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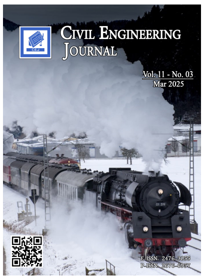

Development and Validation of a Seismic Index for Assessing the Vulnerability of Low-Rise RC Buildings

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Abstract

This research develops a comprehensive framework for evaluating the seismic vulnerability of Afghanistan's low-rise reinforced concrete (RC) structures, aiming to enhance urban resilience and mitigate seismic risks. The primary objective is to improve structural safety and reduce economic losses and casualties during devastating earthquakes. Utilizing a database of low-rise RC buildings constructed between 2001 and 2022 by the Ministry of Urban Development and Housing (MUDH) and the Ministry of Education (MOE), the study analyzes structures with varying materials, architectural styles, construction years, and number of stories. The methodology integrates a modified Japanese Is Index, refined using statistical techniques to incorporate local seismic data and building characteristics across diverse seismic zones. Advanced analyses, including the Capacity Spectrum Method (CSM) and dynamic analysis using STERA 3D software, support the development of the Afghanistan Seismic Index (ASI). Findings confirm ASI's reliability by comparing it to existing seismic assessment methods, demonstrating its suitability for region-specific evaluations. The research proposes a novel, tailored seismic index (ASI) for assessing seismic vulnerability and addressing gaps in Afghanistan's building code (ABC) and standards. This framework enhances structural performance and informs future policy, providing a foundation for safer urban environments and sustainable infrastructure development in earthquake-prone regions.

Keywords: Seismic Index; Mid-Rise RC Buildings; Seismic Zones; Seismic Vulnerability; CSM; Dynamic Analysis.

1. Introduction

Seismic vulnerability is a major concern for RC structures in Afghanistan, where the collision of the Eurasian and Indian plates generates frequent intermediate-depth earthquakes (70–300 km) [1]. Inadequate seismic design and traditional construction methods heighten the probability of structural failure and human fatalities. Historical earthquakes demonstrate this threat: the 1998 Takhar earthquake (M6.1) caused 2,300 mortalities and devastated 8,000 houses [2], the 2015 Hindu Kush earthquake (M7.5) resulted in 115 deaths and 538 injuries [3], and the 2022 Khost earthquake (MW 6.2) led to 1,050 human losses and 3,000 damaged buildings [4]. The Chaman and Paghman fault systems further exacerbate this risk, with the 1505 Kabul earthquake (M7.3) causing widespread destruction, surface rupture, and fault displacement [5]. Recent studies by Shinzai et al. [6] indicate accumulated strain along these faults, signaling the potential for another destructive earthquake. However, limited seismic instrumentation and the lack of a comprehensive ground motion database hinder practical risk assessments, highlighting the urgent need for improved seismic design of buildings, retrofitting, and hazard mitigation strategies [7, 8].

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Afghanistan's vulnerability to seismic hazards is further compounded by reliance on traditional construction practices that rarely adhere to modern seismic design standards [9]. Structural deficiencies such as inadequate reinforcement, poor material quality, and unreinforced masonry significantly increase the likelihood of damage or collapse during earthquakes. Research has revealed multiple failure causes prevalent in Afghan structures. Ismail & Khattak [10] identified diagonal shear cracking and out-of-plane collapse as significant failure modes in masonry without reinforcing structures during the 2015 Hindu Kush seismic event. Furthermore, Sharafi et al. [11] illustrated the impact of brick masonry infill walls (MIW) on improving the seismic capacity of RC structures, observing decreases in damage and story drift ratios when these walls were incorporated correctly. Subsequent research by Sharafi & Saito [12] suggested a factor for calculating the contribution of MIW with central openings in RC structures and emphasized the MIW's effectiveness in the design phase. This highlights a gap in the design of reinforced concrete buildings in Afghanistan, where traditional methods often neglect modern structural principles.

Regional evaluations further underline the widespread vulnerability of existing RC buildings. Raoufy et al. [13, 14] assessed RC hospital buildings in Kabul, finding them all seismically vulnerable due to inadequate detailing and poor construction practices. Similarly, Sharafi & Saito [15] demonstrated that newer RC school buildings designed after 2018 outperformed older RC buildings under seismic loads, showcasing the potential benefits of updated standards. Ismailov et al. [16] assessed seismic risks using ground condition data and microzoning. Their study highlighted amplified seismic risks due to poor soil conditions and proposed targeted strategies to enhance urban resilience. Kumar et al. [17] employed machine learning methods to evaluate the seismic susceptibility of RC educational structures, concentrating on the story shear ratio. Support vector regression outperformed other models, highlighting ML's efficiency for large-scale seismic assessments.

Globally, seismic vulnerability assessments have provided valuable insights into improving building resilience. Foundational studies, such as those by Paulay & Priestley [18], emphasize the importance of ductility and energy dissipation in RC structures to enhance seismic performance. Sezen et al. [19] identified common deficiencies in existing RC buildings, such as inadequate reinforcement detailing and poor construction quality, which contribute to structural failures during earthquakes. Similarly, Lazzali & Farsi [20] emphasized the need for rapid visual screening in historic urban areas to prioritize retrofitting efforts. Advanced methodologies, including vulnerability indices and nonlinear parametric analyses, have been widely employed to evaluate and retrofit structures. For instance, Kassem et al. [21, 22] proposed vulnerability index methodologies to predict structural performance, while Otani [23] reviewed seismic evaluation methods, introducing simple screening techniques alongside detailed evaluations. Maeda et al. [24] updated post-earthquake damage assessment guidelines, incorporating experimental data to enhance accuracy.

Prior studies involved authors and researchers performing numerical analyses to propose a seismic index aimed at enhancing the seismic capacity of RC structures. Fotopoulou et al. [25] evaluated the earthquake vulnerability of educational structures with fragility curves, highlighting the inadequacies of generic curves and promoting the necessity for building-specific evaluations. Yazgan & Nishiyama [26] evaluated the earthquake capacity of constructed RC structures, employing Japanese standards and retrofitting methods, including prestressed precast concrete-filled tube braces. Islam et al. [27, 28] utilized Japanese methodologies to mitigate the seismic susceptibility of low- and medium-rise RC buildings in Dhaka. In a recent study, Islam et al. [29] evaluated a five-story academic building in Bangladesh using the Japanese Index Method, identifying lower stories as vulnerable and proposing retrofitting strategies to enhance seismic resilience. Samuel et al. [30] emphasize that the earthquake susceptibility of RC structures is a significant issue in earthquake-prone locations, especially in locales with inadequate seismic design regulations. These studies underscore the importance of region-specific seismic assessments tailored to local construction practices and seismic hazards. Miceli et al. [31] incorporating confinement effects in seismic design enhances ductility, reliability, and structural overstrength, improving seismic performance and reducing failure probabilities. Panahi Boroujeni et al. [32] explored regional variations in seismic damage to RC structures, demonstrating the importance of localized design parameters in reducing structural failures.

Afghanistan's lack of a comprehensive seismic assessment framework presents unique challenges. While the ABC [33], developed by the Afghan National Standards Authority (ANSA) [34] aims to address local construction practices and seismic risks, but its adoption and enforcement remain limited by design. A recent report by the United Nations Office for Disaster Risk Reduction (UNDRR) [35] many buildings remain unassessed, with no standardized framework to evaluate their post-earthquake performance. Additionally, current building designs in Afghanistan are based on a single generalized seismic zone, overlooking the varying seismic hazards across different regions. This practice can lead to over-designed or under-designed structures and highlights the critical need for tailored design guidelines and response spectra aligned with localized seismic intensities to enhance safety and optimize resource use. This gap in the regulatory framework not only jeopardizes public safety but also hinders the development of effective retrofitting strategies.

This study examines the earthquake performance of low-rise RC structures to meet these concerns. The research employs static analysis, CSM, and dynamic analysis to assess structural vulnerabilities comprehensively. A database of low-rise RC buildings [15, 36] constructed across diverse regions was analyzed using STERA 3D [37], a nonlinear analysis software, incorporating region-specific seismic data and design spectra derived from the ABC Code.

The main aim of this study is to provide the ASI, modified from the Japanese Seismic Index, as an effective instrument for assessing and improving the seismic resilience of reinforced concrete structures. This research article consists of the following sections: Section 1 focuses on a comprehensive RC structure database that includes buildings in all parts of the country. Section 2 concentrates on the static analysis of the selected buildings to determine each RC structure's performance. Section 3 highlights adapting the Japanese standard using parameters related to each specific seismic condition. Section 4 evaluates the dynamic performance of selected RC structures. Section 5 deals with the seismic vulnerability of RC structures. Finally, section 6 emphasizes the analysis results and proposes the ASI for four seismic zones. The Key Contributions of This Research can be outlined as follows:

- Integration of Regional Seismic Data: Incorporates seismic data and the Afghanistan Design Response Spectra (ADRS) for four specific seismic zones, ensuring the results accurately reflect local conditions.
- Development of the ASI: Provides a tailored and practical tool for seismic evaluation and capacity evaluation of low-rise RC structures in four seismic zones.
- Validation of ASI: Demonstrates the reliability of the ASI through comparative analysis with international methodologies such as Japanese Is-index methods.
- Contribution to Global Literature: Offers a region-specific framework adaptable to other developing regions facing similar challenges.
- Recommend incorporating the findings of this research into the ABC to address region-specific seismic challenges and enhance the earthquake resilience of low-rise RC structures.

By addressing critical gaps in Afghanistan's seismic assessment framework, this research lays the foundation for safer construction practices, informed policymaking, and enhanced resilience of the nation's infrastructure to future seismic events. The ASI advances local seismic evaluation methodologies and contributes to the global discourse on seismic vulnerability assessments in developing regions.

2. Research Methodology

2.1. Field Investigation

This study used a research methodology that combines field investigation, data collecting, analytical techniques, and international standards to assess the seismic performance of reinforced concrete structures and formulate the ASI. Two parallel approaches were utilized: the CSM and the Japanese Standard (Is-index) for seismic evaluation. Both approaches aim to comprehensively assess seismic vulnerability and contribute to the development of the ASI. This study analyzed comprehensive low-rise RC buildings constructed across various geographical regions in Afghanistan [15]. These buildings encompass diverse architectural configurations, ranging from single-story to three-story structures. The selection process was carefully designed to ensure representativeness and included criteria such as geographical diversity, architectural styles, construction years, number of stories, and main structural details.

The selected RC structures include those built recently (post-2018, adhering to updated codes and standards) and some other RC buildings built by MOE before 2018. This classification reflects the evolution of building practices and seismic code implementation in the country. Analyzing these buildings provides valuable insights into Afghanistan's diverse structural and seismic characteristics. The collected data serves as the foundation for subsequent analyses using the CSM and the Japanese Standard, contributing to a comprehensive understanding of the seismic vulnerability of low-rise RC structures.

2.2. Capacity Spectrum Method

The initial analytical method entails the utilization of the CSM, which is esteemed for evaluating the seismic resilience of structures. The procedure encompasses the subsequent stages:

- The Afghanistan Design Response Spectrum (ADRS) was derived from the ABC code and utilized to illustrate the seismic demand for the area. This analysis evaluated the seismic resilience of the chosen reinforced concrete low-rise structures.
- STERA 3D Software: The capacity curve is essential in the CSM. STERA 3D software was utilized to model RC buildings and perform a detailed analysis. The capacity curve and the maximum story drift for each building were obtained, which are key indicators of structural performance under loading.

2.3. Application of the Japanese Standard

The following analytical method utilizes the Japanese Standard for seismic assessment, concentrating on the Is index, which quantifies the structure's seismic capability. This approach includes the First Level of Screening. The Is index was calculated for all selected RC buildings in four seismic zones. Detailed calculations are provided in Chapter 4.

2.4. Development of the Afghanistan Seismic Index (ASI)

The Afghanistan Seismic Index (ASI) is developed through a structured methodology integrating static and dynamic seismic assessments of low-rise RC buildings. The process begins with data collection, ensuring a diverse representation of architectural types. A CSM analysis was performed using the ADRS, with further simulations conducted in STERA 3D Software (Version 11.5) [37] to determine the performance point and maximum story drift. Additionally, the Japanese Seismic Index (Is Index) was applied for a first-level screening, evaluating the vulnerability of the selected structures. The ASI is formulated by combining insights from the Is Index calculations and CSM results, tailoring it to Afghanistan's seismic characteristics.

Dynamic analysis was incorporated using recorded ground motion data from PEER [38] to enhance accuracy. These ground motions were adjusted to match local seismic conditions through spectral matching with the Mean Squared Error (MSE) method. The refined motions were then scaled using STERA WAVE (Version 1.0) [39] software and applied in Time History Analysis (THA) with three representative ground motions, enabling the evaluation of maximum story drift under dynamic conditions. By integrating findings from static (CSM + Is Index) and dynamic (THA + Ground Motion Scaling) analyses, the ASI provides a comprehensive framework for assessing seismic vulnerability in Afghanistan. The study introduces the ASI, a tailored metric to reflect Afghanistan's unique seismic profile. The ASI is expected to provide a more accurate assessment of RC buildings' vulnerability by integrating local construction practices and materials, ultimately contributing to region-specific recommendations for seismic design. Figure 1 illustrates the research methodology in a flowchart format, providing a systematic overview of each stage.

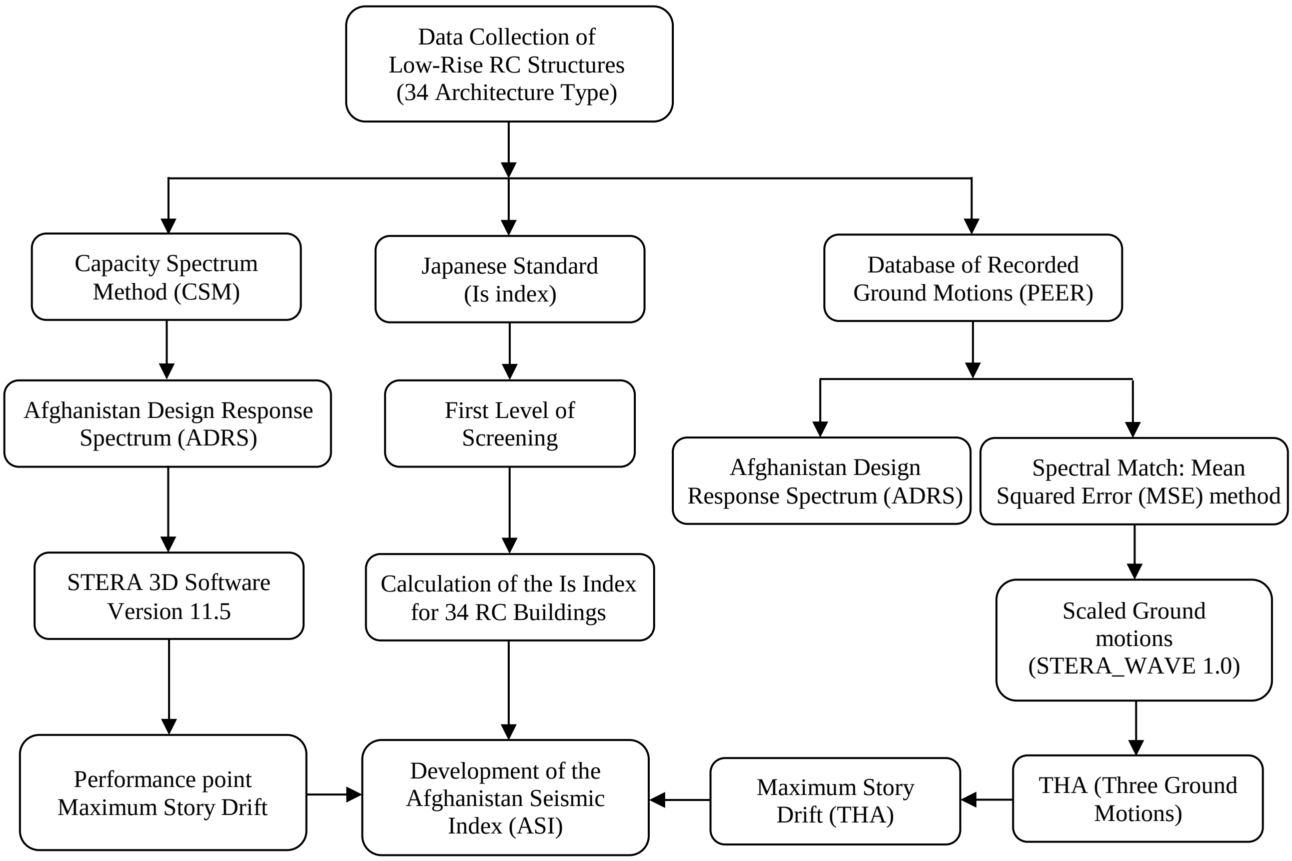


Figure 1. Research flowchart

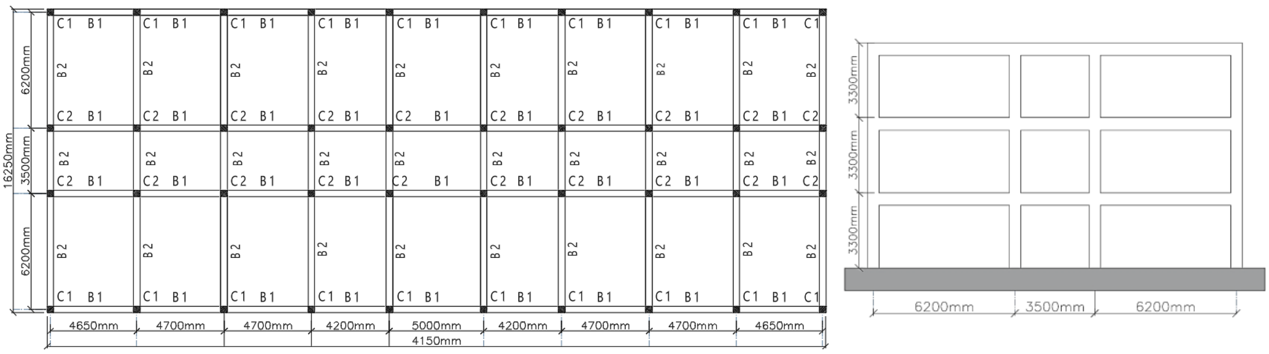
3. Comprehensive Database of RC Structures

The current research focuses on a widespread database of RC structures constructed in different regions between 2001 and 2022 [15]. Based on the yearly report published by MOE [40], Around 15,999 buildings have been constructed, including public schools and private schools. Diverse structural solutions in Afghanistan have been employed for low-rise reinforced concrete (RC) structures, encompassing moment-resisting frame systems, RC frames integrated with masonry, RC frames featuring stone masonry walls, masonry edifices, and stone masonry constructions. For the current research, 34 moment-resisting frame systems have been selected from the database for analysis. For the present research, 34 moment-resisting frame systems were selected from the database for analysis. Their diversity influenced the selection about the number of stories, story height, plan irregularities, beam and column geometries, varying span sizes in the x and y directions, architectural styles, material types, geographical regions, and building years.

Low-rise buildings employ a variety of construction materials for interior and external walls, including stone masonry, concrete masonry units, brick masonry, aerated concrete blocks, and hollow block masonry. Burnt brick masonry has historically been the most commonly used material due to its strength, durability, lower cost, and accessibility to construction sites, particularly for mid- and low-rise buildings. The predominant use of RC as the primary structural material underscores a substantial commitment to enhancing the safety and stability of these buildings, which is crucial for the well-being and safety of their occupants. Predominantly constructed as standard school buildings, these structures were designed and erected nationwide by the MOE and the MUDH across various locations and cities. Sharafi & Saito [15] grouped the database into A-type (constructed after 2018 by MUDH) and B-type (constructed before 2018 by MOE) to delineate the differences in the design and construction standards implemented. A-type buildings include more pronounced structural components, including reinforced concrete columns and beams, elevated concrete compressive strength, and an increased steel proportion. Conversely, B-type RC structures are constructed with diminutive column and beam size, inferior concrete compressive strength, and a diminished proportion of reinforcement.

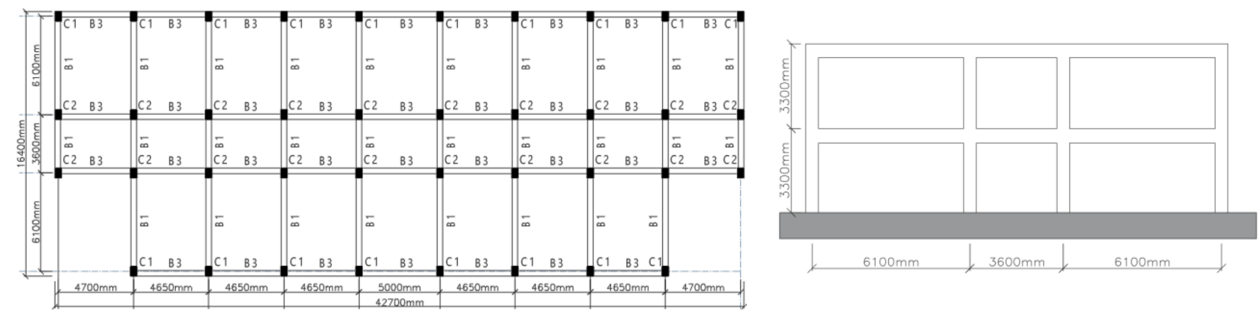
The floor load, consisting of dead and live loads, was calculated to be 11.8 KN/m². Tables 1, 2, and 3 present the dimensions of the structural elements (beams and columns) for one-, two-, and three-story A-type low-rise RC buildings, respectively. Correspondingly, Tables 4, 5, and 6 provide the equivalent data for one-, two-, and three-story B-type low-rise RC buildings. Over the past three decades, variations in concrete and reinforcement strengths have been observed in low-rise buildings. According to the database details, the compressive strength of concrete in B-type buildings was 20 MPa, while A-type buildings utilized concrete with a compressive strength of 28 MPa. Similarly, the tension strength of shear and flexural reinforcement steel rebars was 280 MPa for older buildings, compared to 420 MPa for newer buildings.

Given the significant space needed to display the floor plans, sections, and details for all thirty-four RC buildings, Figures 2 to 6 have been selectively included to represent examples of A-Type and B-Type buildings ranging from one to three stories. The following figures and tables illustrate the structural configurations and reinforcement details of A-type (Figures 2 and 3) and B-type (Figures 4 to 6) RC buildings, ranging from single-story to three-story structures. Figures 1 through 6 visually represent the floor plans and transverse RC frames, offering insights into each building type's architectural layout and structural design. Tables 1 to 4 indicate A-type RC structures, while 5 to 10 represent B-type RC structures. The summaries include dimensions and reinforcement details for columns and beams across the different building types. Figures 7 and 8 illustrate the buildings' geographical locations in different provinces. Additionally, Table 11 provides information on the building type, exact location, seismic zone, construction year, and number of stories for the RC low-rise buildings.



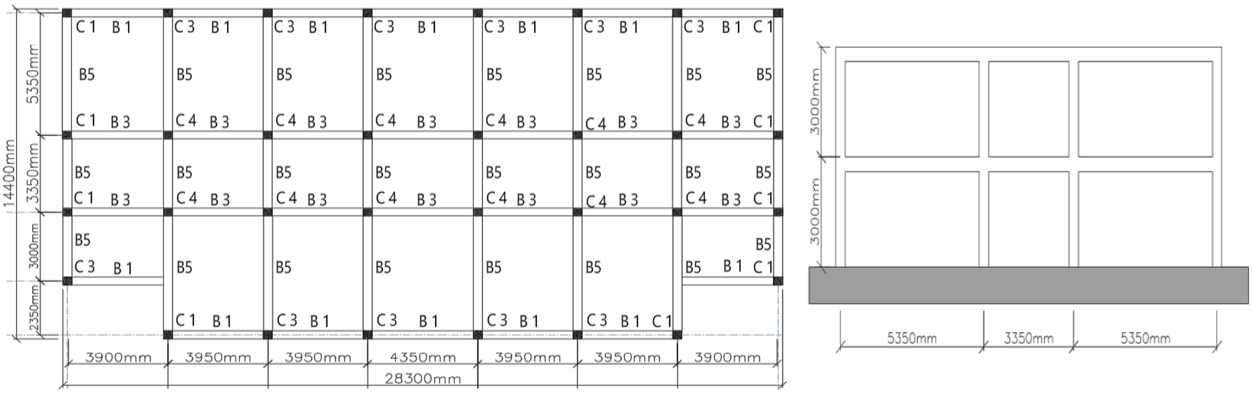
(a) (b)

Figure 2. From Sharafi et al. [41] A-type three-story Structures (a) first-floor plan, (b) RC frame (transverse direction)



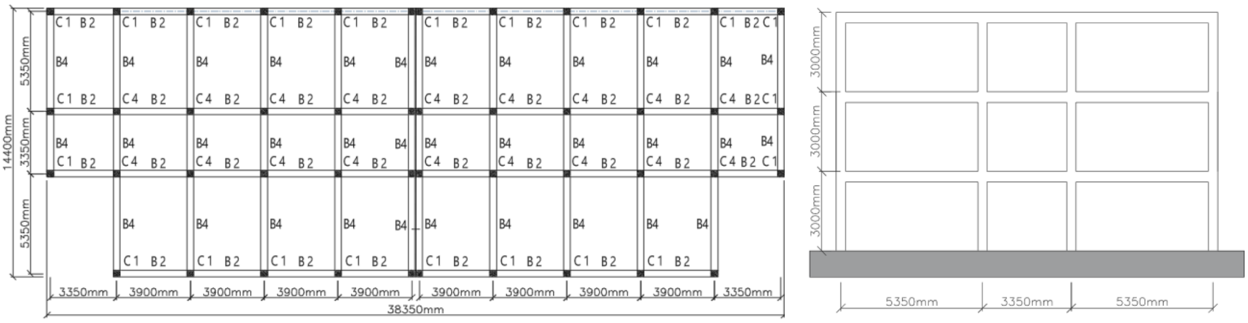
(a) (b)

Figure 3. From Sharafi and Saito [15], A-type two-story RC structure (a) first-floor plan, (b) RC frame (transverse direction)



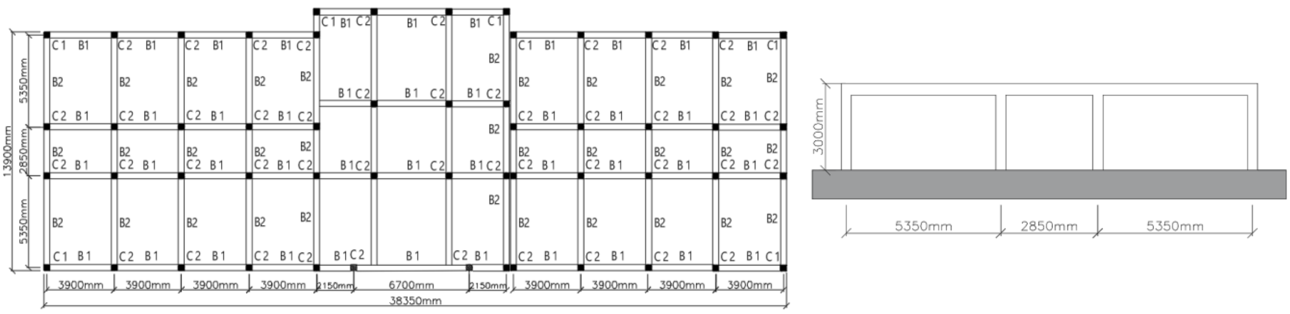
(a) (b)

Figure 4. From Sharafi and Saito [15] B-type two-story RC structure (a) first-floor plan, (b) RC frame (transverse direction)



(a) (b)

Figure 5. B-type three-story RC structure (a) first-floor plan, (b) RC frame (transverse direction)



(a) (b)

Figure 6. B-type single-story RC structure (a) first-floor plan, (b) RC frame (transverse direction)

Table 1. Details of RC Columns and Reinforcement (A-type three-story RC Structure)

No.	Column	Story Level	Depth (cm)	Width (cm)	Main Rebar	Shear Rebar	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	C1	1^{st} 2^{nd} & 3^{rd}	50	45	12 D-20	D10@10 cm	420	28
2	C2	1^{st} 2^{nd} & 3^{rd}	50	45	14 D-20	D10@10 cm	420	28

Table 2. Details of RC Beams and Reinforcement (A-type three-story RC Structure)

No.	Beams	Story Level	Depth (cm)	Width (cm)	Beams reinforcement details	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	B1	1^{st} &2^{nd}	50	35	5 D18 on Top & 4 D18 on Bot.	420	28
2	B2	1^{st} &2^{nd}	55	35	5 D20 on Top & 5 D18 on Bot.	420	28
3	B3	3^{rd}	50	35	5 D16 on Top & 4 D16 on Bot.	420	28
4	B4	3^{rd}	55	35	5 D18 on Top & 5 D16 on Bot.	420	28

Table 3. Details of RC Columns and Reinforcement (A-type two-story RC Structure)

No.	Column	Story Level	Depth (cm)	Width (cm)	Main Rebar	Shear Rebar	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	C1	1st & 2nd	60	40	14 D-18	D10@10 cm	420	28
2	C2	1st & 2nd	60	40	14 D-20	D10@10 cm	420	28

Table 4. Details of RC Beams and Reinforcement (A-type two-story RC Structure)

No.	Beams	Story Level	Depth (cm)	Width (cm)	Beams reinforcement details	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	B1	1st	60	40	5 D18 on Top & 5 D16 on Bot.	420	28
2	B2	2nd	50	40	5 D16 on Top & 5 D16 on Bot.	420	28
3	B3	1st	60	40	5 D16 on Top & 4 D16 on Bot.	420	28
4	B4	2nd	50	40	5 D16 on Top & 4 D16 on Bot.	420	28

Table 5. Details of RC Columns and Reinforcement (B-type two-story RC Structure)

No.	Column	Story Level	Depth (cm)	Width (cm)	Main Rebar	Shear Rebar	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	C1	1st & 2nd	35	35	10 D-20	D 8 @ 15 cm	265	20
2	C2	2nd	35	35	10 D-18	D 8 @ 15 cm	265	20
3	C3	1st	35	35	6 D20 & 4D22	D 8 @ 15 cm	265	20
4	C4	1st	35	35	10 D-22	D 8 @ 10 cm	265	20

Table 6. Details of RC Beams and Reinforcement (B-type two-story RC Structure)

No.	Beams	Story Level	Depth (cm)	Width (cm)	Beams reinforcement details	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	B1	1st	35	35	5 Ø16 on Top & 4 Ø16 on Bot.	265	20
2	B2	2nd	35	35	5 Ø14 on Top & 4 Ø14 on Bot.	265	20
3	B3	1st	35	35	5 Ø18 on Top & 4 Ø18 on Bot.	265	20
4	B4	2nd	35	35	5 Ø16 on Top & 4 Ø16 on Bot.	265	20
5	B5	1st	40	35	5 Ø18 on Top & 4 Ø18 on Bot.	265	20
6	B6	2nd	40	35	5 Ø18 on Top & 4 Ø18 on Bot.	265	20

Table 7. Details of RC Columns and Reinforcement (B-type three-story RC Structure)

No.	Column	Story Level	Depth (cm)	Width (cm)	Main Rebar	Shear Rebar	Rebar Strengths f_y(MPa)	Concrete f_c (MPa)
1	C1	1st	35	35	10 D-20	D 10 @ 10 cm	265	20
2	C2	2nd	35	35	10 D-18	D 10 @ 10cm	265	20
3	C3	3rd	35	35	10 D-16	D 10 @ 15 cm	265	20

Table 8. Details of RC Beams and Reinforcement (B-type three-story RC Structure)

No.	Beams	Story Level	Depth (cm)	Width (cm)	Beams reinforcement details	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	B1	1st & 2nd	35	45	5 D18 on Top & 5 D18 on Bot.	265	20
2	B2	1st & 2nd	35	35	5 D18 on Top & 5 D18 on Bot.	265	20
3	B3	3rd	35	35	5 Ø16 on Top & 5 Ø16 on Bot.	265	20
4	B4	3rd	35	45	5 Ø16 on Top & 4 Ø16 on Bot.	265	20

Table 9. Details of RC Columns and Reinforcement (B-type single-story RC Structure)

No.	Column	Story Level	Depth (cm)	Width (cm)	Main Rebar	Shear Rebar	Rebar Strengths f_y (MPa)	Concrete f_c (MPa)
1	C1	1st	35	35	4 D-18	D 8 @ 10 cm	265	20
2	C2	1st	35	35	8 D-18	D 8 @ 10 cm	265	20

Table 10. Details of RC Beams and Reinforcement (B-type single-story RC Structure)

No.	Beams	Story Level	Depth (cm)	Width (cm)	Beams reinforcement details	Rebar Strengths f_y(MPa)	Concrete f_c (MPa)
1	B1	1st	35	35	5D16 on Top & 5D16 on Bot.	265	20
2	B2	1st	35	35	5 D18 on Top & 5 D18 on Bot.	265	20

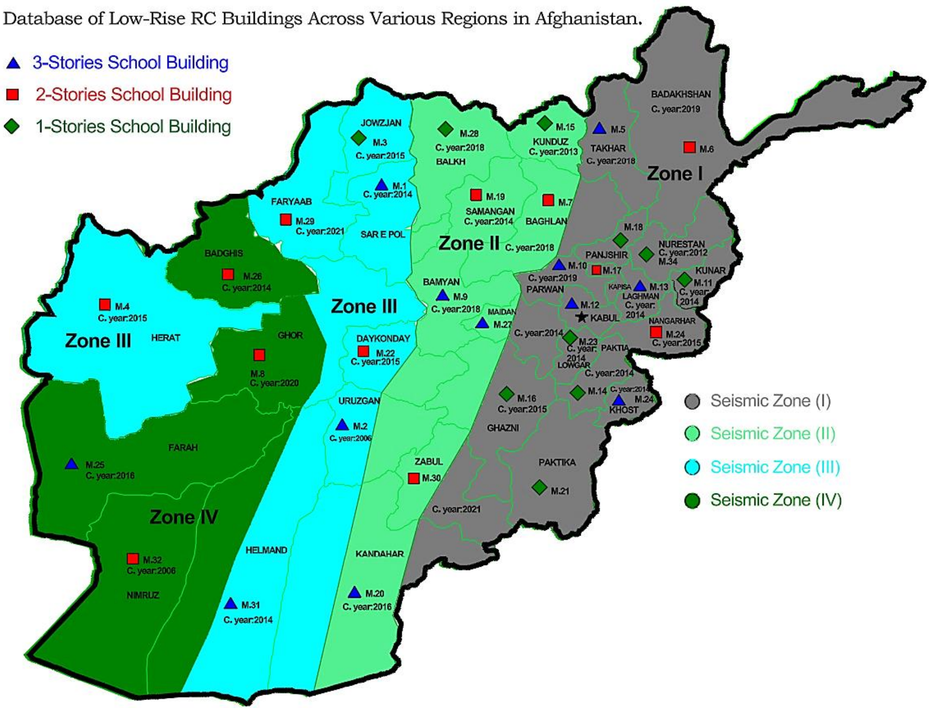


Figure 7. From Sharafi and Saito [15] RC low-rise building locations in different regions of Afghanistan

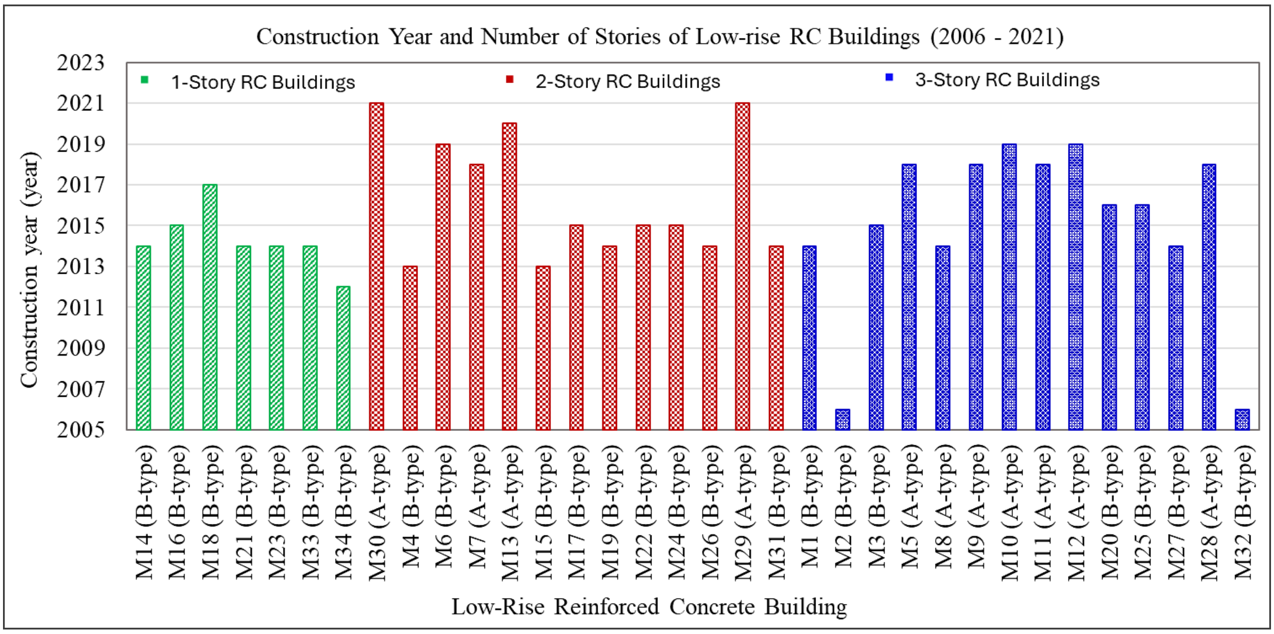


Figure 8. RC low-rise building locations in different regions of Afghanistan

Table 11. Summary of Low-Rise RC Building by Province, Seismic Zone, and Construction Year

Building ID (A-type/ B-type)	Location (Province)	Seismic Zone	Construction Year	Number of Stories
M14 (B-type)	Baghlan	Zone-I	2014	Single story
M16 (B-type)	Ghazni	Zone-I	2015	Single story
M18 (B-type)	Panjsheer	Zone-I	2017	Single story
M21 (B-type)	Paktika	Zone-I	2014	Single story
M23 (B-type)	Logar	Zone-I	2014	Single story
M33 (B-type)	Samangan	Zone-I	2014	Single story
M34 (B-type)	Norestan	Zone-I	2012	Single story
M30 (A-type)	Zabul	Zone-II	2021	Two-story
M4 (B-type)	Herat	Zone-III	2013	Two-story
M6 (B-type)	Badakhshan	Zone-I	2019	Two-story
M7 (A-type)	Parwan	Zone-II	2018	Two-story
M13 (A-type)	Ghur	Zone-I3	2020	Two-story
M15 (B-type)	Kondooz	Zone-II	2013	Two-story
M17 (B-type)	Kapesa	Zone-I	2015	Two-story
M19 (B-type)	Paktya	Zone-II	2014	Two-story
M22 (B-type)	Daikondi	Zone-III	2015	Two-story
M24 (B-type)	Nangerhar	Zone-I	2015	Two-story
M26 (B-type)	Badghees	Zone-IV	2014	Two-story
M29 (A-type)	Faryaab	Zone-III	2021	Two-story
M31 (B-type)	Helmand	Zone-III	2014	Two-story
M1 (B-type)	Sar-e Pol	Zone-III	2014	Three-story
M2 (B-type)	Uruzgan	Zone-III	2006	Three-story
M3 (B-type)	Jowzjan	Zone-III	2015	Three-story
M5 (A-type)	Takhar	Zone-I	2018	Three-story
M8 (A-type)	Laghman	Zone-IV	2014	Three-story
M9 (A-type)	Bamyan	Zone-II	2018	Three-story
M10 (A-type)	Khost	Zone-I	2019	Three-story
M11 (A-type)	Koner	Zone-I	2018	Three-story
M12 (A-type)	Kabul	Zone-I	2019	Three-story
M20 (B-type)	Kandahar	Zone-II	2016	Three-story
M25 (B-type)	Farah	Zone-IV	2016	Three-story
M27 (B-type)	Maidan Wardak	Zone-II	2014	Three-story
M28 (A-type)	Balkh	Zone-II	2018	Three-story
M32 (B-type)	Nemrooz	Zone-IV	2006	Three-story

4. Application of the Japanese Seismic Standard for Existing RC Structures

The Japanese Standard [42] for Seismic Performance Evaluation presents a recognized methodology for assessing the seismic capacity of reinforced concrete structures, mainly concentrating on the estimation of the fundamental seismic index (E_0). The index represents a structure's fundamental seismic performance and is critical in determining its ability to withstand seismic events. The evaluation process consists of three screening stages, each offering an increasingly detailed assessment according to the building's ductility, critical strength, and structural failure mode. The methodology is formulated to consider the intricate interactions among these elements, which are essential for guaranteeing the safety and durability of structures during seismic events. This standard is crucial for this research and the fields of structural engineering and earthquake safety.

The present study rigorously employed the initial screening approach to assess the earthquake resistance of previously constructed reinforced concrete buildings developed in diverse locales. The seismic index was calculated using equations series incorporating multiple structural parameters. For instance, Equation 1 calculates the Is by considering the span length, story height, beam, column dimensions, weight for each story, and other parameters. The fundamental seismic index was (E_0) estimated for each story based on the structure's maximum strength, ductility, and structure mode of failure. In an n-story RC structure, E_0 was determined by assessing the ductility index (F), the strength index (C), and the story shear factor, which characterizes the distribution of lateral seismic force throughout the structure's height.

By integrating the results from these different screening methods, a comprehensive seismic performance index can be established, offering insights into the RC building's overall vulnerability. Applying this standard involves the detailed analysis of 34 RC buildings with varying configurations and seismic demands. By systematically applying these equations, we aim to evaluate the structural performance and propose ASI to improve their seismic efficacy. In the Japanese seismic index methodology, I_s denotes the seismic index of the structure to assess its seismic performance. This is a crucial metric for evaluating the seismic resilience of the structure and is computed as:

$$I_S = E_0 \times S_D \times T \tag{1}$$

where I_S is Fundamental seismic index: This represents the inherent seismic capacity of the building based on its material strength, structural configuration, and design, E_0 is Basic seismic index: This represents the inherent seismic capacity of the building based on its material strength, structural configuration, and design, T is Time index: This accounts for the effects of deterioration, such as cracks, aging, and deflection over time, which reduce the building's seismic performance, and S_D is Irregularity index: This factor modifies the seismic capacity based on structural irregularities, such as asymmetry in mass or stiffness, which can amplify seismic effects.

The equations below detail the calculation process and methodology used for the selected low-rise RC structures.

$$E_0 = \frac{n+1}{n+i}(C_W + \alpha_1 + C_C)F_W \tag{2}$$

$$E_0 = \frac{n+1}{n+i}(C_{SC} + \alpha_2 C_W + \alpha_3 C_3)F_{SC} \tag{3}$$

$$C_W = \frac{\tau_{W1}A_{W1} + \tau_{W2}A_{W2} + \tau_{W3}A_{W3}}{\Sigma W}\beta_C \tag{4}$$

$$C_C = \frac{\tau_C \times A_C}{\Sigma W}\beta_C \tag{5}$$

$$\beta_C = \frac{f_C}{20}F_C \leq 20 \text{ and } \beta_C = \sqrt{\frac{f_C}{20}} \tag{6}$$

where n is the number of levels, i is the number of the concerned level, C_w, C_c,and C_{sc} are Strength indexes of walls, Columns, and extremely short columns, a_1 is Effective strength factor of the columns at the ultimate deformation of walls, a_2 is Effective strength factor of the walls at the final deformation at exceedingly low, a_3 is Effective strength factor of the columns at the ultimate deformation for extremely short columns, C_w is The shear strength coefficient of walls, α_2 is Correction factors, C_c is Shear strength coefficient of columns, F_W and F_{SC} are Correction coefficients for walls and columns, and τ_{W1}, τ_{W2}, and τ_{W3} are Shear stress of wall elements.

5. Design Response Spectrum Based on ABC

The Design Response Spectrum is crucial for predicting the maximum seismic demand on structures during earthquakes. The DRS graphically represents the peak response acceleration of a single degree of freedom (SDOF) system as a function of its natural period or frequency when subjected to specific ground motion. This tool is essential for evaluating the dynamic response of RC buildings and confirming their seismic performance meets safety and resilience standards. According to the ABC code and the USGS report for Afghanistan [33, 43] the spectral response acceleration values, Ss and S1, are indicated for four geological locations or seismic zones. This research has focused on the four seismic hazard zones: Zone-I, Zone-II, Zone-III, and Zone-IV.

The ADRS was computed based on the ABC to integrate seismic hazard data, historical earthquake records, and region-specific soil classifications. ADRS forms the basis for dynamic and static analysis methods, which are crucial to assess the seismic performance of RC structures and are a central focus of this research. By applying the ADRS, the expected seismic demands on RC buildings are determined, ensuring compliance with the ABC's requirements for life safety and structural integrity. In proportion to the ABC, RC structures must be designed to withstand earthquake with a 2% probability of exceeding them in 50 years. The thick lines illustrate the ADRS for four seismic Zones in Figure 9.

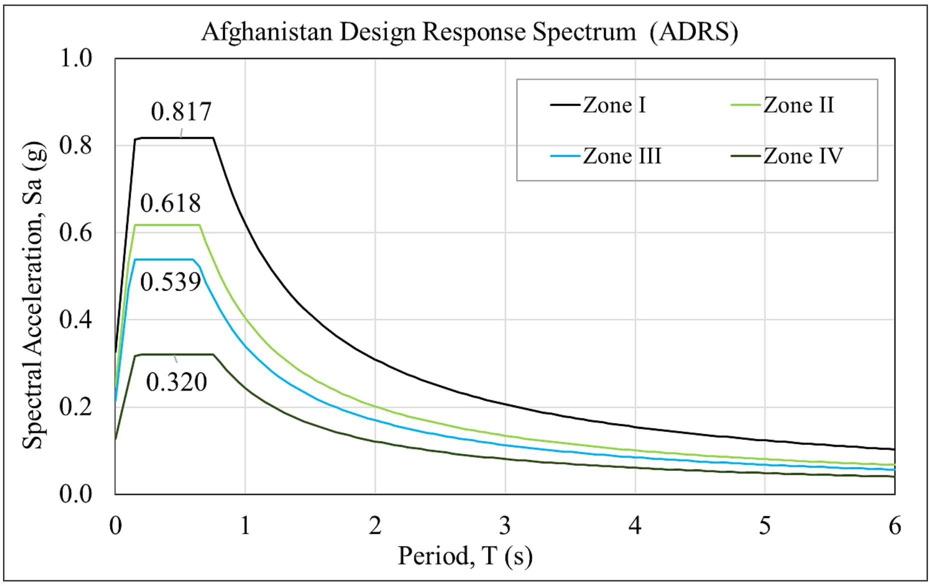


Figure 9. From Sharafi et al. [15] Afghanistan-Designed Response Spectra with 5% damping

6. Selection of Ground Motions for Seismic Analysis

6.1. Spectral Match

Due to limited seismic instrumentation, no local ground motion data is available. However, alternative methods can provide suitable data for seismic performance evaluations. Using records from nearby regions with similar tectonics, like the 2003 Bam or 1976 Gazli earthquakes, offers comparable seismic characteristics. Synthetic ground motions can also be generated based on regional parameters (PGA, magnitude, fault type, etc.). Additionally, global databases like PEER provide extensive seismic records that can be filtered to match Afghanistan's seismic profile. In this research, a comprehensive database of recorded earthquakes was obtained from the PEER database [3, 44], meeting the following criteria:

The Mean Squared Error (MSE) method has been utilized to ensure an accurate spectral match between the selected ground motions and the ADRS. The MSE method quantifies how well a selected set of earthquake records matches a target response spectrum.

- The MSE calculation by using the following formula:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(SF_1 \times Sa_{rec} - Sa_{t\,arg\,et}\right)^2 \tag{7}$$

where MSE is Mean Squared Error method, SF_1 is Scaling factor in obtaining the minimum, Sa_{rec} is Unscaled response spectrum of the evaluated record and, $Sa_{t\,arg\,et}$ is Target response spectrum.

- The epicentral depth affects ground motion features, including frequency content and attenuation parameters. The most significant earthquake in Afghanistan transpired on 26 October 2015, roughly 210 kilometers beneath the Hindu Kush in Northeastern Afghanistan [2].
- The collection of earthquakes contains records from diverse earthquakes, capturing the inherent variability in seismic events.
- The size of an earthquake is directly correlated with the energy released and affects the frequency content, amplitude, and duration of the seismic waves. The chosen earthquake magnitudes span from 5.8 to 8.0 (moment magnitude, Mw).

Figure 10 illustrates the acceleration response spectrum of the selected earthquakes with a damping factor (h) of 0.05. The three base motions were then scaled to align with the ADRS using the STERA_WAVE 1.0 algorithm, developed by Saito [39]. Figure 11 presents the acceleration time histories of the chosen base motions.

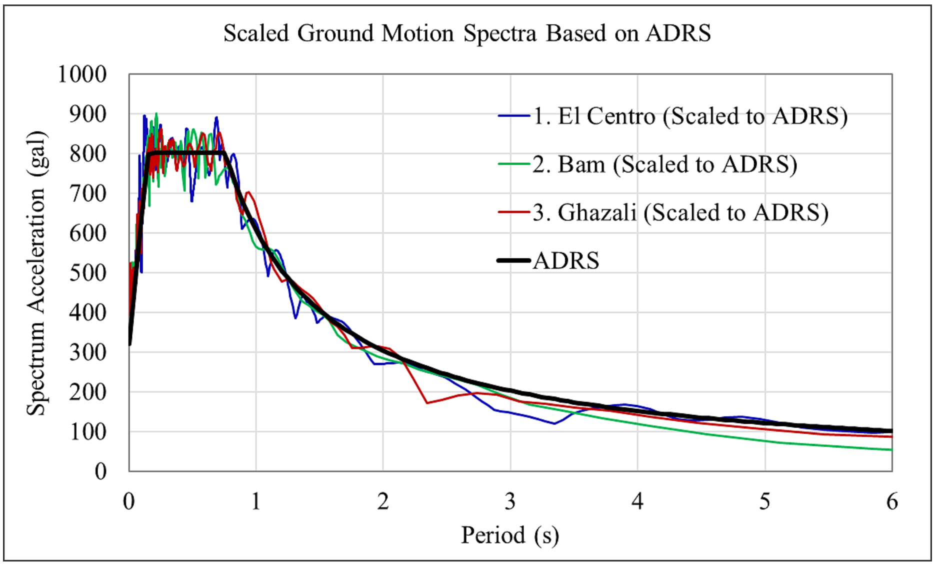


Figure 10. Acceleration response spectrum of the selected ground motions

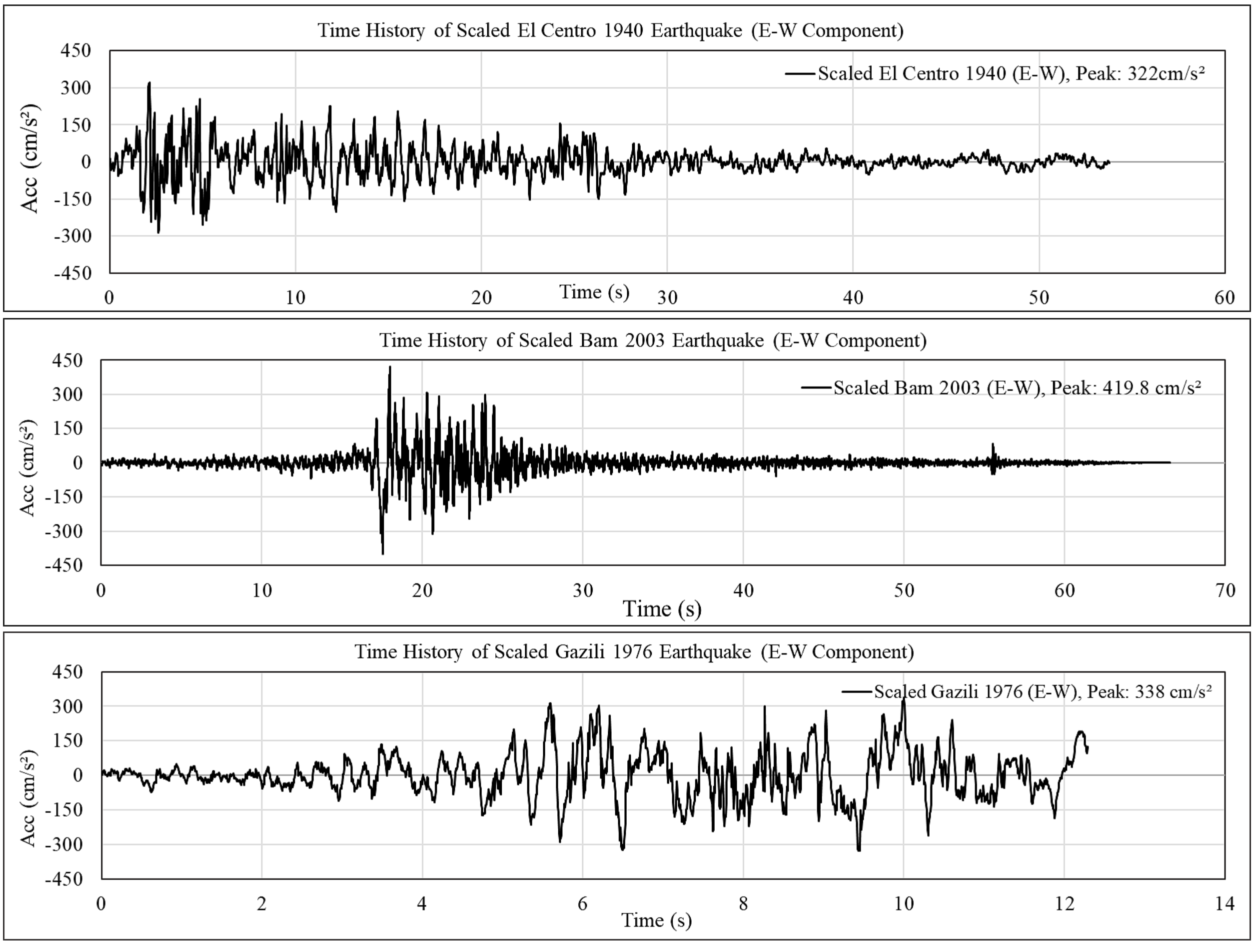
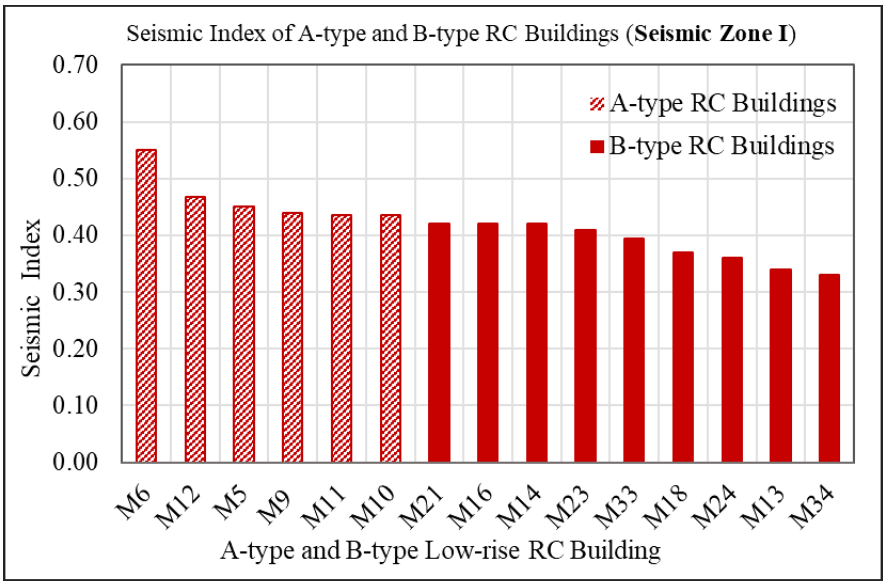


Figure 11. Acceleration of the selected earthquakes

7. Seismic Index Assessment of RC Structures

7.1. Overview of Seismic Index and Story Drift Analysis

The seismic index (Is-index) is a vital indicator of a structure's capacity to support seismic loads. At the same time, the story drift percentage indicates the proportional displacement between floors during seismic occurrence. This section indicates the analysis of the seismic performance of RC buildings with varying numbers of stories constructed from 2006 to 2021 in different locations. Figure 12 indicates the seismic index of RC structures in earthquake zones Zone I to Zone IV. The vertical axis shows the calculated seismic index (Is), and the horizontal axis illustrates the building type and the story number. The Is index was calculated based on the Japanese standard, as detailed in section 4. Similarly, the story drift was driven using the CSM and STERA 3D software. The analysis considers single-story, two-story, three-story RC structure. The buildings were analyzed under the varying seismic conditions defined by Seismic Zones I to Seismic Zone IV. The results of the Is Index calculations for all structures are presented in the bar charts in Figure 12.



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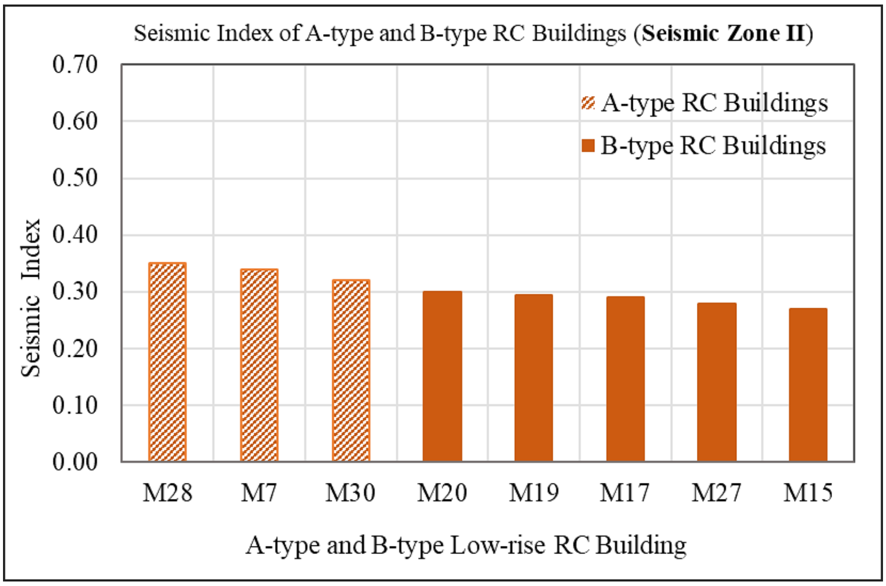

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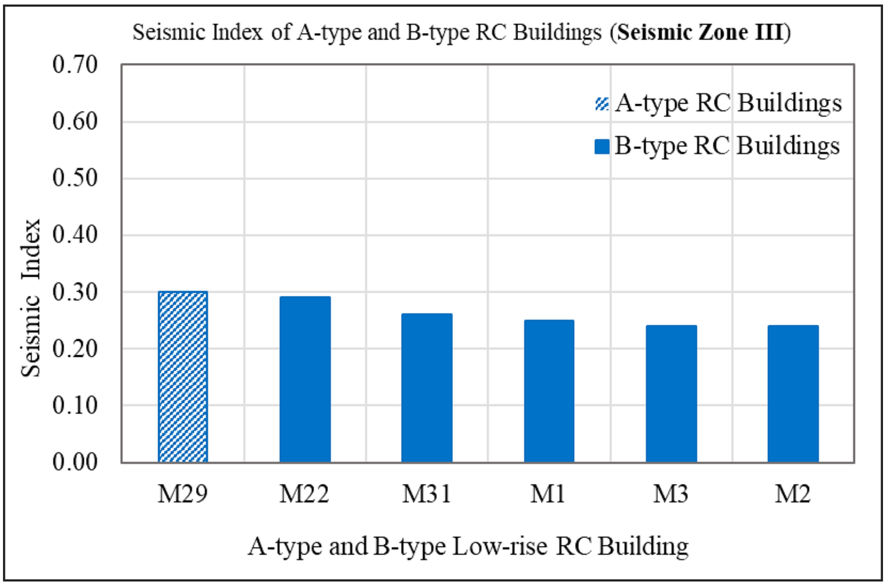

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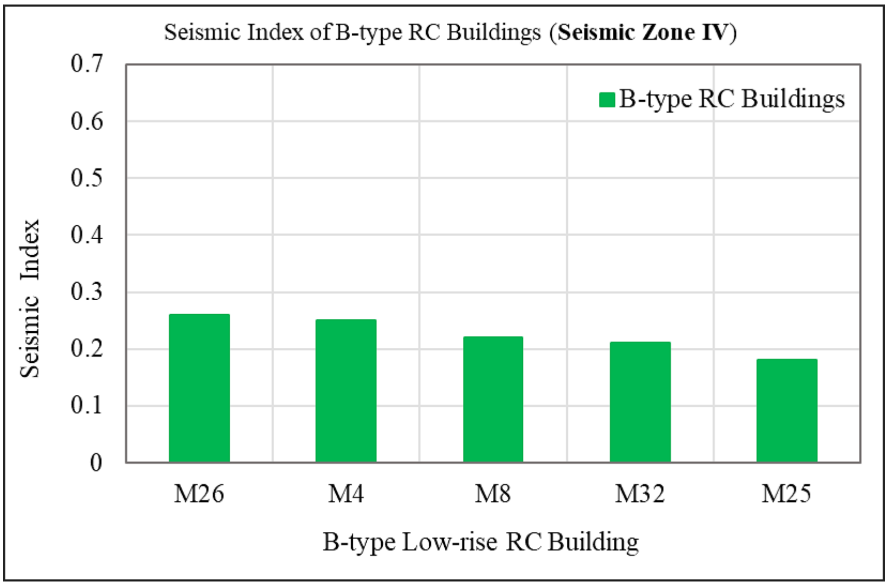


(d)

Figure 12. Seismic Index of Low-Rise RC Buildings: (a) Zone I, (b) Zone II, (c) Zone III, and (d) Zone IV

7.2. Results and Evaluations in Seismic Zone I (Figure 12-a)

The results indicate that A-type buildings, designed after 2018 with improved standards, consistently achieve higher seismic index (Is) values, often exceeding 0.5. This can be attributed to enhanced design practices, including larger column and beam dimensions, higher concrete compressive strengths, and increased reinforcement percentages. Conversely, B-type buildings constructed before 2018 demonstrate lower Is-index values (0.3–0.5) due to smaller cross-sectional elements, reduced reinforcement, and outdated construction practices. These differences highlight the impact of modern design standards on seismic performance. The following trends were observed:

- A-type Buildings (M6, M14, M21, etc.): These buildings generally had higher Is-index, with some exceeding 0.5. This indicates that they are well-designed and likely to perform satisfactorily during a seismic event.
- B-type Buildings (M13, M33, etc.): The B-type buildings, constructed after implementing updated seismic codes, generally had slightly lower Is-index values (between 0.3 and 0.5) in the seismic zone I. These buildings still perform acceptable but may require minor engineering consideration in highly active seismic areas.

Retrofitting strategies, such as adding shear walls, upgrading reinforcement, and improving beam-column connections, are recommended to mitigate the vulnerabilities of B-type buildings. Such measures would increase their seismic resilience, especially in highly active seismic zones like Zone I.

7.3. Results and Evaluations in Seismic Zone II (Figure 12-b)

Seismic Zone II exhibits moderate Is values (0.25–0.35) for A- and B-type buildings. The lower seismic demands in this zone contribute to relatively closer performance levels between the two building types. However, A-type buildings still demonstrate slightly better performance, reflecting the influence of improved design standards. The reduced Is-index values for B-type buildings in this zone highlight their vulnerability to moderate seismic events. Key findings include:

- A-type Buildings (M28, M7, etc.): These buildings perform safer than B-type buildings. However, their lower Is-index values indicate they are more vulnerable to seismic damage than buildings in seismic zone I.
- B-type Buildings (M15, B27, etc.): Although newer, B-type buildings in this zone also display an Is-index value below 0.35, suggesting the need for careful structural assessment and potential upgrades to improve resilience.

Proactive retrofitting for B-type structures, such as strengthening masonry walls, is essential to ensure safety during future seismic events. These measures can prevent significant damage and reduce repair costs.

7.4. Results and Evaluations in Seismic Zone III (Figure 12-c)

In Zone III, where seismic risks are lower, the Is-index values for B-type buildings range between 0.19 and 0.30. This indicates that these buildings are at a higher risk of failure under strong ground motions even in low-risk zones due to inadequate design and construction quality. A-type buildings outperform B-type buildings, showcasing the importance of adhering to modern seismic design principles.

- B-type Buildings (M29, B22, etc.): For cost-effective retrofitting, measures such as localized repairs using fiber-reinforced polymers (FRP) or steel plate jacketing can significantly enhance the resilience of these structures.

7.5. Results and Evaluations in Seismic Zone IV (Figure 12-d)

Seismic Zone IV represents the lowest seismic risk, and the Is indices reflect the vulnerability of buildings in this area, with values between 0.18 and 0.28:

- B-type Buildings (B26, M4, etc.): These buildings are at a critical level of risk, with Is indices suggesting that they would suffer severe damage during a significant seismic event. Retrofitting these structures is imperative to ensure the safety of occupants and reduce potential economic losses.

In Zone I, where seismic activity is the highest, the ASI value is set to 0.50, indicating that buildings meet stricter performance standards to withstand the expected seismic forces. Zone II has a moderate seismic risk; thus, the ASI is set to 0.35, reflecting the reduced demands compared to Zone I. In Zone III, where seismic hazards are lower, the ASI is set at 0.30, ensuring that buildings are adequately designed but without the extreme requirements of the higher zones. Lastly, Zone IV has the lowest seismic risk, and the ASI value is 0.25 seismic activity. This proportionality ensures that resources are allocated efficiently, with higher seismic risk zones receiving more accurate design considerations

7.6. Results and Evaluations in Seismic Zone IV

Although Zone IV represents the lowest seismic risk, B-type buildings remain vulnerable, with Is values between 0.18 and 0.28. The absence of robust design standards during the construction of these buildings exacerbates their susceptibility to damage during rare, high-intensity seismic events. Enforcing minimum design standards is critical even in low-risk zones. Retrofitting methods such as external bracing or upgrading using masonry walls can provide sufficient protection at a reasonable cost.

8. Seismic Index vs. Maximum Story Drift Analysis for RC Structures

This section analyzes the relationship between the Seismic Index (Is) and Maximum Story Drift (%) for RC buildings across Seismic Zones I, II, III, and IV, as depicted in Figure 13. The vertical axis of the scatter plot represents the Seismic Index, calculated based on the Japanese standard outlined in Section 4. In contrast, the horizontal axis shows the maximum story drift obtained through the CSM and STERA 3D software. The study encompasses 34 low-rise RC buildings, including single-story, two-story, and three-story structures, constructed between 2006 and 2021 in various regions and categorized into A-type and B-type buildings.

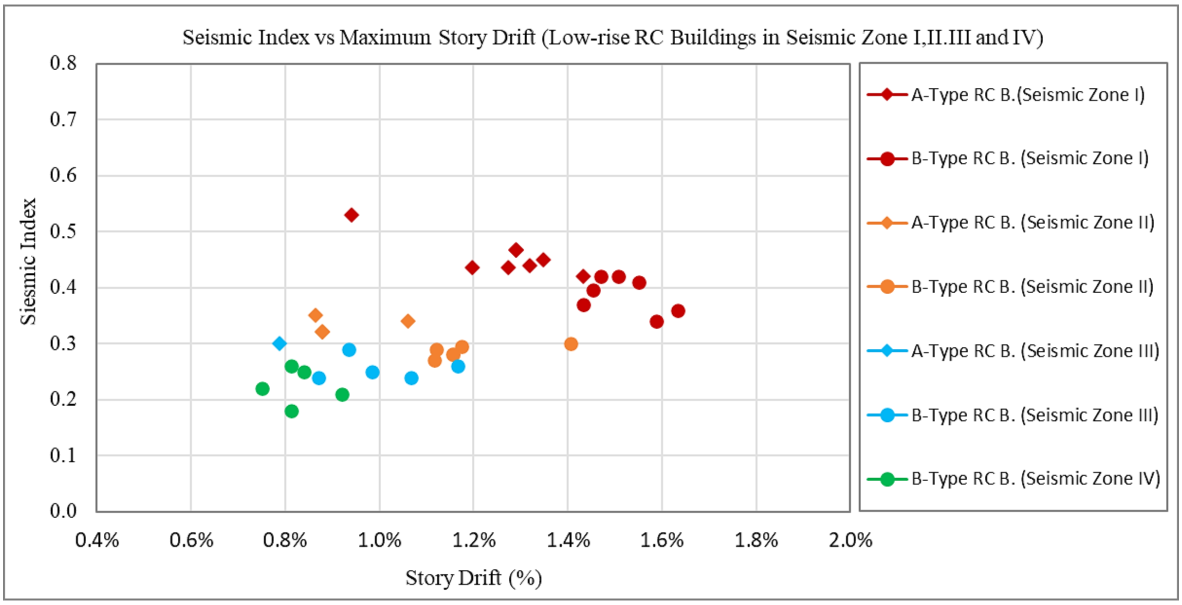


Figure 13. Seismic Index vs. Maximum Story Drift of Low-Rise RC Buildings in Seismic Zones I-IV

The Seismic Index (Is-index) is a critical indicator of a building's capacity to withstand seismic forces, whereas maximum story drift reflects the relative displacement between floors during seismic events. The analysis reveals a clear inverse correlation between the Is-index and maximum story drift: buildings with higher Is-index values exhibit lower story drifts. This trend holds across all seismic zones and building types, affirming the reliability of the seismic index as a predictor of structural performance during earthquakes. A-type buildings, particularly those constructed after 2018, exhibit higher seismic index values and lower drift percentages, reflecting the positive impact of updated design codes (ABC code) and improved construction practices. These buildings feature larger structural elements, increased cross-sectional areas of structural components, and higher percentages of steel reinforcement, contributing to enhanced seismic resilience. In contrast, B-type buildings, especially those constructed between 2006 and 2014, demonstrate lower seismic index values and higher story drifts, indicating increased vulnerability.

The results also show that A-type buildings comply with international drift limits outlined in FEMA 356/ASCE 41 and Eurocode 8 (EN 1998-1) [45, 46]. According to FEMA 356/ASCE 41 [46], the maximum inter-story drift is limited to 1% for immediate occupancy and 2% for life safety. Similarly, Eurocode 8 specifies drift limits based on building importance and seismic design considerations. For high-importance structures (e.g., essential facilities), drift limits typically range from 0.5% to 1%. In contrast, for general-purpose buildings, limits may extend up to 1.5% to 2%, depending on the structural system and ductility class. A-type buildings, particularly in Seismic Zones I and II, consistently perform within these limits, demonstrating compliance with international standards. In contrast, most B-type structures in Seismic Zones I to IV approach or exceed the 2% drift threshold, highlighting the necessity for retrofitting to improve their seismic performance.

Several measures are recommended to address the vulnerabilities of B-type buildings: increasing the stiffness of critical structural components, enhancing the performance of beam-column joints, and infilling masonry walls to the main structure. The observed relationship between the seismic index and story drift underscores the importance of integrating Seismic Index assessments into the design and evaluation of RC buildings, particularly in regions like Zone I and Zone II with significant seismic risk. This approach is essential for ensuring compliance with international standards and improving the seismic resilience of both existing and new structures.

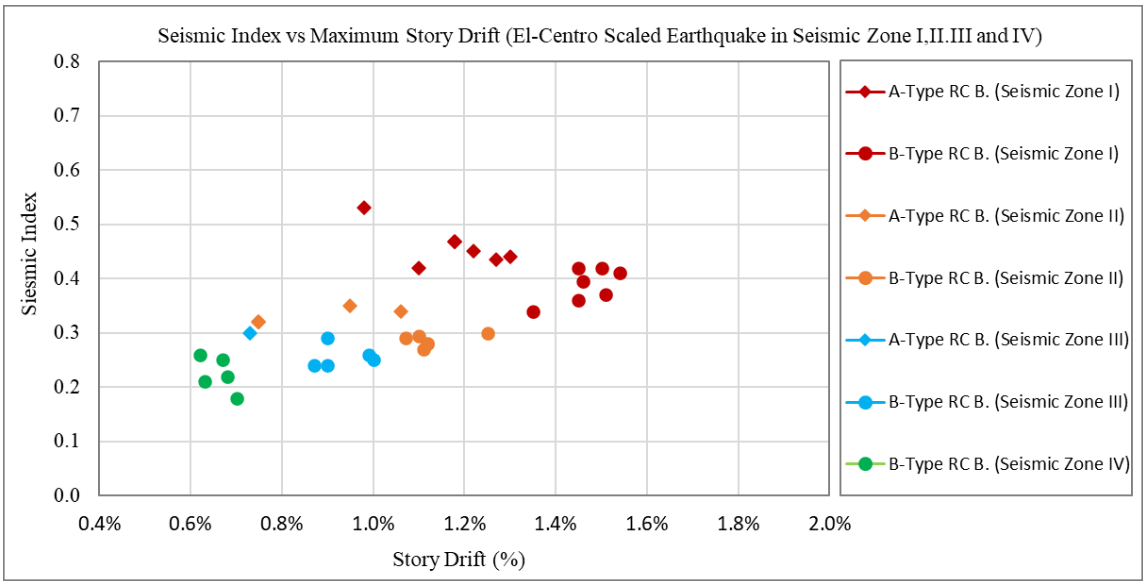
9. Seismic Performance of RC Buildings under three Ground Motions

The seismic performance of RC buildings is a significant aspect of structural analysis, specifically in regions prone to significant seismic activity like Afghanistan. This research section evaluates the seismic response of 34 low-rise RC structures under the influence of three recorded earthquake ground motions. The buildings analyzed represent various structural configurations and were selected to provide insights into the vulnerabilities and strengths inherent in low-rise RC structures.

The dynamic analysis involved applying three distinct recorded ground motions to assess how these low-rise RC buildings respond under different seismic excitations. The recorded ground motions were selected based on their spectral characteristics of ADRS and relevance to the seismic conditions of the buildings' locations. The study utilized non-linear time history analysis to simulate the response of the buildings to each ground motion. Key seismic performance parameters, such as story drift and lateral displacement, were evaluated for each building. The dynamic responses were compared across the 34 buildings, highlighting variations in behavior due to differences in structural configuration, materials, and seismic loadings. The results provide precious insights into the factors influencing the seismic resilience of RC buildings, offering practical recommendations for improving structural design strategies in earthquake-prone regions.

Figure 14 illustrates the relationship between the Seismic Index (Is) and Maximum Story Drift (%) for low-rise RC buildings across Seismic Zones I-IV under three different scaled earthquake records: (a) El-Centro, (b) Bam, and (c) Gaziqi. The graphs are crucial for evaluating the seismic vulnerability of different building types (A-Type and B-Type RC buildings) within various seismic zones, offering insights into structures' relative performance and resilience.

- The X-axis represents the maximum story drift as a percentage, ranging from 0.0% to 2.0%, which quantifies the lateral displacement of each building in relation to its height during the earthquake. Story drift is critical for understanding structural deformation and potential damage during seismic events.
- The Y-axis denotes the Seismic Index (Is), a measure of a building's seismic capacity based on its structural features, materials, and design. The Seismic Index ranges from 0.0 to 0.8 in the presented figures. A higher Seismic Index indicates a better seismic performance and higher capacity to withstand lateral forces.



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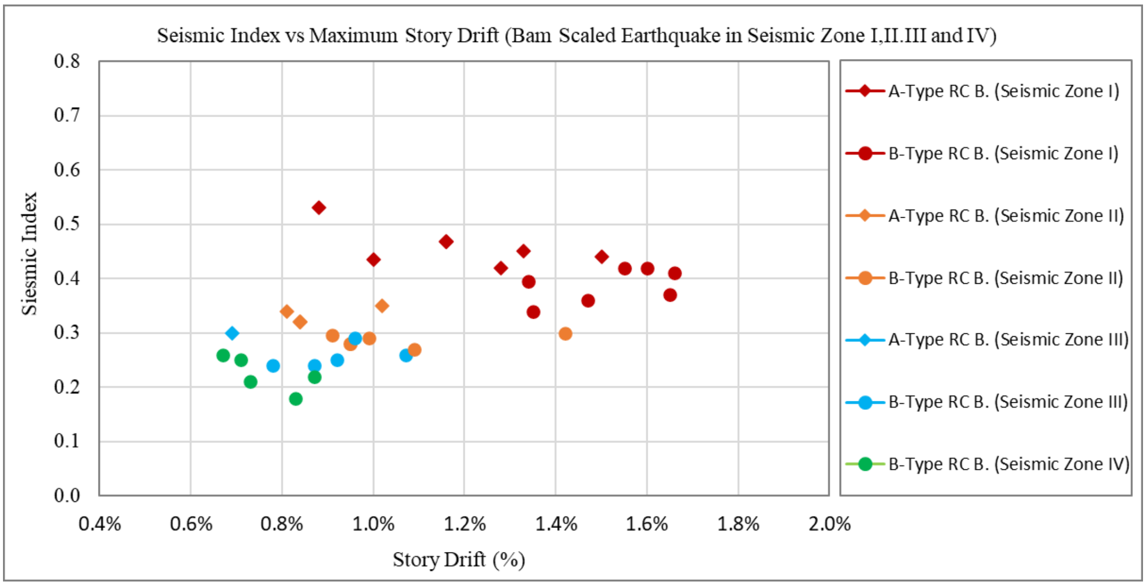

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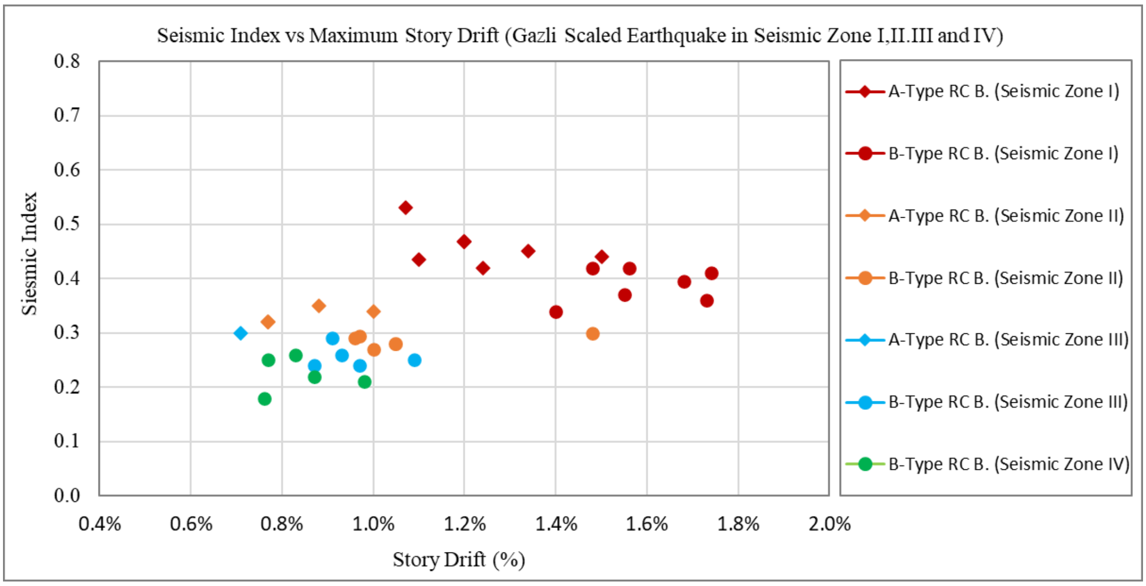


(c)

Figure 14. Seismic Index vs. Maximum Story Drift under Scaled Earthquakes. (a) El-Centro, Bam, and Gazili Earthquakes

Each graph depicts data points corresponding to A-Type and B-Type RC buildings distributed across Seismic Zones I-IV. The classification allows for direct comparisons between different building designs and the influence of varying seismic intensities (represented by seismic zones) on their performance. A black regression line is plotted across the data points in each graph, revealing an overall trend of decreasing Seismic Index values as the story drift increases. This downward trend is expected, as higher story drifts are often associated with higher levels of structural deformation, reducing the building's seismic performance. Across all three earthquake scenarios, the comparative analysis indicates that:

- A-type RC buildings (red and orange points) consistently perform better in higher seismic zones (III and IV), with higher Seismic Index values and lower story drifts. This suggests that A-type RC buildings are designed with greater seismic resistance, likely incorporating more stringent structural reinforcements and detailing to comply with the higher seismic demands of Zones III and IV.
- B-type RC buildings (green and blue points), particularly in Seismic Zones I and II, exhibit lower Seismic Index values and are associated with larger maximum story drifts. These buildings are more susceptible to deformation and damage during seismic events, indicating a lower overall seismic performance. This is likely due to less rigorous design and construction practices in these lower seismic zones, where earthquake loads are typically less severe.
- The blue and green data points, representing B-type buildings initially designed for typical RC construction in Seismic Zone I, have been constructed across all four seismic zones. The analysis indicates a significantly reduced maximum story drift in Seismic Zones III and IV. However, B-type RC buildings exhibit disproportionately larger maximum story drifts in seismic zones I and II.

10. Maximum Story Drift of RC Structures in Different Seismic Zones

10.1. Validation Approach Using Capacity Spectrum Method and Dynamic Analysis

The seismic vulnerability framework developed in this research was validated through an in-depth analysis of 34 RC structures using CSM and dynamic analysis. The analysis incorporated three scaled earthquake ground motions: El Centro (1940), Bam (2003), and Gazli (1976). The validation focused on comparing the maximum story drift percentages of A-type and B-type RC buildings across Afghanistan's four seismic zones (I-IV), representing varying seismic hazard levels. This comprehensive approach ensures the robustness and applicability of the proposed methodology across a range of earthquake intensities. Additionally, Nguyen et al. [47] showed that integrating machine learning (ML) models into seismic fragility analysis enhances computational efficiency while maintaining high prediction accuracy. Their approach aligns closely with traditional fragility assessment methods, reinforcing the reliability of advanced computational techniques in seismic performance evaluation of RC structures. This alignment further validates the incorporation of ML models into the framework developed in this study, highlighting its potential for improving computational precision and scalability.

10.2. Consistency Across Methods

The results illustrate that the CSM provides a conservative estimate of maximum story drift compared to dynamic analysis. The slightly higher drifts obtained from the dynamic analysis highlight the CSM's tendency to idealize structural behavior, while the dynamic analysis captures more detailed, realistic responses to underground motion variability. The overall consistency between CSM and the dynamic analysis, especially for the El Centro and Bam earthquakes, validates the reliability of CSM as an effective tool for assessing seismic vulnerability in low-rise RC buildings.

10.3. Performance of Scaled Earthquake Ground Motions

Using three-scaled earthquake records ensures the robustness of the seismic assessment framework. Across all seismic zones, the results consistently show that El Centro 1940 and Bam 2003 produce slightly higher drift values than CSM. This difference reflects the dynamic nature of actual seismic events and their ability to induce inelastic behavior in structures. Notably, the Gazili 1976 earthquake produced the highest drifts across Seismic Zones I and IV, confirming that older earthquakes with more aggressive ground motions induce greater deformations in buildings that were not designed to modern seismic standards. This emphasizes the need for dynamic analysis to complement CSM when evaluating the seismic vulnerability of RC buildings.

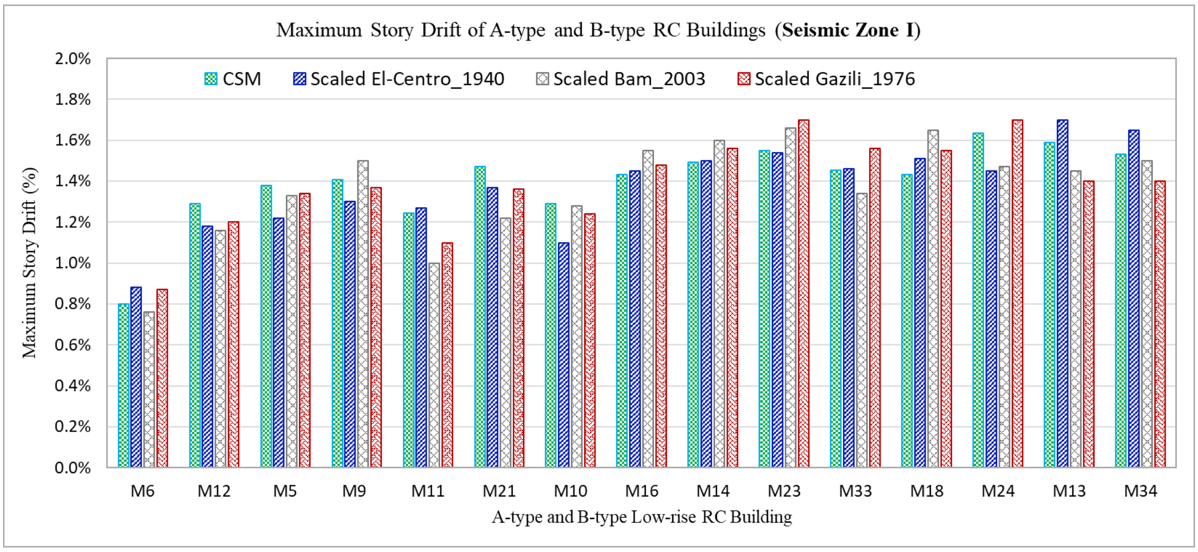
10.4. Seismic Zone-Based Validation

- Seismic Zone I: The drift values range from 0.8% to 1.8%, with dynamic analysis consistently producing higher values than CSM. The results indicate that for regions of moderate seismic risk, both CSM and dynamic analysis provide reliable assessments of structural behavior, validating the applicability of both methods in these zones.

- Seismic Zone II: Maximum drift ranged from 0.6% to 1.4%, with the El Centro and Bam earthquakes producing slightly higher drifts. The scaled Bam 2003 earthquake proved particularly insightful, as it provides a regional context, affirming that scaled analysis for regional earthquake effects strengthens the validation.
- Seismic Zone III: A slight increase in drift (up to 1.2%) was observed, particularly with the Gazili 1976 earthquake. This demonstrates that higher-risk zones require more detailed dynamic evaluations. The results validate that the CSM tends to underestimate drift in these zones but remains a conservative approach.
- Seismic Zone IV: Drift values ranged from 0.5% to 1.0%, with the dynamic analysis showing higher drifts compared to CSM. This zone demonstrated the necessity of including dynamic analysis for buildings in high-risk zones, as older structures in these regions could experience significant deformation during intense earthquakes.

10.5. Regional Considerations and Practical Implications

The validation results provide significant insights into Afghanistan's seismic vulnerability of RC structures. The higher drifts observed in the dynamic analysis using regionally significant earthquakes, such as Bam 2003, highlight the importance of considering local seismic hazards when developing seismic vulnerability indices. This underscores the applicability of the proposed ASI, which is tailored to address the specific seismic risks faced by buildings in the region. The findings confirm that the developed ASI can be a reliable tool for evaluating the seismic vulnerability of RC structures across various seismic zones in Afghanistan. This index, backed by comprehensive dynamic and static analyses, can guide future seismic design practices and contribute to safer construction standards in the region. Figure 15 shows the maximum story drift of low-rise RC buildings subjected to three different scaled earthquake records: El-Centro (1940), Bam (2003), and Gazli (1976) across seismic zones I to IV. The figure illustrates the comparative performance of the buildings under these ground motions in different seismic zones.



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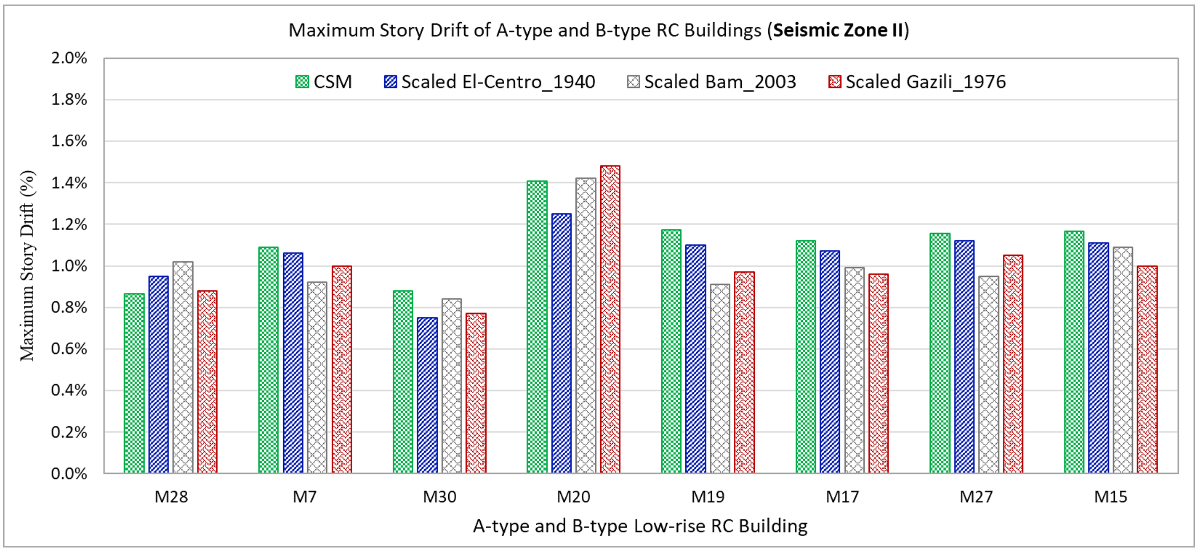

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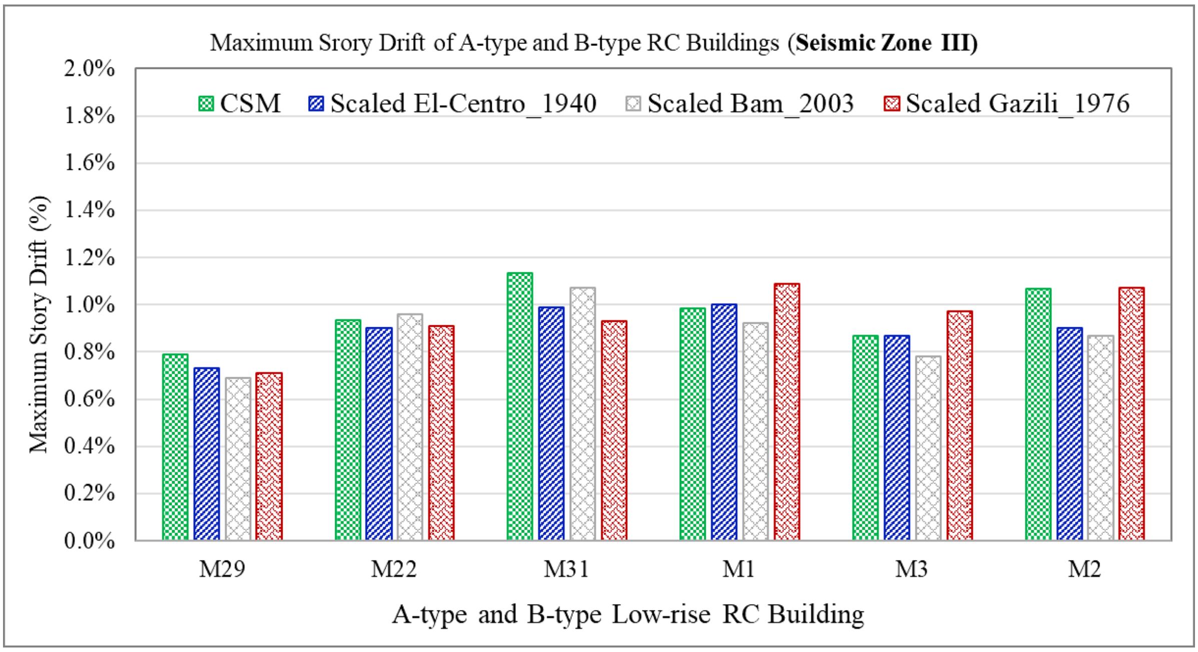

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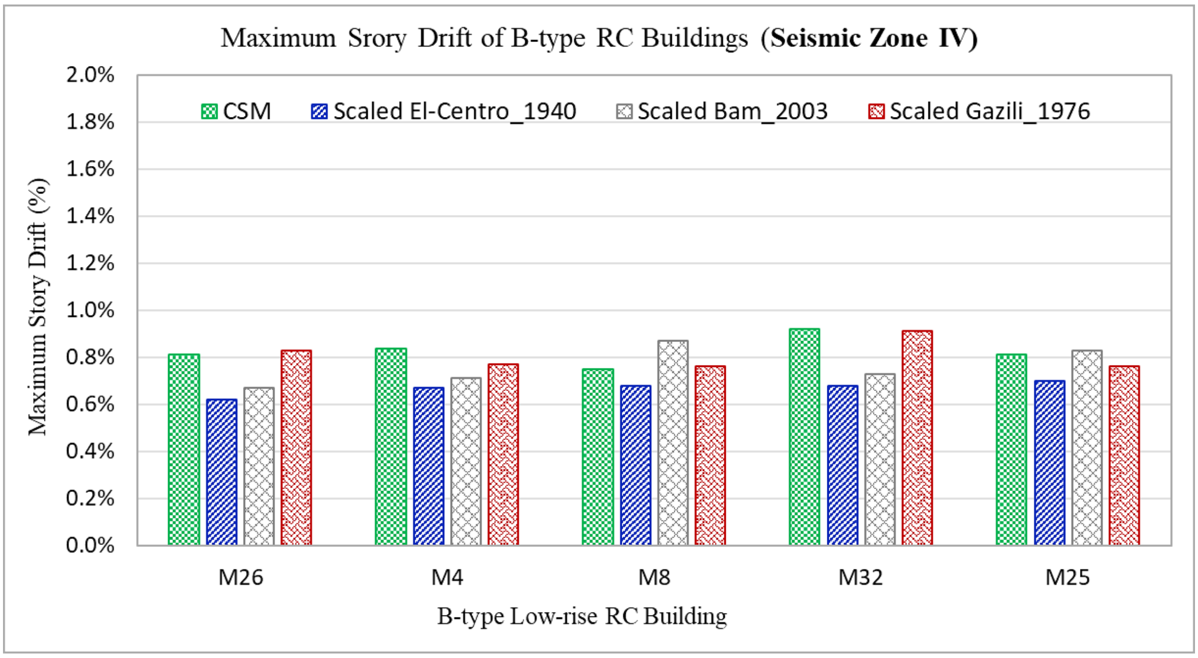

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Figure 15. Maximum Story Drift of RC Structures under Scaled Earthquakes: (a) Seismic Zone I, (b) Zone II, (c) Zone III, and (d) Zone IV

11. Proposed Afghanistan Seismic Index for Low-rise RC Buildings

11.1. Overview of the Proposed Afghanistan Seismic Index (ASI)

Figure 16 and Table 11 illustrate the proposed ASI for low-rise RC structures in seismic zones I to IV. ASI values are shown on the vertical axis and plotted against maximum story drift on the horizontal axis. The ASI has been developed to evaluate the seismic vulnerability of RC structures across Afghanistan's various seismic zones. This framework is based on a detailed structural analysis using the CSM and the Japanese Is Index as foundational references, modified to reflect local construction practices and conditions specific to Afghanistan. The ASI provides a practical, region-specific tool to support engineers, architects, and policymakers in evaluating seismic risks and implementing mitigation strategies for low-rise RC buildings. Each seismic zone has a unique ASI threshold, providing a benchmark for assessing building resilience in varying seismic hazard levels.

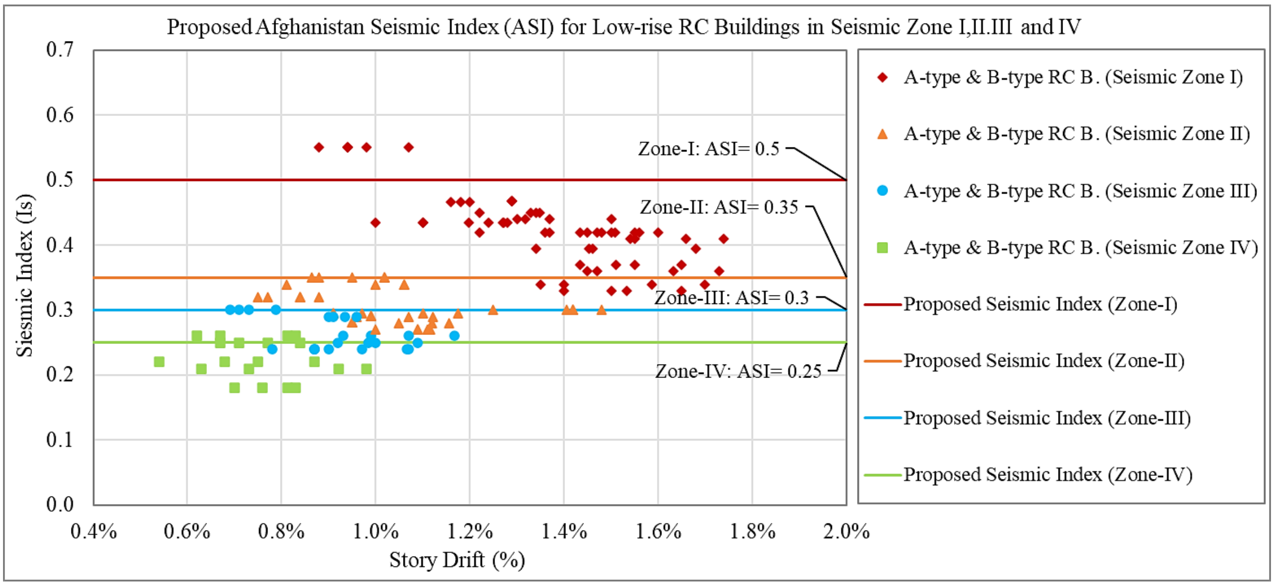

Figure 16. Proposed Afghanistan Seismic Index (ASI) of Low-Rise RC Buildings in Seismic Zone I-IV

Table 12. Summary of the proposed ASI for Low-rise RC building

No.	Building Type	Zone-I	Zone-II	Zone-III	Zone-IV
1	Maximum seismic index of A-type low-rise RC Building	0.55	0.35	0.30	0.26
2	Maximum seismic of B-Type Low-rise RC Building.	0.42	0.30	0.29	0.26
3	Average seismic of A-type and B-type RC Building.	0.49	0.33	0.30	0.26
4	Proposed seismic index for four different zones.	0.50	0.35	0.30	0.25

11.2. Seismic Zones and ASI Values

Afghanistan is divided into four distinct seismic zones, classified according to seismic hazard intensity and local geological conditions. The seismic vulnerability of RC structures varies depending on these zones, each with a proposed ASI that reflects the expected seismic demands and building performance requirements. The proposed ASI thresholds for the four seismic zones reflect the expected seismic demands and building performance requirements. For example, Zone I, with the highest seismic risk, has an ASI threshold of 0.50. This ensures that buildings in this zone are designed to withstand severe ground motions, reducing the likelihood of collapse. In contrast, Zone IV, with the lowest seismic risk, has an ASI threshold of 0.25, balancing safety with cost-effectiveness.

- Zone I (Highest Seismic Risk): The proposed ASI for Zone I is 0.50, indicating significant vulnerability to seismic events. The maximum seismic index for A-type buildings in this zone is 0.55, while B-type buildings reach a maximum index of 0.42. These high values demonstrate the need for rigorous seismic design and construction standards to mitigate the risk in this zone.
- Zone II (Moderate Seismic Risk): The proposed ASI for Zone II is 0.35. A-type buildings exhibit a maximum seismic index of 0.35, while B-type structures show a maximum index of 0.30. This suggests that buildings in Zone II face moderate seismic demands and should be designed accordingly.
- Zone III (Lower Seismic Risk): In Zone III, the proposed ASI is 0.30, reflecting lower seismic demands than Zones I and II. The maximum seismic indices for A-type and B-type buildings are 0.30 and 0.29, respectively, indicating relatively lower vulnerability to seismic events.
- Zone IV (Lowest Seismic Risk): The proposed ASI for Zone IV is 0.25, the lowest among the four zones. A-type and B-type structures have a maximum seismic index of 0.26, suggesting minimal seismic risk in this zone, though basic seismic provisions should still be considered.

11.3. Building Types and Performance

A-type buildings consistently achieve higher ASI values due to their adherence to stricter design standards post-2018. B-type buildings, constructed under less stringent standards, demonstrate lower ASI values and greater vulnerability to seismic forces. Retrofitting strategies must prioritize B-type buildings, especially in Zones I and II, to enhance their resilience. In addition, some buildings constructed before 2014 (B-type) are more vulnerable in seismic zones I and II.

11.4. Interpretation of ASI Values

The proposed ASI values for each seismic zone are derived from the performance points obtained using the CSM, and the seismic indices are calculated based on the Japanese standard. These values are tailored to account for Afghanistan's unique seismic environment and construction practices. The ASI framework offers a simple yet effective method for assessing the seismic vulnerability of low-rise RC buildings and guiding future improvements in building codes and design standards. Implementing the ASI in Afghanistan's building code can improve safety, optimize resource allocation, and reduce earthquake-related losses. Table 12 and Figure 16 illustrate the details of the proposed ASI.

12. Comparison with Previous Studies

The results of this research are consistent with previous studies and emphasize the effectiveness of the ASI. The inverse correlation between the Seismic Index and maximum story drift supports Paulay & Priestley [18], who emphasized the role of ductility and energy dissipation in seismic performance. Buildings with higher Seismic Index values demonstrate lower displacement, reinforcing the Is-index as a reliable predictor of structural vulnerability. The results also validate concerns raised by Sezen et al. [19], observing poor reinforcement detailing and construction quality as key contributors to earthquake-induced failures. This study further confirms these concerns by showing that B-type buildings, particularly those constructed before 2018, have lower seismic indices and higher story drifts due to inadequate design standards. Furthermore, the improved performance of A-type buildings, designed under stricter post-2018 codes, aligns with Sharafi & Saito [15], who highlighted the impact of updated seismic design standards on RC structures in Afghanistan. The reduced story drifts and higher seismic indices of A-type buildings underscore the benefits of modern design codes, improved material quality, and enhanced detailing. Additionally, their compliance with FEMA 356/ASCE 41 and Eurocode 8 confirms the effectiveness of recent design code updates in ensuring seismic safety.

While Kumar et al. [17] employed machine learning to evaluate seismic vulnerability, focusing on shear ratio; using the Seismic Index (Is), this study identifies a similar trend with higher indices corresponding to better seismic performance. The analysis of 34 low-rise RC buildings strengthens this observation, providing a comprehensive dataset for vulnerability assessment. This study advocates tailored seismic assessments, consistent with Fotopoulou et al. [25], who emphasized the limitations of generic fragility curves. The development of ASI accounts for Afghanistan's construction practices, seismic hazards, and material characteristics. Its validation through international standards and the CSM confirms its reliability as a predictive tool for structural performance comparison with Raoufy et al. [14], who identified hospital buildings in Kabul as highly vulnerable due to inadequate detailing, underscores the role of modern design codes in mitigating vulnerabilities. The superior seismic performance of post-2018 A-type structures validates the effectiveness of updated codes. In contrast, the continued vulnerability of B-type buildings in Seismic Zones I and II highlights the need for targeted retrofitting strategies, such as those proposed by Utku & Nishiyama [26].

A broader comparison with international studies further reinforces the advantages of a region-specific seismic assessment approach. Islam et al. [27, 28] demonstrated that Japanese seismic evaluation methods provided a more accurate assessment of RC structures in Bangladesh than global models. Similarly, ASI integrates Afghanistan's construction practices, seismic hazard levels, and material characteristics, making it a precise and applicable tool for assessing seismic vulnerability. The following points can summarize the key contributions and advantages over previous studies:

12.1. Development of a Region-Specific Seismic Index (ASI)

- Unlike previous studies that used global indices, this study introduces the ASI, which integrates local seismic data, construction materials, and architectural styles, making it highly applicable to Afghanistan.

12.2. Integration of Advanced Analysis Methods

- Many past studies relied primarily on static pushover analysis or empirical fragility curves, whereas this study combines the CSM and dynamic analysis using STERA 3D and the Japanese standards.

12.3. Comprehensive Database of RC Buildings

- Unlike past studies that focused on a small dataset or a specific type of structure, this study evaluates 34 low-rise RC buildings constructed between 2001 and 2022 across four seismic zones, representing a diverse range of structural configurations.

12.4. Validation Against International Standards

- The Afghanistan Seismic Index (ASI) was validated against Japanese Seismic Standards, FEMA 356/ASCE 41, and Eurocode 8, ensuring global applicability.

12.5. Potential for Future Policy and Code Updates

- The Afghanistan Seismic Index (ASI) can be a foundation for updating the Afghan Building Code (ABC), providing engineers and policymakers with a scientific basis for seismic design improvements.

Overall, the comparison results validate the methodology and findings of this study while underscoring the necessity of implementing region-specific seismic indices for enhanced risk assessment. The correlation between Seismic Index values and structural drift confirms the reliability of the Is-index as a vulnerability metric. The significant performance gap between A-type and B-type buildings further reinforces the effectiveness of modern design codes in improving seismic resilience

13. Conclusions

This research evaluated the seismic vulnerability of RC structures in Afghanistan by developing and validating the Afghanistan Seismic Index (ASI). The study responded to the critical need for a region-specific tool to evaluate the resilience of buildings constructed under varying conditions in a seismically active region, adapting global seismic assessment methods to Afghanistan's unique construction practices and seismic hazards. A comprehensive database of RC low-rise structures was constructed from 2006 to 2022 in four seismic zones. The key findings of the current research can be summarized as follows:

- B-type RC structures constructed before 2018 exhibited lower seismic performance than newer A-type buildings.
- Buildings in Seismic Zone I (high seismic activity) showed the most significant vulnerability, with many B-type buildings having lower seismic indices.
- A-type buildings, designed under stricter post-2018 standards, had higher seismic indices and lower inter-story drifts, indicating better resilience to seismic forces.
- The CSM and the modified Japanese Seismic Index (Is) proved effective in evaluating the seismic performance of low-rise RC structures.
- The developed ASI provides a reliable tool for assessing and mitigating seismic risks in low-rise RC buildings tailored to Afghanistan's specific seismic zones and construction practices.
- A clear correlation was found between higher seismic indices and lower inter-story drift, demonstrating the reliability of the ASI for predicting building performance during earthquakes.

These findings have substantial implications for improving building safety and resilience in Afghanistan. The proposed ASI offers a practical tool for policymakers, engineers, and urban planners to implement better seismic design standards, promote retrofitting strategies for vulnerable buildings, and mitigate the potential impacts of future earthquakes. The ASI provides a foundation for updating the Afghan Building Code and guiding seismic design practices.

Despite its contributions, this research has certain limitations. The study relies on simulated earthquake data due to a lack of local seismic records. Additionally, the analysis focused solely on low-rise buildings, which may limit the generalizability of the findings to other building types. Further studies should incorporate real seismic data and extend the analysis to include mid-rise and high-rise structures to create a more comprehensive seismic risk assessment framework.

Future research should also focus on experimentally validating the ASI using real-time earthquake data and ground motions from the region. Expanding the database of buildings and exploring different structural systems can help refine the ASI and improve its accuracy in assessing building vulnerability.

In conclusion, this research marks a significant step towards enhancing seismic resilience in Afghanistan. The development of the ASI provides a vital tool for assessing and mitigating seismic risks, offering a pathway to safer urban environments and reducing regional earthquake-related losses.

14. Declarations

14.1. Author Contributions

Conceptualization, S.S.Q. and T.S.; methodology, S.S.Q.; software, T.S.; validation, S.S.Q., T.S., and T.I.M.; formal analysis, S.S.Q.; investigation, S.S.Q.; resources, T.S.; data curation, S.S.Q.; writing—original draft preparation, S.S.Q.; writing—review and editing, T.I.M.; visualization, S.S.Q.; modeling and simulations, S.S.Q.; supervision, T.S.; project administration, T.S.; funding acquisition, T.S. All authors have read and agreed to the published version of the manuscript.

14.2. Data Availability Statement

The data presented in this study are available in the article.

14.3. Funding and Acknowledgements

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14.4. Conflicts of Interest

The authors declare no conflict of interest.

15. References

[1] Kufner, S. K., Schurr, B., Haberland, C., Zhang, Y., Saul, J., Ischuk, A., & Oimahmadov, I. (2017). Zooming into the Hindu Kush slab break-off: A rare glimpse on the terminal stage of subduction. Earth and Planetary Science Letters, 461, 127–140. doi:10.1016/j.epsl.2016.12.043.

[2] Ismail, N., & Khattak, N. (2015). Reconnaissance report on the Mw 7.5 Hindu Kush earthquake of 26th October 2015 and the subsequent aftershocks. United Arab Emirates University: Al Ain, United Arab Emirates.

[3] CESMD | USGS (2025) Center for Engineering Strong Motion Data (CESMD), Geological Survey and California Geological Survey, United States Geological Survey (USGS), Reston, United States. Available online: https://www.strongmotioncenter.org/ (accessed on February 2025).

[4] Yeats, R. S., & Madden, C. (2003). Damage from the Nahrin, Afghanistan, Earthquake of 25 March 2002. Seismological Research Letters, 74(3), 305–311. doi:10.1785/gssrl.74.3.305.

[5] Ambraseys, N. N., & Douglas, J. (2004). Magnitude calibration of north Indian earthquakes. Geophysical Journal International, 159(1), 165–206. doi:10.1111/j.1365-246X.2004.02323.x.

[6] Shnizai, Z., Walker, R., & Tsutsumi, H. (2024). The Chaman and Paghman active faults, west of Kabul, Afghanistan: Active tectonics, geomorphology, and evidence for rupture in the destructive 1505 earthquake. Journal of Asian Earth Sciences, 259. doi:10.1016/j.jseaes.2023.105925.

[7] Chenna, R., Patnala, N., Vemuri, J. P., & Ramancharla, P. K. (2023). Insights on the June 21, 2022, Khost earthquake, Afghanistan. Sādhanā, 48(3), 144. doi:10.1007/s12046-023-02215-y.

[8] Qi, Y., Feng, W., Zhang, Y., Wang, D., Du, Y., Samsonov, S. V., Zhang, P. Z., Zaray, A. H., & Ansari, A. (2023). Fault Geometry, Slip Distribution, and Potential Triggering of the 2022 Mw 6.2 Deadly Afghanistan Earthquake Revealed from Geodetic and Weather Data. Seismological Research Letters, 94(5), 2154–2166. doi:10.1785/0220220341.

[9] Mohammadi, M., & Fujimi, T. (2021). Impact of retrofitting work on vulnerability reduction of local buildings in Kabul, Afghanistan. Jàmbá Journal of Disaster Risk Studies, 13(1), 1-13. doi:10.4102/jamba.v13i1.1062.

[10] Ismail, N., & Khattak, N. (2019). Observed failure modes of unreinforced masonry buildings during the 2015 Hindu Kush earthquake. Earthquake Engineering and Engineering Vibration, 18(2), 301–314. doi:10.1007/s11803-019-0505-x.

[11] Sharafi, Q., Naqi, A., & Taiki, S. (2021). Effect of Brick Masonry Infill Walls on Seismic Performance of Reinforced Concrete Frame Structures in Afghanistan. 1st Croatian Conference on Earthquake Engineering, 921–930. doi:10.5592/co/1crocee.2021.76.

[12] Sharafi, S. Q., & Saito, T. (2023). Effect of infill masonry wall with central opening on seismic behaviour of reinforced concrete structure. International Journal of Masonry Research and Innovation, 8(6), 531–548. doi:10.1504/ijmri.2023.134237.

[13] Raoufy, A. A., Kheyroddin, A., & Naderpour, H. (2024). Comparative Study of Rapid Visual Screening Methods in Determining the Seismic Vulnerability of Existing Reinforced Concrete Hospital Buildings. Iranian Journal of Science and Technology - Transactions of Civil Engineering, 48(4), 2263–2277. doi:10.1007/s40996-023-01288-3.

[14] Raoufy, A. A., Kheyroddin, A., & Naderpour, H. (2023). Seismic Vulnerability Assessment of Reinforced Concrete Hospital Buildings Using Rapid Visual Screening Method According to FEMA P-154 criteria and Iranian Code# 364. Civil Infrastructure Researches, 9(2), 77. doi:10.22091/cer.2023.9178.1462.

[15] Sharafi, S. Q., & Saito, T. (2024). Seismic Damage Probability Assessment of Existing Reinforced Concrete School Buildings in Afghanistan. Buildings, 14(4), 1054. doi:10.3390/buildings14041054.

[16] Ismailov, V. A., Yodgorov, S. I., Khusomiddinov, A. S., Yadigarov, E. M., Aktamov, B. U., & Avazov, S. B. (2024). Regional seismic risk assessment based on ground conditions in Uzbekistan. Natural Hazards and Earth System Sciences, 24(6), 2133–2146. doi:10.5194/nhess-24-2133-2024.

[17] Kumar, T., Al Amin Siddique, M., & Ahsan, R. (2024). Seismic Vulnerability Assessment of Reinforced Concrete Educational Buildings Using Machine Learning Algorithm. Advances in Civil Engineering, 2315316. doi:10.1155/2024/2315316.

[18] Paulay, T., & Priestly, M. J. N. (1992). Seismic Design of Reinforced Concrete and Masonry Buildings. John Wiley & Sons, Hoboken, United States. doi:10.1002/9780470172841.

[19] Sezen, H., Whittaker, A. S., Elwood, K. J., & Mosalam, K. M. (2003). Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey. Engineering Structures, 25(1), 103–114. doi:10.1016/S0141-0296(02)00121-9.

[20] Lazzali, F., & Farsi, M. N. (2020). Rapid seismic vulnerability assessment of buildings in the old Algiers. Journal of Materials and Engineering Structures, 7(3), 377-387.

[21] Kassem, M. M., Mohamed Nazri, F., & Noroozinejad Farsangi, E. (2020). The seismic vulnerability assessment methodologies: A state-of-the-art review. Ain Shams Engineering Journal, 11(4), 849–864. doi:10.1016/j.asej.2020.04.001.

[22] Kassem, M. M., Mohamed Nazri, F., Noroozinejad Farsangi, E., & Tan, C. G. (2021). Comparative seismic RISK assessment of existing RC buildings using seismic vulnerability index approach. Structures, 32, 889–913. doi:10.1016/j.istruc.2021.03.032.

[23] Otani, S. (2000). Seismic vulnerability assessment methods for buildings in Japan. Earthquake Engineering and Engineering Seismology, 2(2), 47-56.

[24] Maeda, M., Matsukawa, K., & Ito, Y. (2014). Revision of guideline for post-earthquake damage evaluation of RC buildings in Japan. Tenth U.S. National Conference on Earthquake Engineering, Anchorage, Alaska, United States.

[25] Fotopoulou, S., Karafagka, S., Petridis, C., Manakou, M., Riga, E., & Pitilakis, K. (2023). Vulnerability Assessment of School Buildings: Generic versus Building-Specific Fragility Curves. Journal of Earthquake Engineering, 27(11), 2994–3023. doi:10.1080/13632469.2022.2121791.

[26] Yazgan, A. U., & Nishiyama, M. (2008). Seismic performance evaluation of existing RC structures according to the Japanese standard and retrofitting with prestressed precast CFT and FRC braces. Bulletin of the International Institute of Seismology and Earthquake Engineering, 42, 115-120.

[27] Islam, N., Roy, K. S., Islam, K., Imran, M., & Hoosain, A. (2015). Seismic vulnerability assessment of existing Reinforced Concrete residential buildings by Japanese Method. First International Conference in Advances in Civil Infrastructure and Construction Materials (CICM 2015), 14-15 December, 2015, Dhaka, Bangladesh.

[28] Islam, N., Roy, K. S., & Islam, K. (2015). Use of design of experiment in seismic vulnerability assessment for existing RC Buildings by Japanese Method. Fifth International Conference on Geotechnique, Construction Materials and Environment, 16-18 November, 2015, Osaka, Japan.

[29] Islam, S., Chowdhury, N. J., Jahan, T., Mahzuz, H. M. A., & Ahmed, S. (2024). Seismic Evaluation of an Existing Building using Japanese Index Method. 12-14 December, 2024, Chattogram, Bangladesh.

[30] Samuel, M. A., Xiong, E., Haris, M., Lekeufack, B. C., Xie, Y., & Han, Y. (2024). Assessing Seismic Vulnerability Methods for RC-Frame Buildings Pre- and Post-Earthquake. Sustainability, 16(23), 10392. doi:10.3390/su162310392.

[31] Miceli, E., Ferrara, S., & Castaldo, P. (2024). Confinement effects within the seismic design of reinforced concrete frames: reliability assessment and comparison. Engineering Structures, 313. doi:10.1016/j.engstruct.2024.118248.

[32] Panahi Boroujeni, M., Zareei, S. A., Birzhandi, M. S., & Zafarani, M. M. (2024). Development of Seismic Fragility Functions for Reinforced Concrete Buildings Using Damage-Sensitive Features Based on Wavelet Theory. Structural Control and Health Monitoring, 2024. doi:10.1155/2024/8754191.

[33] Haziq, D., & Kiyotaka, M. (2017). Afghanistan building codes (ABC): Focused on comparative analysis and the viability of enforcement. Proceedings of the Architectural Engineering Conference, 11-13 April, 2017, Oklahoma City, United States.

[34] ANSA (2025). Afghan National Standards Authority (ANSA), Kabul, Afghanistan. Available online: https://www.ansa.gov.af/ (accessed on February 2025).

[35] UNDRR. (2020). Disaster Risk Reduction in Afghanistan. Status report 2020, Asian Disaster Preparedness Center (ADPC), United Nations Office for Disaster Risk Reduction (UNDRR), Bangkok, Thailand.

[36] Hu, B., Lv, H. L., & Kundu, T. (2019). Experimental study on seismic behavior of reinforced concrete frame in primary and middle schools with different strengthening methods. Construction and Building Materials, 217, 473-486. doi:10.1016/j.conbuildmat.2019.05.040.

[37] Saito, T. (2024). Structural Earthquake Response Analysis 3D, (STERA 3D Version 11.5). Earthquake Disaster Engineering Research Laboratory, Toyohashi University of Technology, Japan. Available online: https://rc.ace.tut.ac.jp/saito/software-e.html#p01 (accessed on February 2025).

[38] PEER (2025). Ground Motion Database, Pacific Earthquake Engineering Research Center (PEER). University of California, Berkeley, United States. Available online: https://ngawest2.berkeley.edu/ (accessed on February 2025).

[39] Saito, T. (2024). Structural Earthquake Response Analysis 3D, (STERA_WAVE. Version 1.0). Earthquake Disaster Engineering Research Laboratory, Toyohashi University of Technology, Japan. Available online: https://rc.ace.tut.ac.jp/saito/software-e.html#p01 (accessed on February 2025).

[40] MOE. (2022). Annual Report. Ministry of Education (MOE), Kabul, Afghanistan.

[41] Sharafi, S. Q., Alberto, M. A. E., & Saito, T. (2024). Assessment of Seismic Fragility Curves for Existing RC School Buildings in Afghanistan. Journal of Japan Association for Earthquake Engineering, 24(5), 5_220-5_233. doi:10.5610/jaee.24.5_220.

[42] JBDPA. (2001). Standard for Seismic Evaluation of Existing Reinforced Concrete Building. The Japan Building Disaster Prevention Association (JBDPA), Tokyo, Japan.

[43] Boyd, O. S., Mueller, C. S., & Rukstales, K. S. (2007). Preliminary earthquake hazard map of Afghanistan. US Geological Survey Open-File Report, 2007, 1137, U.S. Geological Survey, U.S. Department of the Interior, Washington, United States.

[44] Frankel, A. D., Mueller, C. S., Barnhard, T. P., Leyendecker, E. V., Wesson, R. L., Harmsen, S. C., ... & Hopper, M. G. (2000). USGS national seismic hazard maps. Earthquake spectra, 16(1), 1-19. doi:10.1193/1.1586079.

[45] EC-8 | EN 1998-1. (2004). Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization, Brussels, Belgium.

[46] FEMA 356. (2000). Prestandard and commentary for the seismic rehabilitation of buildings. Federal Emergency Management Agency (FEMA), Washington, United States.

[47] Nguyen, H. D., Kim, C., Lee, Y. J., & Shin, M. (2024). Incorporation of machine learning into multiple stripe seismic fragility analysis of reinforced concrete wall structures. Journal of Building Engineering, 97. doi:10.1016/j.jobe.2024.110772.