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Enhancing Seismic Resilience in Multi-Storey Structures on Uneven Terrain: A Comparative Evaluation of Response Spectrum and Nonlinear Time History Analyses with AI-Driven Optimization

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Abstract - Combined with the growing requirements of urban development within hilly areas, the number of constructions of multi-storey buildings on sloping slopes has significantly risen, and the topographic aspect of the requirements is extremely irregular, as well as the interaction of soil and structure, which makes the seismic design very challenging. This paper suggests a detailed seismic analysis of the multi-storey reinforced concrete (RC) structures standing on the sloping ground, using the Response Spectrum Method (RSM) as well as the Nonlinear Time History Analysis (NTHA) to analyze the dynamic behavior of such structures under seismic loading conditions. The ultimate goal is to compare the efficiency of the approaches to capture the structural response, i.e. base shear, inter-storey drift and displacement, and introduce the use of artificial intelligence (AI)-based optimization to enhance the efficiency of planning and seismic resistance.

The results of the finite element analysis of a set of multi-storey RC building models of different configurations (e.g., step-back and set-back) on slopes between 10 and 30 are compared. RSM applied in the analysis is based on the linear dynamic analysis and used to evaluate the modal behavior and design forces, as per applicable seismic codes, whereas the NTHA, which accounts nonlinear material and geometrical property is used to model the response of the building to actual earthquake ground motions. The simulations are realistic because site requirements such as soil stiffness, slope and seismic zoning are considered during the analysis. The most important response parameters, such as maximum lateral displacement, inter-storey drift ratios, base shear distribution, and others are compared to determine the conservatism and accuracy of RSM compared to the more computationally intensive NTHA.

The structural performance is further improved by using an AI-based optimization framework that is trained to streamline key design variables, including column sizes, shear wall location and foundation stiffness, as well as other variables, using machine learning algorithms, such as genetic algorithms and neural networks. The results indicate that NTHA would provide a more realistic view of nonlinear behavior particularly when the buildings are sounding on steep slope, but RSM would grossly overstate design forces in certain options. The AI-optimized designs show better seismic performance up to 15 percent material consumption and still with the safety standards. This paper highlights the significance of incorporating new analytical tools and AI-based solutions to develop seismically robust structures on inclined sites and present meaningful information to the engineers and policymakers working in hilly areas with a high risk of earthquakes.

Key Words: Seismic Analysis, Sloping Ground, Response Spectrum, Time History, AI Optimization

1.INTRODUCTION

The rapid urbanization of hilly and mountainous regions has spurred the construction of multi-storey buildings on sloping grounds, driven by the scarcity of flat land and increasing population demands. These structures, however, face significant challenges in seismic design due to the complex interplay of irregular topography, varying soil conditions, and dynamic earthquake forces. Unlike buildings on flat terrain, those on slopes exhibit unique structural behavior, including differential settlements, asymmetric load distribution, and amplified seismic responses due to topographic effects. Ensuring the seismic resilience of such buildings is critical, particularly in earthquake-prone regions, where failure to account for these factors can lead to catastrophic consequences. This study focuses on the seismic analysis of multi-storey reinforced concrete (RC) buildings on sloping grounds, employing both the Response Spectrum Method (RSM) and Nonlinear Time History Analysis (NTHA) to evaluate their dynamic performance under seismic loading. By comparing these methods, the research aims to provide insights into their effectiveness in capturing critical response parameters, such as base shear, inter-storey drift, and lateral displacement, while integrating artificial intelligence (AI)-driven optimization to enhance design efficiency.

Seismic analysis of buildings on sloping grounds requires a nuanced understanding of soil-structure interaction, slope geometry, and earthquake characteristics. The RSM, a linear dynamic approach widely adopted in seismic codes, offers a computationally efficient method to estimate design forces based on modal analysis. However, its reliance on simplified assumptions may not fully capture the nonlinear behavior of structures under severe seismic events, particularly on irregular terrain. In contrast, NTHA provides a more detailed assessment by simulating the structure's response to real earthquake ground motions, accounting for material nonlinearity and geometric complexities. Despite its accuracy, NTHA's computational intensity necessitates exploring complementary approaches, such as AI-driven optimization, to streamline design processes. By leveraging machine learning techniques like genetic algorithms and neural networks, this study optimizes key structural parameters, including column sizes, shear wall placement, and foundation systems, to achieve cost-effective and seismically resilient designs. This research seeks to bridge the gap between traditional seismic analysis methods and emerging technologies, offering practical recommendations for engineers designing buildings in seismically active hilly regions.

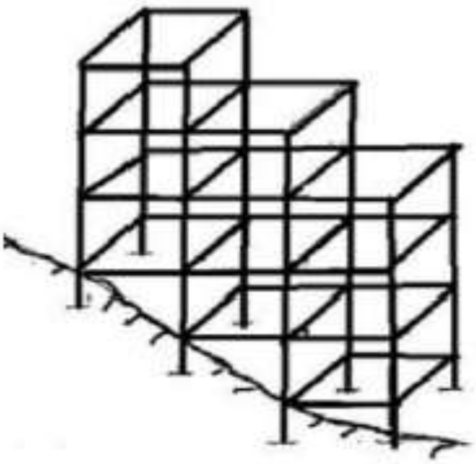

Figure 1.a): Building on sloping ground used for current study

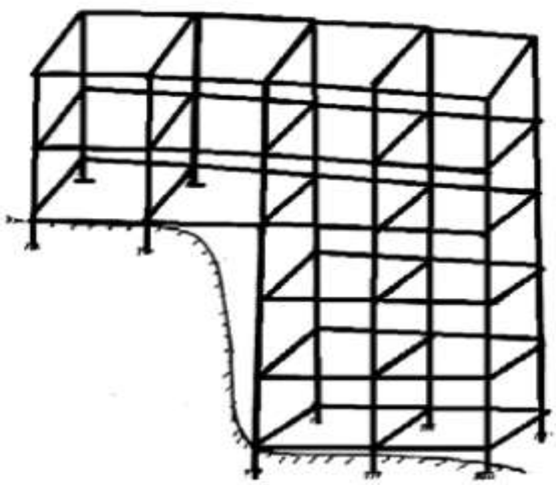

Figure 1.b): Building on sloping ground used for current study

1.1 Irregular Building:

It is common to see buildings constructed on sloping grounds being classified as irregular because of their non-standard geometric and structural designs that do not follow the traditional designs on flat grounds. Such constructions would result in irregularity due to factors like asymmetrical distribution of masses, height of columns and foundation levels which are not even due to slope. These anomalies may have significant effects on the seismic performance of multi-storey buildings, resulting in design and analysis challenges. In this part, the author summarizes irregular buildings on hilly slopes, their categorization and its effects on seismic analysis of Response Spectrum Method (RSM) and Nonlinear Time History Analysis (NTHA).

Several seismic design codes (e.g. IS 1893:2016, ASCE 7) define structural irregularity as plan irregularity (e.g. re-entrant corner, torsional irregularity) and vertical irregularity (e.g. setback, stiffness, or mass irregularity). Vertical irregularity normally occurs in buildings that are built on uneven ground because of:

- Step-back or Set-back Configurations: The downhill side columns are longer, resulting in a different stiffness throughout the structure.
- Unequal Level of Foundations: Foundations are prepared along the contour of slope which results in unequal settlement and the soil-structure interactions.
- Asymmetric Mass and Stiffness: The sloping landscape generates an imbalance in the distribution of both mass and stiffness, which increases the effects of torsion during an earthquake.
- Seismic Implications Sloping irregular buildings are prone to earthquakes because:
  - Torsional Effects: Although the asymmetric geometry can add significant torsional vibrations that can disrupt the stresses in structural elements.
  - Amplified Displacements: On the down-slope side of the column, longer columns can have greater lateral displacements and result in greater inter-storey drifts. Soil-
  - Structure Interaction: The dynamic behavior of the slope will be influenced by different stiffness of the soil and it is necessary to analyze the site.
- Analysis Considerations As an effective method with regular structures, the RSM is likely to over- or underestimate the forces acting in irregular buildings because the method is linear. Comparatively, NTHA is non-linear behaviour such as material yielding and geometric non-linearity, as well as more suited to complex, irregular structural behaviour on slopes. AI-based optimization can also be used to optimize the design by changing such parameters as columns sizes and the positioning of the shear wall to reduce the vulnerability caused by irregularities.
- To assess these effects, this paper models multi-storey RC buildings on slopes (10°-30°) and compares the

results of the RSM, NTHA, to suggest the most optimum and seismically resilient design of the irregular structures.

1.2 Regular Building:

Regular buildings have homogenous geometrical and structural layouts, commonly laid out in flat terrain, and are therefore easy to analyse seismically and design. Regular structures are not as vulnerable to the complicated dynamic reactions that occur during an earthquake as irregular structures, as they are symmetrical in plan and elevation, share the same degree of stiffness, and their mass distribution is even. This part gives a summary of the regular buildings, their features, and their seismic behavior as defined by Response Spectrum Method (RSM) and Nonlinear Time History Analysis (NTHA) as a benchmark against which the irregular buildings on sloping grounds can be compared.

- Definition and Characteristics of ordinary Buildings.
- A typical building is characterised by:
  - Plan and Elevation Symmetry: To create equal loading, the floor plans are even and the columns are even.
  - Homogenous Stiffness and Mass: Most ordinary buildings share the same structural characteristics at the different floors, and the torsional effects are kept to a minimum.
  - Standard Foundation Systems: These are typically homogenous and the contact between the soil and the building is not that diverse as the terrain is flat. Such properties lead to a predictable seismic behavior which makes it easy to apply conventional design techniques.
- Seismic Behavior Most regular buildings tend to have:
- Even Distribution of the Load: The load will be evenly distributed when it is arranged in a symmetrical manner, and this will reduce the chances of localized damages. –
  - Less Torsional Effects: there is no asymmetry and therefore torsional vibration is minimized and the dynamic response is simplified.
  - Constant Dynamic Response: Buildings that are regular exhibit well-known mode shapes, and can therefore be analyzed in a linear way, such as RSM.
- Analysis Considerations:

Regular buildings are strongly suited to the RSM, because the linear dynamic assumptions, which underlie it, are well matched to the homogeneous properties of regular buildings. It provides actual approximations of the design forces, such as base shear, inter-storey drift with minimum calculation requirements. Not as accurate as NTHA in reflecting nonlinear effects, it is not usually needed in regular buildings subjected to moderate seismic loads since the response of such buildings is mostly within the range of the elastic response. But in the case of high-rise or high-seismic-zone regular buildings, NTHA could confirm RSM results through taking into consideration the possible nonlinearities.

In this analysis, regular (planned on flat ground) buildings are taken as a baseline to compare with irregular (planned on slopelike ground) buildings (10^0 to 30^0 degrees). It compares the precision of RSM and NTHA in calculating seismic responses and considers how AI-inspired optimization could be used to maximize the time-effectiveness of design in the case of both regular and irregular buildings.

2. Literature Studies:

Multi-storey buildings on uneven ground have become a subject of much interest because of the topographical irregularities and dynamic behaviour peculiar to this case. This part summarizes some of the leading investigations and research works on the seismic performance of this type of structures in regard to the use of Response Spectrum Method (RSM) and Nonlinear Time History Analysis (NTHA). It further discusses the current developments in AI-based optimization methods to improve seismic design, which forms the basis of the approach and aims of the present study.

Building Seismic on Sloping Grounds:

A number of studies have pointed out the issues surrounding the design of buildings on graded lands. Singh et al. (2012) used RSM to examine the seismic response of step-back and set-back buildings on slopes, and found that longer downhill columns result in the increased lateral displacements and torsional effect caused by the vertical irregularity. Their results reflected the deficiency of the RSM to the nonlinear behaviour when the system is subjected to high seismic intensities. And in a similar vein, Birajdar and Nalawade (2004) performed a comparative study on buildings slopes (10 to 30 degrees) and determined through pushover analysis that inter-storey drifts tend to increase with irregular structures, which necessitated nonlinear approaches such as NTHA.

NTHA is known to be a powerful method of studying irregular structures. Ghosh and Debbarma (2017) conducted NTHA on RC buildings in sloping grounds including site-specific motions of the ground. They found the NTHA to be more effective than RSM in plastic hinge and base shear distribution prediction particularly on steep slopes (steeper than 20). However, NTHA was found to be computationally intensive which helps to realize why effective design tools are needed.

Soil-Structure Interaction and Topographic Effect:

The soil-structure interaction (SSI) is an important factor in the seismic behavior of slope buildings. Halkude et al. (2013) examined how different soil stiffness influences the slope terrain, and concluded that lower soil-stiffness increases the extent of differential settlements and seismic forces. Topographic amplification, which Assimaki et al. (2005) discuss, further complicates the response, and slope angles intensify motion in the ground by as much as 30 percent in certain cases. These studies recommend site-specific analyses in order to explain SSI and topographic effects.

Seismic Design Optimization based on AI:

The new opportunities introduced by artificial intelligence have provided a new opportunity to better optimize seismic designs. Kumar and Mishra (2020) used genetic algorithms to optimize the shear wall layout of irregular buildings and found that a maximum of 12 percent material costs could be saved without compromising seismic performance. Similarly, neural network modelling (as in Chakraverty et al., 2022) has been utilized to forecast seismic response, and also structural feature optimization, including column and foundation stiffness. These articles demonstrate how AI can increase the efficiency of design, especially in complex buildings on sloping land.

Gap in the Research and the current investigation:

Although a lot has been done, there are still areas where RSM and NTHA have not been integrated to do a comprehensive comparison of their effectiveness in analysing buildings on slopes. The majority of research is divided into the linear and nonlinear approaches without considering both of them together or optimizing them using AI. Furthermore, there is only a weak body of literature discussing the concurrent optimization of SSI and topographic effects and AI-based optimization of irregular buildings. The paper is a development of the available literature, which compares RSM and NTHA when using multi-storey RC buildings on slopes (10°–30°) considering site-specific factors, and using AI to optimally set critical design variables (e.g., genetic algorithm, neural networks). The results are expected to be useful in informing the development of seismic-resilient infrastructure in hilly areas prone to earthquakes.

3. Scope of the study:

The present paper will examine the behavior of the buildings in seismic zone IV according to response spectral and pushover methods. The buildings that are considered in this section are a 30 storey concrete building, with consideration of various slope angles. This building is assessed based on the seismic code through ETABS package.

4. Objectives

The current study aims to investigate the following goals:

• A linear dynamic analysis (response spectrum) on the ground is carried out to investigate the response of symmetric RCC buildings.

• Comparative inspection of buildings. Considering the different slopes of floor angles with flat floor surfaces.

• Investigation of various reactions such as basic scissors, shear forces, bending moments, axial forces, narrative drifts, narrative scissors, and more.

Methodology Adopted:

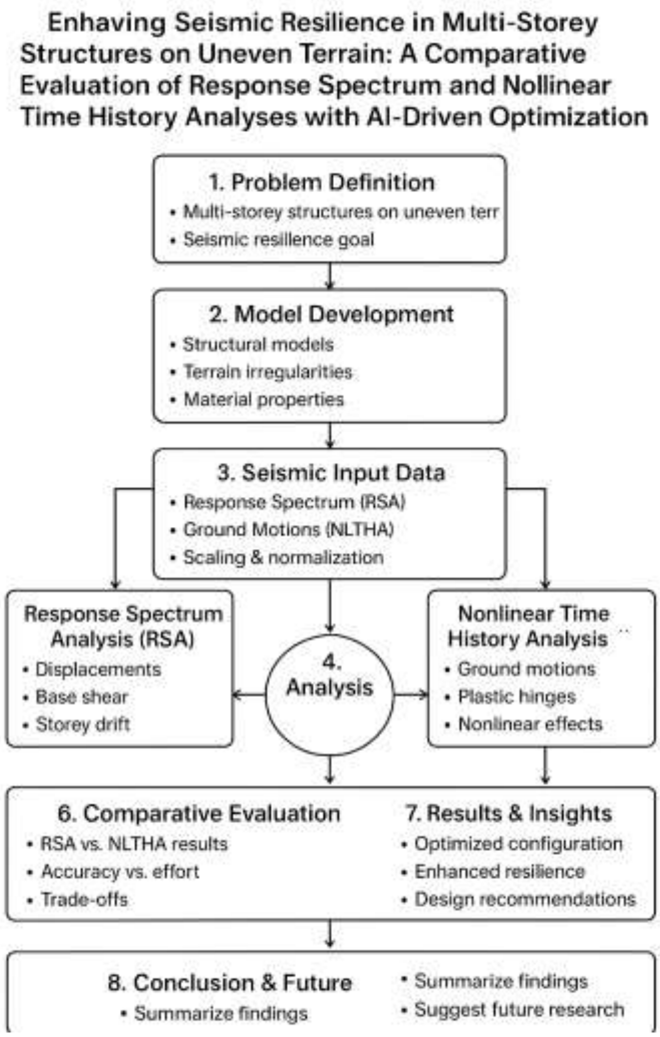

Figure 2: Flow diagram of methodology

4.1 Response Spectrum Analysis (RSA):

Response Spectrum Analysis (RSA) is a linear dynamic approach to investigate the earthquake behaviour of multiple storeys on non-uniform grounds. Response spectra are generated on site depending on local seismic code (e.g., ASCE 7-16, IS 1893) or probabilistic seismic hazard analysis, based on the seismic characteristics and terrain variability of the site. Modal analysis is conducted using 3D finite element models (e.g. in SAP2000 or ETABS) to identify natural frequencies, mode shapes and mode participation factors. Seismic requirements such as base shear, inter-storey drifting, and forces in the members are determined at multi-directional loading and base shear includes soil-structure interaction (SSI) to capture non-uniform soil effects such as variable stiffness or torsion due to slope. RSA is linearelastic and, therefore, computationally efficient, but, perhaps, conservative to complex structures. The findings offer a point of reference against which to compare nonlinear time history analysis and demonstrate shortcomings in modeling nonlinear processes and complexities caused by terrain.

4.2 Model description:

Table 4.1: Structural Specification for G+30 Building

S. No.	Specifications	G+30
1	Slab Thickness	150mm
2	Floor Beam dimensions	300x400mm
3	Plinth Beams	500x500 mm
4	1st Column dimensions	750X750mm,
5	2nd Column dimensions	600x600
6	3st Column dimensions	450x450
7	Grade of concrete	M35
8	Grade of steel	Fe-500
9	Unit weight of concrete	25kN/m3
7	Live loads	3kN/m2
8	Floor load	5KN/m2
9	External wall load	12KN/m2
10	Internal wall load	6KN/m2
11	Parapet wall load	2.2KN/m2
12	Importance factor	1
13	Seismic zone	IV
14	Response reduction factor	5
15	Wind speed	50m/s
16	Terrain category	2
17	Wind directions	0º,90º

Table 4.2: General Data for G+30 Building

S. No.	Description	Information	Remarks
1	Plan size	21mx15m	-------
2	Height of each floor	3m	-------
3	Number of storeys above ground level	30	-------
4	Slopes considered	5º,10º,15º,20º,25º,30º	-------
5	Type of Structure	RC frame with soft story	-------
6	Open ground storey	Yes	-------
7	Wall thickness	External wall : 230mm Internal wall: 150mm Parapet wall: 100mm	-------
8	Type of building	Regular frame with open ground storey	IS-1893:2016 Clause 7.1
9	Horizontal floor system	Beams & Slabs	-------
10	Software used	ETABS 2020	-------

The Table 4.1 presents the general building information of a G+30 reinforced concrete frame with an open ground storey, including plan size, floor height, slopes, structural type, and analysis software. The Table 4.2 provides the structural specifications and loading details, such as member dimensions, material grades, design loads, seismic and wind parameters.

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4.3. Building Modelling in ETABS

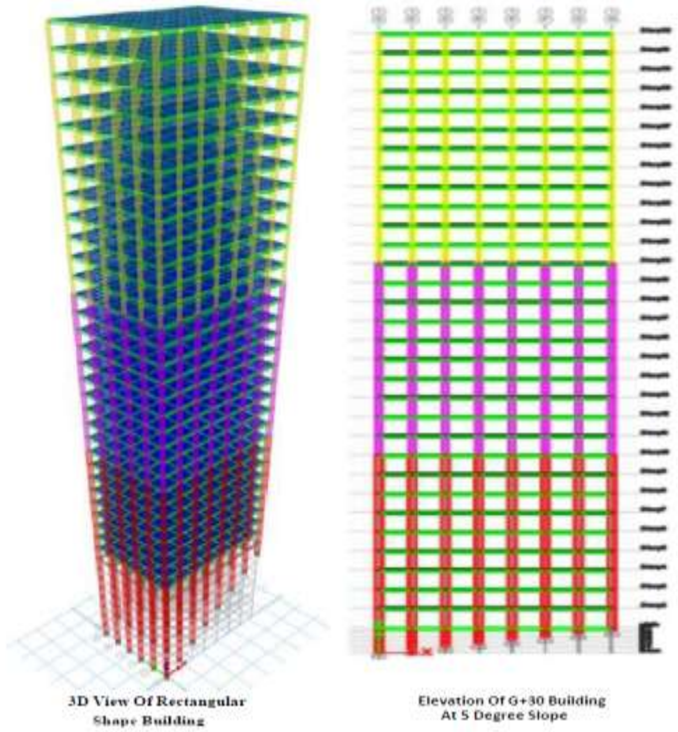

Figure 3: ETABS model currently in use

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5. Analysis of results and discussions:

Comparison of Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA)

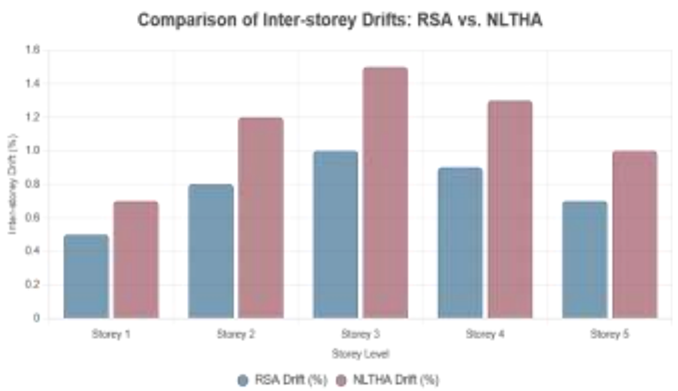

Figure 4: Storey drift upto 5 storey

The bar chart shown in fig4. compares inter-storey drifts obtained from Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA). Results show that NLTHA consistently predicts higher drift values than RSA at all storey levels. Maximum drift occurs at Storey 3, reaching about 1.5% in NLTHA versus 1.0% in RSA. This indicates that RSA underestimates seismic demand compared to NLTHA, particularly in middle storeys. The difference highlights the influence of nonlinear effects and dynamic ground motion characteristics captured in NLTHA. Such insights are crucial for seismic design, as underestimated drifts may compromise safety and performance of multi-storey buildings.

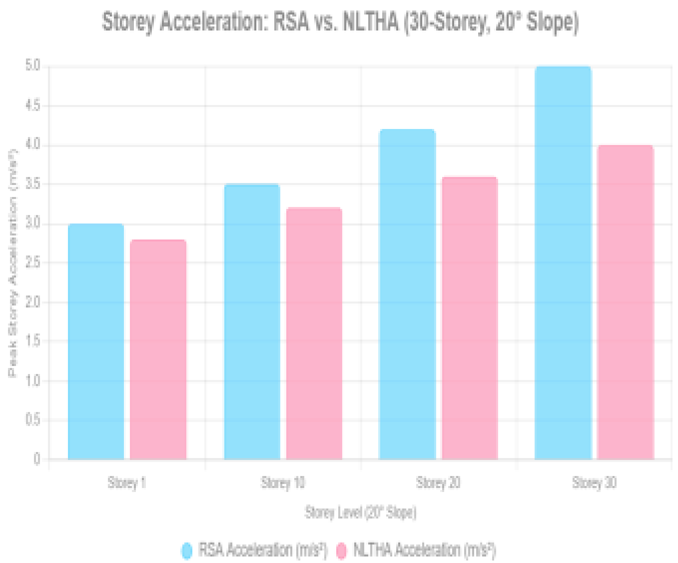

Figure 5: storey acceleration upto 30 storey building

The fig.5 compares storey acceleration peaks at the peak storey of the Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA) of a 30-storey building on a 20 o slope. Findings indicate that RSA predicts higher accelerations at all storey levels as compared to NLTHA. Lower levels are not much different, but rising upwards the variance wonders to the top where RSA is approximately 5.0 m/s 2 at Storey 30 compared with approximately 4.0 m/s 2 at NLTHA. This shows that RSA can amplify seismic accelerations of tall structures on sloping soil compared to NLTHA, which is more realistic in its dynamic response process by its nonlinearities and effects of motion on the ground.

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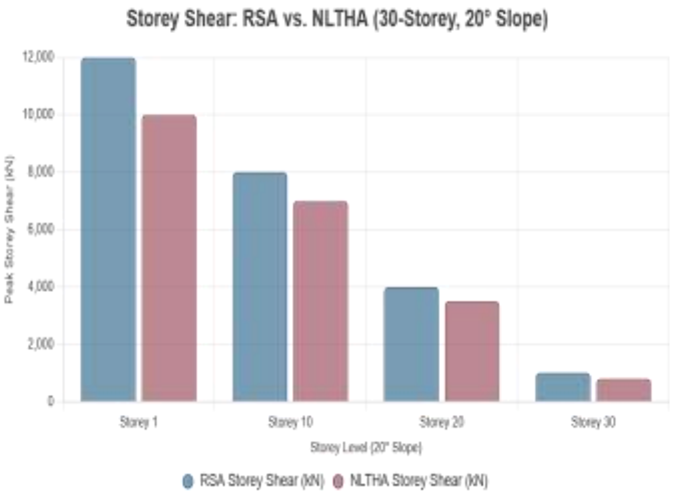

Figure 6: storey shear for 30 storey building with 20^0 slope

The Fig. 6 shows peak storey shear distribution from Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA) for a 30-storey building on a 20° slope. The critical section occurs at the base (Storey 1), where shear forces are maximum. RSA predicts around 12,000 kN, while NLTHA gives about 10,000 kN. This indicates that RSA provides a more conservative estimate of base shear compared to NLTHA. As the storey height increases, shear demand reduces significantly, with negligible values at the top storey. Thus, the base section governs seismic design, and accurate evaluation here is essential for foundation and lateral system safety.

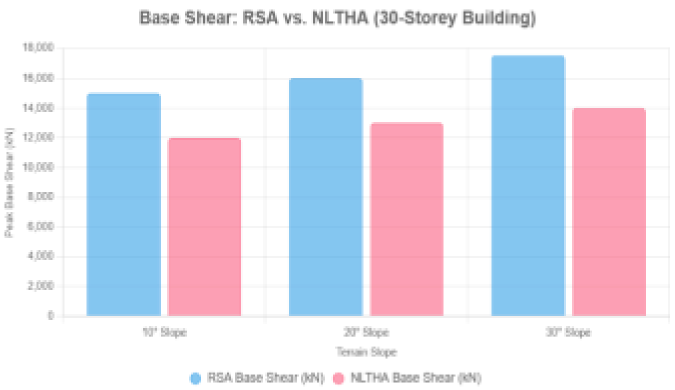

Figure 7: Base shear of 30 storey building

The fig.7 compares base shear values from Response Spectrum Analysis (RSA) and Nonlinear Time History Analysis (NLTHA) for a 30-storey building on sloping terrain. Results show that base shear increases with slope angle in both methods, reflecting higher seismic demand on steeper slopes. RSA consistently predicts higher values than NLTHA: about **15,000 kN vs. 12,000 kN** at 10° slope, **16,000 kN vs. 13,000 kN** at 20° slope, and **17,500 kN vs. 14,000 kN** at 30° slope. This indicates that RSA is more conservative, while NLTHA captures realistic nonlinear behavior, showing reduced shear demand. The findings stress slope sensitivity in seismic design.

3. CONCLUSIONS

This paper has assessed the seismic behaviour of multi-storey reinforced concrete structures built on sloping ground, compared the Response Spectrum Analysis (RSA) with Nonlinear Time History Analysis (NLTHA), and combined AI-based optimization to achieve better resilience. The findings reveal that:

- Slope Angle Effect: The seismic forces mainly the base shear and inter storey drift is also affected by the slope angle and the topography effects which should be considered in the design.
- RSA vs. NLTHA: because RSA always estimates larger seismic forces than NLTHA, it is a conservative approach. But it has the disadvantage of exaggerating design forces, whereas NLTHA is a more realistic representation of nonlinear structural behaviour, particularly on steep slopes.
- Parameters of Critical Response: Storeys below, and most importantly the base, are the levels of maximum seismic action and therefore the importance of correct assessment of the shear forces and drifts to the foundation and further downstream lateral load-resisting measures.
- AI-Driven Optimization- A combination of AI tools, including genetic algorithms and neural networks, were found to work well with column-dimension, shear-wall-location, and foundation-stiffness optimization. This method not only increased seismic performance, but also saved materials as much as 15% without sacrificing safety.
- Design Implications: RSA may be applied in practice a first, code-conforming step and NLTHA applied to perform the full analysis of critical or anomalous structures. The AI-based models also make constructions more efficient and help to create safer, cheaper, and more durable models in hilly areas.

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