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Simplified Seismic Resilience Index for Bridges

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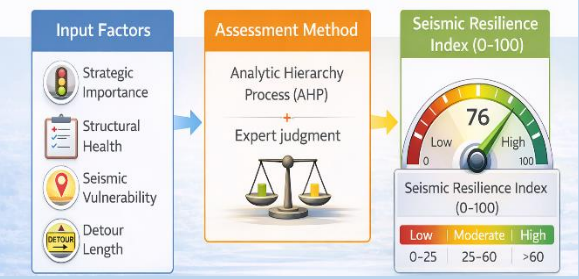
Abstract: Bridges are vital elements for the continuity of transportation networks, requiring a precise assessment of their earthquake resilience. This study proposes a methodology based on the Simplified Seismic Resilience Index (SSRI), using the analytic hierarchy process method (AHP) combined with technical expertise to define the relative importance of influencing criteria, thus ensuring a model representative of real-world conditions environments. The results identify structural health and seismic vulnerability as the major drivers of resilience. Validated through case studies in Algeria and Canada and compared to complex models, the tool demonstrates strong consistency and reliability for rapid qualitative assessment. In conclusion, this simplified tool enables a rapid and reliable estimation of resilience while reducing computational complexity and data requirements compared to traditional methods, thus providing crucial decision support for infrastructure maintenance.



Keywords: AHP, bridge, environmental conditions, seismic resilience, seismic resilience index, structural health.

Introduction

Bridges play a vital role in modern transportation networks, connecting cities, regions, and communities, thereby fostering economic and social dynamism. However, their vulnerability to natural and man-made hazards, which can partially or completely disrupt their services, makes it crucial to ensure their structural integrity. The importance of bridges becomes even more evident in times of crisis, particularly during seismic disasters, where they play a critical role in facilitating humanitarian operations and relief efforts, as demonstrated by the tragic events in Haiti [1], Kahramanmaraş [2], and Myanmar [3]. Therefore, protecting these vital infrastructures requires rigorous assessment and a thorough understanding of the concepts of resilience and robustness to ensure their ability to withstand future challenges.

These events serve as a reminder that bridges are more than just engineered structures; they are a first line of defense protecting supply chains and emergency services. Thus, ensuring the capacity of bridges to withstand seismic risks has become a fundamental requirement for governments, engineers, and decision-makers. In recent decades, the concept of "resilience" has emerged as an analytical framework for understanding how systems, including infrastructure, respond to shocks and recover rapidly. This concept began to be used in environmental fields in the 1970s, focusing on the ability of ecosystems to adapt to sudden changes [4]. In civil engineering, the concept of resilience has evolved beyond basic seismic resistance, emphasizing the ability of a structure to return to its functional state as quickly as possible while also considering economic and social impacts [5]. Since 2003, this engineering approach to resilience has gained significant traction, with growing interest in measuring and assessing resilience, both quantitatively and qualitatively, to ensure the continuity of essential services in the event of natural disasters.

The concept of resilience has emerged as a pivotal framework in the design and assessment of infrastructures, particularly bridges. It focuses on their capacity to withstand, recover from, adapt to, and restore essential functions following extreme events. These characteristics are fundamental to ensuring that critical infrastructure remains operational after being exposed to natural hazards, such as earthquakes. In the context of bridge engineering, resilience denotes the ability to endure seismic loading, minimize structural damage, and efficiently restore functionality within a minimal timeframe [6]. Furthermore, this concept has evolved to encompass the assessment of structural performance, the efficiency of recovery strategies, and the associated economic and social impacts of service interruptions [7].

Recently, the field of seismic resilience assessment of bridges has undergone significant development thanks to various methodologies. Many researchers have conducted in-depth studies, leading to the emergence of various methods aimed at improving accuracy and comprehensiveness. These methodologies rely on quantitative approaches based on mathematical models and numerical simulations to measure the behavior of bridges during earthquakes, including dynamic modeling that requires highly accurate data. For example, the study of Rajkamal et al. focused on developing fragility curves for bridges via Incremental dynamic analysis (IDA) to relate earthquake intensity to damage probability [8]. Htay et al. proposed a study on an improved fragility curve through a hybrid

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analysis combining pushover and incremental dynamic analyses (PO-ID) to accurately assess the seismic vulnerability of bridges [9]. Similarly, Dong et al. used nonlinear dynamic time history analyses and fragility analyses, considering maximum and residual drift ratios as engineering demand parameters, to evaluate the seismic performance of reinforced concrete bridges equipped with SCEB-SMAUs and EDB-Sus [10].

Furthermore, quantitative approaches include probabilistic risk assessment under different seismic scenarios. Qian et al. developed a methodology to calculate the vulnerability of bridges subjected to time-varying earthquakes, taking deterioration into account using a Brownian-motion model [11]. Li et al. proposed a probabilistic methodology to assess bridge resilience by combining the maximum drift ratio (MDR) and residual drift ratio (RDR) indicators [12]. In 2023, Wei et al. presented a framework for assessing the seismic resilience of bridges, taking into account both MDR and RDR, through a probabilistic damage study using a joint probability density function to assess the loss of functionality and recovery of bridges after earthquakes [13]. Liu et al. presented a new seismic analysis framework based on the pair copula function, thus enabling a deeper understanding of the complex interdependence between bridge components and their impact on the overall resilience [14]. On the other hand, qualitative methods based on expert opinion and field engineering assessments have emerged, leveraging techniques such as multi-criteria decision matrices. For example, Patel et al. developed an assessment index using a resilience matrix by integrating the AHP-TOPSIS method to assess seismic resilience in a structured manner [15]. Vishal et al. proposed a framework integrating BIM-GIS models and digital twins to assess resilience by combining field data and digital visualization [16]. In 2022, Khan used the Dempster-Shafer combination rule to assess the seismic resilience of a highway bridge, proposing a resilience index based on the analysis of qualitative evidence.

In the field of machine learning, recent research has explored the use of artificial intelligence techniques to develop more effective assessment methods. For example, Mangalathu et al. developed machine learning models such as random forest and active learning to quickly and accurately assess seismic damage [17]. Yoon et al. proposed artificial neural networks (ANNs) to monitor and assess the resilience of bridge networks during earthquakes [18]. Similarly, Huang et al. suggested the use of graph neural networks to model seismic damage in distributed infrastructure systems [19]. In addition, the study [20] highlighted the contribution of image processing and advanced techniques for the automated identification of structural degradation, thus strengthening the reliability of structural diagnoses.

Despite the surge in scientific developments, decision-makers face major challenges in assimilating and operationalizing existing studies. This difficulty stems primarily from the scarcity of accurate data required by complex quantitative models, such as dynamic modeling or fragility analysis, which rely on in-situ measurements and geophysical information that are often absent or incomplete in many strategic regions [21]. Furthermore, the complexity of these approaches—whether purely quantitative or based on machine learning—requires high-level technical skills and expensive software, limiting their accessibility in resource-constrained contexts [20,22,23].

As for qualitative approaches, although theoretically simpler, methods such as TOPSIS or Dempster-Shafer theory demand advanced analytical rigor that is often unfamiliar to non-specialist practitioners. This reduces their impact on decision-makers and complicates their large-scale deployment. It therefore appears that the fundamental challenge lies not in the sophistication of theoretical models but in their simplification to meet the imperatives of speed, reduced cost, and practicality.

In response to the limitations of current methods, this research proposes an agile methodology accessible to engineers and decision-makers without requiring heavy computational resources or inaccessible data. This approach combines simplified technical assessments and qualitative considerations derived from professional expertise, all structured through the analytic hierarchy process (AHP). This framework offers a flexible multi-criteria solution, allowing for the prioritization of influencing parameters through simple pairwise comparisons, thus facilitating the reliable assessment of the seismic resilience of bridges.

Materials and Methods

To assess the seismic resilience of bridges using an approach that combines scientific rigor with practical applicability for decision-makers, this study adopted a mixed methodology based on four main steps, as illustrated in Figure 1. These steps include: the selection of fundamental criteria for assessing the seismic resilience of bridges based on previous studies and specialized international reports; the calculation of their relative importance using the analytic hierarchy process (AHP) method; the evaluation of the criteria by experts to ensure a balance between theoretical and practical aspects; and finally, the development of a simplified tool for assessing the seismic resilience of bridges (SSRI).

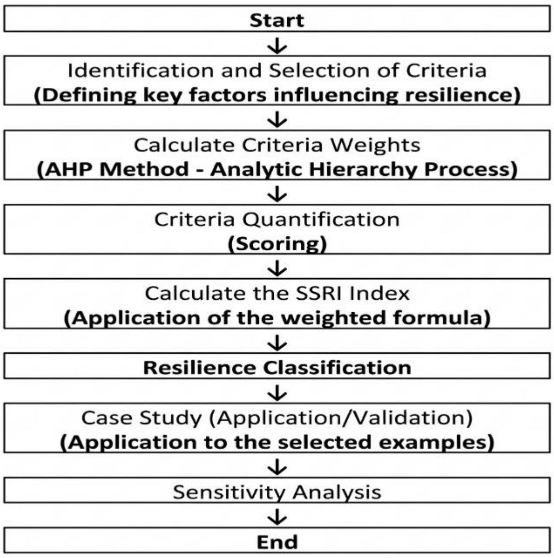

Figure (1): Flowchart of the (SSRI) methodology**.**

Criteria Selection

The selection of the four criteria used in this methodology for assessing the seismic resilience of bridges is based on a comprehensive review of previous studies and consultations with specialists in earthquake and bridge engineering. The process began with an extensive preliminary list encompassing a wide range of factors, such as soil type, maintenance level, repair history, and the availability of detailed modeling data. However, several of these variables require information that is difficult to obtain for all assessed bridges, or rely on advanced models that do not align with the methodological objective of developing a simplified, rapid tool compatible with the constraints of field assessment. Consequently, this initial list was streamlined, and its components were grouped into four main categories representing, in an integrated manner, the most influential factors affecting bridge resilience and those most readily available in technical and administrative databases. This approach ensures a balance between comprehensiveness and practical applicability, paving the way for the detailed presentation of the four selected criteria.

The four selected criteria are presented in detail below, outlining for each the methodological basis for its adoption, the methods of its evaluation, and its role in determining the overall level of seismic resilience. This presentation also aims to demonstrate how these criteria cover the structural, functional, environmental, and operational dimensions of resilience, as well as to explain the process of transforming descriptive indicators into quantitative scores that can be integrated into the SSRI formula.

Strategic Importance

The importance of a bridge reflects its impact on traffic and its role in the transport network. Bridges with high traffic density play a vital role in connecting regions, and their disruption leads to significant imbalances in traffic flow, negatively affecting the economy, social life, and safety [24,25]. Therefore, integrating this criterion into bridge resilience assessments is essential to limit risks and ensure service continuity. To assess importance, bridges are classified into three main categories based on their role in the transport network and traffic volume: strategic, important, and less important.

Structural Health

The structural health of a bridge is defined as the overall condition of its structure, influenced by influenced by construction material quality (e.g., concrete and steel), structural age, and the condition and deterioration of the materials (such as corrosion and aging), which are among the main factors leading to a significant reduction in its capacity to withstand loads [26,27], particularly seismic loads.

Although recent innovations in image processing and artificial intelligence have transformed the automation of structural deterioration diagnosis, the high costs and complex technical requirements of these systems make field engineering expertise the most realistic basis for assessment, particularly in developing countries, remote areas, and within small or resource-limited institutions [20]. Therefore, this study relies on rigorous visual inspections conducted by experts to identify signs of corrosion, cracking, and material degradation. These observations are then translated into a descriptive scale that defines the bridge's safety level according to three main categories: highly detrimental (HD), detrimental (D), and not detrimental (ND).

Seismic Vulnerability

The seismic vulnerability of bridges is defined as their degree of exposure to earthquake-induced damage, which negatively affects their resilience and threatens their structural integrity and functions during and after seismic events [28]. It encompasses geotechnical characteristics, including soil type and foundation stability under seismic loads; the type of structural design; as well as seismic hazards such as the intensity of regional seismic activity and the seismic history of the bridge, which determine its susceptibility to failure or collapse under seismic effects [29]. To assess this criterion, a simple and comprehensive method is used. This method is based on the collection of field and structural data, as well as the analysis of geotechnical and seismic hazards [30]. The bridge is classified according to specific criteria to determine a seismic vulnerability index within three categories: low, medium, and high.

Detour Length

Detour length in the event of bridge failure is defined as the additional distance that users (such as vehicles or emergency crews) must travel to reach their destination via alternative routes when the bridge becomes unusable due to seismic damage or structural failure. This factor is a crucial indicator for assessing the functional importance of the bridge within the transportation network [15], as a long detour distance affects emergency response time and increases the economic and social costs associated with bridge disruption, highlighting the need to strengthen its seismic resilience to minimize these impacts.

Quantification of Influencing Criteria

The quantification of criteria influencing the seismic resilience of bridges is based on a rigorous methodology combining the calculation of relative criterion weights and expert evaluation to ensure accurate and practical results. After identifying the main criteria, their weights are calculated using the AHP method developed by Saaty [31], considered one of the most widely used decision-support tools due to its precision, flexibility, and ease of application [32]. In this method, experts perform pairwise comparisons between criteria to determine their relative importance using the Saaty scale, which ranges from 1 (equal importance) to 9 (absolute importance). The experts' opinions are then grouped into a pairwise comparison matrix, and the relative weights of each criterion are calculated by extracting the eigenvalues from this matrix. A consistency test of the judgments is an essential step in the process: the consistency ratio (CR) must be less than 0.1 to ensure the reliability of the assessment; if this ratio is higher, the judgments are revised and re-evaluated. These weights are reinforced by expert assessments via questionnaires or discussion sessions, where they are asked to rate each criterion on a scale that considers importance and feasibility.

Each criterion is assigned a score ranging from 0 to 100 points, with a higher score indicating greater importance and feasibility. Expert scores are collected, and an average is calculated for each criterion to objectively and accurately confirm priorities. This approach integrates quantitative analysis with practical expertise, providing decision-makers with an understanding of the relative impacts of each criterion and an efficient allocation of resources to strengthen bridge resilience, particularly in contexts where data are insufficient or implementation challenges are numerous.

Seismic Resilience Assessment of Bridges

A simplified tool was developed to assess the seismic resilience of bridges (SSRI). It is based on multiplying the relative weight of each criterion, calculated using the AHP method, by its evaluation score (from 0 to 100) based on expert opinions. Equation (1) was used to obtain a numerical result that facilitates the rapid and efficient determination of intervention priorities by decision-makers.

$$SSRI = \sum_{i=1}^{4} W_i \times S_i \qquad (1)$$

where:

Wi - represents the weight assigned to factor i

Si - represents the score associated with the category of factor i.

Table 1 was created based on the overall score calculated for the seismic resilience index, classifying resilience levels according to score ranges. This ranking aims to simplify the assessment of the bridge and determine its capacity to withstand earthquakes.

Table (1): Distribution of factor weights and Scores associated with each category.

Factors	Weight	Category	Scores
Structural Health	W1	HD	S1
		D	S2
		ND	S3
Strategic Importance	W2	STRATEGIC	S1
		IMPORTANT	S2
		LESS IMPORTANT	S3
Seismic Vulnerability	W3	LOW	S1
		MEDIUM	S2
		HIGH	S3
Detour Length(km)	W4	<5	S1
		5-15	S2
		>15	S3

After calculating the Simplified Seismic Resilience Index (SSRI), bridge resilience is classified into three main performance categories, as detailed in Table 2. This classification structure reflects the standards used in current resilience assessments, e.g., [33–35], which typically divide performance into three distinct levels. To ensure ease of interpretation and consistency with established academic frameworks, the thresholds for our index were determined based on a consensus of experts in bridge engineering, seismic design, and risk assessment. Their opinions converged on three clear categories corresponding to practical technical evaluation:

Low Resilience: Requires major structural and operational intervention.

Medium Resilience: considered acceptable but requires improvements to enhance robustness.

High Resilience: Indicates structural durability and operational reliability.

The numerical thresholds used in Table 2 represent the central tendencies and breakpoints proposed by these experts, thus ensuring strong practical and technical significance for the classification.

Table (2): Classification of seismic resilience of bridges according to the SSRI.

Seismic resilience classes	SSRI
Low	$0 < SSRI < 25$
Medium	$25 \le SSRI < 60$
High	$SSRI \ge 60$

Results and Discussion

Case Study

Initially, a written questionnaire was developed, including pairwise comparisons between criteria using the AHP method, with a scale ranging from 1 to 9 to determine the relative importance of each criterion. Seventeen (17) experts participated in the implementation of the AHP method. Their selection was carried out to ensure a diversity of scientific and professional profiles relevant to the seismic resilience assessment of bridges. The panel included specialists in bridge and structural engineering (9 experts), seismology and earthquake engineering (5 experts), and transportation planning and risk analysis (3 experts). These experts are affiliated with academic institutions, engineering consulting firms, and public bodies responsible for infrastructure management and public works. They possess high levels of scientific and professional qualifications, with professional experience ranging from 15 to 36 years, which enhances the reliability of their assessments.

The opinions of all experts were considered equally, without differential weighting. The individual pairwise comparison matrices were aggregated using the geometric mean, in accordance with Saaty's recommendations, to obtain a representative collective matrix. To analyze potential discrepancies in the assessments, a group discussion session was held, allowing the experts to justify their differing viewpoints without forcing an artificial consensus. When no agreement was reached, the individual judgments were retained and mathematically aggregated. A consistency ratio (CR) check was then performed on the final matrix, and the results showed that the values obtained met the accepted methodological thresholds, thus confirming the validity and reliability of the weighting vector used in the proposed index.

Within the same methodological framework, the various criteria were assigned scores using a predefined rating scale from 0 to 100 points. Experts were asked to provide quantitative assessments representing the performance level of each criterion, based on their professional experience and engineering judgment. The expert panel emphasized that extreme numerical values, such as 0 or 100, generally do not reflect realistic engineering conditions of existing bridges. Therefore, the authors calculated the average of the experts' responses for each rating level and then performed a limited numerical adjustment to harmonize the scale and improve the usability of the scale without altering the experts' original intent. For example, the values 19.65 and 9.89 were rounded to 20 and 10, respectively, after validation by the expert committee. The resulting spacing between scores reflects the experts' perceptions of the relative differences in importance and influence between performance levels, rather than a uniform subdivision of the numerical scale, and is consistent with the hybrid qualitative-quantitative approaches commonly used in assessing the seismic resilience of infrastructure. The final results are presented in Table 3.

To demonstrate the effectiveness of the proposed methodology for assessing the seismic resilience of bridges, two case studies from the scientific literature were selected. Each bridge was analyzed separately, and its seismic resilience index was calculated independently using Equation (1).

Table (3): Final factor weightings and scores assigned to each category.

factors	Weight	Category	Scores
Structural Health	0.38	HD	10
		D	50
		ND	90
Strategic Importance	0.22	STRATEGIC	20
		IMPORTANT	50
		LESS IMPORTANT	90
Seismic Vulnerability	0.30	LOW	90
		MEDIUM	50
		HIGH	10
Detour Length(km)	0.10	<5	95
		5-15	50
		>15	10

The first case study focuses on the Baghlia Bridge, located in the Boumerdès Province of Algeria, an area classified as Zone IIb (high seismic activity). This bridge is considered a strategic and vital infrastructure asset; it spans the Sebaou River, with a total length of 251.3 meters and a height of 10 meters, and is designed to remain functional and open to traffic after an earthquake. It was rebuilt in 2004, with prestressed concrete beams and reinforced concrete piers. In the event of structural damage, the available detour is approximately 20 km long, highlighting the bridge's functional and strategic importance within the road network. It is also worth noting that the current physical condition of the bridge is relatively degraded, according to the latest inspection, with tilted support elements, cracked foundations, and scattered cracks in the piers. After identifying these characteristics, the Simplified Seismic Resilience Index (SSRI) of the Baghlia Bridge was calculated using Equation (1), based on the values assigned to the selected evaluation criteria, as follows:

$$SSRI= 0.38 \times 10 + 0.22 \times 20 + 0.30 \times 10 + 0.10 \times 10 = 12.20$$

The second case study concerns a bridge located on the Trans-Canada Highway on Vancouver Island, British Columbia, Canada. It is a multi-span bridge featuring continuous concrete girders, carrying a highway with two traffic lanes in each direction. The total length of the bridge is 116.0 meters. The span lengths, from south to north, are 45.5 meters, 34.0 meters, and 36.5 meters, respectively, and the total width of the bridge is 16.12 meters. The cast-in-place deck is supported by five precast, prestressed concrete girders. Structurally, the bridge has traditional "seat"-type abutments at both ends and rests on piers in the inner spans. Its social significance and current structural condition are classified as average. Furthermore, the bridge is exposed to high expected seismic activity and has a detour length in the event of failure. The Simplified Seismic Resilience Index (SSRI) was calculated for this bridge independently using Equation (1).

$$SSRI= 0.38 \times 50 + 0.22 \times 90 + 0.30 \times 10 + 0.10 \times 10 = 42.80$$

The results obtained are presented in Table 4.

Discussion of Results

The results of calculating the weights of the four criteria used to construct the index showed that Structural Health received the highest weight (0.38), highlighting its crucial role in determining the seismic resilience of bridges. This is followed by the seismic vulnerability criterion with a weight of 0.30, reflecting the severity of surrounding risks, then Strategic Importance with a weight of 0.22, and finally detour length with the lowest weight (0.10), indicating that the existence of bypass roads remains an influential factor but is less decisive than the other criteria.

Regarding practical results, the index value for the Baghlia Bridge is 12.20, placing it in the low resilience category. This classification reflects the bridge's vulnerability to seismic risks and highlights the need for enhanced measures to ensure its functionality in the event of earthquakes, especially since it is a strategic bridge. It should be noted that this result is consistent with the study by Abdellaoui et al.[36], who ranked the Baghlia Bridge among the bridges with a high priority for maintenance and strengthening.

As for the bridge located on Vancouver Island, the index is 42.80, which corresponds to a medium resilience level. This classification is consistent with the results of Khan's study [37], given its average structural condition, its average strategic importance, its exposure to significant seismic activity, and the existence of a relatively long detour route.

Table (4): Classification of seismic resilience of bridges: Comparison of the (SSRI) index of bridges and previous studies.

BRIDGES	SSRI Index Value	Resilience class (proposed method)	Resilience class (previous studies)
Baghlia (Algeria)	12.20	Low	Low resilience, high maintenance priority [36]
Vancouver Island (British Columbia, Canada)	42.80	Medium	Medium [37]

Sensitivity Analysis

The reliability of the proposed tool was evaluated using a sensitivity analysis (SA) to examine the effect of variations in input parameters on the value of the simplified seismic resilience index (SSRI). In this context, the weights of the criteria, determined using the AHP method, were kept constant, while the scores assigned to the different criteria were modified progressively and independently.

A parametric approach, varying one factor at a time, was adopted to identify the specific influence of each parameter on the results obtained, as illustrated in Tables 5 and 6 and graphically represented in Figure 2.

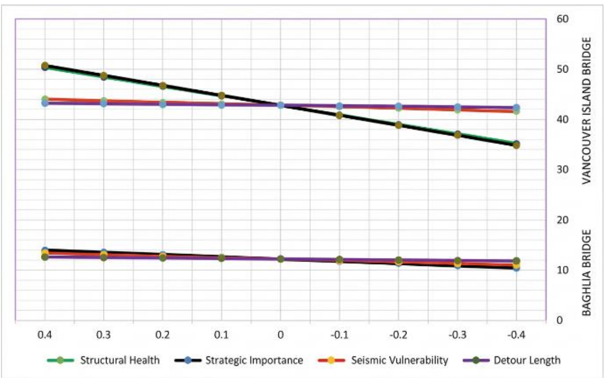

Figure (2): Sensitivity analysis of the SSRI model: Comparative study of the robustness of the parameters for the Baghlia and Vancouver Island bridges.

The analyses show that the variations in the SSRI follow a consistent and regular trend, without significant discontinuities or reversals in the ranking of the structures. It also appears that the impact of these variations is directly proportional to the relative weights of the criteria: thus, a change affecting a criterion with a high weight has a more pronounced influence on the final value of the index than a comparable change applied to a criterion with a lower weight, which is consistent with the mathematical structure of the indicator.

Overall, the SSRI maintains satisfactory stability in the ranking of bridges within realistic ranges of variation for the evaluation parameters, demonstrating the robustness of the proposed methodology and its limited sensitivity to uncertainties inherent in expert judgment. This stability confirms the suitability of the SSRI index as a simplified, reliable, and operational tool for assessing the seismic resilience of bridges in a context of rapid analysis and decision support.

Conclusion

This study proposes a simplified and effective methodology for assessing the seismic resilience of bridges using the Simplified Seismic Resilience Index (SSRI). The calculation of the weights of the four criteria clearly demonstrated their relative importance: Structural Health has the highest weight, followed by Seismic Vulnerability, followed by Strategic Importance, and finally Detour Length. These weights reflect the relative influence of each factor on a bridge's ability to withstand earthquakes and restore its functions.

The application of the model to two case studies (the Baghlia Bridge in Algeria and the Vancouver Island Bridge in Canada) showed good agreement with previous studies, confirming that the simplified index accurately reflects the structural and strategic reality of the structures and confirming the reliability of the resilience estimation methodology. Furthermore, sensitivity analysis revealed that the SSRI maintains satisfactory stability in ranking bridges across realistic parameter ranges, highlighting the robustness of the proposed methodology and its limited sensitivity to uncertainties inherent in expert judgment.

In conclusion, this simplified tool enables a rapid and reliable estimation of seismic resilience while reducing computational complexity and data requirements compared with traditional methods. This operational framework offers the possibility of prioritizing bridge maintenance and reinforcement, thereby enhancing the continuity of critical infrastructure in the face of seismic risks.

Study Limitations

While the SSRI index provides a practical and effective framework for preliminary assessment, it relies on a deterministic approach that prioritizes simplicity and operational speed. Consequently, it does not explicitly model uncertainties related to expert judgment, the actual condition of the structure, or the stochastic nature of seismic hazards and soil-structure interactions, although these factors are essential components of resilience. For this reason, this method is not a substitute for detailed seismic analysis and may require adaptation when applied to bridges with complex structural systems, unconventional materials, or atypical configurations.

Table (5): Sensitivity analysis of the SSRI index applied to the Baghlia bridge.

Factors	Weights	Scores	SSRI								
			-40%	-30%	-20%	-10%	0%	+10%	+20%	+30%	+40%
Structural Health	0.38	10	10.68	11.06	11.44	11.82	12.2	12.58	12.96	13.34	13.72
		50	-	-	-	-	-	-	-	-	-
		90	-	-	-	-	-	-	-	-	-
Strategic Importance	0.22	20	10.44	10.88	11.32	11.76	12.2	12.64	13.08	13.52	13.96
		50	-	-	-	-	-	-	-	-	-
		90	-	-	-	-	-	-	-	-	-
Seismic Vulnerability	0.30	90	-	-	-	-	-	-	-	-	-
		50	-	-	-	-	-	-	-	-	-
		10	11	11.3	11.6	11.9	12.2	12.5	12.8	13.1	13.4
Detour Length	0.10	95	-	-	-	-	-	-	-	-	-
		50	-	-	-	-	-	-	-	-	-
		10	11.8	11.9	12	12.1	12.2	12.3	12.4	12.5	12.6

Table (6): Sensitivity analysis of the SSRI index applied to a bridge on Vancouver Island.

Factors	Weights	Scores	SSRI								
			-40%	-30%	-20%	-10%	0%	+10%	+20%	+30%	+40%
Structural Health	0.38	10	-	-	-	-	-	-	-	-	-
		50	35.2	37.1	39	40.9	42.8	44.7	46.6	48.5	50.4
		90	-	-	-	-	-	-	-	-	-
Strategic Importance	0.22	20	-	-	-	-	-	-	-	-	-
		50	-	-	-	-	-	-	-	-	-
		90	34.88	36.86	38.84	40.82	42.8	44.78	46.76	48.74	50.72
Seismic Vulnerability	0.30	90	-	-	-	-	-	-	-	-	-
		50	-	-	-	-	-	-	-	-	-
		10	41.6	41.9	42.2	42.5	42.8	43.1	43.4	43.7	44
Detour Length	0.10	95	-	-	-	-	-	-	-	-	-
		50	-	-	-	-	-	-	-	-	-
		10	42.4	42.5	42.6	42.7	42.8	42.9	43	43.1	43.2

Future research

To improve the generalizability and applicability of the index, the following research directions are recommended:

Large-scale validation: Extend the application of the model to a larger sample of bridges with varying types, materials, and structural configurations.

Uncertainty management: Incorporate the variability and uncertainty of expert assessments into the model (using fuzzy logic or probabilistic approaches).

Seismic scenarios: Include probabilistic seismic scenarios and couple the SSRI index with fragility curves to transform it from a preliminary diagnostic tool to a comprehensive probabilistic assessment tool.

Digital transformation: Explore integrating the index into Building Information Modeling (BIM) platforms and automating data input using computer vision and artificial intelligence technologies to reduce the subjectivity associated with visual inspection, particularly in remote areas.

Recommendations

Based on the results of this study, the following recommendations are proposed to the relevant authorities and decision-makers:

Prioritizing maintenance and strengthening: Give absolute priority to bridges classified with "low" resilience, particularly strategic structures that form vital transport arteries.

Adopting the SSRI index as the initial protocol: Use this simplified tool for rapid resilience assessment, especially when data is limited, while using more advanced methods for confirmation when necessary.

Regular data updates: Establish continuous monitoring of the structural and operational condition of bridges, as well as changes in seismic and environmental risks, to ensure the accuracy of the index.

Integration into emergency plans: Use the assessment results to plan alternative routes and estimate recovery times after an earthquake, thereby improving disaster preparedness.

Expanding scope: Apply this model at the regional or national level to classify the entire bridge infrastructure, thereby facilitating proactive maintenance planning.

Training technical teams: Train field engineers and technicians in the use of the simplified index and the interpretation of its results to ensure data-driven decision-making.

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- **Ethics approval and consent to participate:** Not applicable
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