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Prioritizing Bridges for Seismic Resilience Enhancement: A Case Study of Algeria

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Abdellaoui Mohammed
ORCID: https://orcid.org/0009-0003-6766-4485
(LDMM) Laboratory, Department of Civil Engineering, University of Djelfa, Algeria
E-mail: mohammed.abdellaoui@univ-djelfa.dz
Badaoui Mohamed
ORCID: https://orcid.org/0000-0003-1289-020X
(LDMM) Laboratory, Department of Civil Engineering, University of Djelfa, Algeria
E-mail m.badaoui@univ-djelfa.dz
Bensaibi Mahmoud
ORCID: https://orcid.org/0000-0003-1409-4610
Group of infrastructures studies, control and assistance (GEICA), Algiers, Algeria
E-mail: bensaibim@yahoo.co.uk
Koriga Said
ORCID: https://orcid.org/0009-0000-5744-3521
(LDMM) Laboratory, Department of Civil Engineering, University of Djelfa, Algeria
E-mail: koriga_said@hotmail.com

Abstract

Algeria is located in an active seismic zone, making its bridges vulnerable to damage, especially older ones. Due to the importance of bridges in terms of safety, social, and economic factors, competent authorities must prepare for disasters, particularly earthquakes, by enhancing bridge resilience. However, due to the large number of bridges and lack of funding, it is not feasible to improve all bridges at once. This article proposes a model to determine priorities for enhancing bridge resilience to earthquakes based on expert opinions in three main steps. Step 1: Identification of key criteria, where design phase, bridge health, seismic zone, bridge importance, availability of alternative roads, and disaster insurance are defined as key criteria. Step 2: Calculation of criteria weights using the analytic hierarchy process (AHP) and integration of expert opinions using the Euclidean distance-based aggregation method (EDBAM). Step 3: Calculation of the priority index after evaluating criteria categories. The model was applied to six bridges, and their ranking was established based on the priority index. The model has proven its accuracy and ability to assist decision-makers in identifying priority bridges.

Keywords: Seismic resilience. Bridges. Prioritization. AHP. EDBAM. Algeria.

1. Introduction

Algeria is periodically exposed to several earthquakes of varying intensities due to its location in a seismically active region. The country has experienced over 4021 earthquakes between 1960 and 2020 (Mazari *et al*., 2023). Among the most destructive earthquakes are:

- The Elasnam earthquake in 1980, with a magnitude of 7.3 (Taibi *et al*., 2020), resulted in the collapse of numerous buildings, including bridges, and caused significant damage to infrastructure, leading to human losses exceeding 2630 deaths and significant direct and indirect economic losses.

- The Boumerdès earthquake in 2003, with a magnitude of 6.8, caused the collapse and damage of many bridges, leading to the isolation of certain areas, disruption of basic services, and leaving behind human losses exceeding 2287 deaths (Sabeur *et al*., 2023).

Bridge damage and collapse result in road closures, isolation of areas and cities, disruption of transportation and commerce, and even difficulties for emergency and security interventions. It becomes challenging for rescue teams to reach affected areas during natural disasters such as earthquakes and floods, as well as human-made disasters such as explosions and collisions, as bridges are considered one of the weakest and most accident-prone points (Chen *et al*., 2023; Dong *et al*., 2022; Gidaris *et al*., 2022).

Modern societies aim to strengthen their resilience to extreme events, recognizing that they cannot prevent all risks and threats, especially seismic ones, as they are inevitable (Román *et al*., 2022a).

The concept of resilience has received significant attention in disaster prevention and mitigation in recent years (Forcellini, 2023; Mitoulis *et al*., 2022; Xiaohui *et al*., 2021). Resilience 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). Bridge seismic resilience refers to the bridge's ability to withstand the impact and quickly recover to its original state after an earthquake (Fu *et al*., 2024; Hu *et al*., 2022), ensuring the bridge's fundamental functions and maintaining traffic flow after the disaster.

Algeria has over 11,000 bridges spread across the country (Abdellaoui *et al*., 2023), with most located in areas classified according to the Algerian code for their considerable seismic activity (MTPT, 2024). Constructed at different periods, many old bridges do not meet modern seismic resistance standards (Kehila, F. *et al*., 2023). Regulatory authorities should work on enhancing bridge performance before seismic risks occur. To reach this goal, some studies on seismic vulnerability bridges were conducted for reinforced concrete bridges (Djemai *et al*., 2019).

However, due to the large number of bridges and limited budg*et al*located for this purpose, hindering simultaneous reinforcement and improvement of the resilience of all existing bridges, it is necessary to identify priority bridges to enhance their seismic resilience.

Several rich pieces of literature and existing studies have been reviewed. Kramer (1996) concluded that a higher risk of bridge collapse (Kramer, 1996), the more priority should be given to its reinforcement compared to others, focusing on a single technical criterion. The Federal Highway Administration (FHWA) (2006) considers technical criteria such as seismic risks and structural weaknesses to classify bridges, then uses social and economic criteria to adjust the bridge list with balanced weights. Montepara *et al*. (2008) proposed a two-level scheme: deterioration affecting structures (project level) and the importance of each structure in the network (network level) (Montepara *et al*., 2008).

Another approach by Pellegrino *et al*. (2011) relies solely on the level of deterioration (Pellegrino *et al*., 2011). Yang *et al*. (2018) proposed prioritizing bridge maintenance by also focusing on deterioration (Yang & Frangopol, 2018). Abarca *et al*. (2022) emphasized the importance of bridges in terms of indirect losses (Abarca *et al*., 2022). In 2022, a "mixed" approach was adopted by D'Apuzzo *et al*. (2022), considering seismic risks, assessing the actual state of bridge deterioration, and social costs (D’Apuzzo *et al*., 2022). In 2023, Saler *et al*. (2023) proposed a method based on the level of deterioration and susceptibility to earthquakes (Saler *et al*., 2023), and Yau *et al*. (2023) ranking bridges post-disaster based on their susceptibility to disaster-induced damage and strategic importance (Yau *et al*., 2023).

These methods rely solely on engineering judgment or technical aspects in the classification and ranking of bridges.

This study proposes a simplified qualitative approach that considers comprehensive criteria of resilience characteristics and dimensions, relying on multi-criteria decision-making systems to prioritize bridges for enhancing their seismic resilience before disasters occur, using a prioritization index based on a weight calculation tool and ranking of existing alternatives. The following sections provide an explanation of the criteria and methodology followed, along with a case study illustrating the approach.

2. Methodology

The research method adopted in our article is divided into three basic steps:

2.1 Identification of Preference Criteria

Based on existing literature and expert opinions specialized in this field, criteria with a significant and comprehensive impact on all the above-mentioned seismic resilience characteristics have been selected and collected as follows:

Seismic zone: Patel *et al*. (2020) stated that predicting the severity of future shocks is one of the organizational dimensions of resilience (Patel *et al*., 2020). Algerian national territories are divided into five seismic activity zones, 0, I, IIA, IIB, and III, ranging from negligible to very high, respectively (RPOA, 2008; Sebahi *et al*., 2023). Thus, priority is given to bridges located in higher activity zones.

Design phase: This is the first stage of the bridge's life and is usually the cause of collapse if the design is inappropriate or insufficient (Peng *et al*., 2020). Bridge reliability mainly depends on design (Khan *et al*., 2022). Bridges in Algeria were built at different periods without considering seismic effects in their design. Up until the El Asnam earthquake of 1980, which led to a shift in design perceptions towards applying seismic calculations to bridges, relying solely on static calculations of seismic forces as a percentage of the bridge's weight, after the Boumerdes earthquake in 2003, the Algerian seismic regulation code for bridge structures, RPOA (2008), was introduced in 2010 (Kehila *et al*., 2021), replacing old methods with modern ones. To assess this aspect, we evaluate the seismic vulnerability of a bridge based on the principle that newer designs generally exhibit better seismic performance compared to older ones, and vice versa.

Bridge health: With increasing bridge age, vehicle loads, and the impact of adverse environmental conditions, bridges are significantly affected and deteriorate more rapidly (Buranapin *et al*., 2023; Skorpen & Kearsley, 2023; Vitanova *et al*., 2023).

Bridge importance: Román *et al*. (2022) and Khan *et al*. (2022) identified the importance factor as one of the most important factors affecting bridge seismic resilience (Khan *et al*., 2022; Román *et al*., 2022b). The RPOA (2008) classifies bridges into three groups: strategic, important, and moderately important based on their role and traffic flow.

Availability of alternative roads: It is necessary to consider this factor when determining the bridge's resilience, as it represents the indirect losses incurred if the bridge is damaged (Andrić & Lu, 2017). In this case, we consider the parameter of detour length in the classification. Bridges with remote alternative routes, which require longer detours, are given priority for maintenance.

Disaster insurance: Disaster insurance accelerates the recovery process and mitigates risks economically (Wang *et al*., 2023). Therefore, priority is given to uninsured bridges.

These criteria form the basis for evaluating and prioritizing bridges to enhance their seismic resilience.

2.2 Calculation of Criterion Weights

As mentioned earlier, to find the priority index, it is necessary to calculate the weights of the selected criteria. There are several methods to do this, with the most notable being the Analytical Hierarchy Process (AHP). It is a widely used decision-making method in various fields, including engineering, management, and the social sciences. It is a structured approach that helps decision-makers determine priorities and choose alternatives based on a set of criteria and their relative importance. AHP involves breaking down complex decisions into a hierarchy of criteria and then comparing them pairwise to determine their relative importance. The method uses mathematical algorithms to calculate the weights of each alternative, which can then be used to make informed decisions.

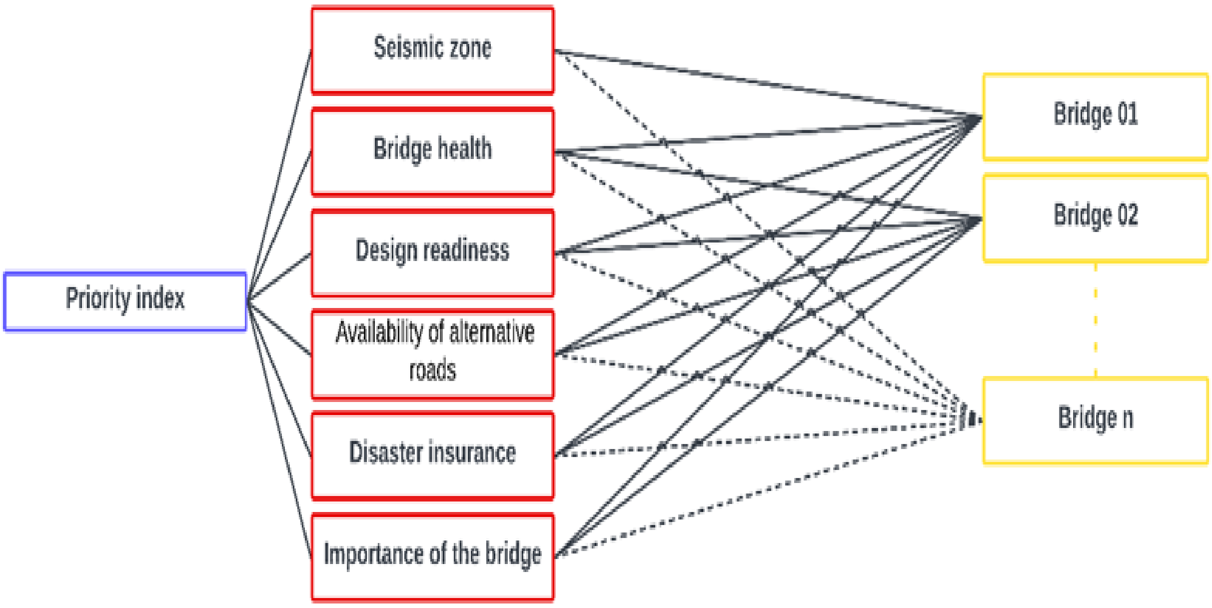

Figure 1 - Hierarchical Representation of the Objective.

Generally, calculating criterion weights involves three basic steps:

1. Preparation of the objective structure (the hierarchical diagram).
2. Conducting pairwise comparisons.
3. Verifying consistency with experts.

After preparing the hierarchical diagram as shown in Figure 1, we presented a written questionnaire to 10 experts in the field of bridges, with an average of 12 years of experience. The questionnaire is based on pairwise comparisons between the selected criteria, as mentioned earlier. Experts were asked to compare numbers ranging from 1 for equal importance to 9 for maximum importance. At the end of the questionnaire, consistency was checked using Equation1 :

$$CR = \frac{CI}{RI} \tag{1}$$

Where CR is the consistency ratio, CI is the consistency index, and RI (random index) is 1.24 in our case (n is 6). Slight inconsistencies in experts' judgments on pairwise comparisons are acceptable as long as the CR value is less than 0.1 (Saaty, 1990).

Finally, integration between weights is achieved using the Euclidean Distance-Based Aggregation Method (EDBAM) for its superiority over other traditional methods (Duleba & Szádoczki, 2022). Please refer to (Moslem & Pilla, 2023) for a detailed explanation of the method.

2.3 Calculation of Priority Index

Based on expertise from existing research and recent studies, scores were assigned to each criterion category, as indicated in Table 1.

Table 1. Scores assigned to criteria categories.

Criteria	weights	categories	scores
Disaster Insurance / #	W_1	Yes	10
		No	90
Design Phase/year	W_2	< 1980	90
		1980 - 2010	60
		≥ 2010	30
Bridge Health/level	W_3	Excellent	10
		Normal	60
		Critical	90
Availability of Alternative Roads/km	W_4	<10	10
		10-30	55
		>30	90
Bridge Importance / Category	W_5	1	90
		2	70
		3	20
Seismic Zone/Level	W_6	0	0
		I	10
		IIA	40
		IIB	80
		III	90

Using the weights obtained from the experts and the assigned scores, the priority index is calculated using Equation 2:

$$PI = \sum_{i=1}^{n} W_i \, X \, S_i \quad (2)$$

where: Wi is the weighting coefficient of criterion i and Si is the score of the category of each criterion.

3. Results

The weights of the six selected criteria were obtained following the questionnaire presented to the ten experts, and the results are presented in Table 2.

Table 2. Presents the weights of the criteria provided by the experts.

Experts	CR	Design Phase	Bridge Health	Bridge Importance	Disaster Insurance	Availability of Alternative Roads	Seismic Zone
E1	0.09	0.31	0.35	0.11	0.03	0.07	0.13
E2	0.08	0.40	0.20	0.14	0.05	0.04	0.17
E3	0.04	0.35	0.21	0.08	0.10	0.03	0.23
E4	0.03	0.12	0.37	0.02	0.13	0.22	0.12
E5	0.09	0.37	0.22	0.11	0.06	0.03	0.20
E6	0.07	0.27	0.25	0.13	0.03	0.02	0.3
E7	0.02	0.17	0.10	0.38	0.17	0.05	0.13
E8	0.01	0.48	0.17	0.07	0.06	0.04	0.18
E9	0.02	0.22	0.28	0.05	0.05	0.19	0.21
E10	0.04	0.19	0.25	0.06	0.08	0.27	0.15
EDBAM		**0.29**	**0.24**	**0.11**	**0.07**	**0.1**	**0.19**

The results showed that the criterion of the design phase received the highest relative importance at 29% compared to other criteria, followed by the criterion of bridge health at 24%. The experts assigned a weight of 19% to the seismic zone criterion, while the importance of the bridge itself was 11%. The criteria of availability of alternative routes and disaster insurance were considered the least important by the experts, at 10% and 7%, respectively. Regarding the consistency ratio, it was below 0.1 for all experts.

4. Case Study

To illustrate the proposed methodology for identifying priority bridges to enhance their seismic resilience, it was applied to five bridges exposed to potential seismic risk in Algeria.

The first case is the Baghlia Bridge, located in the wilaya of Boumerdes, classified according to RPOA 2008 in zone IIB (high seismic activity). The bridge spans the Sibao Valley over a length of 251.3 meters and a height of 10 meters. It is considered one of the strategic bridges that should remain operational for traffic after being exposed to earthquakes. It was rebuilt in 2004, and its physical condition is poor, according to the latest inspection conducted by the Ministry of Public Works. It exhibits inclined support elements, cracked foundations, and various cracks in the piles. As shown in Figure 2, the length of the detour road is 20 km. As for insurance, it is self-insured against natural disasters by the Algerian authorities.

Figure 2 - shows the condition of the foundations of Baghlia Bridge.

The priority index is calculated using Equation 2 as follows:

$$\begin{aligned} PI &= (W_1 \,\mathrm{X}\, S_1) + (W_2 \,\mathrm{X}\, S_2) + (W_3 \,\mathrm{X}\, S_3) + (W_4 \,\mathrm{X}\, S_4) + (W_5 \,\mathrm{X}\, S_5) + (W_6 \,\mathrm{X}\, S_6) \\ &= (0.07 \,\mathrm{X}\, 10) + (0.29 \,\mathrm{X}\, 60) + (0.24 \,\mathrm{X}\, 90) + (0.1 \,\mathrm{X}\, 55) + (0.11 \,\mathrm{X}\, 90) + (0.19 \,\mathrm{X}\, 80) \\ &= 70{,}3. \end{aligned}$$

Similarly, the priority indices for the remaining bridges listed in Table 3 were computed. The final results are presented in Table 4.

Table 3. shows a description of the bridges studied.

	Harbil Bridge (Tipaza, Algeria)	**Sidi Amar Bridge** (Tipaza, Algeria)	**Damous Bridge** (Tipaza, Algeria)	**Mazafran Bridge** (Algiers/Tipaza)	**Mazoum Bridge** (Gouraia,tipaza)
Location	NR11	NR67	NR11	NR67	NR11
Year Built	2003	1993	1987	1961	1999
Physical Condition	Good	Good	Average	Good	Good
Seismic Zone	III	III	III	III	III
Detour Distance / km	42	20	28	07	32
Bridge Importance	1(strategic)	2(Important)	1(strategic)	2(Important)	2(Important)
Disaster Insurance	Y	Y	Y	Y	Y

Table 4. displays the order of the bridges according to priority.

Bridges	**PI**	**Rank**
Baghlia Bridge	70.3	1
Harbil Bridge	56.5	3
Sidi Amar Bridge	50.8	6
Damous Bridge	65	2
Mazafran Bridge	55	4
Mazoum Bridge	54.3	5

The Baghlia Bridge obtains the highest priority index (70.3), making it the foremost in terms of the need for seismic intervention and reinforcement. This is attributed to its current poor physical condition compared to all the other studied bridges. Therefore, the relevant authorities must promptly commence maintenance and seismic reinforcement procedures. Following closely is the Damous Bridge (65), primarily due to its current physical condition. The third position is held by the Harbil Bridge (56.5), owing to its strategic significance and the lengthy detour road (42 km) compared to the remaining bridges. The priority indices progressively decrease for the remaining bridges: Mazafran (55), Mazoum (54.3), and Sidi Ammar (50.8).

An important aspect to note is the design methodology used for these bridges, which predates 2010, i.e., before the adoption of the updated Algerian code (RPOA2008), relying solely on static calculations of seismic forces. This approach fails to account for the dynamic effects of earthquakes, which can lead to significant structural damage. The Mazafran Bridge in terms of design, as it was designed before the destructive El-Asnam earthquake without considering the seismic impact on the structures at all, potentially increasing their vulnerability to earthquakes.

Furthermore, all the bridges listed in Table 4 have been rated excellent in terms of natural disaster insurance. This is attributed to the Algerian national authorities, under the supervision of the Ministry of Public Works, financing the repair or reconstruction of bridges damaged by earthquakes.

4. Conclusion

In this study, a simplified method was proposed to identify priority bridges for reinforcement in terms of seismic resilience by calculating a priority index. The model was developed using the analytic hierarchy process (AHP) to calculate the weights of important criteria in the selection process after collecting opinions from 10 experts specializing in the field of bridges. The Euclidean distance-based aggregation method (EDBAM) was used to obtain consensus weights from the experts. This method was applied to six bridges considered priorities for seismic reinforcement according to the Algerian seismic regulation code for bridge structures (RPOA 2008). It should be noted that this methodology yielded broadly acceptable results and can be applied by competent authorities due to its simplicity and accuracy in identifying priorities between given bridges.

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