Journal of Civil Engineering, Science and Technology
Volume 15, Issue 2, September 2024, 90-95

EDITORIAL SCOPE: BEYOND RESILIENCE – INDEX FOR THE NEXT-GENERATION OF SEISMIC VULNERABILITY FOR RC STRUCTURE

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Date received: 10/09/2024 Date accepted: 20/09/2024
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DOI: 10.33736/jcest.7804.2024

Abstract — Seismic vulnerability assessment has become an indispensable tool in earthquake engineering, especially for reinforced concrete (RC) structures, which are prevalent in urbanized regions worldwide. In this editorial note, we expand on key contributions from recent papers published in the Journal of Building Engineering and Journal of Earthquake Engineering, merging these insights with findings from the book "Seismic Vulnerability Index Assessment Framework of RC Structures." Together, these works form a cohesive narrative around the development of a more refined and globally applicable Seismic Vulnerability Index (SVI) framework for RC structures. Moreover, this editorial note discusses the advancements in the seismic vulnerability assessment of RC buildings through the development of an SVI methodology. This methodology uses advanced nonlinear parametric analyses to quantify the seismic vulnerability of RC buildings, contributing significantly to disaster risk reduction efforts. Thus, the contribution lies in developing improved methodologies for assessing seismic vulnerability and quantifying seismic risk, ultimately aiding in enhancing earthquake resilience. This comprehensive framework is globally applicable, adaptable to any geographical region, and suitable for a wide range of structural types and systems.

Keywords: analytical approach, damage state, framework, nonlinear analysis, seismic vulnerability index

1.0 INTRODUCTION

The increase in seismic events across various regions highlights the need for uniform assessment methods to predict the vulnerability of structures, particularly reinforced concrete (RC) buildings, which form the backbone of modern infrastructure. The book "*Seismic Vulnerability Index Assessment Framework of RC Structures*" complements the findings from the recent studies "*Improved Vulnerability Index Methodology to Quantify Seismic Risk and Loss Assessment in Reinforced Concrete Buildings*" and "*Development of a uniform seismic vulnerability index framework for reinforced concrete building typology*" by providing a detailed guide on the development, implementation, and validation of SVI methodologies [1–3]. These works underscore the urgency of establishing frameworks that are adaptable to both seismic-prone and non-seismic regions. Seismic vulnerability assessments are essential for understanding how structures perform during earthquakes. RC buildings, widely used in urban construction, must be evaluated for their resilience against seismic forces, especially in regions with increasing seismic activity. While local seismic codes have evolved, global variations in construction practices necessitate a standardized approach to seismic risk assessment. This editorial note outlines the advancements in creating a uniform Seismic Vulnerability Index (SVI) framework, focusing on how the integration of empirical data, advanced analytics, and probabilistic modeling has enhanced the accuracy of predicting the seismic behavior of RC buildings. This editorial outlines the SVI methodology developed to classify RC buildings based on their expected seismic performance, enhancing both pre-earthquake preparation and post-earthquake recovery strategies.

2.0 DEVELOPMENT OF SEISMIC VULNERABILITY INDEX (SVI) FRAMEWORK

Kassem et al. [1] develop the Seismic Vulnerability Index (SVI) framework and provide complementary insights into the development of an SVI model that applies uniformly across different geographical regions and construction typologies. The SVI model, refined through non-linear parametric analysis (NLPA) and incremental dynamic analysis (IDA), serves as the core methodology in both studies, allowing for consistent classification of building vulnerabilities into low, moderate, and high categories.

The SVI method integrates critical structural factors, such as beam-column joint conditions, irregularities in mass and stiffness, and the impact of material properties on the dynamic behavior of buildings under seismic loads. By focusing on these parameters, the SVI framework allows for a detailed analysis of the performance of reinforced concrete (RC) structures, identifying areas where design improvements are necessary to enhance seismic resilience. The integration of this framework with probabilistic seismic risk assessment models ensures that vulnerability assessments are not limited to a single event but encompass a range of potential seismic scenarios.

Establishing a global SVI helps mitigate the reliance on expert opinion and damage assessments in rapid visual screening procedures, providing a valuable framework in earthquake field.

3.0 EMPIRICAL AND ANALYTICAL APPROACH INTEGRATION

The SVI framework is refined by emphasizing the integration of empirical post-earthquake survey data with advanced analytical tools [2]. According to Kassem et al. [2], visual post-event assessments should be replaced by data-driven insights.

On the other hand, Kassem and Mohamed Nazri [1] describe how to move from empirical field observations to analyses. SVI simulates real-world seismic conditions and predicts structural damage across earthquake intensities using non-linear dynamic analysis (NLDA) and ground motion recordings from worldwide databases like PEER and COSMOS. Because it accounts for past earthquake damage and theoretical scenarios, this hybrid method makes the model more durable and reliable.

The empirical-to-analytical integration validates the SVI framework using historical earthquake events, such as the 2015 Ranau earthquake in Malaysia [3]. SVI's structural vulnerability prediction accuracy is confirmed by this validation method, which gives crucial insights for locations without post-seismic data.

4.0 KEY METHODOLOGICAL IMPROVEMENTS

One of the central contributions of Kassem et al. [1-3] research work is the transition from purely empirical vulnerability assessments denoted by GNDT [4], which often rely on visual inspections and post-earthquake damage surveys, to a more rigorous analytical approach. The SVI framework integrates NLPA and IDA to simulate the behavior of RC buildings under different earthquake scenarios.

In order to evaluate RC structures' seismic response, the framework uses ground motion recordings from worldwide databases such as PEER and COSMOS. This allows for the detection of crucial structural defects such as mass irregularities, inadequate shear capability, and poorly detailed beam-column joints. The SVI uses models of these criteria to categorize structures into three levels of susceptibility, low, moderate, and high, according to how effectively they can withstand seismic loads. The SVI framework's analytical approaches enable the development of fragility and vulnerability curves, which measure the possibility of a structure attaining different damage states. Important for disaster preparedness plans, these curves show the likelihood of partial or complete collapse during an earthquake.

Italian GNDT and European Macroseismic (EMS-98) methods were modified to form the basis of the SVI methodology [5]. It analyzes the response of reinforced concrete structures to earthquakes by using Nonlinear Static Analysis (NL-SA) and Nonlinear Time History Analysis (NL-THA). Three separate vulnerability classes were established for the eight factors that made up the Earthquake Resistant Design (ERD) model: Low, Moderate, and High. Connections between beams and columns, boundary conditions, soil type, ductility level, vertical and horizontal irregularities, concrete strength, and horizontal diaphragm systems are all examples of such parameters.

SVI frameworks can be used to develop a model that is applicable in all regions and types of buildings [6]. Building vulnerabilities are consistently classified into low, moderate, and high categories using the SVI model, which was refined by NLPA and IDA. This model forms the basic approach of both investigations.

The SVI framework allows for a detailed analysis of the performance of RC structures, identifying areas where design improvements are necessary to enhance seismic resilience. The integration of this framework with probabilistic seismic risk assessment models ensures that vulnerability assessments are not limited to a single event but encompass a range of potential seismic scenarios.

4.1. Key Parameters

1. Beam-Column Joint Connection (P1): The vulnerability of the beam-column joints, which are critical in resisting seismic forces, is modeled based on the rigidity of the connections. The methodology assesses the performance of flexible, semi-rigid, and fully rigid joints, assigning vulnerability scores accordingly.

2. Boundary Condition Support (P2): The boundary conditions, representing the type of foundation or ground interaction, are essential in determining how the structure dissipates seismic energy. The model considers hinged, semi-rigid, and fully fixed boundary conditions to assess the building's resilience under seismic forces.

3. Horizontal Diaphragm System (P3): The horizontal diaphragm transfers lateral forces to the building's vertical elements. The SVI methodology models diaphragms as rigid, semi-rigid, or flexible, each contributing differently to the overall seismic performance.

4. Type of Soil (P4): The soil structure interaction (SSI) is a key parameter, as different soil types affect the building's response to seismic forces. The methodology uses soil types classified as C, D, and E, calculating the stiffness of soil through spring models to understand how different foundation conditions impact vulnerability.

5. Ductility Level (P5): Ductility refers to the structure's ability to undergo deformation without significant damage. This parameter is modeled based on the building's structural system, with low-ductility (ordinary moment-resisting frames), moderate-ductility (intermediate moment-resisting frames), and high-ductility (special moment-resisting frames) categories.

6. Horizontal and Vertical Irregularities (P6 and P7): The mass distribution in a building can significantly influence its seismic response. Irregular mass ratios between floors (greater than 1.5, as per UBC97 code) indicate higher vulnerability. The methodology models both horizontal and vertical irregularities, providing an accurate vulnerability assessment.

7. Concrete Strength (P8): The strength of concrete plays a critical role in resisting seismic forces. Lower-strength concrete results in higher vulnerability, whereas buildings with high-grade concrete exhibit greater resilience. The methodology categorizes concrete strength into classes such as C16, C25, and C35, with C35 being the most resistant.

4.2. Analytical Approach

To determine how RC buildings behave to seismic forces, the SVI technique employs nonlinear analysis. Particularly, nonlinear-time history analysis (NL-THA) analyzes the building's behavior dynamically during seismic events, while NL-SA evaluates the building frames for failure mechanisms and the production of plastic hinges using pushover analysis. The IDA and Pushover Analysis (POA) curves, which measure the building's susceptibility according to its maximum top displacement, are generated by these assessments.

Next, the eight parameters are given weights based on the displacement data; higher displacements indicate a higher level of vulnerability. The total weights determine the SVI, which can take on values between zero (the least vulnerable) and one hundred (the most vulnerable). Each building can be categorized into one of five vulnerability levels according to this index: Green 1 indicates negligible damage (range: [10-20]), Green 2 indicates minor damage (range: [20-40]), Orange 3 indicates moderate damage (range: [40-55]), Orange 4 indicates severe damage (range: [55-70]), and Red 5 indicates total collapse (range: [70-100]).

4.3. Mean Damage State and Vulnerability Curves

Predicting structural performance, economic losses, and human lives are all possible with the use of the SVI technique. The mean damage state is obtained once the SVI is computed. Based on the building's susceptibility and the seismic intensity peak ground acceleration (PGA), this is the anticipated amount of damage. Vulnerability curves show the average damage condition versus seismic intensity, and damage ratings go from minor (D1) to extensive (D5). In order to accurately estimate possible losses and recovery requirements, this predictive capability is vital for emergency preparedness.

5.0 SAMPLE OF SVI CALCULATION FOR A PARTICULAR PARAMETER

Step 1: Maximum Displacement Calculation

The maximum displacement values (D_{max}) are calculated for each seismic record across different vulnerability classes (Low-ERD, Moderate-ERD, High-ERD) of the hospital building. These values represent the maximum lateral displacement that the structure experienced during the seismic event, considering the type of soil it is built on.

- Low-ERD: Represents buildings with low earthquake resistance.
- Moderate-ERD: Represents buildings with moderate earthquake resistance.
- High-ERD: Represents buildings with high earthquake resistance.

For example, for seismic record 1, the maximum displacements for the three classes are:

- Low-ERD: 22.883 mm
- Moderate-ERD: 12.683 mm
- High-ERD: 9.594 mm

These values indicate how much each building class displaces under seismic loading.

Step 2: Displacement Capacity Ratio (DCR) Calculation

The Displacement Capacity Ratio (DCR) is the ratio of the maximum displacement experienced by the structure in a specific seismic record and vulnerability class, relative to the sum of the maximum displacements across all vulnerability classes for that record.

The formula to calculate K_i for each vulnerability class is:

$$\text{Ki} = \frac{D_{max}}{\sum D_{max}\,(\text{all classes})} \tag{1}$$

For example, for seismic record 1, the total maximum displacement across all classes is:

$$\sum D_{max} = 22.883+12.683+9.594=45.16 \tag{2}$$

Then, calculate Ki for each class:

$$\text{Low-ERD: } = \ \text{Ki}=\frac{22.883}{45.16}=0.507$$

$$\text{Moderate-ERD: } = \ \text{Ki}=\frac{12.683}{45.16}=0.281$$

$$\text{High-ERD: } = \text{Ki}=\frac{9.594}{45.16}=0.212 \tag{3}$$

This process is repeated for all seismic records to determine the DCR for each class.

Step 3: Average Factor Calculation

The average factor K_L is the mean value of the DCR across all seismic records for each vulnerability class. This average value gives an overall indication of the vulnerability of the structure for each class considering the type of soil.

For example, for the Low-ERD class, the average factor is calculated by averaging the DCR values for all seismic records:

$$K_L\text{ (Low-ERD)} = \frac{0.507+0.458+0.482+0.453+0.440+0.515+0.528+0.433}{8} = 0.477 \quad (4)$$

This process is repeated for the Moderate-ERD and High-ERD classes, resulting in:

Low-ERD: K_L=0.477
Moderate-ERD: K_L=0.300
High-ERD: K_L=0.233

Step 4: Seismic Vulnerability Index (SVI) Calculation

The SVI is a normalized value that quantifies the overall vulnerability of the structure for each vulnerability class. The SVI is calculated based on the $K_L$values, typically normalizing them to a scale where the most vulnerable class (in this case, Low-ERD) is assigned a value of 1.

The SVI for the other classes is then calculated as the ratio of their K_L values to that of the most vulnerable class (Low-ERD):

$$\text{SVI (Moderate-ERD)} = K_L\text{ (Moderate-ERD)}/K_L\text{ (Low-ERD)} = 0.300/0.477 = 0.630$$
$$\text{SVI (High-ERD)} = K_L\text{ (High-ERD)}/K_L\text{ (Low-ERD)} = 0.223/0.477 = 0.467 \quad (5)$$

Thus, the final Seismic Vulnerability Index values for the “Type of Soil” parameter are:

Low-ERD: SVI=1.0
Moderate-ERD: SVI=0.630
High-ERD: SVI=0.467

These calculations quantify the vulnerability of the hospital building based on its resistance class and soil type. A higher SVI value indicates greater vulnerability, with the Low-ERD class being the most vulnerable. The SVI provides an essential metric for understanding how different building classes perform under seismic forces, which can help inform retrofitting and design improvements for earthquake-prone areas.

6.0 GLOBAL IMPLICATIONS OF THE SVI FRAMEWORK

By standardizing the assessment of RC building vulnerabilities, the SVI framework offers a consistent methodology for evaluating seismic risk across different regions. This is particularly important for countries with varying seismic codes and construction standards. The framework's adaptability makes it a valuable tool for regions that have yet to experience a major seismic event but are at risk due to outdated building stock or inadequate seismic design codes. The ability to integrate the SVI framework with the Global Earthquake Model (GEM) further enhances its utility, allowing governments and policymakers to use it as part of their disaster risk reduction strategies. Moreover, the SVI framework's probabilistic approach, which is emphasized in the book, allows for the estimation of both human and economic losses due to seismic events. This comprehensive risk assessment tool is essential for guiding resource allocation and developing policies aimed at mitigating the impact of future earthquakes.

7.0 CONCLUSION

The synthesis of insights from the SVI assessment framework of RC Structures developed by Kassem et al. [1] provides a thorough understanding of the advancements in seismic vulnerability assessment for RC buildings. This framework introduces a new analytical approach, improving upon the empirical methods derived from the GNDT and European Macroseismic approaches, which primarily relied on field damage observations and lacked the data necessary for broader application. By integrating empirical data with advanced analytical modeling and probabilistic risk assessment, the improved SVI framework offers a more comprehensive and accurate tool for predicting structural vulnerabilities and enhancing earthquake resilience strategies.

As urban areas continue to expand and seismic risks remain a significant concern, the development and implementation of standardized assessment frameworks like the SVI are crucial. The case study validation using the 2015 Ranau earthquake demonstrates the effectiveness of the SVI framework, while its global applicability ensures that it can be used to enhance disaster preparedness and risk mitigation efforts worldwide.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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