

INFLUENCE OF SLOPE INCLINATION ON STRUCTURES FOUNDED ON SLOPES DURING SEVERE WIND EVENTS

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ABSTRACT

High-rise buildings are subject to significant wind loads that depend on their location. In some cases, wind pressure is the main design concern, especially in northern India, where wind speeds are higher. Building on sloped land in hilly areas adds more structural challenges. This study examines how high-rise buildings on sloping ground respond to severe winds. The research used SAP2000 software for numerical analysis and simulations, focusing on base reactions, natural time period, and overall lateral displacement under strong wind.

KEYWORDS: Wind load, Base reaction, Displacement, Time period, Modal analysis, SAP2000

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1. BACKGROUND AND SIGNIFICANCE OF THE STUDY

Structures experience various types of loads throughout their lifetimes. Static loads are always present, but dynamic loads such as wind and earthquakes can be much stronger and pose a safety threat. Wind and seismic forces are especially important, but wind loads are often overlooked in design. In areas with high wind speeds, wind forces can be two to three times greater than seismic forces. So, engineers must carefully verify that buildings and their components are strong and stable enough to withstand these forces through thorough design methods.

A Times of India report indicates that Nainital is situated in a high-seismic risk zone, and many contemporary buildings in the area are more susceptible to earthquakes, challenging the perception that seismic activity is less significant. Consequently, structural performance assessments should account for both wind pressures and earthquake risk.

Engineers usually focus more on seismic loads than wind loads during design. This can lead to structural weaknesses, especially in areas with strong winds or sloped terrain.

This study looks at how buildings on sloped or mountainous ground behave when exposed to both wind and earthquakes. The research has two parts, with the first focusing on how structures respond to earthquakes. Earlier studies suggest using setback designs to handle uneven ground, but these can make the building's shape uneven and misalign the center of mass and rigidity. This misalignment leads to twisting effects that can make buildings react more strongly during earthquakes or strong winds. Measuring the distances between the center of mass and center of rigidity compared to the building's size helps us understand how these irregular shapes increase twisting forces.



Figure 1: An Indicative RC Structure positioned on inclined ground

2. PREVIOUS RESEARCHES

Swathi A.S et al [2015] carried out comparison of seismic performance of soft storey building on sloping grounds and soft storey building retrofitted with shear wall. Five storey building built on a slope of 30° is analysed to find out the seismic performance. Then the building is retrofitted with shear wall and it is analysed to find if the seismic performance is been improved. Structural engineering software SAP-2000 is used for analysis with Seismic coefficient method. The Non-linear Static Pushover analysis carried out for analysing the structure. Five-storied building with open ground storey on sloping ground is modelled and pushover analysis is performed. The seismic performance of open ground storey buildings is very less according to the author's observation. The performance is improved by addition of shear wall. Addition of shear wall is an ideal solution to improve the seismic performance of open ground storey building constructed on a sloping ground. Improvement in performance is shown by the building with shear wall as the deformation is increased.

Sujit Kumar et al [2014] carried out the seismic analysis of a five storied RC building on varying slope angles i.e. 7.5° and 15° and compared with the building resting on the flat ground. The effect of sloping ground on the seismic performance of building during earthquake is studied by linear static analysis by using the structural analysis software STAAD Pro. v8i. The author discussed briefly the performance of hill buildings and structural behavior of short column subjected to lateral load. Authors concluded that, the critical horizontal forces and bending moment in footing increases significantly with increase in slope of the ground. However vertical reaction is almost same for different ground slopes. Critical bending moments in the column increases significantly for a sloping ground compared to plane ground. However critical value of axial force in column remains almost same for column for different ground slopes. Thus the section of these columns required to contain more steel to provide greater resistance.

Ajay Kumar Sreerama et al [2013] studied the behavior of a G+3 building on varying slope angles i.e., 15° , 30° , 45° and 60° and compared with the same on the flat ground. Building is designed as per IS456 and later subjected to earthquake loads. It was observed that as the slope angle is increasing, building is becoming stiffer. Two types of analyses were conducted viz., lateral load analysis and incremental dynamic analysis. It was observed from the initial results that the columns on the higher side of the slope i.e., short columns were subjected to more shear force than longer columns on the lower side. Finite element method is used to study the static behavior whereas Applied Element Method (AEM) is used to perform IDA. The study clearly helps us to understand the significant difference between the seismic behaviors of building on slopes to building on flat surface. As the slope angle increases, it is observed that the short column resist almost all the storey shear since other columns are flexible and tend to oscillate. A hinge mechanism is formed near the shorter column zone and is damaged earlier as the slope angle increases. From the fragility curve they have observed the damage of the structure is more when it is on steep angle. After studying all the above discussed literatures and other materials available in this research area, it was realised that though a lot of research has been carried out in this research area but influence of wind flow on such structures hasn't been considered yet.

3. RESEARCH METHODOLOGY

The study gives a detailed analysis of wind loads on buildings located on sloped hills. A report from Science Publishing Group used finite element macro-modelling to study how non-engineered masonry buildings perform during earthquakes, comparing different cases. The article "Seismic Analysis of Multi-Storey Building Resting On Flat Ground and Sloping Ground" notes that the main parameters to measure are the natural period, base shear, and maximum lateral displacement. It also found that base shear was highest for buildings on a 20-degree slope. The next table summarises the setup and features of all nine models studied.

Table1: Model Development

Model Designation	Inclination of the slope	Structural specifications
ILNS-20	20 ⁰	Bare Frame
ILNS-30	30 ⁰	Bare Frame
ILNS-40	40 ⁰	Bare Frame
ILSI-20	20 ⁰	Shear walls in the internal area
ILSI-30	30 ⁰	Shear walls in the internal area
ILSI-40	40 ⁰	Shear walls in the internal area
ILSE-20	20 ⁰	Shear walls on the external periphery
ILSE-30	30 ⁰	Shear wall on the external periphery
ILSE-40	40 ⁰	Shear wall on the external periphery

The following tables show the materials, structural details, and load factors used in this study.

Table2: Material Specifications

1.	Grade of Concrete	M30
2.	Grade of reinforcement	Fe500
3.	concrete Density	25 KN/m3
4.	masonry Density	19 KN/m3
5.	Damping Percentage	5%

Table 3: Building Geometry

1.	dimensions of the plan	18m X 18m
2.	building height Effective	48 m
3.	Typical storey height	3m
4.	Thickness of Slabs	150 mm
5.	Internal Wall thickness	150 mm
6.	External wall thickness	150 mm
7.	Depth of Foundations	Varied

Table4: Loadings

1.	Dead load of slab	3.75 KN/m2
2.	Superimposed load	3.0KN/m2
3.	External wall load	15KN/m
4.	Internal wall load	15KN/m
5.	Code for RCC	IS456(2000)
6.	Code for Earthquake analysis	IS1893 (2002)

7.	Zone	IV (severe)
8.	Zone factor (Z)	0.24
9.	Importance factor	1.0
10.	Structural frame type	SMRF
11.	Response reduction factor	5.0
12.	Type of soil	Medium(II)

Table 5: Structural Specifications

1.	Section type	Reinforced concrete
Sizes of column sections		
2.	Columns (C1)	300X600
Sizes of beam sections		
3.	Primary Beams	300 X 530

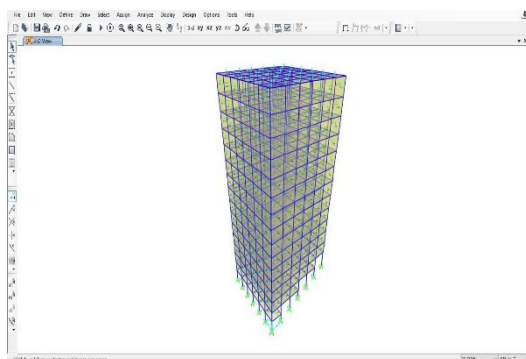


Figure 2: Typical view of ILNS-20 (Wind)
view of ILSE-20 (WIND)

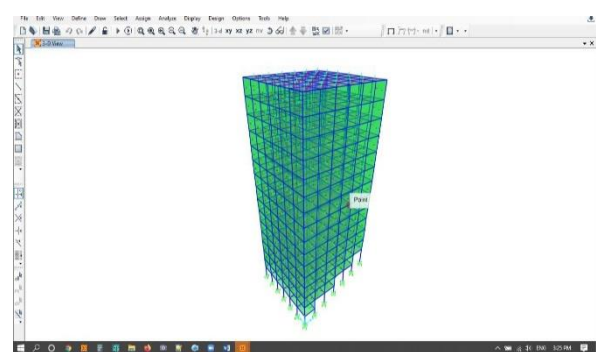


Figure 3 Typical

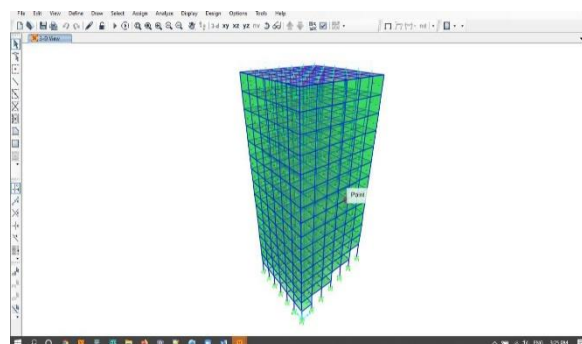


Figure 4 Typical view of ILSI-20 (WIND)

Lateral Wind Force (F_z) as per IS 875 (Part 3): 2015

IS 875 (Part 3): 2015 provides guidelines for assessing wind effects on buildings and recommends dynamic wind analysis for tall or flexible structures. The code also requires checking for wind-induced movement by calculating the gust response factor. In this study, the building does not fully meet the criteria for required dynamic analysis, but because it is in a high-wind area (Nainital), a wind load analysis was still done. All wind factors were checked according to IS 875 (Part 3): 2015 and used in SAP2000 for automated wind load analysis.

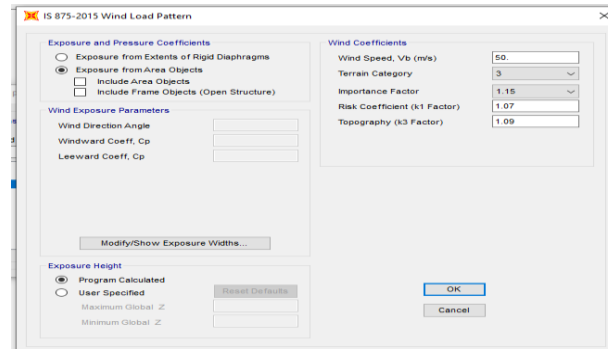


Figure5: Wind Load Parameters

4. RESULTS AND DISCUSSION

After analysing the structures, the main results focused on base shear, natural time periods, column forces, and sideways movement. This section summarizes those findings. A linear modal time-history analysis was performed in SAP2000 using Altadena earthquake records from Reference [8].

Base Shear

Base shear is key for understanding how earthquakes affect buildings. Mahesh S Mudigowdar and Savan R G Basavaraj studied buildings on slopes with different angles using the Response Spectrum Method in TEKLA Structural Designer, showing why base shear matters. Their results show that buildings on steep slopes experience lower X-direction inertia forces.



Figure 6: Base Shear in EQX

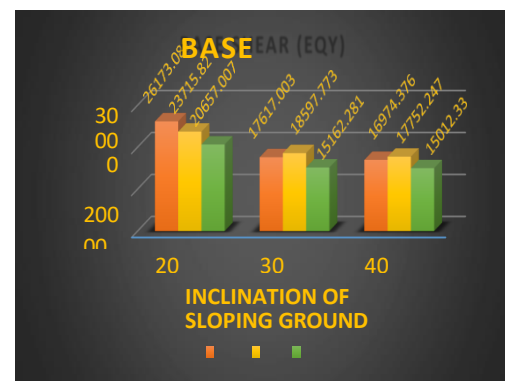


Figure 7: Base Shear in EQY

Bare frame systems (ILNS series) face higher force demands, while buildings with internal shear walls (ILSI) have lower forces. The lowest base shear was found in buildings with shear walls around the whole outside, thanks to their greater stiffness and better resistance to side loads.

Figure 6 shows that when earthquakes push in the Y-direction, buildings on moderate slopes have higher base shear than those on steeper slopes. Once a certain slope angle is reached, base shear changes very little, so making the slope steeper does not greatly affect the building's response.

Fundamental Time Period

The fundamental time period, which affects how a building reacts to earthquakes, was a main focus in this study. Following IS 1893 (2002), the first vibration modes were checked because they are important for dynamic behavior. Figure 7 shows that buildings without shear walls on steeper slopes have the shortest time periods, while those on gentler slopes have longer ones.

Buildings with internal shear walls have slightly longer time periods on all slopes. Still, as the slope gets steeper, the time period goes down. Figure 9 shows that buildings with shear walls around the outside have much shorter time periods than other types, and this also drops as the slope increases. In general, adding shear walls makes the building stiffer and reduces the fundamental time period.

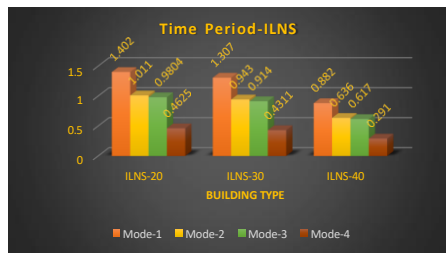


Figure 8: Time period of bare frames (ILNS)

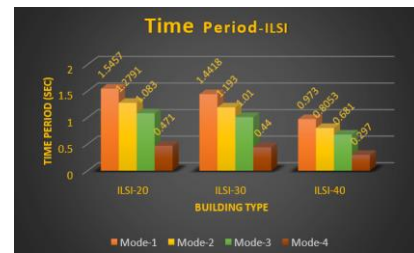


Figure 9: Time period of frames with internal shear

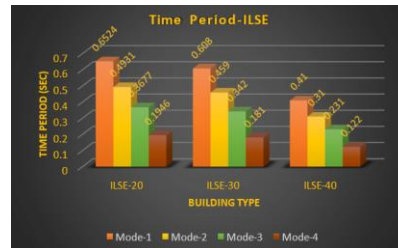


Figure 10: Time period of frames with external shear

Story Displacements

All the models studied showed their maximum storey displacements, as shown in the figures below. The results show that storey displacements increase significantly as the slope steepens. Buildings with shear walls around the outside had much lower displacements because they are stiffer.

In contrast, buildings with internal shear walls recorded higher displacements than those with peripheral configurations, although both outperformed bare-frame structures. These findings highlight the superior lateral displacement control provided by shear walls, especially in peripheral arrangements.

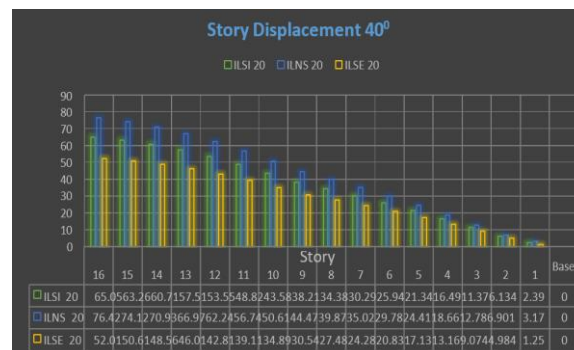


Figure 11: Story Displacements for the structures subjected to wind (40-degree slope)

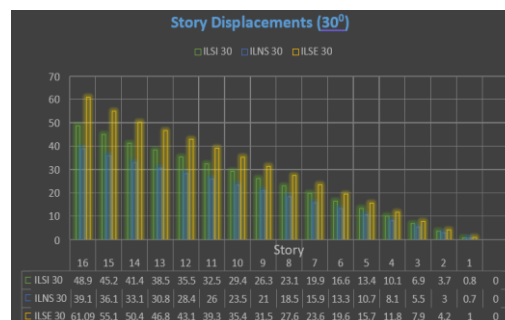


Figure 12: Story Displacements for the structures subjected to wind (30-degree slope)

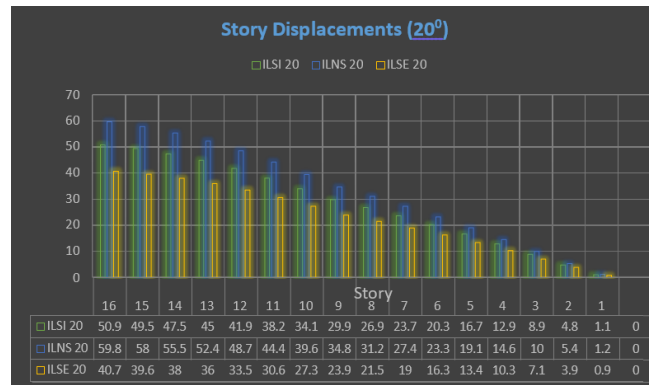


Figure 13: subjected to wind (20-degree slope)

5. CONCLUSIONS

Based on the numerical simulations of the structures under the specified loading conditions and design parameters, the following conclusions are presented:

1. The results show that as the ground slope increases from gentle to moderate, the inertia forces in buildings decrease. But on steeper slopes, these forces level off and change little compared to moderate slopes.
2. Smriti Singh and Afzal Khan found that buildings with internal shear walls have higher base forces on steep slopes, while bare frames have higher base shear on gentle slopes. The fundamental time period gets shorter as the slope angle increases.
3. Internal shear walls make buildings more flexible, while shear walls around the outside (ILSE) make them stiffer. The highest storey displacements happen on the steepest slopes, then on gentle slopes, with moderate slopes giving the best balance.

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