

Seismic Fragility Assessment of Reinforced Concrete Buildings in Delhi Using IS 1893:2016 and Monte Carlo Simulation

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Abstract

Rapid urbanization and inconsistent enforcement of seismic design provisions have increased the vulnerability of reinforced concrete (RC) buildings in Delhi, a Seismic Zone IV region under IS 1893:2016. This study presents a probabilistic seismic fragility assessment of RC frame buildings using a Monte Carlo simulation framework based on IS 1893:2016 provisions. Structural response was evaluated using the IS 1893:2016 design response spectrum, and damage probabilities for slight, moderate, and collapse damage states were estimated using lognormal fragility functions. The results indicated a progressive increase in damage probability with increasing spectral acceleration. Estimated peak ground acceleration values ranged from approximately 0.002 g to 0.025 g across simulated earthquake scenarios. Slight damage probabilities were consistently high across the simulated scenarios, while moderate damage probabilities ranged from approximately 0.02 to 0.95 depending on seismic intensity levels. Collapse probabilities remained relatively low under moderate seismic demand and increased under elevated spectral acceleration levels, indicating greater structural vulnerability under severe ground-motion conditions. The proposed framework demonstrates the applicability of probabilistic seismic fragility assessment for evaluating seismic risk in Indian urban regions and supports earthquake risk mitigation and resilience planning.

Categories: Structural Analysis and Finite Element Analysis, Structural Engineering, Data Science and Analytics for Engineering

Keywords: seismic fragility, reinforced concrete building, monte carlo simulation, probabilistic seismic assessment, earthquake risk, is 1893:2016

Introduction

India lies in one of the most seismically active regions of the world due to the ongoing collision between the Indian and Eurasian tectonic plates [1,2]. Northern India has experienced several damaging earthquakes in the past and continues to face considerable seismic hazard. According to IS 1893:2016 [3], Delhi is classified under Seismic Zone IV, indicating a high level of expected ground shaking. Historical events, such as the 1803 Mathura earthquake and the 1960 Delhi-Haryana earthquake, demonstrate the region's vulnerability to moderate and strong seismic events [4].

In addition to seismic hazard, the built environment's vulnerability significantly contributes to overall seismic risk. Rapid and often unplanned urbanization has resulted in a large inventory of reinforced concrete (RC) buildings that lack adequate seismic detailing [5]. Many structures were constructed before the strict implementation of modern seismic codes, making them particularly susceptible to earthquake-induced damage. Deterministic seismic assessment approaches are often insufficient to capture the inherent uncertainties associated with earthquake occurrence, ground motion variability, and structural response [6].

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Probabilistic methods based on fragility analysis and Monte Carlo simulation have therefore gained prominence in seismic risk assessment. Such approaches enable the explicit consideration of uncertainty and variability, providing a more realistic estimation of seismic performance. This study adopts a probabilistic framework to evaluate the seismic fragility of RC buildings in Delhi using IS 1893:2016-compliant modeling.

Seismic hazard and vulnerability of Indian buildings

The Indian subcontinent is characterized by complex tectonic settings, with active fault systems concentrated along the Himalayan belt and several intraplate regions. Numerous studies have highlighted the high seismic potential of northern India and the associated risk to densely populated urban centers such as Delhi. Alluvial soil conditions prevalent in the region further amplify seismic demand, increasing the likelihood of structural damage. Previous investigations have emphasized that a significant proportion of Indian urban buildings are non-engineered or inadequately detailed, resulting in high seismic vulnerability.

Several previous studies have investigated seismic vulnerability in Indian urban regions using probabilistic and analytical approaches. Ramkrishnan et al. developed seismic hazard models for northern India and highlighted the influence of regional tectonic characteristics on earthquake demand estimation [7]. Similarly, Jena et al. employed data-driven and machine-learning approaches for seismic risk prediction and demonstrated improved regional hazard characterization [8]. However, many existing studies primarily focused on hazard assessment or vulnerability mapping rather than detailed probabilistic fragility assessment of RC structures under IS 1893:2016 provisions. This limitation indicates the need for integrated frameworks capable of combining hazard uncertainty and structural response variability.

Recent data-driven and machine-learning-based studies have also explored probabilistic earthquake occurrence and vulnerability assessment across the Indian subcontinent, providing complementary insights into regional seismic risk patterns.

Fragility-based seismic risk assessment

Fragility curves provide a probabilistic relationship between seismic intensity measures and structural damage states [9,10]. They are widely used in regional seismic risk assessment and loss estimation because they explicitly account for uncertainty in structural response [11]. In the Indian context, fragility models developed for RC buildings have been applied in several studies to estimate damage probabilities. However, many existing assessments are limited in scale or scenario coverage, restricting their ability to capture the full variability of seismic demand and building response.

Previous researchers have widely applied fragility analysis to estimate seismic damage probabilities for RC buildings. Several studies demonstrated that fragility functions effectively capture uncertainty associated with material properties, structural configurations, and earthquake intensity measures. However, considerable variation exists in assumptions regarding structural modeling and uncertainty representation. In particular, studies focused on Indian RC building inventories remain relatively limited, thereby creating a need for additional investigations under region-specific seismic conditions.

Monte Carlo simulation in earthquake engineering

Monte Carlo simulation is a stochastic technique used to model systems influenced by multiple sources of uncertainty [12,13]. In earthquake engineering, it has been extensively applied to simulate variability in earthquake characteristics, ground motion intensity, and structural properties. By generating a large number of plausible earthquake scenarios, Monte Carlo simulation enables a robust probabilistic assessment of seismic risk. When combined with code-based design spectra and fragility functions, this approach provides a comprehensive framework for evaluating seismic performance.

Despite these advances, most existing seismic fragility studies for Indian urban regions are limited by small scenario sets, simplified hazard representations, or partial alignment with Indian seismic design provisions. In particular, large-scale probabilistic fragility assessments explicitly conforming to IS 1893:2016 for RC buildings in Delhi remain scarce. This

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limitation motivates the present study, which integrates Monte Carlo simulation with code-compliant structural response modeling to generate physically consistent fragility estimates for RC buildings in a high-seismic-risk urban environment.

Although substantial research has been conducted on seismic hazard analysis and structural vulnerability assessment, relatively fewer studies have integrated Monte Carlo simulation with IS 1893:2016-compliant modeling for probabilistic fragility assessment of RC buildings in Delhi. Existing studies often focus on deterministic approaches that inadequately represent uncertainty in seismic demand and structural response. Therefore, this study aims to bridge this research gap by integrating probabilistic simulation methods with structural fragility analysis to improve seismic risk estimation.

Materials And Methods

Seismic hazard characterization

The seismic hazard for the study region was characterized in accordance with the provisions of IS 1893 (Part 1):2016. Delhi lies in Seismic Zone IV, indicating a high level of seismic risk. Region-specific seismic parameters, including earthquake magnitude, rupture distance, and site conditions, were considered to represent realistic seismic scenarios relevant to the study area. These parameters were selected within ranges consistent with historical seismicity and regional tectonic settings to ensure representative hazard modeling.

Building typology and structural parameters

The study focuses on typical low- to mid-rise RC frame buildings commonly found in Delhi. Key structural parameters, such as building height, fundamental natural period, and material properties, were defined in accordance with prevailing construction practices and codal recommendations. The selected parameter ranges ensure adequate representation of variability in the existing building stock.

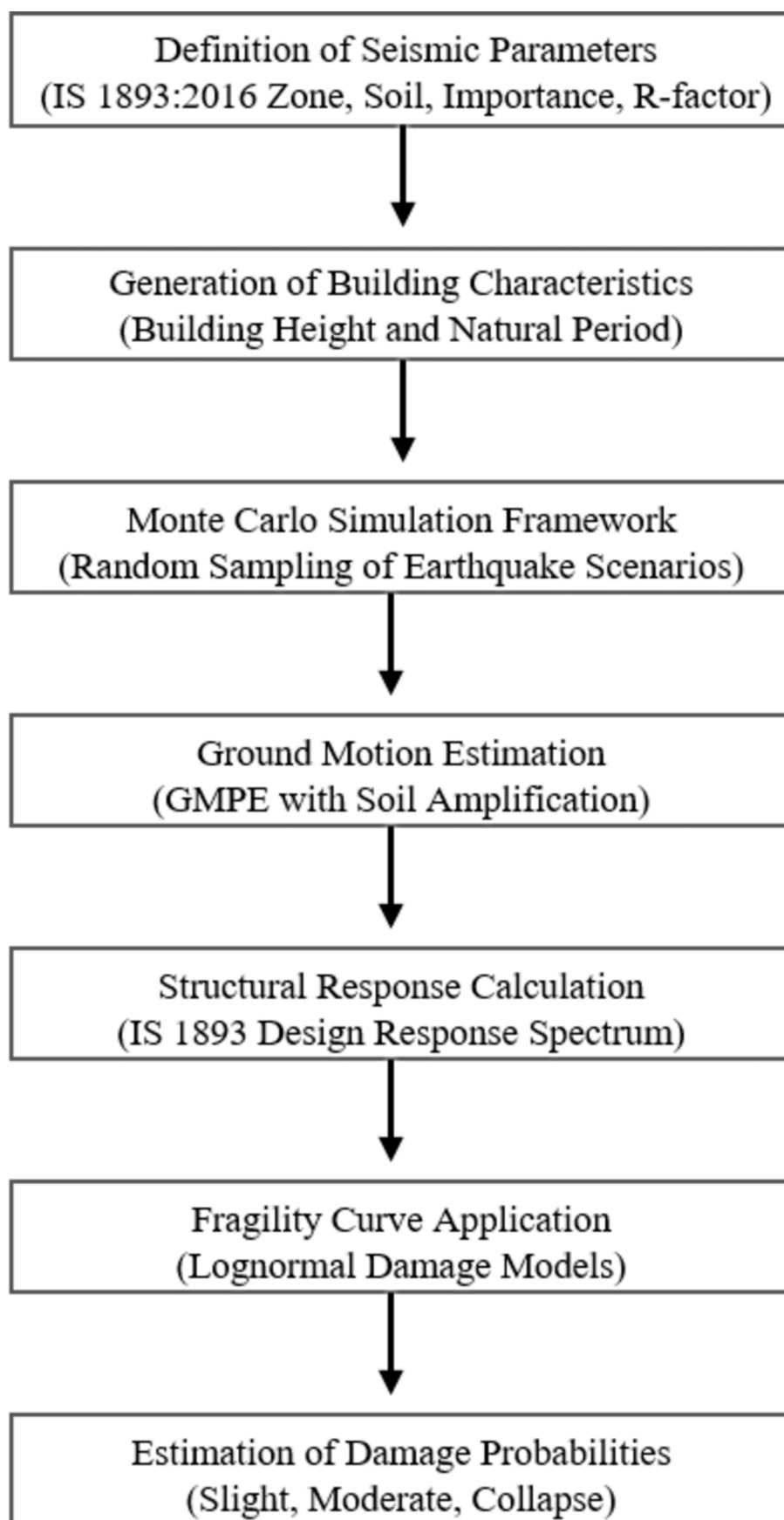
Monte Carlo simulation framework

A Monte Carlo simulation framework was adopted to account for uncertainties associated with seismic input parameters and structural characteristics. Random sampling of earthquake magnitude, rupture distance, and building properties was performed to generate a large number of earthquake-structure interaction scenarios. This probabilistic approach enables a comprehensive assessment of seismic demand variability and its impact on structural response.

The overall workflow of the adopted Monte Carlo-based seismic fragility assessment framework is illustrated in Figure 1.

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FIGURE 1: Overall methodology adopted for probabilistic seismic fragility assessment using Monte Carlo simulation**Seismic demand estimation**

Seismic demand was quantified in terms of Peak Ground Acceleration (PGA) derived using a Ground Motion Prediction Equation (GMPE) framework adapted from regional seismic hazard studies for northern India and incorporating earthquake magnitude, rupture distance, and site amplification effects. The PGA on bedrock was estimated using:

$$\ln(PGA_{rock}) = 1.684 + 0.139M - 1.521\ln(Rrup + 10) + 0.004Rrup$$

where M is the earthquake moment magnitude and $Rrup$ is the rupture distance (km). Soil amplification effects and aleatory variability were incorporated within the Monte Carlo simulation framework. The resulting PGA values were subsequently used to estimate spectral acceleration through the IS 1893:2016 design response spectrum and served as the basis for damage probability estimation.

Fragility curve development

Damage probabilities were evaluated using lognormal seismic fragility functions corresponding to slight, moderate, and collapse damage states. The probability of exceeding a damage state was calculated as:

$$P(DS \geq ds_i | Sa) = \Phi\left(\frac{\ln(Sa) - \ln(\theta_i)}{\beta}\right)$$

where Sa is the spectral acceleration, θ_i is the median spectral acceleration capacity associated with damage state i , β is the logarithmic standard deviation, and Φ denotes the standard normal cumulative distribution function. Median spectral acceleration thresholds (θ) of 0.15 g, 0.30 g, and 0.60 g were adopted for slight, moderate, and collapse damage states, respectively, with corresponding dispersion parameters of 0.30, 0.30, and 0.40, consistent with IITK-GSDMA guideline recommendations.

Study area and seismic context

Delhi, the capital city of India, is located in a seismically active region and is classified as Seismic Zone IV according to IS 1893 (Part 1):2016. The region has experienced moderate seismic activity in the past and remains vulnerable due to high population density and rapid urban development. The seismic characteristics of Delhi, including regional tectonics and proximity to active faults, make it an appropriate case for evaluating the seismic vulnerability of RC buildings.

Building typology considered

The case study focuses on typical low- to mid-rise RC frame buildings commonly found in Delhi. These buildings represent prevalent construction practices and are characterized by variations in height, structural configuration, and material properties. The selected building typology reflects a significant portion of the existing building stock and is therefore suitable for assessing regional seismic fragility.

Parameters and scenario definition

Key seismic and structural parameters considered in the case study include earthquake magnitude, rupture distance, site conditions, building height, and fundamental natural period. The fundamental natural period was estimated using the empirical relationship prescribed in IS 1893 (Part 1):2016:

$$T = 0.075H^{0.75}$$

where T is the natural period (s) and H is the building height (m).

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The adopted parameter ranges were selected to capture realistic variability in seismic demand and structural response representative of the study area. A summary of the seismic input parameters used in the analysis is presented in Table 1, while the associated structural characteristics of the considered building typologies are summarized in Table 2.

Variable	Symbol/Name in Code	Range/Values	Distribution/Method	Source/Standard
Zone Factor	Z	0.24 (Zone IV)	Fixed	IS 1893:2016 Table 3
Soil Amplification Factor	S	1.33 (Medium soil)	Fixed	IS 1893:2016 Table 4
Importance Factor	I	1.0 (Residential)	Fixed	IS 1893:2016 Table 8
Response Reduction Factor	R	3.0 (Ordinary RC frame)	Fixed	IS 1893:2016 Table 7
Moment Magnitude	M	4.0 to 6.5	Uniform Distribution	User-defined (typical for Delhi)
Rupture Distance	R_rup	12 km to ~200 km	Lognormal Distribution (median 50 km, $\sigma=0.5$)	Hazard Model Assumption
Building Height	Building_height	5 m to 30 m	Uniform Distribution	Represents typical Delhi buildings
Natural Period	structure_T	0.26 s to 0.96 s	Derived from height: $T = 0.075H^{0.75}$	IS 1893:2016 Clause 7.6.2
Peak Ground Acceleration	PGA_g	Computed using GMPE-based formulation; predominantly low values due to far-field moderate-magnitude scenarios	Computed via GMPE + Soil Factor + Aleatory Variability	Region-specific GMPE Model
Spectral Acceleration	Sa_g	0.13 g to 0.50 g	Computed via IS 1893 Design Spectrum	IS 1893:2016 Design Spectrum
Random Seed	np.random.seed(42)	42	Fixed	To ensure reproducibility

TABLE 1: Seismic, structural, and ground-motion input parameters used in the Monte Carlo simulations

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Variable	Symbol/Name in Code	Range/Values	Distribution/Method	Source/Standard
Slight Damage Probability	Prob_Slight	0.35 to 1.0	Computed via Fragility Curve ($\beta = 0.3$, median = 0.15 g)	IITK-GSDMA Guidelines
Moderate Damage Probability	Prob_Moderate	0.02 to 0.95	Computed via Fragility Curve ($\beta = 0.3$, median = 0.30 g)	IITK-GSDMA Guidelines
Collapse Probability	Prob_Collapse	0.0001 to 0.28	Computed via Fragility Curve ($\beta = 0.4$, median = 0.60 g)	IITK-GSDMA Guidelines
Number of Scenarios	num_scenarios	1,250,000	Fixed	User-defined

TABLE 2: Fragility-function parameters and resulting damage-probability ranges used in the seismic vulnerability assessment

Scenario illustration

To illustrate the variability in the selected seismic and structural parameters, the distributions of earthquake magnitude, rupture distance, and building heights considered in the case study are shown in Figures 2-4. These distributions provide representative coverage of plausible seismic scenarios relevant to the study region and serve as the basis for subsequent probabilistic analysis. For visual clarity, Figures 2-4 present only a representative subset of the generated scenarios, whereas the Monte Carlo analysis was performed using the complete set of 1,250,000 simulated realizations.

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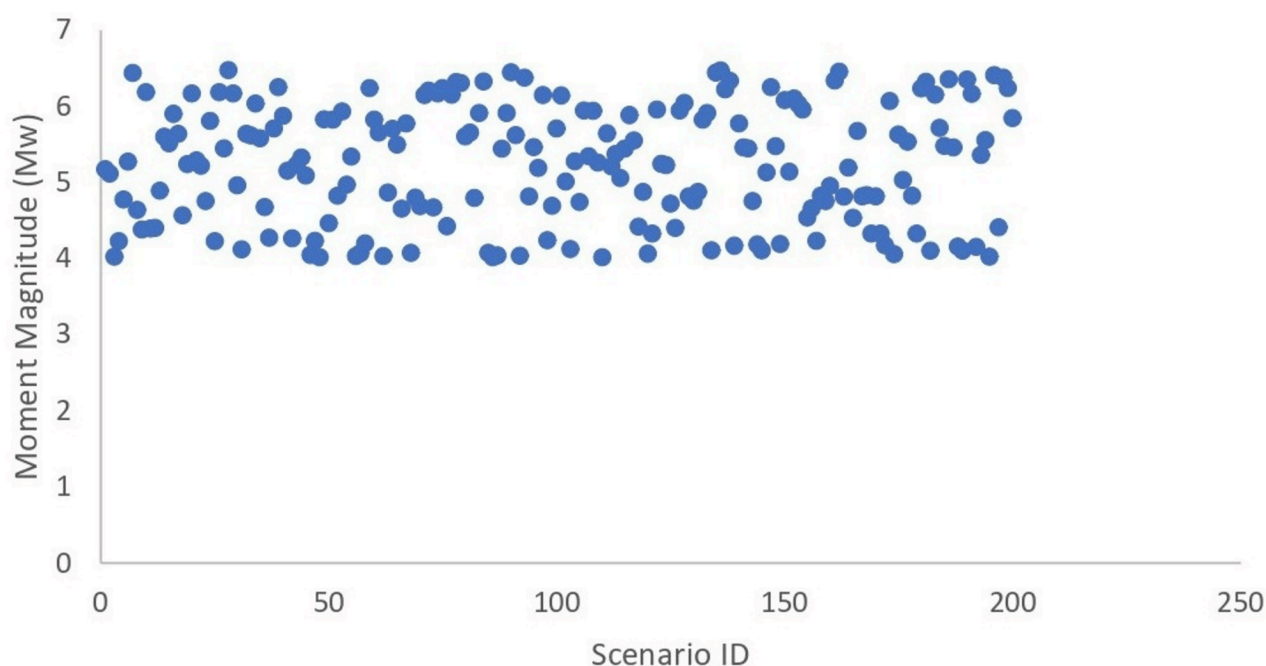


FIGURE 2: Distribution of earthquake moment magnitude across generated seismic scenarios

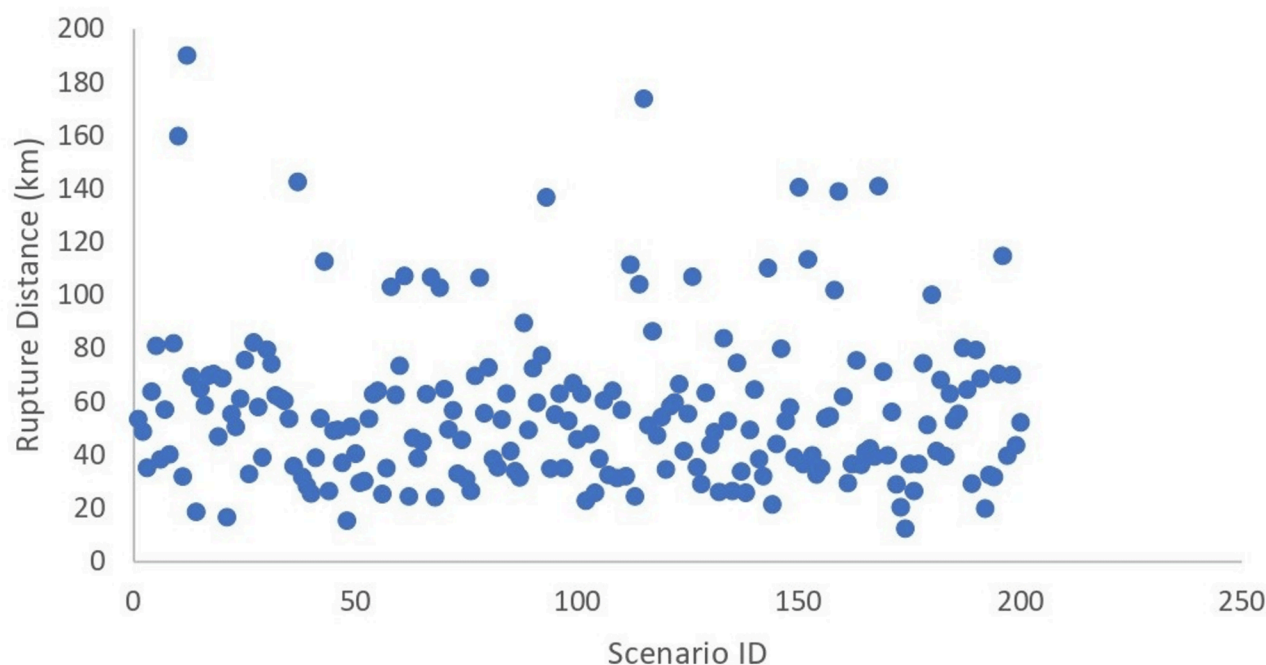


FIGURE 3: Distribution of rupture distance across generated seismic scenarios

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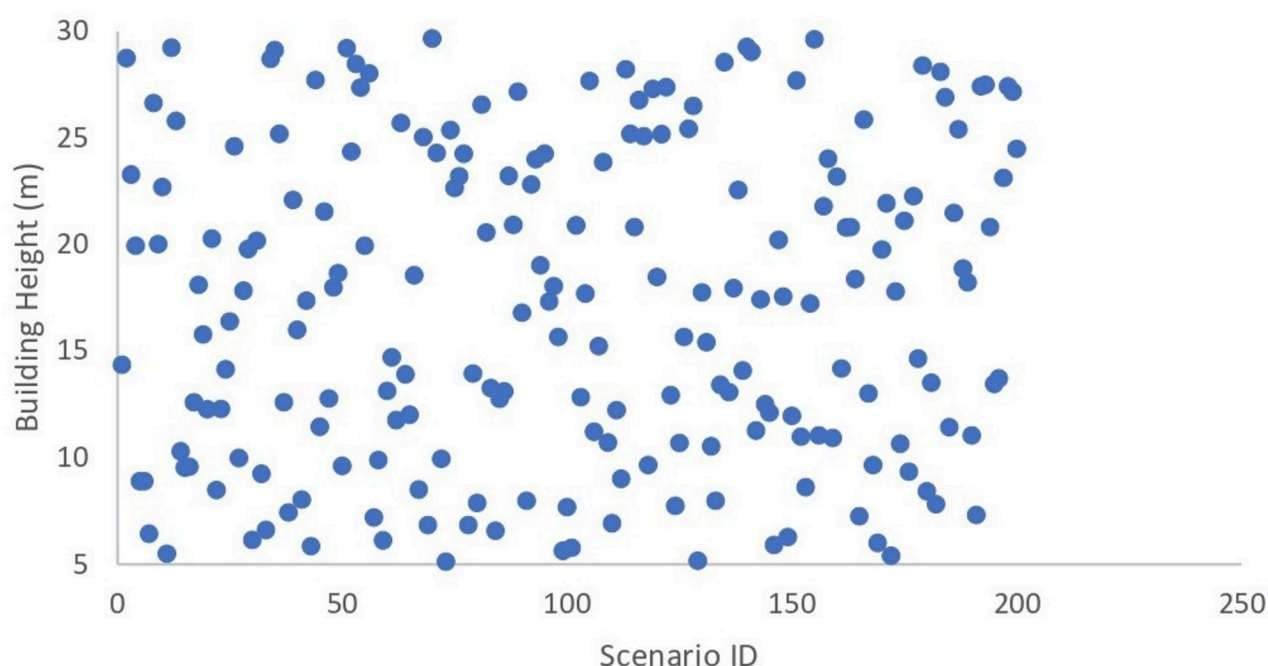


FIGURE 4: Uniform distribution of building heights (5–30 m) across generated building scenarios

Artificial intelligence (AI)-based language assistance tools were used during manuscript preparation for language refinement and paraphrasing purposes. The authors carefully reviewed, edited, and verified all AI-assisted content and take full responsibility for the accuracy, interpretation, and integrity of the manuscript. AI tools were not used for data analysis, result generation, interpretation of findings, or scientific decision-making.

Results And Discussion

The Monte Carlo simulation framework generated a comprehensive set of earthquake-building interaction scenarios representative of Delhi's seismic environment. The distribution of fundamental natural periods across the generated building scenarios reflects realistic variability in structural properties and confirms adequate representation of the considered building typologies (Figure 5).

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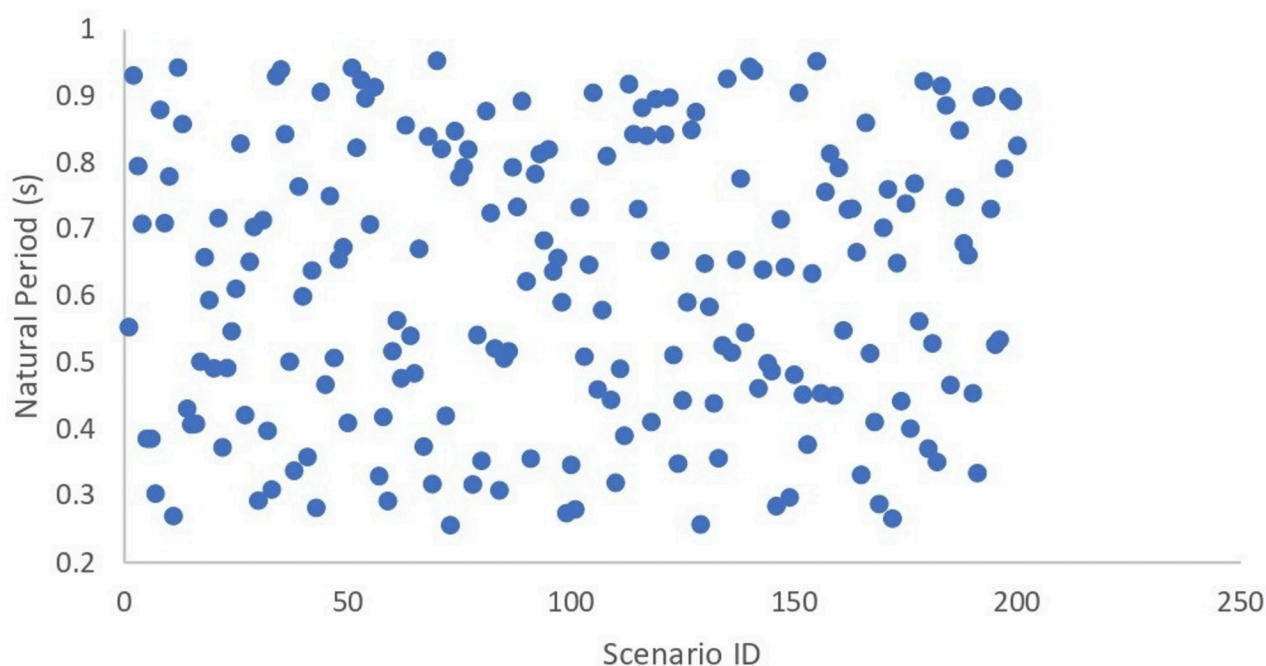


FIGURE 5: Distribution of fundamental natural period across generated building scenarios

Seismic demand was quantified as PGA for each simulated scenario. The estimated PGA values exhibit considerable variability, highlighting the combined influence of earthquake magnitude, rupture distance, and site conditions. This variability underscores the importance of adopting a probabilistic framework to capture uncertainty in seismic demand estimation (Figure 6).

The observed variability in PGA values can be attributed to differences in earthquake magnitude, rupture distance, and source characteristics considered during Monte Carlo simulation. Most simulated scenarios produced relatively lower PGA values because moderate-magnitude events and larger source-to-site distances dominated the generated earthquake catalogue. However, a limited number of high PGA observations were recorded for scenarios associated with shorter rupture distances and stronger seismic sources. These findings demonstrate the importance of uncertainty representation in probabilistic seismic assessment.

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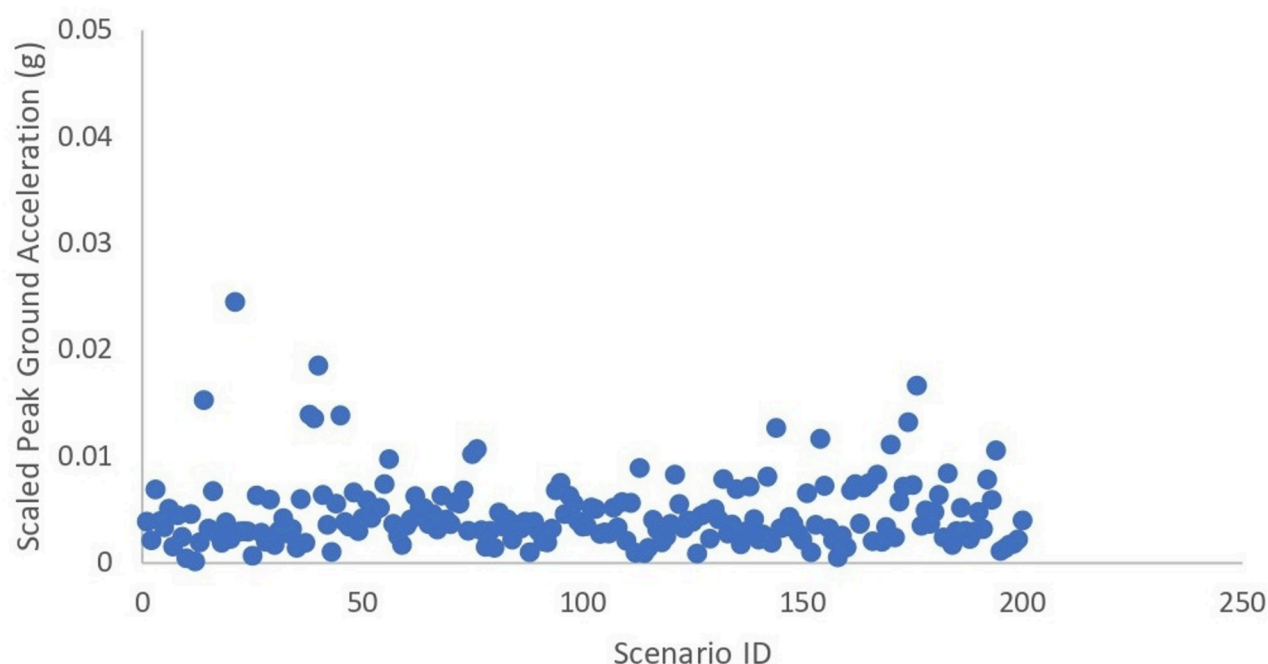


FIGURE 6: Scaled peak ground acceleration (PGA) values derived from GMPE-based estimates

Based on the computed seismic demand, a fragility analysis was conducted to estimate the probability of exceeding different damage states. The probability of slight damage exceeded 90% for several simulated scenarios and remained elevated across a substantial portion of the generated seismic demand range, reflecting the sensitivity of RC buildings to moderate ground motions (Figure 7). Moderate damage probabilities ranged approximately from 0.02 to 0.95 and were primarily associated with scenarios experiencing higher seismic demand levels (Figure 8).

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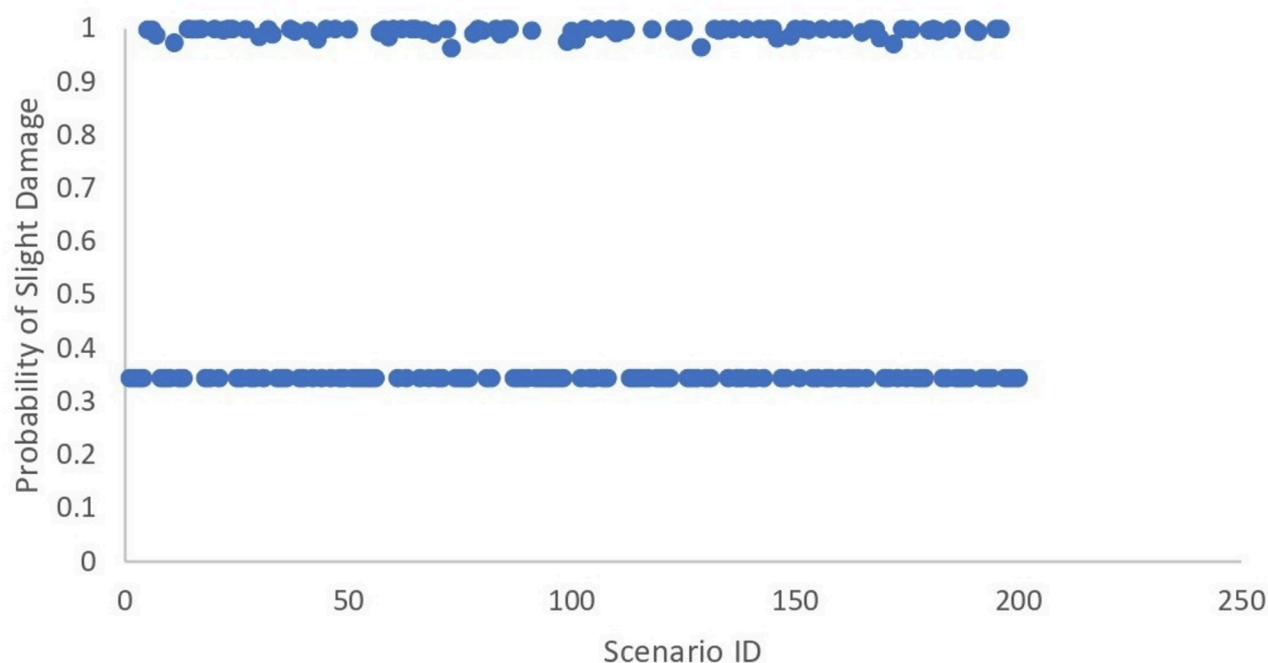


FIGURE 7: Probability of slight damage obtained from fragility analysis across generated seismic scenarios

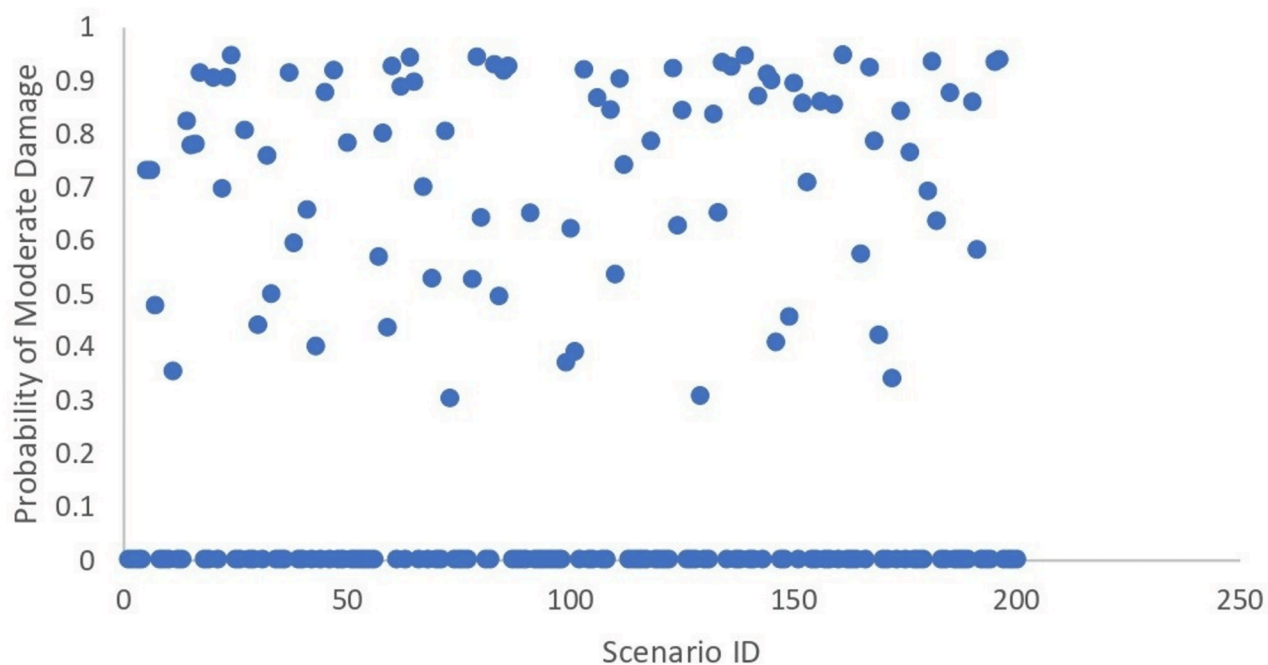


FIGURE 8: Probability of moderate damage obtained from fragility analysis across generated seismic scenarios

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Collapse probabilities remained relatively low for the majority of simulated scenarios and increased under higher levels of seismic demand. The highest collapse probabilities were observed under elevated spectral acceleration levels, indicating increased structural vulnerability under severe ground-motion conditions. This behavior reflects the nonlinear response characteristics of RC buildings subjected to strong ground motions (Figure 9).

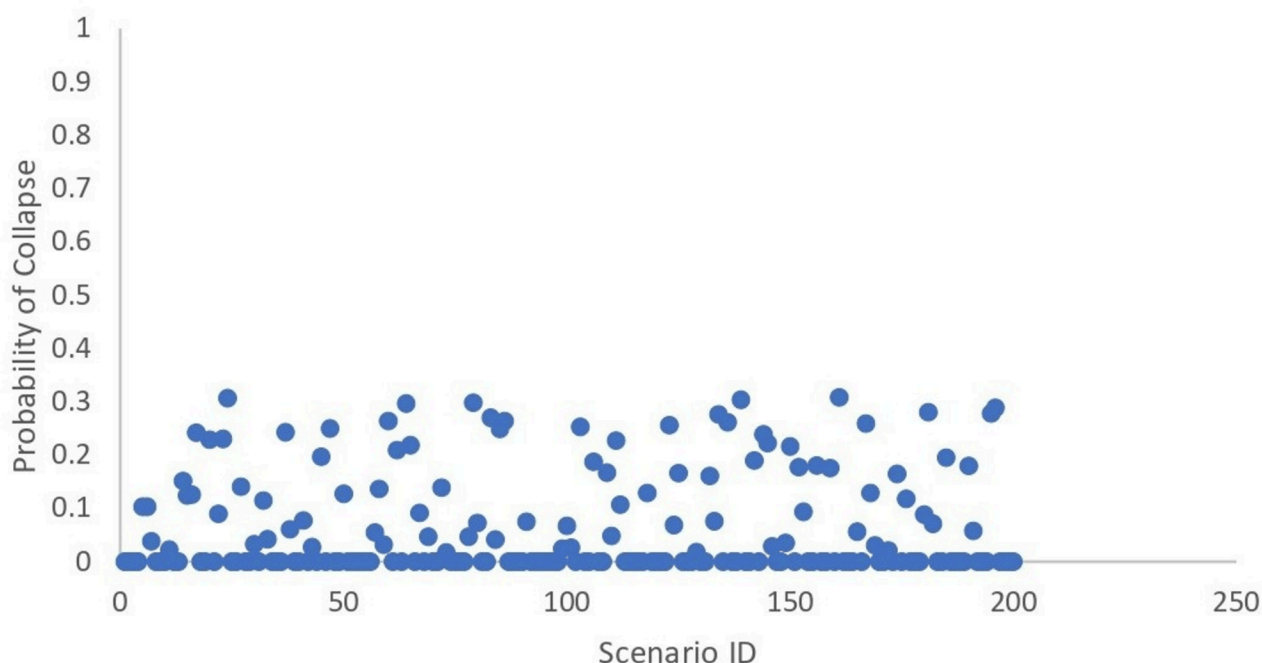


FIGURE 9: Probability of collapse obtained from fragility analysis across generated seismic scenarios

Comparative analysis with existing studies

To place the obtained results in context, the derived fragility trends were compared with those reported in previous studies on RC building fragility. The observed increase in slight and moderate damage probabilities with increasing seismic intensity, together with the gradual increase in collapse probability under stronger ground motions, is consistent with earlier probabilistic and code-based fragility assessments. Minor variations in damage probabilities can be attributed to differences in regional seismic parameters, building typologies, and modeling assumptions. The observed agreement in seismic response trends supports the applicability of the adopted framework for probabilistic seismic fragility assessment.

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Study	Method	Key Findings from the Literature	Present Study Observation	Validation Outcome
Ramkrishnan et al. [7]	Ground motion prediction and seismic hazard modeling	Increased seismic demand associated with regional seismic variability	PGA values varied significantly due to earthquake magnitude and rupture distance	Consistent
Freddi [10]	Probabilistic fragility analysis	Damage probability increases with increasing seismic intensity	Slight and moderate damage probabilities increased with spectral acceleration	Consistent
Rudman et al. [12]	Monte Carlo seismic risk assessment	Structural uncertainty significantly affects risk estimates	Variability in simulated parameters influenced damage prediction	Consistent
Present study	Monte Carlo + IS 1893:2016	Probabilistic seismic assessment incorporating uncertainty in seismic demand and structural response	Increasing damage probability with increasing seismic intensity and uncertainty in seismic demand	Reference case

TABLE 3: Validation of the present study with published literature

The validation results presented in Table 3 indicate good agreement between the present Monte Carlo-based framework and previously published studies. Ramkrishnan et al. [7] reported a significant influence of regional seismic variability on ground-motion estimation, which is reflected in the observed variability of PGA values in the present study. Previous fragility investigations, such as Freddi [10], similarly demonstrated increasing damage probabilities with increasing seismic intensity measures. Furthermore, Rudman et al. [12] highlighted the importance of uncertainty representation in probabilistic seismic assessment using Monte Carlo approaches. The observed agreement in seismic response trends supports the reliability and applicability of the adopted framework for probabilistic seismic fragility assessment.

Conclusions

This study presented a probabilistic seismic fragility assessment of RC buildings in Delhi using a Monte Carlo simulation framework consistent with IS 1893:2016. The results demonstrated that RC buildings in Delhi exhibit increasing probabilities of damage with increasing seismic intensity levels. Slight damage probabilities were consistently high across the simulated scenarios, whereas moderate damage probabilities ranged from approximately 0.02 to 0.95 depending on seismic demand conditions. Collapse probabilities remained relatively low at moderate seismic intensity levels but increased under stronger ground-motion conditions, indicating greater vulnerability during severe earthquake events.

A key contribution of this study is the integration of Monte Carlo simulation with IS 1893:2016-based seismic demand estimation and fragility analysis to explicitly account for uncertainties in earthquake characteristics and structural properties. The proposed framework provides a probabilistic alternative to deterministic seismic assessment approaches

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and enables a more comprehensive evaluation of seismic risk.

The findings highlight the importance of incorporating uncertainty in seismic demand and structural response when evaluating earthquake performance. By accounting for variability in seismic and structural parameters, the adopted probabilistic framework provides a more realistic assessment of damage potential than deterministic approaches. The proposed methodology can be extended to other seismic regions through the incorporation of region-specific seismic parameters and may support seismic risk mitigation, retrofit prioritization, and urban resilience planning in earthquake-prone areas.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Shweta V. Bawaskar

Drafting of the manuscript: Shweta V. Bawaskar

Acquisition, analysis, or interpretation of data: Deepak N. Kakade

Critical review of the manuscript for important intellectual content: Deepak N. Kakade

Supervision: Deepak N. Kakade

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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