

A COMBINED FRAMEWORK FOR ASSESSING BRIDGE RESILIENCE AGAINST SEISMIC HAZARDS USING THE ANALYTICAL HIERARCHY PROCESS

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ABSTRACT: Lifeline networks are crucial components of civil infrastructure systems, they offer essential services and systems that support daily life, ensure public safety, and contribute to the overall functioning of society. Bridges are a vital part of the transportation system, they ensure connectivity, maintain access, support economic activities, and enable emergency response. On the other hand, these bridges are particularly vulnerable to extreme natural hazards, such as earthquakes, which can cause severe damage and disturb the entire transportation system. The impact of bridge damage includes not only direct economic losses from repairs and restoration but also indirect losses due to network shutdowns and traffic delays. Therefore, it is important to reduce these negative effects and enhance bridges resilience against such disaster.

The main objective of this study is to develop a combined framework in order to assess the resilience of existing bridges subjected to seismic hazards based on the analytical hierarchy process method (AHP). Through a literature review, several resilience parameters were identified to assess seismic bridge resilience, categorized into two main aspects: reliability and recovery. The relative contribution of each parameter inside these categories have been determined using the AHP process. For this purpose, pairwise comparisons have been inputted into a reciprocal comparison matrix for each hierarchical level to compute the weighting coefficient of every parameter. Then, the bridge seismic resilience has been assessed on the basis of seismic resilience index value derived from the combination of all weighting coefficients. The obtained resilience index value enables the estimation of a bridge's overall performance against seismic hazards, which offers an efficient way to assess structural resilience by translating complex concepts into an accurate resilience index, using objective criteria and factors to improve or update traditional subjective methods. This proposed resilience framework can assist infrastructure authorities in developing effective strategies against seismic hazards and improving overall safety and reliability of bridges.

1. INTRODUCTION

In recent decades, societies around the world have faced to increasing number of natural disasters, such as floods, earthquakes, tsunamis, landslides, hurricanes, and wildfires, which have catastrophic effects on global economies and communities. Earthquakes are among the most hazardous natural disasters, they have severe socioeconomic consequences such as devastating infrastructure, delaying emergency response, disrupting transportation and lifeline networks that impinge the recovery process. Owing to this, infrastructure performance is considered indispensable and ensuing its longevity is a big challenge.

Therefore, the concept of infrastructure resilience should be incorporated, and for this reason scientists and researchers are focusing their efforts on determining infrastructure resiliency.

The concept of resilience is explored across various research domains, ranging from engineering to psychology and economics. Resilience is progressively essential in designing, assessing, monitoring, maintaining, and managing infrastructure systems. It has gained considerable emphasis in the fields of disaster prevention and mitigation in latest years (Forcellini, 2023), (Mitoulis, et al., 2021), (Xiaohui, et al., 2022). Researchers defined resilience as the ability of a system to sustain against any hazard and return to its desired performance level during or after the occurrence of the hazard (Bruneau, et al., 2003), (Fu & Zhang, 2024). It was first introduced in the engineering domain by Bruneau, et al. (2003), where they proposed its four characteristics: robustness, rapidity, redundancy, and resourcefulness, along with technical, organizational, social, and economic dimensions (Bruneau, et al., 2003).

Various frameworks and models have been proposed for resilience quantification and determination in different fields (Omidian & Khaji, 2022), (ChienKuo, et al., 2020), (Skondras, et al., 2020). Thus, several methodologies have been proposed for the proper quantification of resilience, which can be divided into two categories: analytical methods (Cimellaro, et al., 2010), (Tamvakis & Xenidis, 2012) and simulation methods. In this context, many research studies have focused on developing methodologies to evaluate the resilience of infrastructure systems (Sun, et al., 2020). Lu et al. (2016) proposed a bi-level resource allocation framework to enhance the resilience of at-risk bridges in a transportation network. That integrates the network protection problem based on traffic optimization at the network level with the structural enhancement problem at the bridge level to achieve cost-effective retrofit strategies (Lu, et al., 2016).

Currently, MCDM techniques have been used to derive priority weights over resilience cycle and dimensions for bridge resilience evaluation (Patel, et al., 2020). There are various approaches in MCDM that help weigh decision criteria and score decision alternatives according to how well they satisfy respective criteria (Huang, et al., 2011), by computing the weights of each criterion of a model. These MCDM methods are frequently used to facilitate the resolution of real-world decision-making problems. Based on the methods advantages and disadvantages, the choice of the suitable method to apply should be matched with the problems at hand. Although the method development advancements, there is still a notable research gap in the area of assessing the resilience of bridges against seismic hazards. Therefore, significant challenges remain, particularly when using MCDM methods, due to the variability of the parameters involved. The major challenge is the prioritizing and weighting the criteria used in the assessment of resilience.

For this purpose, all aspects and criteria should be treated fairly in accordance with their respective interests, and among the above mentioned methods the Analytical Hierarchy Process (AHP) method is most likely to be applied as it helps to solve complex problems by structuring a hierarchy of aspects and criteria, and by drawing various considerations for developing weights or priorities.

Besides, the AHP are chosen for their notable ability to handle complex connections between multiple parameters, to integrate both qualitative and quantitative factors as well as to its compatibility and appropriateness of the acquired decision in dealing with the problem. Moreover, it can be used to provide a complete and rational framework for structuring decision-making, to represent and evaluate elements, and to connect them to objectives.

This paper presents a decision-making framework which aims at developing a higher fidelity assessment procedure that may be used in the evaluation process of seismic resilience for bridges. This integrate framework requires an analytical methodology that includes both the reliability and recovery aspects of bridges, where each parameter is interconnected and significantly influences the overall assessment of bridge resilience.

2. AHP DECISION-MAKING METHOD

AHP was created by Saaty (1980) to deal with decision making problems in complex and multicriteria situations (Saaty, 1990), (Dyer & Forman, 1992). AHP assists in making decisions that are characterized

by several interrelated and often competing criteria, and it establishes priorities among decision criteria when set within the context of the decision goal (Shapira & Goldenberg, 2005).

AHP is used to review the problems by describing them first carefully and then compiling them into a hierarchy system, consisting of several levels or stages, ie goal level, criteria, and alternatives. After composing the hierarchy, the next step is assigning numerical values to subjective considerations of the degree of preference between elements at each hierarchical level. The ultimate outcome of AHP is a priority for existing alternatives to meet the objectives of the encountered problem. Then, the significance of each alternative is assigned a subjective numerical weight, reflecting its relative importance compared to other variables. Based on the various considerations, a performed synthesis are carried out to extract the variables that have the highest priority and the greatest influence on the system's outcomes (Saaty, 1990).

The AHP consists of three principal steps:

(1) Construction of hierarchies: This phase consists to decompose the decision-making problem into its main components. The first level of the hierarchy deals with the decision goal, whereas the subsequent lower levels represent the progressive breakdown of the decision criteria, sub-criteria and the alternatives for reaching the decision goal, this involves structuring the complex reality into a hierarchical tree structure.

(2) Structuring the priorities: Priorities are defined by completing pairwise comparisons of the elements at each level of the hierarchy, with assuming the elements are independent of each other. In this regard and considering the decision goal, comparisons are made between the relative importance of every two criteria, at the second level of the hierarchy. Every two sub-criteria under the same criterion are also compared, and so on and so forth.

The pairwise comparison process is applied at all levels of the hierarchy according to the notion of Relative Importance of Criteria (IRC). From these IRC values, the reciprocal square matrix is defined.

Once the binary comparisons have been completed, the right eigenvector is calculated for the matrix, which is used to obtain the relative weights for the different criteria.

(3) Verification of consistency: The construction of the hierarchy and the structuring of priorities must ensure consistency in relation to two main aspects;

- Group homogeneity and relevance.
- Consistency of preference intensities.

After completing all the necessary pairwise comparisons, revisions, and consistency checks, the judgments can be synthesized to prioritize the decision criteria along with their corresponding sub-criteria.

As the most commonly used MCDM method, AHP attracts the most attention from decision-makers because of the availability of extensive literature on its application (Jato-Espino, et al., 2014). It is thus essential to better understand the specific decision problems that AHP can resolve. Such an understanding would greatly stimulate interest in AHP applications within the wider areas of construction management (Darko, et al., 2018).

Since AHP has an important aptitude to deal with various types of decisions, it has been widely applied in many different areas of construction management research over the last decades (Chan, et al., 2006) (Ruiz, et al., 2012), (Nassar & AbouRizk, 2014), (Jato-Espino, et al., 2014). Although the risk management and sustainable construction were the most popular AHP application areas in construction management (Darko, et al., 2018), there has been limited research on assessing seismic vulnerability and resilience of different infrastructures types using the AHP, such as the study of road vulnerability to earthquakes (Adafer, et al., 2024), the assessment of the seismic vulnerability of tunnels (Ghribi & Bensaibi, 2024), the estimation of seismic vulnerability of bridge (Djemai, et al., 2019), the determination of priorities for improving bridge seismic resilience (Abdellaoui, et al., 2024).

3. SEISMIC RESILIENCE ASSESSEMENT FRAMEWORK

In order to achieve the objective of this study, the decision-making framework was developed. The proposed framework aims toward a higher fidelity assessment procedure. Thus, it may be used in the evaluation process of seismic resilience for bridges. The main steps of the present framework are detailed in Figure 1.

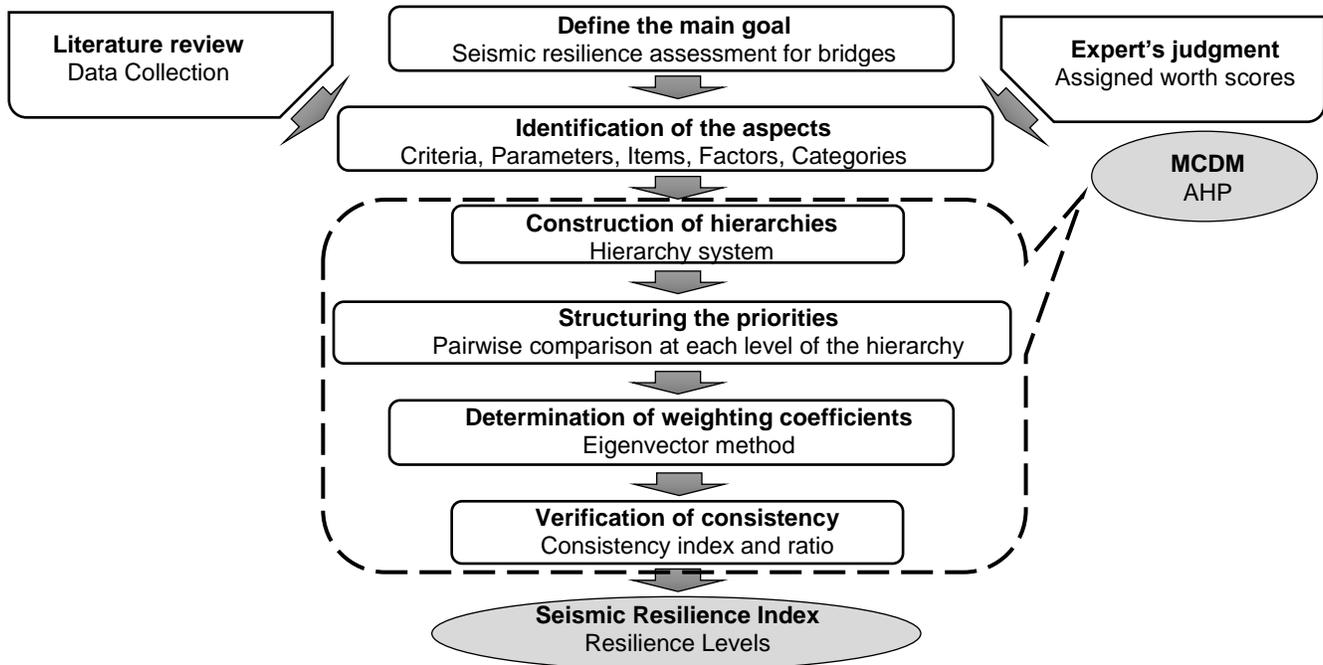


Figure 1: Hierarchical Framework for Seismic Resilience Assessment of Bridges.

3.1 Identification of the factors

Based on the literature reviews (Gimez, et al., 2002), (Kubo & Katayama, 1977), (Khan, et al., 2022), multi criteria nature of the decision making involves various parameters with different importance level. These parameters are defined from post-seismic observations as well as insights seismic experience feedbacks. To achieve the overall goal of this study, a combination of reliability and recovery criteria; as the two crucial criterions; is recommended.

Each criterion is subdivided into two parameters groups, structural and hazard for the reliability, management and availability for the recovery criteria. The structural parameters serve to distinguish the structural aspects that make bridge systems less or more resilient, when the aim of hazard parameters is to consider the influence of the seismic area. On the other hand, the recovery management ensure retrofitting prioritization and control maintenance requirements to increase and return previous functionality of a bridge system. In the same way, availability and accessibility parameters support the governance of timely and effective recovery.

Selected parameters of combined framework are classified into items; each item is divided into a certain number of factors; these factors are also composed of several categories. The hierarchy of the integrated framework, ranging from criteria to factors, along with the corresponding scores for each category used to evaluate the seismic resilience of bridges, is summarized in Table 1.

Each criterion, parameter, item and factor have a related weight noted as W_i , W_{ij} and W_{ijk} , W_{ijkl} , respectively, which reflects its importance relative to the other parameters and their factors. The aim is to determine the weight coefficients value.

Table 1: Hierarchy of parameters, items, factors and score of each category.

Goal	Criteria	Parameters	Items	Factors	Categories	Scores
Seismic Resilience	Reliability	Structural	Superstructure	Girder type	Arch or rigid frame	50
					Continuous Girder	30
					Simple Girder	20
				Number of spans	1 Span	40
					2 Spans or more	20
				Skew	Straight deck (No skewed)	40
					Low skew deck angle	30
					Medium skew deck angle	20
				Curvature	High skew deck angle	10
					Straight deck (No curvature)	40
			Low curvature deck bridge		30	
			Medium curvature deck bridge	20		
				High curvature deck bridge	10	
				Bearings	Min. bridge seat width	Wide: 70cm or wider
			Narrow: less than 70cm			20
			No seat: 0cm			30
			Bearing type		With specific device (prevent girder from falling)	40
					Bearing (with clear design concept)	20
					Movable bearing (it can move axial direction)	10
			Ground and Foundation	Ground type	Others (no bearing, etc)	20
		Stiff/Hard: slightly/no weathered rock			50	
		Medium: weathered/moderately weathered rock			40	
		Soft: deposited soil/diluvium			10	
		Foundation type		Very soft: deposited soil/alluvium	0	
				Pile Bent	20	
		Piers and Abutments	Max. height of Abutment / Pier (m)	Others Pile	40	
				Expanded	30	
				Less than 5m	50	
				Between 5 to10m	30	
			Construction Materiel of Abutment / Pier	More than 10m	10	
				Reinforced Concrete	20	
				Masonry	30	
			Pier type	Others	40	
				No piers for masonry structure	40	
				No piers for other than masonry structure	10	
				Columns piers	20	
			Abutment type	Massive piers	40	
				Backfilled abutment	20	
				Buried abutment	30	
		Abutment Superficially Founded		40		
Hazard	Seismic intensity	MMI < VIII	50			
		VIII ≤MMI< IX	40			
		IX ≤MMI< X	30			
		X ≤MMI< XI	20			
		XI ≤MMI	10			
	Liquefaction potential	No liquefaction	50			
		Low liquefaction potential 0 <PL ≤ 5	40			
		Medium liquefaction potential 5<PL ≤15	30			
		High liquefaction potential 15 < PL	10			
		No Damage	50			
Recovery	Management	Degree of damage	Minor Damage	40		
			Moderate Damage	30		
			Severe Damage	20		
			Critical Damage (Collapsed bridge)	10		
		Structural importance	Ordinary bridges	50		
			Important bridges	10		

		Maintenance	Cyclical Preventive Maintenance	50
			Corrective Maintenance	40
			No Maintenance	10
		Structural Monitoring	Real-Time monitoring	40
			Regular monitoring	30
			Basic/Visual Inspection Monitoring	20
			No monitoring	10
	Availability & Accessibility	Availability of resources	Sufficient Availability of Resources	40
			Limited Availability of Resources	20
		Approachability	Easy access	50
			Slightly difficult to access	30
			Difficult to access	10

3.2 Quantification of the identified factors

This section applies aforementioned AHP steps to determine the weighting coefficients of the different criteria and factors. The pair-wise comparisons are entered in a reciprocal comparison matrix for each level of the hierarchy. Each comparison matrix is then solved by an eigenvector method in order to determine the weighting coefficients. Finally, the verification of consistency of pairwise comparisons will be established according to consistency index and ratio. The obtained weights for each level criteria, parameters, items and factors are summarized in Table 2.

Table 2: Weighting factors, items and parameters

Criteria	W*	Parameters	W*	Items	W*	Factors	W*
Reliability	0.667	Structural	0.250	Superstructure	0.512	Girder type	0.574
						Number of spans	0.232
						Skew	0.097
						Curvature	0.097
				Bearings	0.120	Min. bridge seat width	0.667
						Bearing type	0.333
				Ground and Foundation	0.281	Ground type	0.750
						Foundation type	0.250
				Piers and Abutments	0.086	Max. height of Abutment / Pier (m)	0.491
						Construction Material of Abutment / Pier	0.268
						Pier type	0.160
						Abutment type	0.081
				Hazard	0.750	-	-
-	-	Liquefaction potential	0.200				
Recovery	0.333	Management	0.750	-	-	Degree of damage	0.593
				-	-	Structural importance	0.225
				-	-	Maintenance	0.112
		Availability & Accessibility	0.250	-	-	Structural Monitoring	0.069
				-	-	Availability of resources	0.750
						Approachability	0.250

*Weight.

After finding the weights for each level, a numeric worth score S_{ijkl} from 0 to 50 is assigned to every category. This reflects the one-dimensional value of the performance level of each category. The last column of Table 1 shows the score values of all categories.

3.3 Determination of resilience index

Using the weighting coefficients obtained for the four level hierarchy and the assigned scores, the resilience index "RI" is defined as a function of them and formulated as given in "Eq. 1" below.

$$[1] \quad RI = \sum_{i=1}^2 W_i \sum_{j=1}^2 W_j \sum_{k=1}^{2 \text{ or } 4} W_{ijk} \sum_{l=1}^{2 \text{ or } 4} W_{ijkl} S_{ijklm}$$

Where:

- W_i : The weighting coefficient of reliability or recovery criterions.
- W_j : The weighting coefficient of parameters.
- W_{ijk} : The weighting coefficient of items.
- W_{ijkl} : The weighting coefficient of factors.
- S_{ijklm} : The score of category.

The limits of resilience levels were established after evaluating multiple scenarios, estimating the best-case outcome for each interval, and validating the results against previous studies. According to the obtained resilience index values, and based on analysis and comparison of outcomes, three resilience levels are suggested for the bridge classification. The three resilience levels; low, moderate and high; and their ranging are summarized in Table 3.

Resilience Levels	RI
Low Resilience	$0 < VI < 30$
Moderate Resilience	$30 \leq VI < 45$
High Resilience	$VI \geq 45$

4. CASE STUDY VALIDATION

To further validate the strength and the relevance of the proposed decision-making framework in practical situations, a comparison of the results obtained from the present framework with those from the study by Khan et al. (2022) is established. The bridge considered in this case study validation is a multi-span continuous concrete girder bridge that supports a double carriageway consisting of two traffic lanes in each direction and located on the Trans-Canada Highway in Vancouver Island, British Columbia, Canada.

The resilience index of the aforementioned bridge was estimated according to two data sources, the detailed inspection report obtained from the concerned authority and the detailed vulnerability assessment from finite element analysis performed by (Muntasir Billah & Shahria Alam, 2021).

On the other hand, the analysis results of the bridge in question using the proposed framework are summarized in Table 4. Consequently, the supposed bridge is moderately resilient against seismic hazards with resilience index equal to 44.5.

Table 4: Analysis results of the proposed bridge

Criteria	Parameters	Items	Factors	Categories	Scores	
Reliability	Structural	Superstructure	Girder type	Continuous Girder	30	
			Number of spans	2 Spans or more	20	
			Skew	Straight deck (No skewed)	40	
			Curvature	Straight deck (No curvature)	40	
				Min. bridge seat width	Wide: 70cm or wider	50
				Bearing type	With specific device (prevent girder from falling)	40
				Ground type	Medium: weathered/moderately weathered rock	40
		Bearings	Foundation type	Pile Bent	20	
			Max. height of Abutment / Pier (m)	More than 10m	10	
			Construction Material of Abutment / Pier	Reinforced Concrete	20	
			Pier type	Columns piers	20	
			Abutment type	Backfilled abutment	20	
		Hazard	-	Seismic intensity	$IX \leq MMI < X$	30
-	Liquefaction potential		No liquefaction	50		
Recovery	Management	-	Degree of damage	Moderate Damage	30	
		-	Structural importance	Important bridges	10	
		-	Maintenance	Corrective Maintenance	40	
		-	Structural Monitoring	Basic/Visual Inspection Monitoring	20	
		-	Availability of resources	Sufficient Availability of Resources	40	
	Availability & Accessibility	-	Approachability	Easy access	50	
	Resilience Index (RI)				44.5	
Resilience Level				Moderate Resilience		

Furthermore, the results obtained for the bridge from the three approaches to seismic resilience assessment are presented in Table 5. The comparison of the final outcomes reveals almost identical results. The examined bridge is in moderate level of resilience for all of them. The results obtained are in good agreement.

Table 5: Summary of the three approaches results

	(Khan, et al., 2022) Study		Proposed Framework
	Physical Inspection	FE Analysis	
Resilience Index	BRI ^{Average} = 57.2%	BRI ^{Average} = 54.5%	RI = 44.5
Resilience Levels	Moderate Resilience	Moderate Resilience	Moderate Resilience

5. APPLICATIONS AND RESULT DISCUSSION

In order to apply the developed combined framework, a number of concrete bridges located in the north of Algeria, near the seismogenic basin of Mitidja, beside several active faults were selected and analysed. The seismic movements caused by those faults can be felt with different intensities. The strongest events are the Chenoua (Tipaza) and Zemmouri (Boumerdes) earthquakes. They were occurred on October 29th, 1989 (6.0) and on May 21st, 2003 (M 6.8) respectively. According to the (RPOA, 2008), this region is

considered seismically active. The results obtained from the application of the eleven selected bridges are summarized in Table 6.

Table 6: Seismic resilience assessment of selected bridges

Bridge	Resilience Index (RI)	Resilience Levels
Baghlia Bridge (Boumerdes)	27.9	Low
Boukadir Bridge (Tipaza)	45.5	High
Bouyaghsane Bridge (Tipaza)	41.3	Moderate
Damous Bridge (Tipaza)	29.5	Low
El Harrach Bridge (Algiers)	32.7	Moderate
Fadjana Bridge (Tipaza)	45.7	High
Harbil Bridge (Tipaza)	29.0	Low
Mazafran Bridge (Tipaza)	36.9	Moderate
Mazoum Bridge (Tipaza)	36.2	Moderate
Sebaou Bridge (Boumerdes)	27.5	Low
Sidi Amar Bridge (Tipaza)	30.8	Moderate

As it can be seen in Table 6, the Sebaou Bridge, located in the wilaya of Boumerdes, gets the lowest resilience index, this matched with results of post-earthquake field investigation done after the destructive Zemmouri (Boumerdes) earthquake (EERI, 2003). Which indicates the high occurrence of liquefaction around some piers foundation that contributes to the displacement of some girders due to those piers movement.

In addition, the low level of resilience obtained for Baghlia Bridge (Boumerdes) corresponds to the appeared deteriorations and damages, and which was confirmed by the latest inspection conducted by the Ministry of Public Works. For this reason seismic intervention and reinforcement are required.

The rest of bridges have a low resilience levels, such as Damous and Harbil Bridges located in the west of Tipaza province, primarily due to some poor reliability criteria as a result of current structural conditions.

In contrast, El Harrach Bridge, located in Algiers province, is considered as one of the major bridges affected by the Zemmouri (Boumerdes) earthquake. According to the post-earthquake field investigation report (EERI, 2003), the torsion resulting from the skew caused the escape of the last southeast frame from the elastomeric bearing and landing on the bent cap, leading to both transverse and longitudinal displacements at one end of the frame. The eastbound lane was closed, but the westbound lane continued to carry traffic on both directions. The bridge was repaired a few weeks after the earthquake and put back into service. Hence, the result obtained for this bridge from the proposed framework, indicates a moderate level of resilience showing a good matching.

Based on the aforementioned result discussions, the outcomes obtained for the application of this framework are in good adequacy with in-situ observations and investigations.

6. CONCLUSIONS

To analyse seismic resilience of existing bridges, a combined framework was developed and presented in this paper. It mainly aims to determine seismic resilience index for bridges and classify them according to their resilience levels. The outcome of the proposed framework enables the development of an efficient system for decision-making in seismic disaster management.

The suggested framework was carried out using the AHP procedure by identifying and quantifying the critical parameters and factors affecting the seismic resilience of bridges, with both reliability and recovery criteria integrated.

The proposed framework offers a practical and efficient approach to evaluate structural resilience by streamlining the assessment process through a structured multi-criteria decision-making methodology. By

integrating both quantitative and qualitative parameters, it translates complex resilience concepts into a consistent resilience index. This not only links the gap between theoretical models and real applications, especially in post-disaster contexts, but also enhances or potentially replaces existing evaluation practices by introducing objective accurate variables in place of traditional subjective assessment systems.

Compared to other seismic resilience evaluation approaches, the proposed AHP resilience framework offers greater advantages, clearly evident in its simplicity, accuracy, and practicality for quickly identifying the seismic resilience of bridges. Additionally, it can also be used to create seismic scenarios for decision-making about the disaster preparedness.

Future studies could include this assessment to validate and apply the developed resilient bridge framework. Furthermore, it could be applied to other types of civil infrastructure, such as dams, tunnels, roads, and buildings. Additionally, it could be extended to other hazards, such as floods and tsunamis. The proposed approach could be further advanced by integrating a real-time information system to update bridge resilience index and generate time-varying resilience assessments.

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