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RESEARCH ARTICLE

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DEVELOPMENT OF A MODEL FOR ASSESSING THE SEISMIC RELIABILITY OF BRIDGES TO ENHANCE THEIR RESILIENCE

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ABSTRACT

Bridges are essential elements of transportation networks due to their strategic role and their vulnerability to natural and man-made hazards, particularly earthquakes, which can lead to partial or total service interruptions. This study proposes an improved model for assessing the seismic reliability of reinforced concrete bridges before a seismic event to enhance their resilience and improve disaster preparedness. In the first step, factors influencing reliability were identified based on a literature review and expert opinions. Next, the Analytical Hierarchy Process (AHP) was used to determine the relative weight of each factor, and a Seismic Reliability Index (RSI) was calculated by combining these weights with bridge-specific data. The model proposes three levels of reliability: low, medium, and high. It was applied to several bridges located in seismic zones in Algeria. Finally, this study presents and discusses the main results obtained, highlighting their usefulness for decision-makers in infrastructure resilience improvement strategies.

I. INTRODUCTION

It All Bridges are a vital part of global transportation networks, connecting communities, supporting economies, and ensuring the continuity of humanitarian services during disasters. Given the strategic importance of these infrastructures, any damage caused by natural disasters, including earthquakes, can lead to serious consequences, such as traffic interruptions, the collapse of supply chains, and increased human losses, as occurred during the Kahramanmaraş earthquake in Turkey (2023), and the Myanmar earthquake (2025), causing considerable human and economic losses. Algeria is located in a region known for its high seismic activity, experiencing frequent earthquakes along major fault lines[1], [2], with the most recent significant event being the 2003 Boumerdes earthquake[3]. These seismic activities pose a major threat to bridges, particularly as bridges are considered one of the weakest elements of infrastructure[4], [5], [6], [7]. It should be noted that most bridges in Algeria were designed without considering the seismic impact[8], highlighting the need to conduct a proactive assessment of bridges' seismic reliability.

These assessments aim to enhance their resilience and ability to withstand earthquakes[9]. The reliability of a bridge is defined by its ability to meet the requirements imposed on it under specific conditions and within a defined time period[10] .Khan et al .defined reliability as the level of service maintained by an infrastructure after a disaster[11]. Numerous researchers have proposed various methods for assessing the seismic reliability of bridges. For example, Chen et al.[12] calculated the seismic reliability of bridge networks using machine learning techniques and network analysis, Asghshahr [13] conducted a seismic reliability analysis based on samples of corroded reinforced concrete bridges, Zanini et al.[14] assessed the seismic reliability of open arch bridges made of reinforced concrete, Yuan et al.[15] calculated reliability over time for a coastal bridge column, considering uncertainty, irregular corrosion, and the random nature of seismic events; Franchin et al.[16] conducted a probabilistic seismic reliability assessment based on failure rates using risk curves .Yang et al. conducted a quantitative evaluation of the time-dependent seismic reliability of cold-formed steel structures[17].

Zhang et al. pointed out that, nowadays, scientists generally use the Monte Carlo method and the response surface method to study the seismic reliability of bridges[18]. Based on the above, the majority of previous studies have relied exclusively on quantitative approaches to assess the seismic reliability of bridges, primarily focusing on the technical aspect of the problem. Conversely, this study adopts a qualitative approach by using multi-criteria decision-making methods (MCDM) as assessment support tools, enabling the structured integration of human expertise and specialist judgments. This methodological choice is particularly relevant in contexts marked by a lack of accurate and reliable quantitative data, as is often the case in many developing environments. This model was applied to a group of bridges located in areas with seismic activity according to the classification of the Algerian seismic regulation code for bridge structures[19], allowing for the construction of a more flexible model adapted to local specificities and available data. The main objective of this work is to develop a qualitative model for the evaluation of the seismic reliability of bridges, to support decision-making, strengthen their resilience, and define intervention priorities in the event of an earthquake.

II. MATERIALS AND METHODS

To achieve the desired objective, a working methodology has been adopted, consisting of three main steps, briefly explained as follows:

II.1 IDENTIFICATION OF INFLUENCING FACTORS

Factors having a significant impact on the seismic reliability of bridges have been identified through a comprehensive review of existing research and international experiences. Five main factors have emerged, encompassing technical, environmental, and social aspects.

I. The structural integrity of the bridge (level of damage) (SI): Bridges with physical damage are more vulnerable to risks than their undamaged counterparts [14]. The assessment is conducted through inspections, whether visual or test-based.
II. Seismic hazard (SH): Whenever the bridge site is subjected to seismic activity, the seismic reliability of the bridge significantly decreases, in an inversely proportional manner[16]. The assessment of seismic hazards involves determining the seismic classification of the bridge site following the current Algerian code. According to the[19], Algeria has been classified into five seismic zones: Zone III, IIb, IIa, I, and 0, ranging from high activity to negligible activity, respectively.
III. Seismic design (SD): It is considered the initial stage in the bridge's lifespan, and complete collapse may occur if the design is inadequate [20]. Additionally, Roman et al. [21] emphasize that the reliability of bridges depends on the design period. The assessment is conducted based on the adoption or non-adoption of the new Algerian code (RPOA2008) in the design.
IV. Traffic movement (bridge importance) (TM): According to Kwon et al. [22], traffic significantly impacts the seismic reliability of bridges. The measurement of this factor depends on the type of road on which the bridge is located, whether it is a highway, a National Road (NR), or another.
V. Bridge geometry (BG): straight bridges are less susceptible to seismic damage than skewed and curved bridges [11], [23]. Additionally, curved bridges are more vulnerable to earthquakes than skewed bridges.

II.2 QUANTIFICATION OF INFLUENCING FACTORS

The weights of each factor are calculated using the Analytic Hierarchy Process (AHP) developed by Saaty[24]. The AHP method is the most widely used among existing decision support tools, due to its accuracy, flexibility, and ease of application [25], [26]. The main steps of the method are shown in Figure 1.

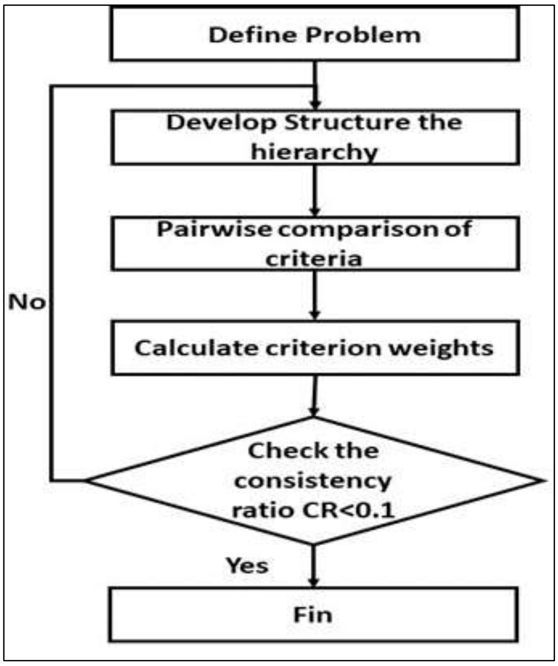

Figure 1: AHP steps flowchart.
Source: Authors, (2026).

After consulting a group of bridge experts, engineers, and researchers, a score is assigned to each factor on a scale of zero to (100), with a higher score indicating a greater positive impact on the bridge's seismic reliability.

II.3 SEISMIC RELIABILITY INDEX OF BRIDGES

Finally, to obtain the Seismic Reliability Index (RSI), the relative weights and numerical assessments of the five factors are combined as shown in Equation 1:

$$RSI = \sum_{\mathrm{i}=1}^{5} \mathrm{W_i} \text{ x } SC_{\mathrm{i}} \tag{1}$$

where:

Wi - refers to the weight of criterion i. SCi - represents the score or value associated with that criterion. Based on the values obtained, the levels of reliability range from zero (complete absence of reliability) to 100 (highest level of reliability). These values enable owners to compare different bridges and make necessary decisions. Three classifications of seismic reliability have been proposed and are presented in Table 1 as follows:

Table 1: Levels of Bridge Seismic Reliability.

Reliability levels	RSI score
Low	0-35
Medium	36-70
High	71-100

Source: Authors, (2026).

III. RESULTS AND DISCUSSION

A team of fifteen (15) experts was selected to participate in the survey, based on their academic and professional expertise in the field studied, to determine the relative importance of the influencing factors. This process relied on precise pairwise comparisons between the five factors affecting the seismic reliability of bridges, using the (AHP) methodology, on a scale ranging from 1 to 9. The experts' decisions were then grouped into a single set using the average of the extracted weights, resulting in final weights for each factor. The final weights are presented in Table 2.

Table 2: Factors Weights and Score of Each Category.

factors	Weight	Category	Scores
SI	0.30	Critical	0
		Medium	40
		Good	70
		Excellent	100
SH	0.34	Zone III	20
		Zone IIb	40
		Zone IIa	70
		Zone I	90
SD	0.18	Before RPOA2008	20
		After RPOA2008	90
TM	0.10	Highway	20
		NR	50
		Others	90
BG	0.08	Straight	90
		Skew	40
		Curve	30

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

IV.1 CASE STUDY RESULTS

To apply the developed model, we selected many concrete bridges located in the provinces of Boumerdes, Tipaza, and Médéa, which are considered seismically active areas according to the [19]. The Damous Bridge is a straight bridge located in the province of Tipaza, Algeria. It is located in an area classified as having high seismic activity, designated as zone III according to RPOA (2008), along kilometer point 147+400 of the national road No. 11. Built in 1987, the Damous Bridge stretches 280 meters long, 13 meters wide, and rises to a height of 17 meters. Currently, the structural condition of the bridge is rated as medium, raising concerns about its safety in the event of an earthquake. The second case concerns the Harbil Bridge, a curved bridge located in the province of Tipaza (Damous), Algeria. It is situated in an area with high seismic activity, at kilometer point 63+250 of national route No. 11. Constructed in 2003, the Harbil Bridge measures 300 meters in length, 9 meters in width, and has a height of 19 meters. Currently, the structural integrity of the bridge is rated as good. In the event of a bridge collapse, users will have to take a detour of 42 kilometers. The third case is the Mazafran Bridge located on the border between the provinces of Algiers and Tipaza, among the important bridges in Algeria. The bridge is straight and is situated in an area with high seismic activity, at kilometer point 12+235 of National Route No 67. The Mazafran Bridge was built in 1961, with a length of 95 meters, a width of 11 meters, and a height of 5 meters.

The structural integrity of the bridge is currently rated as good. The fourth case concerns the Sebaou Bridge, located in the province of Boumerdes, Algeria. The bridge is straight and is situated in an area with high seismic activity, at kilometer points 99+500 of National Route No 24. It was built en 1972 and measures 345 meters in length, 9.6 meters in width, and has a height of 7 meters. Currently, The structural integrity of the bridge is rated as medium. The last case concerns the Sidi Naamane Bridge, located in the Province of Medea, Algeria. The bridge is straight and is situated in an area with moderate seismic activity, at kilometer points 83+200 of National Route No 18. It was built en 2022 and measures 40 meters in length, 7 meters in width, and has a height of 6 meters. Currently, The structural integrity of the bridge is rated as excellent. The seismic reliability index for the Damous Bridge is calculated using Equation 1 as follows:

$$\begin{aligned} RSI &= (W_1 \,\mathrm{X}\, SC_1) + (W_2 \,\mathrm{X}\, SC_2) + (W_3 \,\mathrm{X}\, SC_3) + (W_4 \,\mathrm{X}\, SC_4) + (W_5 \,\mathrm{X}\, SC_5) \\ &= (0.30\mathrm{X}\ 40) + (0.34\ \mathrm{X}\ 20) + (0.18\ \mathrm{X}\ 20) + (0.10\ \mathrm{X}\ 50) + (0.08\ \mathrm{X}\ 90)\ = 33. \end{aligned}$$

Similarly, the (RSI) for the remaining bridges was computed. The final results are presented in Table 3.

Table 3: Seismic Reliability Assessment of Concrete Bridges.

Bridges name	RSI	Reliability levels
Damous (Tipaza)	34.6	Low
Sebaou (Boumerdes)	34.6	Low
Harbil (Tipaza)	38.8	Medium
Mazafrane (Tipaza)	43.6	Medium
Sidi Naamane (Medea)	82.2	High

Source: Authors, (2026).

The results from applying the proposed seismic reliability model clearly show that the Damous Bridge and Sebaou Bridge have low seismic reliability scores, ranking the lowest among the bridges studied. Several factors contribute to their poor performance. Firstly, both bridges are located in Zone III, an area of exceptionally high seismic activity. This parameter was assigned the highest weight of (0.35), given its substantial influence on a bridge's ability to withstand earthquakes. As this risk factor was rated the lowest score (20), it significantly reduced the bridges' overall scores. Secondly, the structural integrity of the Sebaou and Damous Bridges was determined to be medium based on inspections, earning a relative weight of (0.30). Their substandard structural integrity would impair seismic resistance. Thirdly, as the bridges were designed and constructed before recent updates of the RPOA (2008), seismic engineering was not adequately incorporated into their original design. This parameter was assessed with an influential weight of (0.18). Not meeting current codes detracted from their calculated reliability. In contrast, the Harbil Bridge and Mazafran Bridge had a medium seismic reliability rating of (38.8) and (43.6), respectively. This is primarily a result of their good physical condition. As for the Sidi Naamane Bridge, its seismic reliability is high (82.2). This high reliability is attributed to its excellent physical condition, compliance with the current Algerian code in its design, and its location in an area with moderate seismic activity.

IV.2 VALIDATION

Verification is an essential element to ensure the accuracy and quality of the adopted methodology. In this study, two main techniques were used: First, normative validation, based on measuring the degree of correlation between two different indicators, to verify the concordance of the results with theoretical expectations. To this end, the results of the proposed model for assessing the seismic reliability of bridges (RSI) were compared with those of a previous study that established intervention priorities to improve the seismic resilience of bridges, based on the performance indicator (PI) [4]. All the comparative results are presented in table 4.

Table 4: Comparison of RSI and Pi Index Values.

Bridges Name	RSI	PI
Damous (Tipaza)	34.6	65.0
Sebaou (Boumerdes)	34.6	69.6
Harbil (Tipaza)	38.8	56.5
Mazafrane (Tipaza)	43.6	55.0
Sidi Naamane (Medea)	82.2	40.2
Baghlia (Boumerdes)	29.4	70.3

Source: Authors, (2026).

To assess the relationship between the two indices, the Pearson correlation coefficient was calculated, yielding a value of (-0.93), indicating a very strong negative correlation between the two indicators. This means that the higher the seismic reliability (RSI) of a bridge, the lower its intervention priority (PI). For example, the Sidi Naamane bridge, which has a high-reliability index (RSI = 82.2), is ranked as a low priority in the PI index (40.2), while the Baghlia bridge, with a low-reliability index (RSI = 29.4), is ranked as a priority index (PI = 70.3). This inverse relationship confirms the effectiveness of the proposed model in identifying the most vulnerable bridges and highlights the importance of the complementarity between the RSI and PI indices in supporting decision-making and guiding strategies for strengthening the resilience of critical infrastructure to seismic risks. Second, reliability was assessed through a rigorous sensitivity analysis (SA), consisting of modifying the relative weights of the influencing factors while maintaining the other variables at their reference or average values. In this context, the following variation percentages were applied: -30%, -20%, -15%, -10%, -5%, +5%, +10%, +15%, +20%, +30%, which made it possible to observe the individual effect of each input factor on the final results, The relative weights of all influencing factors were calculated and documented in figure 2.

Based on these relative weights (taking into account the percentage variations), the values of the SRI indicators for each of the six bridges were estimated, and the results were reported in figure 3. The sensitivity analysis showed that the relative variations of the influential weights resulted in a small and reasonable impact on the values of the SRI indicator. This indicates that the proposed methodology has high stability and reliability, with the results not being sensitive to moderate fluctuations in the input data. Thus, the developed indicator faithfully reflects the seismic reliability of bridges without excessive dependence on specific weights, which strengthens its scientific credibility and supports its use in similar future assessments.

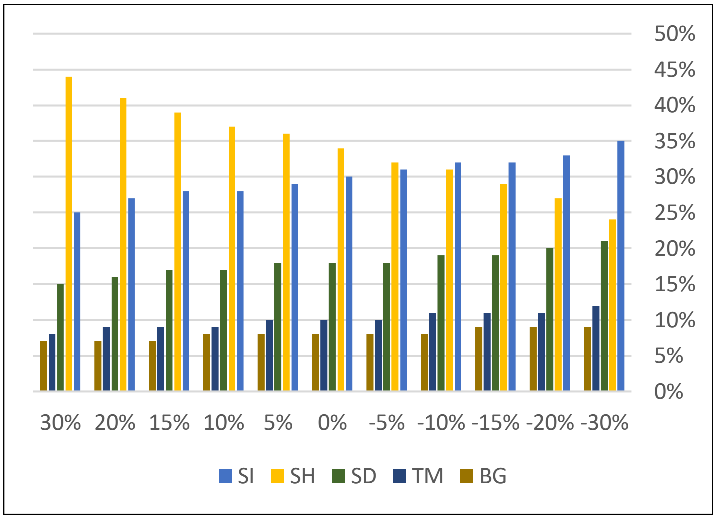

Figure 2: AHP steps flowchart.
Source: Authors, (2026).

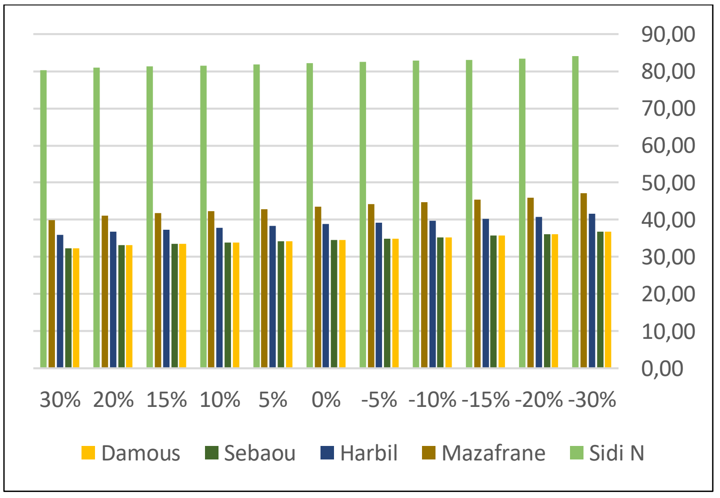

Figure 3: AHP steps flowchart.
Source: Authors, (2026).

This approach makes it possible to assess the stability of the developed indicator in the face of potential variations in the basic data, thus strengthening the robustness and sustainability of the methodology. This type of validation is widely used in the scientific literature to ensure the credibility of the proposed indicators and models[27].

IV.3 CONCLUSION

This study aimed to develop an improved model for assessing the seismic reliability of reinforced concrete bridges. Five influential factors were selected based on previous research and expert opinions in the field of bridges. The analytical prioritization method (AHP) was used to determine the relative weights of these factors based on questionnaires distributed to a group of experts. The weights were then integrated with the results for each case, following the classifications of the Algerian Seismic Regulatory Code (RPOA 2008), and the seismic reliability index was calculated using the weighted sum method. As a result, the bridges were classified into three reliability levels: low, medium, and high. The model was applied to a set of bridges located in seismically active areas. This model provides valuable information for assessing bridge reliability in Algeria and can help decision-makers take proactive measures to improve disaster preparedness and strengthen bridge resilience. Furthermore, engineers and technicians can easily implement this model to prioritize maintenance tasks. To ensure the effectiveness of the proposed methodology, the model was validated through a sensitivity study and normative validation. These studies showed that the model remains stable even when there are variations in input criteria, strengthening its reliability and confirming its applicability in various scenarios. However, this study focuses solely on the seismic reliability of bridges and recommends that future research consider the impacts of other hazards, such as flooding and anthropogenic hazards.

V. AUTHOR’S CONTRIBUTION

Conceptualization: Mohammed Abdellaoui, Mohamed Badaoui.
Methodology: Mohammed Abdellaoui, Mohamed Badaoui, Said Koriga.
Investigation: Mohammed Abdellaoui, Mohamed Badaoui**.**
Discussion of results: Mohammed Abdellaoui, Mohamed Badaoui, Mahmoud Bensaibi, Said Koriga..
Writing – Original Draft: Mohammed Abdellaoui.
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Resources: Mohamed Badaoui.
Supervision: Mohamed Badaoui, Mahmoud Bensaibi.
Approval of the final text: Mohammed Abdellaoui, Mohamed Badaoui.

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