, while the longer columns and walls on the downhill side are relatively more flexible. This uneven stiffness distribution means that the structure is less stiff overall in the Y-direction (sloping direction) than in the X-direction, leading to higher lateral displacement.
5. The modal time periods of the building structure decrease as the slope increases due to the inverse relationship between the modal time period and the structural stiffness.
6. As the ground slope of the building structures increases, the overturning moments due to earthquakes also increases in both directions. The overturning moment is maximum at the 25° slope in both the X and Y-directions, with the X-direction exhibiting a higher value compared to the Y-direction (sloping direction). The building structure should be designed carefully to ensure stability against overturning.
7. The models are safe due to Storey drift, and the maximum storey drift is at storey 9, i.e. 0.001284 due to Spec-Y at 25˚ sloping ground.
8. The models are safe against torsional irregularity caused by mass and stiffness based on Table 6 clause 7.1 of IS 1893 (Part-1) 2016.
9. Reducing shear wall thickness along the structure's height can reduce the building's overall stiffness and make the construction more cost-effective.

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