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Article

Seismic Performance Assessment of Regular and Irregular Reinforced Concrete Buildings under Long-Period Ground Motions in the Himalayan Region

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Abstract: Long-period ground motions (LPGMs) generated by earthquakes in the Himalayan tectonic region significantly influence the seismic performance of medium- and high-rise Reinforced Concrete (RC) buildings, particularly those with structural irregularities. This study investigates the seismic response of regular and irregular RC building configurations, including Regular (R10), L-shaped (L10), T-shaped (T10), and Setback (S10) buildings, subjected to representative LPGMs. Three long-period ground motion records, namely the 2015 Gorkha earthquake, the 2005 Muzaffarabad earthquake, and a synthetic long-period ground motion, were selected and analyzed using nonlinear time-history analysis in ETABS v20. Structural performance was evaluated based on the Peak Inter-storey Drift Ratio (PIDR), Maximum Roof Displacement, Base Shear, and Plastic Hinge Formation. The results indicate that the regular building exhibited the best seismic performance, with an average PIDR of 1.08%, roof displacement of 136.6 mm, and base shear of 2213 kN. In contrast, the T-shaped building exhibited the highest seismic response, recording an average PIDR of 1.78%, roof displacement of 210.6 mm, base shear of 2424 kN, and the formation of 29 beam plastic hinges and 11 column plastic hinges, indicating significantly greater seismic vulnerability under long-period earthquake excitation.
Keywords: Long-Period Ground Motions (LPGMs), Seismic Response Analysis, Irregular Reinforced Concrete Buildings, Nonlinear Time-History Analysis, Himalayan Tectonic Region

1. Introduction

Earthquakes are one of the most destructive natural hazards impacting civil infrastructure, especially in tectonically active areas where strong ground shaking can result in significant economic losses and damage to structures [1]. The structural properties of buildings are not the only factor that determine the seismic response of buildings; the frequency content, duration and amplitude of the ground motion also influence the seismic response of buildings [2]. The focus became Long Period Ground Motion (LPGM) in recent decades because of their special properties with exciting flexible and medium and high-rise structures. LPGMs are distinguished from conventional short-period seismic waves as they have dominant periods typically in the order of 2-10 seconds or longer that allow them to resonate with structures with similar natural periods [3,4]. These ground motions are often associated with long shaking duration, high requirements for displacement, and continuous cyclic loading, and are especially dangerous for modern steel and Reinforced Concrete (RC) buildings, long span bridges, communication towers and critical infrastructure [5].

Large-magnitude earthquakes, deep sedimentary basins, and complex geology that intensifies low frequency seismic waves are associated with the generation of LPGMs. These waves travel far distances with only moderate attenuation and can reach areas hundreds of kilometers from the epicenter of the earthquake [6]. A number of catastrophic earthquakes such as Chi-Chi (Taiwan) in 1999, Wenchuan (China) in 2008, Tohoku (Japan) in 2011 and Gorkha (Nepal) in 2015 have shown that LPGMs can cause severe lateral movements, resonance, non-structural damage, or even collapse in high-rise and irregular structures [7]. These events put emphasis on the fact that the traditional seismic design methods based on peak ground acceleration and short period response may not fully account for the demands imposed by long-period seismic excitations [8].

The Himalayas are one of the most seismically active regions in the world, where the convergence of the Indian and Eurasian tectonic plates occurs [9]. This continental collision happens at an average rate of about 40–50 mm per year, which leads to continuous build-up of strain energy along the large fault systems like the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) [10]. This stored energy is released periodically, leading to moderate to great earthquakes that can produce significant ground shaking over a wide region in northern India, Nepal, Bhutan and the surrounding areas [11]. There was catastrophic damage due to historical earthquakes such as the 1905 Kangra Earthquake, 1934 Bihar–Nepal Earthquake, 2005 Kashmir Earthquake, and 2015 Nepal earthquake, and the urgent need for seismic assessment methodology to be improved for the structures located in the above-mentioned tectonically active environment [12].

In the cities of the Himalayas, rapid urbanization has resulted in the development of a number of multi-story residential, commercial and institutional buildings of diverse architectural designs [13]. In today's modern urban planning, there are many cases that require irregular structures because of space restrictions, aesthetics needs, functional requirements, and new constructions [14]. Thus, many buildings have irregularities in their plans, irregularities along their heights, discontinuities in mass, setbacks, soft stories, re-entrant corners, and torsional asymmetry [15]. These disparities substantially affect the distribution of stiffness, mass and strength across the structure, causing it to be more prone to torsional effects, stress concentrations, excessive inter-story drift and local damage during an earthquake [16]. On the contrary, the regular buildings are in general characterized by uniform geometry and stiffness distribution that enable the prediction of a more predictable seismic behaviour and superior energy dissipation [17].

Therefore, a comprehensive investigation of the seismic response of regular and irregular shaped buildings subjected to LPGMs is essential for enhancing earthquake-resistant design practices in Himalayan tectonic regions. The purpose of this study is to assess and contrast the dynamic response of various geometric configurations of buildings to representative LPGM records using detailed numerical analysis. Several critical parameters of structure response such as peak displacement, story drift ratio, base shear, story acceleration, overturning moment and time history response are studied to quantify the effects of long-period excitation. This research is projected to yield significant insights into the vulnerability of irregular buildings, better understanding of long period seismic effects, and help develop more performance-based seismic design guidelines for structures in the highly seismic region of the Himalayas. Here are the research objectives as shown below:

- To investigate the influence of Long-Period Ground Motions (LPGMs) on the seismic response of RC buildings in the Himalayan tectonic region.
- To develop and analyze regular (R10) and irregular (L-shaped, T-shaped, and setback) RC building models using nonlinear time-history analysis.
- To evaluate the seismic performance of the selected building configurations based on Peak Inter-storey Drift Ratio (PIDR), Maximum Roof Displacement, Base Shear, and Plastic Hinge Formation.
- To compare the seismic behavior of regular and irregular building configurations under representative long-period ground motion records, including the Gorkha, Muzaffarabad, and synthetic earthquake motions.
- To identify the most vulnerable building configuration and provide recommendations for improving earthquake-resistant design of structures subjected to LPGMs in the Himalayan tectonic region.

2. Review of Literature

In recent years, the understanding of LPGMs, seismic hazard characterization and seismic behavior in the active region of the Himalayas have gained considerable improvements. To assess the performance of various Ground Motion Prediction Equations (GMPEs), Yang et al. (2026) [18] compared them using the residual-based and information theory-based ranking methods and showed that the information theory-based method gave more stable and accurate model ranking for recent and historical earthquakes in the Himalayas. Likewise, Bind et al. (2026) [19] created a framework for probabilistic seismic hazard assessment (PSHA) for estimation of the peak ground acceleration (PGA) for the engineering bedrock surface in the Himalayan region by combining multiple tectonic source models, eighteen

GMPEs, and site response analyses. In their study, they emphasized the need to consider site amplification and epistemic uncertainty in the regional seismic hazard estimation. Zonara et al. (2026) [20] have also shown that when nonlinear soil–foundation interaction is included in seismic response analyses, the effects of sequential earthquake loadings on deformation and internal force demands are significant for long span structures, suggesting that these may be underestimated by the conventional fixed-base approach. Jayasri et al. (2026) [21] combined machine learning algorithms with several seismic intensity parameters and found that the use of combined velocity and energy-based parameters enhance the susceptibility to landsliding caused by earthquakes. Furthermore, Malakur et al., 2025 [22] assessed the impact of climatic and hydrological changes on seismicity in the Himalaya and found only a few statistics relationships between climate and seismicity in the region, with the strongest being for terrestrial water storage. All these studies highlight the need for proper description of ground motion, site effects and regional tectonic characteristics for reliable seismic hazard assessment in the Himalayan region. Table 1 presents the methodologies, key findings, and research gaps reported in recent studies on long-period ground motion and the seismic performance of regular and irregular buildings.

Table 1. Comparative Review of Recent Studies on LPGMs and Seismic Response of Buildings

Reference	Method/Study	Major Findings	Limitation
Yang et al. (2026)	Evaluation of GMPEs using residual and information theory approaches	Information theory-based evaluation provided stable GMPE rankings for Himalayan earthquakes.	Structural response under LPGMs was not investigated.
Bind et al. (2026)	PSHA with multiple GMPEs and site response analysis	Developed hazard maps considering site amplification in the Himalayan region.	Building performance under LPGMs was not evaluated.
Fujii et al. (2022)	Nonlinear time-history analysis of irregular base-isolated buildings	Long-period pulse-like motions significantly influenced structural response depending on seismic incidence angle.	Limited to base-isolated buildings only.
Poudel et al. (2025)	Seismic assessment of regular and irregular hill buildings	Building configuration and soil interaction significantly affected seismic response.	Long-period earthquake records were not considered.
Kushwaha et al. (2026)	Incremental Dynamic Analysis of RC hill buildings	Taller hill buildings exhibited higher collapse probability.	Regular and irregular buildings under LPGMs were not compared.
Bohara et al. (2025)	Seismic analysis of L-shaped RC buildings	Proper shear wall placement improved seismic performance.	Influence of LPGMs was not studied.
Blasi et al. (2025)	Incremental dynamic analysis of irregular buildings	Structural irregularities increased inter-storey drift and floor acceleration.	Himalayan LPGMs were not considered.

The performance of structures under seismic excitation with various structures has been a focus of a significant amount of research. Fujii et al. (2022) [23] examined the effect of the seismic incident angle on irregular base-isolated structures under long-period pulse-like ground motions, and found that base-isolated structures responded best when considering the cumulative energy of the principal axes, as opposed to the traditional method. Poudel et al. (2025) [24] made a comparative study between regular and irregular buildings constructed on sloping site, taking into account soil–structure interaction, and concluded that the displacement, base shear, inter-storey drift and torsional behaviour are greatly influenced by the structural configuration. Khadka et al. (2023) [25] surveyed traditional Himalayan masonry houses after the earthquake in 2015 and showed that a better detailing of construction materials can greatly improve seismic resistance. Poreddy et al. (2022) [26] investigated the correlation between ground motion parameters and seismic damage in low, mid and high-rise buildings and found that ground motion parameters related to displacement show a strong correlation with structural response, whereas some ground motion parameters, which are traditional, show relatively weak correlation with damage. Kushwaha et al. 2026 [27] conducted incremental dynamic analysis on RC hill buildings and noted that higher collapse probabilities in the tall buildings are observed in the slope direction. Additionally, Bohara et al. (2025) [28] concluded that, in irregular L-shaped RC buildings, optimal placement of shear wall significantly enhances shear wall performance in terms of reducing lateral displacements and torsional effects, while Blasi et al. (2025) [29] found that irregularities in mass and stiffness have a significant effect on inter-storey drift and floor acceleration. Overall, the studies have demonstrated that the structural irregularities, soil characteristics, and long-period seismic excitation, all play an important role in defining the seismic response of buildings; however, detailed studies on the effect of LPGMs on structures with both regular and irregular plans and elevations in the Himalayan tectonic zone are still scarce.

3. Research Methodology

3.1.Building Models and Structural Configuration

The effect of LPGMs on structural behavior was evaluated by considering four RC building configurations: one regular and three irregular structural models. The regular building (R10) is a symmetric rectangle plan building with a uniform stiffness and mass distribution throughout its height. Three irregular configurations were chosen to represent typical architectural irregularities in urban buildings such as L10 (L shape), T10 (T shape), and S10 (vertically irregular setback building). Figure 1 shows the three-dimensional views, plan layouts and Elevation views for selected building configurations, emphasizing the geometric variations used for comparative seismic analysis.

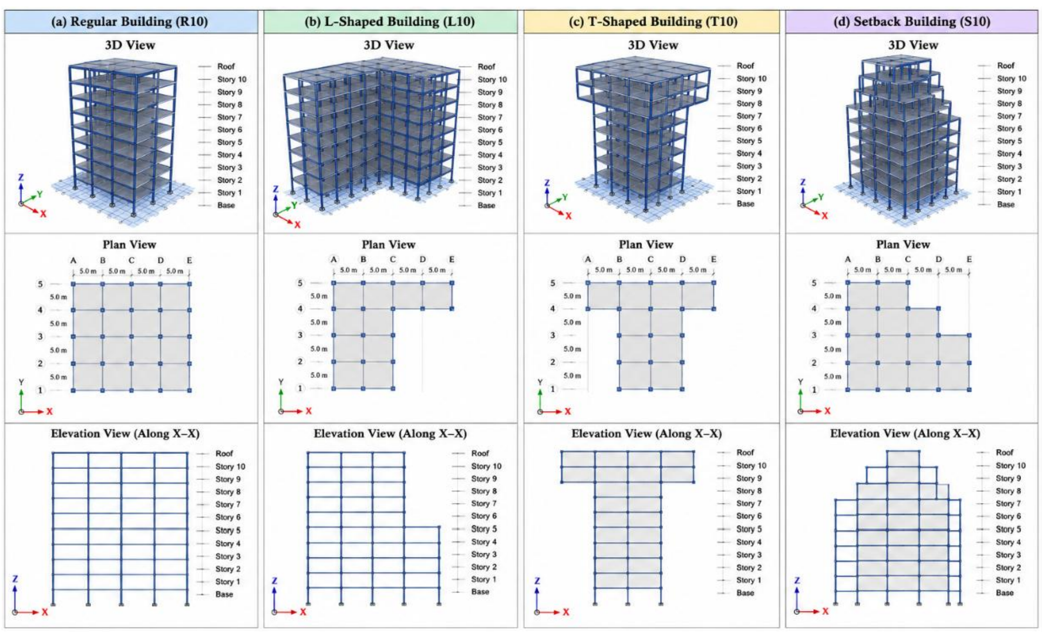

Figure 1. Building Configurations Considered in the Study.

The buildings were designed with special moment resisting frame structure to ten storeys in accordance with IS 456:2000 and seismic provisions as per IS 1893 (Part 1):2023. All analyses were made with the assumption of medium soil (Type II) conditions. All models were constructed with the identical material properties, loading conditions, storey heights, and structural member characteristics for a fair comparison, only the geometric configuration was changed. This allows for a direct comparison of seismic response of regular and irregular buildings when excited by LPGMs. For the purpose of seismic evaluation, all regular and irregular building models were assumed to be located in Dehradun, Uttarakhand, India, representing the Himalayan tectonic region. The selected location was considered to evaluate the structural response under representative long-period ground motions associated with Himalayan seismic activity. The structural characteristics of the regular and the irregular RC building models are summarised in Table 1.

Table 1. Structural characteristics of the building models

Parameter	Regular (R10)	L-Shaped (L10)	T-Shaped (T10)	Setback (S10)
Structural system	RC Moment Resisting Frame	RC Moment Resisting Frame	RC Moment Resisting Frame	RC Moment Resisting Frame
Number of storeys	10	10	10	10
Building configuration	Rectangular	L-shaped	T-shaped	Vertical setback
Plan geometry	Symmetric	Plan irregular	Plan irregular	Vertical irregular
Plan dimensions	30 m × 20 m	Equivalent floor area	Equivalent floor area	Reduced upper floor area
Storey height	3.0 m	3.0 m	3.0 m	3.0 m
Total building height	30 m	30 m	30 m	30 m
Concrete grade	M25	M25	M25	M25
Reinforcement steel	Fe500	Fe500	Fe500	Fe500
Soil type	Medium Soil (Type II)	Medium Soil (Type II)	Medium Soil (Type II)	Medium Soil (Type II)
Seismic code	IS 1893 (Part 1):2023	IS 1893 (Part 1):2023	IS 1893 (Part 1):2023	IS 1893 (Part 1):2023
Design code	IS 456:2000	IS 456:2000	IS 456:2000	IS 456:2000

3.2.Material Properties and Design Parameters

The seismic performance of reinforced concrete (RC) buildings is significantly influenced by the material properties and design parameters adopted during structural modeling. To ensure consistency in the comparative analysis, identical material properties and seismic design parameters were assigned to all building configurations. The structures were designed in accordance with the provisions of IS 456:2000 for reinforced concrete design and IS 1893 (Part 1):2023 for earthquake-resistant design of structures. M25 grade concrete and Fe500 reinforcement steel were adopted because of their widespread use in medium- and high-rise RC buildings. The building models were assumed to be located in Dehradun, Uttarakhand, India, representing the Himalayan tectonic region. The seismic design parameters were selected considering Seismic Zone V, Medium Soil (Type II) conditions, and a 5% damping ratio, in accordance with the provisions of IS 1893 (Part 1):2023.

The elastic modulus of concrete was calculated using the following expression:

$$E_c = 5000\sqrt{f_{ck}}$$

where E_c is the modulus of elasticity of concrete (MPa) and f_{ck} is the characteristic compressive strength of concrete (MPa).

The design base shear adopted in seismic design is expressed as

$$V_b = A_h W$$

where V_b is the design base shear, A_h is the horizontal seismic coefficient, and W is the seismic weight of the structure. These parameters provide a uniform design basis for evaluating the influence of structural irregularities under long-period ground motions. Table 2 summarizes the material properties and seismic design parameters adopted for structural modeling.

Table 2. Material properties and design parameters adopted for structural modeling

Parameter	Value
Structural system	RC Moment Resisting Frame
Concrete grade	M25
Reinforcement steel	Fe500
Number of storeys	10
Storey height	3.0 m
Total building height	30 m
Building Location	Dehradun, Uttarakhand, India
Soil type	Medium Soil (Type II)
Seismic zone	Zone V
Importance factor (I)	1.0
Response reduction factor (R)	5.0
Damping ratio	5%
Design code	IS 456:2000
Seismic code	IS 1893 (Part 1):2023

3.3.Selection of Long-Period Ground Motion Records

LPGMs are defined as ground motions with low frequencies and long shaking time which can have a significant impact on the dynamic response of medium and high-rise structures. These are typically created when large earthquakes occur and can cause resonance when the dominant period of the earthquake is close to the natural period of a structure. As a result, excessive lateral movements, inter-storey movements and damage to the structure can be experienced, especially in irregular structures. A total of three representative LPGM records were selected for the evaluation of seismic behavior of regular and irregular RC buildings in this study. An earthquake with magnitude 2015 Gorkha (Mw 7.8), a long-period synthetic ground motion created through broadband simulation techniques and an earthquake of Muzaffarabad (Mw 7.6) in 2005, are selected. All the records were baseline corrected, filtered and amplitude scaled to the target response spectrum as defined by the IS 1893 (Part 1):2023 for Seismic Zone V at 0.36 g of PGA. These ground motion records were selected to represent the seismic characteristics of Dehradun, Uttarakhand, India, located within the Himalayan tectonic region. The peak ground acceleration is determined as

$$PGA = \max |a(t)|$$

where $a(t)$ represents the ground acceleration at time t.

The spectral acceleration used during record scaling is expressed as

$$S_a(T,\xi) = \omega_n^2 x(T,\xi)$$

where S_a denotes the spectral acceleration, T is the structural natural period, ξ represents the damping ratio, $x(T,\xi)$ is the maximum relative displacement response, and ω_n is the natural circular frequency. The period range for the spectral matching was selected between 1–4s to match the dynamic characteristics of medium- and high-rise RC buildings with the ground motions. The properties of the selected long-period ground motion records for nonlinear time-history analysis are summarized in Table 3.

Table 3. Characteristics of selected long-period ground motion records

Record ID	Earthquake Event	Year	Magnitude (Mw)	Tectonic Region	Ground Motion Type	PGA (g)
LPGM1	Gorkha, Nepal	2015	7.8	Himalayan Thrust Fault	Recorded	0.36
LPGM2	Muzaffarabad, Pakistan	2005	7.6	Himalayan Fold Belt	Recorded	0.36
LPGM3	Synthetic Long-Period Motion	N/A	Equivalent Mw 7.5–8.0	Broadband Simulation	Synthetic	0.36

3.4.Numerical Modeling and Nonlinear Time-History Analysis

3.3.1 Structural Modeling

In this study, a 3D numerical model was created to study the seismic response of regular and irregular RC buildings under LPGMs. ETABS v20 has been used to model four structural configurations: Regular (R10), L-shaped (L10), T-shaped (T10) and Setback (S10) buildings. Beams and columns were defined as frame elements and floor slabs were defined by rigid diaphragm constraints for the proper distribution of the lateral seismic forces through the structural members. The structural models were derived as per IS 456: 2000 and IS 1893 (Part 1): 2023 with M25 Grade Concrete, Fe500 Reinforcement Steel and Medium Soil (Type II). The effects of gravity load on lateral deformation were included by using the P–Delta effects for the geometric nonlinearity. The damping ratio of 5% was used as a constant to represent the energy dissipation of the structure under dynamic excitation. The structural stiffness matrix governing the elastic behavior of the system is represented by

$$[K]\{u\} = \{F\}$$

where $[K]$ is the global stiffness matrix, $\{u\}$ is the nodal displacement vector, and $\{F\}$ is the applied load vector.

3.3.2 Nonlinear Time-History Analysis

The transient dynamic response of the chosen building models was investigated using nonlinear time-history analysis under long-period earthquake excitations. Nonlinear time-history analysis, in contrast to linear static or response spectrum analysis, accounts for the full development of inelastic structural response, as well as the development of displacement, velocity, and acceleration, over the course of the earthquake. The selected long-period ground motion records were applied separately to each building model in order to assess the seismic performance of the models under different earthquake characteristics. The structural system's governing dynamic equilibrium equation is:

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = -[M]\{r\}\ddot{u}_g(t)$$

where $[M]$, $[C]$, and $[K]$ represent the mass, damping, and stiffness matrices, respectively; $\{u(t)\}$, $\{\dot{u}(t)\}$, and $\{\ddot{u}(t)\}$ denote the displacement, velocity, and acceleration vectors; $\ddot{u}_g(t)$ is the ground acceleration; and $\{r\}$is the influence vector.

The natural circular frequency of the structure is determined as

$$\omega_n = \sqrt{\frac{k}{m}}$$

where k represents the structural stiffness and m is the structural mass.

The corresponding fundamental natural period is calculated using

$$T = \frac{2\pi}{\omega_n}$$

where T is the natural period and ω_n is the natural circular frequency. The nonlinear time history analysis results yielded the dynamic response, which was then used to assess the effect of LPGMs on the seismic performance of regular and irregular building layouts.

3.5.Seismic Response Parameters

Develop engineering demand parameters that reflect the structural response to LPGMs. These parameters give important data about lateral deformation, stiffness degradation, distribution of forces and possible damage of the structure. The selected response parameters are widely used in performance-based earthquake engineering for structural safety and serviceability assessments such as Peak Inter-storey Drift Ratio (PIDR), Maximum Roof Displacement, Base Shear, and Plastic Hinge Formation. The results from the nonlinear time history analysis under each earthquake record were compared to study the effect of irregularities in the plan and vertical directions on the structural response.

One of the most significant indicators of structural and non-structural damage is the PIDR which is calculated as:

$$IDR = \frac{\Delta_i - \Delta_{i-1}}{h_i}$$

where Δ_i and Δ_{i-1} are the lateral displacements of the i^{th} and $(i-1)^{th}$ storeys, respectively, and h_i is the storey height.

The Maximum Roof Displacement is a measure of the total lateral displacement of the building and is given by

$$\delta_{max} = \max(\delta_i)$$

where δ_i is the lateral displacement of the roof obtained during the earthquake excitation.

The Base Shear is the sum of all the lateral seismic forces that are transmitted to the foundation and is calculated by

$$V_b = \sum_{i=1}^{n} F_i$$

where V_b is the total base shear, F_i is the lateral force acting at the i^{th} storey, and n is the total number of storeys.

The formation of plastic hinges was assessed using FEMA-356 performance criteria to determine the development and decay of the nonlinear behavior of beams and columns. To evaluate the structural damage mechanism and seismic performance under the LPGMs, the distribution of hinges was used.

3.6.Comparative Performance Assessment

A comparative performance study was performed to measure the impact of structural irregularity on the seismic response of RC structures to long period ground shaking. The L-shaped building (L10), T-shaped building (T10), and setback building (S10) were then compared against the regular building (R10) in order to get a baseline understanding of the responses of these three building designs. Comparisons were made for important engineering demand parameters: inter-storey drift ratio, roof displacement, base shear, and plastic hinge development. The percentage increase in seismic responses was determined as:

$$\% \; Increase = \frac{R_i - R_r}{R_r} \times 100$$

where R_i represents the response of the irregular building and R_r denotes the response of the regular building.

The response reduction between two structural configurations was determined as

$$\Delta R = R_i - R_r$$

where ΔR is the variation in structural response. Comparative analysis helped to identify the most vulnerable building configuration under the given long-period seismic excitation and give an insight into the impact of plan and vertical irregularities on the structural performance in the Himalayan tectonic region. The effectiveness of regular and irregular structural configurations under representative earthquake loading conditions is assessed based on this assessment.

4. Results and Discussion

This section introduces long-period seismic response of regular and irregular RC building configurations for long-period ground motion. The effect of irregularities in the structure on the seismic behaviour is analyzed by applying PIDR, roof displacement, base shear, comparative performance assessment and plastic hinge formation.

4.1 Peak Inter-storey Drift Ratio (PIDR)

The deformation and seismic vulnerability of a structure is one of the most important indicators to be considered and one of them is PIDR. The higher the drift the greater the lateral flexibility and the more prone the structure is to non-structural and structural damage. Table 4 shows the maximum inter-storey drift ratios calculated for the various building configurations for LPGMs. The regular building (R10) showed the smallest average drift ratio, which is 1.08%, suggesting excellent lateral stiffness and stability. The maximum drift ratio observed was 1.78% for the T-shaped building (T10) and 1.63% for the setback (S10) and L-shaped (L10) buildings. The results show that structural irregularities greatly magnify inter-storey deformations, and cause irregular buildings to be more vulnerable to longer period seismic excitations.

Table 4. Peak Inter-storey Drift Ratio (%) for Different Building Types under LPGMs

Building Type	**LPGM1 (Gorkha)**	**LPGM2 (Muzaffarabad)**	**LPGM3 (Synthetic)**	**Average PIDR**
Regular (R10)	1.05	1.12	1.08	1.08
L-Shaped (L10)	1.38	1.44	1.41	1.41
T-Shaped (T10)	1.72	1.85	1.78	1.78
Setback (S10)	1.61	1.68	1.65	1.65

The PIDsr of regular and irregular RC buildings under 3 long-period ground motion (LPGM) records are shown in Figure 2. The drift ratio of Regular building (R10) showed the lowest values ranging from 1.05% to 1.12% with an average value of 1.08%, suggesting excellent lateral stiffness and seismic stability. The T-shaped building (T10) had the highest PIDR ranging from 1.72% to 1.85% with an average of 1.78% which is about 64.8% higher drift when compared with the regular configuration. The average drift ratio for the Setback building (S10) and L-shaped building (L10) was 1.65% and 1.41%, respectively. Moreover, the Muzaffarabad (LPGM2) record always resulted in the highest drift values for all structural configurations indicating that irregular structures are more susceptible to long-period seismic vibrations as they have considerable torsional effects and stiffness discontinuities. These results do confirm earlier studies that showed inter-storey drift under long-period seismic input is significantly increased for plan irregularities.

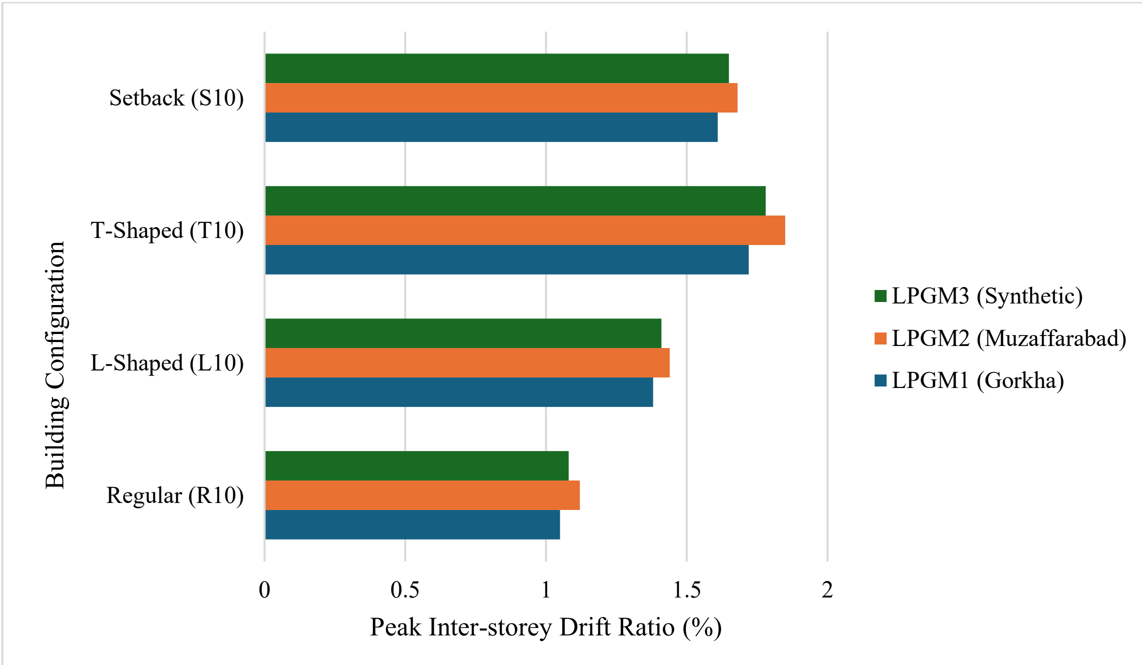

Figure 2. Comparison of PIDR of Regular and Irregular Building Models under LPGMs.

4.2 Maximum Roof Displacement

Maximum roof displacement is an important indicator of the overall lateral flexibility and seismic performance of a structure under earthquake loading. Roof displacement tends to increase as the structural stiffness decreases, and as the deformation demands increase, especially in response to long-period ground motion. Non-uniform stiffness and mass distribution in structures also exacerbates lateral displacement due to structural irregularities. Table 5 shows the maximum roof displacement of the models selected in this study that were subjected to the three long-period ground motion records. The lateral deformations under long period earthquake excitation showed that the regular building (R10) had the lowest average roof displacement of 136.6 mm, while the T-shaped building (T10) had the highest average roof displacement of 210.6 mm followed by the Setback (S10) and L-shaped (L10) buildings, suggesting that the irregularity of the building structure has a significant impact on inducing lateral deformation under long period earthquake excitation.

Table 5. Maximum Roof Displacement (mm) of Different Building Configurations under LPGMs

Building Type	LPGM1	LPGM2	LPGM3	Average Displacement
Regular (R10)	132.5	140.1	137.2	136.6
L-Shaped (L10)	172.8	180.3	176.4	176.5
T-Shaped (T10)	205.4	214.7	211.6	210.6
Setback (S10)	198.9	207.2	202.5	202.9

Figure 3 compares the maximum roof displacement of the regular and irregular RC building model under three ground motion records for long period. The Regular building (R10) had the least roof displacement ranging from 132.5 mm for LPGM1 to 140.1 mm for LPGM2 and an average displacement of 136.6 mm, which shows that this building has higher lateral stiffness. The roof of the T-shaped building (T10) had the highest displacement, which was from 205.4 mm to 214.7 mm and the average displacement was 210.6 mm or about 54.2% higher than the regular building. The average roof displacement of Setback (S10) and L-shaped (L10) buildings were 202.9 mm and 176.5 mm, respectively. The roof displacement results are found that LPGM2 Muzaffarabad gives the highest roof deformation for all the structural set ups as the long period of seismic excitation tends to increase the lateral deformation of geometrically irregular structures because of the lack of stiffness continuity and greater torsional effects. The measured roof displacement agrees with the previous investigations and emphasizes the effect of the structural irregularity on the lateral flexibility in a strong earthquake load.

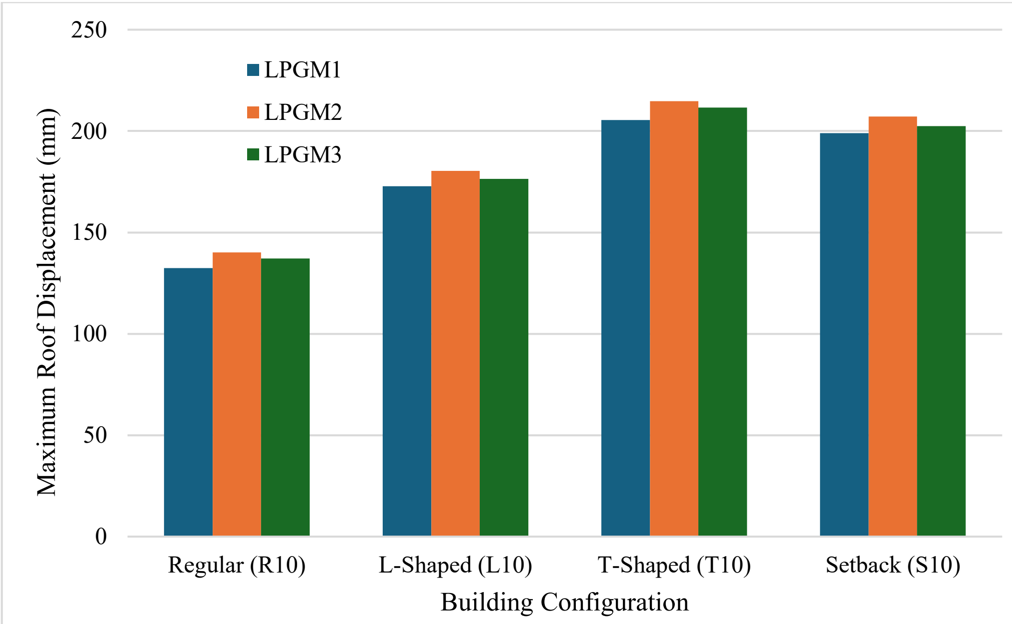

Figure 3. Comparison of Maximum Roof Displacement of Regular and Irregular Building Configurations under Long-Period Ground Motion Records.

4.3 Base Shear

Base shear is the lateral seismic force that is applied to the foundation from the superstructure during earthquake loading, and it is an important measure for the seismic force demand. The irregular stiffness and mass distribution will lead to higher seismic force demand, which is represented by the higher base shear. Table 6 shows the maximum base shear values obtained for the regular and irregular building models with respect to the applied long-period ground motion records. The highest average base shear obtained was from the T-shaped building T10 with value of 2424 kN, the Setback (S10) with value of 2397 kN, the L-shaped (L10) with value of 2327 kN and the lowest value of 2213 kN was obtained from the Regular building (R10). The results show that the seismic force demand has been significantly increased under the long-period earthquake excitation, when the structural irregularities are taken into consideration.

Table 6. Maximum Base Shear (kN) of Different Building Configurations under LPGMs

Building Type	LPGM1	LPGM2	LPGM3	Average Base Shear
Regular (R10)	2185	2238	2216	2213
L-Shaped (L10)	2296	2354	2331	2327
T-Shaped (T10)	2398	2450	2424	2424
Setback (S10)	2365	2428	2398	2397

Figure 4 shows the comparison of the maximum base shear for the regular and irregular RC building models to the selected long-period ground motion records. The Regular building (R10) had the lowest average base shear of around 2213 kN, with this being a more even distribution of seismic forces. The T-shaped building (T10) had the maximum average base shear value of approximately 2424 kN, the Setback building (S10) had the second maximum value of 2397 kN and the L-shaped building (L10) had the third maximum value of 2327 kN. The additional base shear is thought to be caused mostly by the torsional effects and by the stiffness discontinuities, which are amplified effect during the seismic excitation in irregular buildings. Also, LPGM2 (Muzaffarabad) had the highest base shear for all the structural configurations, showing a relatively higher seismic intensity compared to the other ground motion records selected. The same has been observed also in earlier studies, with irregular structures having higher base shear due to torsional response and stiffness discontinuity.

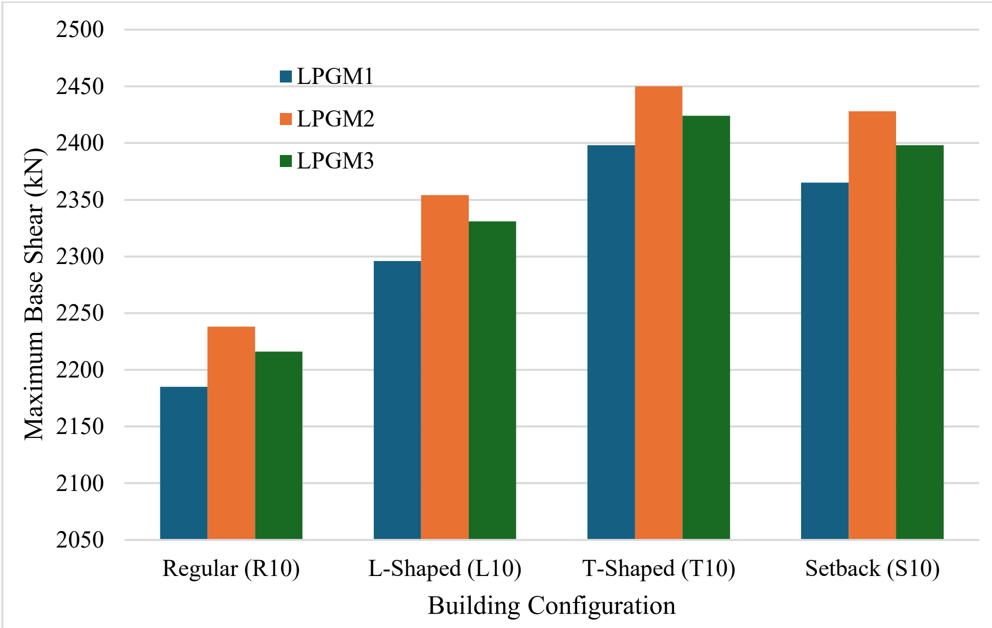

Figure 4. Comparison of Maximum Base Shear of Regular and Irregular Building Configurations under Long-Period Ground Motion Records.

4.4 Comparative Performance Assessment

The comparative evaluation of seismic response parameters gives in-depth knowledge on the effect of structural irregularities on building response in the context of LPGMs. The inter-storey drift ratio, the roof displacement and the base shear together reflect the deformation capacity, and the lateral flexibility and the seismic force demand of a structure. Table 7 indicates that the Regular building (R10) has the lowest average PIDR (1.08%), roof displacement (136.6 mm) and base shear (2213 kN), thus having the best overall seismic performance. The T-shaped building (T10) had the highest response values (1.78%, 210.6 mm and 2424 kN), which showed that it was most vulnerable to seismic effects, and the L-shaped (L10) and Setback (S10) buildings exhibited intermediate results.

Table 7. Comparative Seismic Performance of Regular and Irregular Building Configurations

Building Configuration	**Average PIDR (%)**	**Average Roof Displacement (mm)**	**Average Base Shear (kN)**	**Overall Performance Rank**
Regular (R10)	1.08	136.6	2213	1
L-Shaped (L10)	1.41	176.5	2327	2
Setback (S10)	1.65	202.9	2397	3
T-Shaped (T10)	1.78	210.6	2424	4
Note: Rank 1 represents the best seismic performance, whereas Rank 4 indicates the highest seismic vulnerability				

among the selected building configurations.				

The overall comparative seismic performance of the regular and irregular RC building configurations under the following LPGMs is shown in Figure 5 in terms of normalized response parameters. The comparison has been made by including the PIDR, Maximum Roof Displacement and Base Shear to assess the seismic vulnerability of each building configuration relative to each other. The Regular building (R10) had the highest overall performance with lowest average PIDR (1.08%), lowest roof displacement (136.6 mm), and lowest base shear (2213 kN) so it shows that there is stable structural performance. The normalized response of the T-shaped building (T10) showed the highest value with an average PIDR of 1.78%, roof displacement of 210.6 mm and base shear of 2424 kN, indicating its higher seismic vulnerability. The performance of the L-shaped (L10) and Setback (S10) buildings was intermediate. In general, the irregular plan and vertical configurations show a large deformation demand and seismic force transfer under long-period earthquake excitation, as clearly shown in the radar plot.

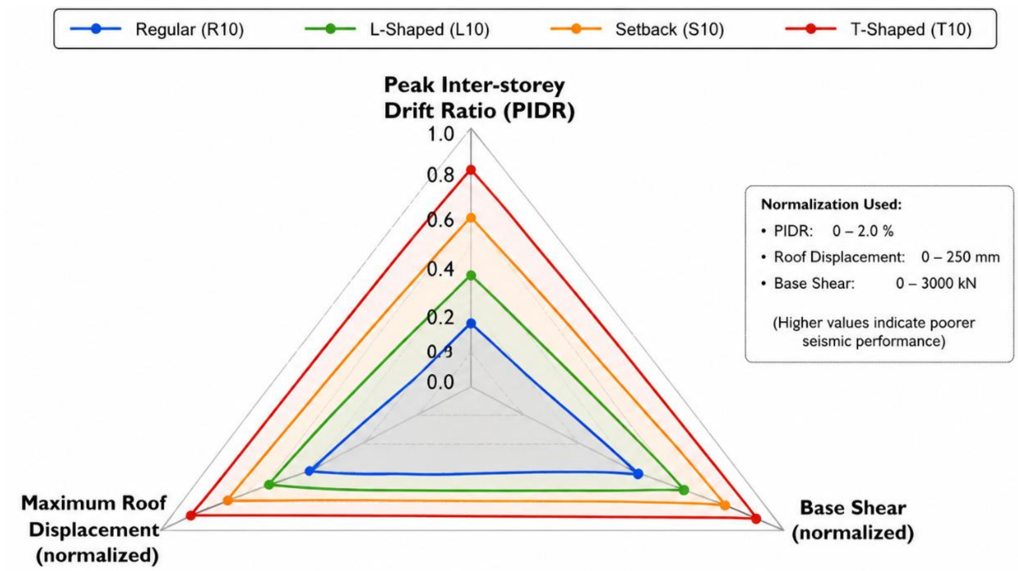

Figure 5. Overall Comparative Seismic Performance of Regular and Irregular Building Configurations.

4.5 Structural Damage Assessment Based on Plastic Hinge Formation

The formation of plastic hinges is one of the important signs of damage and inelasticity in structures under strong earthquake excitations. The distribution and concentration of plastic hinges can give an insight into the failure mechanism, ductility demand and overall seismic performance of a RC building. The Regular building (R10) was found to develop the least number of plastic hinges (16 of beam and 4 of column) as shown in Table 8 which shows a higher structural stability. The T-shaped building (T10) had the most plastic hinges (29 beam plastic hinges and 11 column plastic hinges), mostly at the re-entrant corners and around the central core. The Setback (S10) and L-shaped (L10) buildings exhibited intermediate hinge formation, and structural irregularities also had a significant effect on inducing localized damage and increasing seismic vulnerability under long-period ground motion.

Table 8. Plastic Hinge Distribution in Different Building Configurations

Building	Beam Hinges	Column Hinges	Critical Region	Damage Level
R10	16	4	Base Storey	Moderate
L10	22	7	Re-entrant Corner	High

T10	29	11	Core and Corners	Very High
S10	26	9	Setback Level	High
Note: Damage levels are classified based on the relative concentration of plastic hinges observed during nonlinear time-history analysis.				

The distribution of plastic hinges generated in the regular and irregular RC building structures under long-period ground motion excitation is shown in figure 6. The formation of plastic hinge is indicative of the onset of inelastic behavior and is a significant measure of structural damage and energy dissipation during large earthquakes. The R10 (Regular) building had the least plastic hinges, 16 beam hinges and 4 column hinges, which had the lowest plastic hinges. The Setback (S10) developed 26 beam hinges and 9 column hinges, compared to 22 beam and 7 column hinges in the L-shaped (L10) and 29 beam and 11 column hinges in the T-shaped (T10) building. Irregular buildings have more plastic hinges, which show that the stress is localized, the demand for inelastic deformation is larger, and the seismic vulnerability is higher in long-period earthquake excitation. The high number of plastic hinges observed in irregular buildings substantiates the theory that plan and vertical irregularities contribute to greater damage to the structure during long period ground motion.

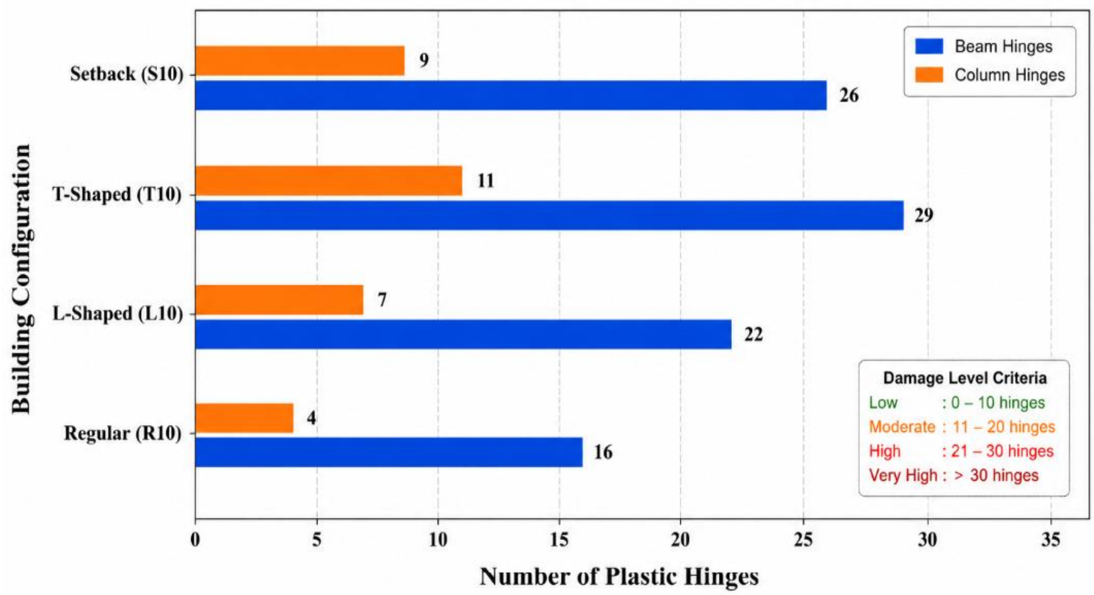

Figure 6. Plastic Hinge Distribution in Regular and Irregular Building Configurations.

5. Conclusion and Future Scope

The effect of the application of LPGMs on the seismic response of regular and irregular configurations of RC buildings has been explored in the Himalayan tectonic zone by employing nonlinear time-history analysis. The four different models of ten-storey buildings considered, R10, L10, T10 and S10, were tested with three typical long-period earthquake records. The results shown from this study clearly indicate that the seismic demand on the obtained structures is significantly higher than those of regular structures. The regular building performed best in terms of seismic performance having the lowest average PIDR (1.08%), roof displacement (136.6 mm), and base shear (2213 kN). The T-shaped building, in contrast, had the largest average PIDs (1.78%), roof displacement (210.6 mm), and base shear (2424 kN), with the highest number of plastic hinges (29 beam and 11 column) suggesting greater seismic vulnerability. Setback buildings and buildings that are L-shaped also exhibited high deformations and high force demands, due to discontinuities in stiffness and torsional effects. Overall, the results validate that LPGMs are more damaging to irregular buildings and should be taken into account during their seismic design and performance evaluation in Himalayan tectonic regions.

Further studies could be conducted on higher structures, soil–structure interaction and base-isolated structures with LPGMs. The use of machine learning techniques and probabilistic seismic evaluation can further enhance the prediction of structural performance and aid the design of more resilient earthquake resistant strategies.

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