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SEISMIC VULNERABILITY ASSESSMENT OF CONSTRUCTION PROJECTS: A MULTI-CRITERIA APPROACH

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ABSTRACT

In seismic-prone regions, construction projects face elevated vulnerability risks that extend beyond structural design. While technical evaluations are common, few frameworks integrate managerial, human, and logistical dimensions into seismic risk assessment. This study addresses this gap by applying the Analytic Hierarchy Process (AHP) to evaluate seismic vulnerability using a structured multi-criteria decision-making model. Key parameters—including human resources, materials, supply logistics, and organizational practices—are weighted through expert input and analysed in three Algerian case studies across various seismic zones. Findings reveal that human and organizational factors significantly influence overall vulnerability. The study offers a replicable framework and highlights opportunities for enhancing decision-making through AI integration.

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INTRODUCTION

The impact of natural disasters, particularly earthquakes, on construction projects is a critical concern for both engineers and policymakers. Regions with high seismic activity require robust risk assessment and mitigation strategies to ensure the safety and sustainability of infrastructure. In this context, construction projects must integrate effective methodologies to evaluate vulnerabilities and prioritize risk management measures. One such approach is the Analytic Hierarchy Process (AHP), which allows decision-makers to systematically assess multiple risk factors and structure complex decision-making problems into hierarchical models [1].

Despite increasing awareness of seismic risks, existing risk assessment frameworks often lack a structured, multi-criteria approach tailored to construction project management. Many studies focus on technical aspects of seismic resistance, such as structural design, material strength, and seismic reliability calculations [2]. However, few provide a comprehensive decision-making framework that integrates human resources, organizational factors, material availability, and logistics into seismic vulnerability assessments. This gap in the literature highlights the need for a holistic model that incorporates both engineering and management perspectives in seismic-prone regions.

Several risk analysis methods have been explored in the literature. Weibull analysis has been used to predict the performance of repetitive construction projects under uncertainty [3], while neural networks have been applied to improve project duration estimates [4]. The fuzzy AHP method has also been successfully implemented to assess risks in public infrastructure projects [5]. However, these methods are often applied in isolation, without integration into a broader project management framework. Artificial intelligence (AI) has also been recognized as a valuable tool for improving construction risk assessment and decision-making [6], yet its integration with multi-criteria decision-making remains limited.

Despite advancements in structural engineering and seismic resistance design, the literature reveals a significant gap in integrating managerial, logistical, and human factors into seismic risk models. Previous studies often isolate technical variables without accounting for how workforce structure, material availability, and project organization contribute to vulnerability. This paper addresses this gap by proposing a multi-criteria framework that incorporates these underrepresented but critical factors.

To address this gap, this study investigates the following research questions:

- How can seismic vulnerability in construction projects be systematically assessed using a multi-criteria decision-making approach?
- Which project parameters (human resources, material logistics, planning, etc.) contribute most significantly to seismic risk?
- How can the AHP method be adapted to enhance risk assessment and decision-making in construction project management?

In this context, seismic vulnerability refers to the degree of susceptibility of a project's components—such as human resources, material logistics, and organizational processes—to damage when an earthquake occurs. Seismic risk, on the other hand, is defined as the combination of the probability of a seismic event occurring and the severity of its potential consequences on construction projects. This distinction is essential to understand the prioritization model proposed in this study.

This research aims to develop a systematic framework for assessing seismic risk in construction projects by applying the AHP method. The key contributions include:

- Developing a multi-criteria model that evaluates the influence of human resources, material availability, and organizational factors on seismic vulnerability [7].
- Demonstrating the applicability of AHP through case studies in Algeria's seismic-prone regions, where seismic

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risk classification is guided by national standards (D.T.R. BC.248, RPA 2024) [8].

- Providing insights into how decision-making models can improve construction project resilience in high-risk areas [9].

The following section presents a comprehensive literature review on seismic risk assessment methodologies and multi-criteria decision-making models, drawing on foundational works by Vincke [10], Roy [11], and Scharlig [12]. This is followed by a detailed presentation of the research methodology, including data collection and expert evaluation, before discussing the case study findings and their implications.

LITERATURE REVIEW

Seismic vulnerability assessment has traditionally emphasized structural, geotechnical, and architectural dimensions. Early studies largely concentrated on the performance of buildings and infrastructure under seismic loads, employing models such as fragility curves and the HAZUS (Hazards U.S. Multi-Hazard) methodology, developed by FEMA as a standardized framework for estimating disaster-related losses [13]. The foundational concept of risk expressed as Risk = Hazard × Vulnerability × Exposure has guided much of this research, although its application has often been restricted to structural perspectives.

Over the past two decades, however, scholars have increasingly recognized the importance of adopting multi-criteria evaluations that integrate social, economic, and managerial aspects. Cardona [14] emphasized a holistic perspective by incorporating socio-economic dimensions into disaster risk models, while Calvi et al. [15] advanced performance-based methodologies for assessing building vulnerability. Akkar et al. [16] refined probabilistic seismic hazard assessments for infrastructure systems, and Kappos [17] combined vulnerability functions with GIS-based analyses to enhance urban-scale seismic risk modeling. Despite these advances, project-specific managerial vulnerabilities remain underexplored.

Multi-criteria decision-making (MCDM) tools have emerged as valuable approaches for structuring and prioritizing seismic risk factors. The theoretical foundations of MCDM were laid by Vincke [10], Roy [11], and Scharlig [12], while subsequent applications in construction contexts have demonstrated their relevance for practical decision-making. Fong and Choi [18], for example, applied the Analytic Hierarchy Process (AHP) in contractor selection, supplier evaluation, and resource allocation, thereby establishing AHP as a flexible and widely applicable tool in the construction industry. Building on these contributions, recent research has increasingly employed hybrid approaches to capture the multidimensional nature of seismic risk. Beltrão and Carvalho [5] implemented fuzzy AHP to prioritize risks in Brazilian infrastructure projects, Kumar et al. [19] combined AHP with TOPSIS to evaluate safety performance in earthquake-prone zones, Dikmen et al. [20] applied multi-criteria tools for contractor risk assessments under uncertainty, and Yildiz and Duzgun [21] integrated GIS with AHP to assess urban vulnerability. These studies collectively demonstrate a growing interest in incorporating expert judgment and qualitative dimensions into seismic risk modeling.

The selection of parameters in the present study is grounded in both the literature and professional experience. Human resources have repeatedly been identified as a major determinant of project resilience, particularly in relation to training, leadership, and health, safety, and environment (HSE) compliance [7,9]. Material resources are equally crucial, as their availability and reliability directly influence project continuity; studies by Baqerin et al. [3] and Stepanov [2] highlight the risks associated with shortages or delays in material provision. The supply chain represents another critical factor, with disruptions in transportation and logistics often cited as significant weaknesses in disaster-prone contexts [6,22]. Finally, organizational capacity—particularly in terms of planning, coordination, and communication—has been identified as a decisive element in ensuring resilience, as emphasized in the works of Fan et al. [4] and Pettersen [7].

Despite these insights, few studies have attempted to combine these dimensions into a unified framework for seismic risk assessment in construction projects. This research addresses this gap by applying the AHP methodology [23] to quantify the relative influence of human, material, organizational, and logistical parameters across real-world case studies in Algeria.

METHODOLOGY

Definition of the Identified Parameters

The four parameters playing a critical role in managing seismic risk in construction projects are detailed below.

Human Resources (CH)

The quality of personnel is a key factor in the success of an organization or a project's accomplishment. A company's competitive advantage lies in the immense potential offered by its human resources. This aspect becomes even more significant in a context of global competition, increasing technological complexity, and increasingly decentralized management. To fully harness this potential, it is essential that strategic and operational decisions consider the talents of each individual, whether during the selection or assignment of personnel [7].

To ensure that the human component fulfils its role, it must adhere to four major principles:

- Development of a human resources plan.
- Formation of a project team.
- Continuous improvement of the team.
- Effective team management.

The configuration of the human component for a construction project is illustrated in Figure 1.

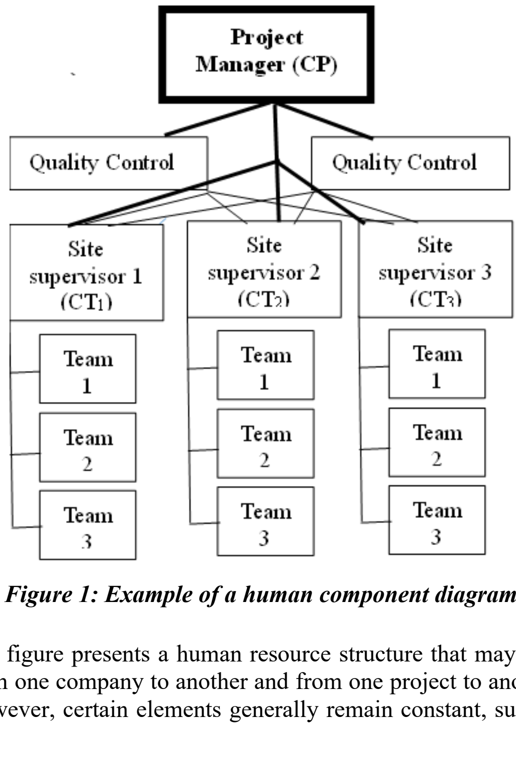

Figure 1: Example of a human component diagram.

The figure presents a human resource structure that may vary from one company to another and from one project to another. However, certain elements generally remain constant, such as the presence of a project manager, HSE (Health, Safety, and Environment) control, quality control, as well as at least one site supervisor and a team. The teams shown in the diagram are each specialized in a particular field.

Material Resource

The construction industry provides powerful and specialized equipment, such as transport vehicles, lifting machinery, earth-moving equipment, and power generators. These resources are a critical component for the success of any project. Material resources are divided into three subcategories (Fig. 2):

- Execution Resources: Machinery and tools needed on-site (e.g., formwork, shears).
- Lifting Resources: Cranes, hoists, and elevators.
- Logistical Resources: Transportation of materials and personnel, energy generators.

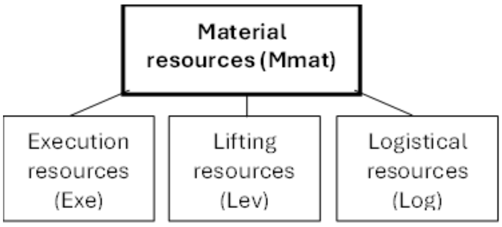

Figure 2: Material resources diagram.

Supply Chain

The supply chain for a construction site must align with the progress of the work, taking into account key criteria such as cost, proximity, and availability (Figure 3). The elements to consider include:

- The quantity of materials available.
- Coordination between delivery and the progress of the work.
- Storage methods and conditions.

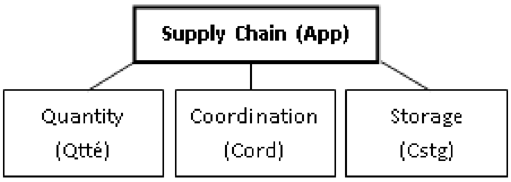

Figure 3: Material Supply diagram.

Organization

The organization of a construction project is crucial for managing human, material, and financial resources. It ensures effective project structuring, adherence to deadlines, and quality assurance. Organization consists of three sub-parameters:

- Planning: describe the extent, quality, or effectiveness of a planning process
- Coordination: describe its effectiveness, quality, scope, or extent in each context.
- Communication: describe its effectiveness, quality, clarity, or scope.

The organization is sketched in Figure 4 here after.

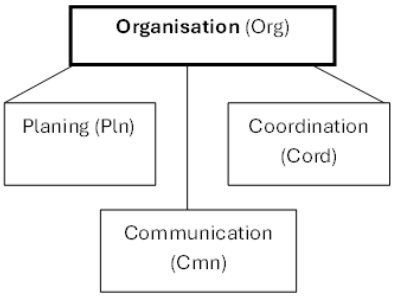

Figure 4: Organizational diagram.

AHP Model Application

The Analytic Hierarchy Process (AHP), developed by Saaty [23], is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It helps decision-makers model a problem in a hierarchical structure showing the relationships of the goal, criteria (parameters), sub-criteria, and alternatives (Fig. 5).

Steps followed:

- Define the problem and objectives.
- Form an expert panel with criteria based on professional experience (10+ years), academic background, and seismic project experience.
- Structure a hierarchy: goal → criteria → sub-criteria.
- Construct pairwise comparison matrices and calculate weights.
- Perform consistency checks.
- Aggregate expert scores to rank vulnerabilities.

Definition of the Problem

The central problem addressed in this study is the lack of a structured framework that integrates non-structural parameters—such as human resources, material availability, organizational practices, and supply chain logistics—into seismic vulnerability assessment. Most existing models prioritize engineering and structural considerations, overlooking the critical influence of project management and operational factors. This study aims to bridge this gap by applying the AHP method to assess and prioritize these parameters within construction projects located in seismic-prone regions of Algeria.

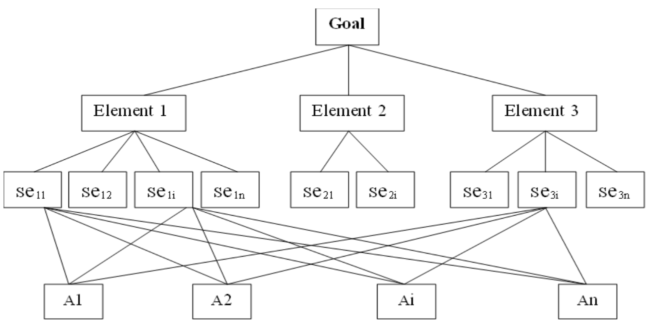

Figure 5: Hierarchical structure of a problem according to AHP [22].

Expert Selection and Evaluation Process

The evaluation of parameters was conducted by a panel of experts specializing in construction project management and seismic risk assessment. The selection of these experts was based on their professional experience, academic background, and direct involvement in construction projects in seismic-prone areas.

The experts were chosen based on the following criteria:

1) Professional Experience – Minimum of 10 years of experience in construction project management, structural engineering, geotechnical engineering, or risk assessment.
2) Academic Qualifications – Holding at least a master's degree or Ph.D. in civil engineering, seismic engineering, or project management.
3) Project Involvement – Direct participation in at least three major construction projects located in seismic-prone regions.
4) Decision-Making Role – Occupying a senior-level position (e.g., project manager, head of a geotechnical lab, structural engineer, or consultant).
5) Regional Expertise – Familiarity with Algerian seismic regulations (and D.T.R. BC.248, RPA2024) [8] and practical experience in the country's high-risk zones.

The final expert panel consisted of:

- Project managers (30%) – Professionals responsible for overseeing construction projects in seismic regions.
- Structural engineers (25%) – Specialists in earthquake-resistant design and risk mitigation strategies.
- Geotechnical engineers (20%) – Experts analyzing soil-structure interactions and ground stability.
- Academics and researchers (15%) – University professors and Ph.D. holders in seismic risk assessment.
- Regulatory officials (10%) – Government representatives responsible for enforcing building codes and seismic regulations.

By ensuring a balanced representation of industry and academia, the evaluation process incorporated practical, regulatory, and theoretical perspectives, strengthening the reliability of the assigned scores.

Determined Weights

The evaluation is project-specific since each project is different in terms of its consistency, specific challenges, cost, site location, etc. Each parameter consists of sub-parameters, and its value is a weighted sum of its sub-parameters, with the weighting coefficients determined by AHP. Scores are assigned by experts to the attributes. This is summarized in Table 1 below. E_{MH}, E_{Mmat}, $_{App}$, and EOrg vary from one project to another; and their values are given in Table 1.

Table 1: Parameters governing the vulnerability of a construction site.

Parameter	Weight	Factor	Weight	Category	Score
Human Resources	E_{CH}	Project Manager	0.45	Presence	4.5
				Absence	0
		HSE Controller	0.20	Presence	2
		Quality Controller		Absence	0
		Site Supervisor	0.35	Presence	3.5
				Absence	0
Material Resources	E_{Mmat}	Execution Resources	0.50	Available	5
				Partially	2.5
				Unavailable	0
		Lifting Resources	0.30	Available	3
				Partially	1
				Unavailable	0
		Logistical Resources	0.20	Available	2
				Partially	1
				Unavailable	0
Supply Chain	E_{App}	Quantity	0.45	Plenty	4.5
				A few	2.5
				Limited	1
		Coordination	0.25	Complete	2.5
				Partial	1.5
				Limited	0.8
		Storage	0.3	Optimized	3
				Suboptimal	1.5
				Inefficient	0.05
Organization	E_{Org}	Planification	0.5	Efficient	5
				Moderate	2.5
				Weak	1
		Coordination	0.3	Effective	3
				Fair	1.5
				Poor	0.5
		Communication	0.2	Clear	2
				Vague	1
				Unclear	0.5

Seismic Vulnerability Index

The seismic vulnerability index is calculated for each project, thus allowing for the classification of parameters according to their vulnerability, highlighting the most vulnerable parameter in a construction project.

Parameter Vulnerability Index

The parameters characterizing the project in question will each have a value Ipi. Let the seismic vulnerability index of parameter i be given by the following formula:

$$I_{pi}=E_i * V_i/R_j \quad (1)$$

where, E_i: priority order of parameter "i", determined by AHP, V_i: value of parameter "i" estimated by experts during the project analysis, and R_j: coefficient given by the RPA2024 (Algerian seismic regulations) based on the seismic zone.

Indeed, Algeria is divided into seven seismic zones: zone 0, I, II, III, IV, V, and VI; each zone has its own seismic soil acceleration, and the coefficient R_j depends on the zone, the usage group, and the importance of the project.

$$R_j = A.I.g \quad (2)$$

where, A: acceleration coefficient, I: degree of importance, and g: gravitational acceleration

Reference zone acceleration *A*:

The coefficient represents the acceleration of the zones and is provided in Table 2.

Table 2: Reference acceleration of different zones [8].

Seismic zone	Seismicity	Reference Zone Acceleration Coefficient (A)
0	Very low	-
I	Low	0.07
II	Low to Moderate	0.1
III	Moderate	0.15
IV	Moderate to High	0.2
V	High	0.25
VI	Very High	0.3

Importance coefficient *I*:

According to [8], buildings are classified into 4 importance groups:

- Group 1A: Vital importance buildings
- Group 1B: High importance buildings
- Group2: Medium importance buildings
- Group3: Low importance buildings

Table 3 summarizes the values assigned to the importance coefficients of buildings.

Table 3: Importance Coefficients [8].

Importance Coefficient	Importance Group			
	1A	1B	2	3
I	1.4	1.2	1	0.8

Gravitational acceleration *g*:

In this case, g=10 m/s2

By using formula (2) and Tables 2 and 3, we obtain the different values that R_j can take, which are grouped in Table 4.

Table 4: Values of R_j [8].

Group	1A	1B	2	3
Importance Coefficient	I = 1.4	I = 1.2	I = 1.0	I = 0.8
Zone 0	-	-	-	-
Zone I	0.98	0.84	0.7	0.56
Zone II	1.4	1.4	1	0.8
Zone III	2.1	1.8	1.5	1.2
Zone IV	2.8	2.4	2	1.6
Zone V	3.5	3	2.5	2
Zone VI	4.2	3.6	3	2.4

Project Vulnerability Index

To obtain an overall seismic vulnerability index of the ongoing project, we will sum the indices of all the parameters. This gives the formula for the overall seismic vulnerability index of the project I_T.

$$I_T = \sum_{i=1}^{4} I_{pi}$$

RESULTS

The methodology developed in the previous section is applied to three case studies encountered in Algeria.

Case 1

It deals with a vital importance project consisting of two large buildings with a cost of $6 million USD. The site is located in Zone V1 (Blida). Based on Table 4, Rj=4.2.

Study of Parameter Priority Order Using AHP

The priority order of the parameters is determined from the pairwise comparison matrix.

Pairwise Comparison Matrix

The rank of the parameter comparison matrix is four, corresponding to the number of parameters to be compared. The comparisons are made using Saaty's table, based on [19] and the opinions of construction experts such as project managers, architects, civil engineers, and consulting firms (see Matrix below).

$$\begin{array}{ccccc} & CH & MM & App & Org \\ CH & 1 & 4 & 5 & 2 \\ MM & 1/4 & 1 & 4 & 1/4 \\ App & 1/5 & 1/4 & 1 & 1/5 \\ ORG & 1/2 & 4 & 5 & 1 \end{array} \quad (4)$$

From the comparison matrix (4), the priority order of the parameters is determined as follows:

$E_{CH} = 0.465$

$E_{MM} = 0.144$

$E_{App} = 0.064$

$E_{Org} = 0.328$

Table 5: Values of Parameters and Factors for Project 1.

Parameter	Weight (%)	Factor	Weight (%)	Value (/10)	Category	Score (/10)
Human Resources	46.5%	Project Manager	61.9%	8	Presence	4.952
		HSE Controller	9.6%	6	Presence	0.576
		Site Supervisor	28.4%	7	Presence	1.988
Total value of the *Human Resources* parameter						**7.516**
Material Resources	14.4%	Execution Resources	63.9%	8	Available	5.512
		Lifting Resources	29.4%	6	Available	1.764
		Logistical Resources	8.7%	6	Available	0.522
Total value of the *Material Resources* parameter						**7.398**
Supply Chain	6.4%	Quantity	45%	6	Plenty	4.110
		Coordination	25%	7	Complete	1.547
		Storage	30%	4	Optimized	0.372
Total value of the *Supply Chain* parameter						**6.029**
Organization	32.8%	Planification	50%	7	Efficient	4.697
		Coordination	30%	8	Effective	1.056
		Communication	20%	6	Clear	0.51
Total value of the *Organization* parameter						**6.263**

Verification

The maximum eigenvalue of the pairwise comparison matrix is $\lambda max = 4.2427$

The consistency index is IC= 0.081. Similarly, the consistency ratio is RC = 0.091, which indicates that the judgment is acceptable.

Parameter Evaluation

The values of the parameters (denoted as Vi in the formula 1) and their factors, along with their weights and corresponding scores, are summarized in Table 5.

Values of Partial Seismic Vulnerability Indices (using Eq.1)

$I_{CH} = 0.465*7.75/4.2 = 0.858$

$I_{MM} = 0.144*7/4.2 = 0.24$

$I_{App} = 0.064*5.65/4.2 = 0.086$

$I_{Org} = 0.328*7.1/4.2 = 0.554$

Value of the Overall Seismic Vulnerability Index (using Eq. 3)

$I_T = 1.738$

It is observed that *human resources* are the most vulnerable parameter during an earthquake, followed closely by *organizational resources*

Case 2

It concerns a project involving 700 housing units, classified as a project of great importance, with a cost of $22 million USD. The project is located in Bouira, Zone V. According to Table 4, Rj=3.5.

As in Case 1, the priorities for comparing the parameters will be established using the pairwise comparison matrix (Eq. 5).

Pairwise Comparison Matrix

$$\begin{array}{c|cccc} & CH & MM & App & Org \\ CH & 1 & 4 & 9 & 5 \\ MM & 1/4 & 1 & 5 & 4 \\ App & 1/9 & 1/5 & 1 & 1/4 \\ ORG & 1/5 & 1/4 & 4 & 1 \end{array} \quad (5)$$

The priorities of the parameters for this project are:

$E_{CH} = 0.584$

$E_{MM} = 0.249$

$E_{App} = 0.046$

$E_{Org} = 0.121$

Verification

Consistency IC = 0.088<0.1, indicating that the judgment is acceptable.

Evaluation of Parameters and Factors

As in Project 1, the weights of the sub-parameters remain the same, but other values change. The results are presented in Table 6.

Values of Partial Seismic Vulnerability Indices (using Eq.1)

$I_{CH} = 0.584*6.805/3.5 = 1.135$

$I_{MM} = 0.249*7.950/3.5 = 0.566$

$I_{App} = 0.046*6.157/3.5 = 0.080$

$I_{Org} = 0.121*7.99/3.5 = 0.276$

Value of the Overall Seismic Vulnerability Index (using Eq. 3)

$I_T = 2.027$

It is observed that *human resources* are the most vulnerable parameter during an earthquake, followed by *material resources*

Table 6: Values of Parameters and Factors for Project 2.

Parameter	Weight (%)	Factor	Weight (%)	Value (/10)	Category	Score (/10)
Human Resources	58.4%	Project Manager	61.9%	7	Presence	4.333
		HSE Controller	9.6%	8	Presence	0.768
		Site Supervisor	28.4%	6	Presence	1.704
Total value of the *Human Resources* parameter						**6.805**
Material Resources	24.9%	Execution Resources	63.9%	9	Available	5.751
		Lifting Resources	29.4%	6	Available	1.764
		Logistical Resources	8.7%	5	Available	0.435
Total value of the *Material Resources* parameter						**7.950**
Supply Chain	4.6%	Quantity	68.5%	6	Plenty	4.110
		Coordination	22.1%	8	Complete	1.768
		Storage	9.3%	3	Optimized	0.279
Total value of the *Supply Chain* parameter						**6.157**
Organization	12.1%	Planification	67.1%	8	Efficient	5.368
		Coordination	26.4%	8	Effective	2.112
		Communication	8.5%	6	Clear	0.510
Total value of the *Organization* parameter						**7.990**

Case 3

It is a project of 500 housing units, considered a project of high importance, located in Boumerdes, seismic zone IV. According to table 4, Rj = 2.5, and the project cost is 8.5 million US $.

The weighting coefficients for the sub-parameters remain the same, while the other coefficients and values will differ based on the evaluation of the experts.

Pairwise Comparison Matrix

$$\begin{array}{c|cccc} & CH & MM & App & Org \\ CH & 1 & 5 & 7 & 4 \\ MM & 1/5 & 1 & 4 & 1/3 \\ App & 1/7 & 1/4 & 1 & 1/5 \\ ORG & 1/4 & 3 & 5 & 1 \end{array} \quad (6)$$

The consistency index IC = 0.092<0.1, which makes the judgment is acceptable. The priorities of the parameters are determined from the comparison matrix and are as follows:

$E_{CH} = 0.576$

$E_{MM} = 0.132$

$E_{App} = 0.053$

$E_{Org} = 0.239$

Evaluation of Parameters and Factors

The results are presented in Table 7.

Values of Partial Seismic Vulnerability Indices (using Eq.1)

$I_{CH} = 0.576*7.8/2.5 = 1.79$

$I_{MM} = 0.132*7.485/2.5 = 0.395$

$I_{App} = 0.053*7.121/2.5 = 0.151$

$I_{Org} = 0.239*6.706/3.6 = 0.641$

Value of the Overall Seismic Vulnerability Index (using Eq. 3)

$I_T = 2.977$

It is observed that *human resources* are the most vulnerable parameter during an earthquake, followed by *organization*.

Note that this last project is the most vulnerable one compared to the other two projects.

DISCUSSION

Key Findings and Analysis

The results from the AHP-based seismic vulnerability assessment highlight the dominance of human resources as the most critical vulnerability factor across all case studies. The findings indicate that poor workforce management, inadequate training, and lack of preparedness significantly increase seismic risk, which aligns with prior research emphasizing the role of human factors in project success [18].

The second most significant parameter varied between projects:

- In Case 1 (Zone VI, Blida) and Case 3 (Zone IV, Boumerdes), organizational factors were the second most vulnerable, emphasizing the impact of project planning, communication, and coordination.
- In Case 2 (Zone V, Bouira), material resources emerged as the second most critical factor, suggesting that project scale and logistical constraints can influence risk prioritization.

The seismic vulnerability index calculations further reinforced these observations. Projects in higher seismic zones (Blida, Zone VI) exhibited greater overall vulnerability, demonstrating the influence of seismic intensity on risk factors. However, the fact that human resources consistently ranked highest suggests that technical improvements alone are insufficient without addressing workforce preparedness and management.

Table 7: Values of Parameters and Factors for Project 3.

Parameter	Weight (%)	Factor	Weight (%)	Value (/10)	Category	Score (/10)
Human Resources	57.6%	Project Manager	61.9%	8	Presence	4.952
		HSE Controller	9.6%	6	Presence	0.576
		Site Supervisor	28.4%	8	Presence	2.272
Total value of the *Human Resources* parameter						**7.800**
Material Resources	13.2%	Execution Resources	63.9%	9	Available	5.112
		Lifting Resources	29.4%	6	Available	1.764
		Logistical Resources	8.7%	5	Available	0.609
Total value of the *Material Resources* parameter						**7.485**
Supply Chain	5.3%	Quantity	68.5%	6	Plenty	4.795
		Coordination	22.1%	8	Complete	1.768
		Storage	9.3%	3	Optimized	0.558
Total value of the *Supply Chain* parameter						**7.121**
Organization	23.9%	Planification	67.1%	8	Efficient	4.697
		Coordination	26.4%	8	Effective	1.584
		Communication	8.5%	6	Clear	0.425
Total value of the *Organization* parameter						**6.706**

The three main contributions of this study are also directly supported by previous research and regulatory frameworks, which reinforces their scientific and practical relevance. First, the integration of human resources into seismic vulnerability assessment aligns with Pettersen's work [7], which emphasized the importance of evaluating human potential and workforce capacity as critical determinants of organizational resilience. Second, the application of the proposed AHP-based model to case studies in Algeria builds on the regulatory context provided by the national seismic code [8], which establishes the official framework for seismic risk classification and underlines the need for structured approaches to project vulnerability assessment. Third, the focus on improving decision-making models for construction project resilience resonates with the findings of Kazaz et al. [9], who identified organizational and managerial deficiencies as major causes of delays and vulnerabilities in construction projects. By explicitly connecting these contributions to established research and standards, the present study demonstrates both its novelty and its consistency with prior work in the field.

Implications for Construction Project Management

Strengthening human resource management in seismic zones:

The prominence of human resources in the results suggests an urgent need for capacity-building initiatives in construction teams.

- Training programs on seismic risk preparedness and emergency response should be integrated into project planning.
- Mandatory certification in earthquake-resistant construction techniques could enhance worker readiness.
- Incorporation of AI-driven workforce management tools [6] to optimize personnel allocation and skill matching.

Improving organizational resilience through risk-aware planning:

The high vulnerability of organizational factors in seismic-prone areas suggests that poor planning and coordination exacerbate risks. Effective strategies include:

- Adopting real-time project monitoring systems using AI to enhance responsiveness [4].
- Implementing risk-sensitive scheduling techniques (e.g., integrating seismic risk forecasts into project timelines).
- Strengthening communication channels between stakeholders, ensuring faster decision-making during emergencies.

Optimizing material and supply chain management:

For projects where material resources and logistics were significant risk factors, several mitigation strategies are necessary:

- Enhancing supply chain resilience by securing alternative material sources and optimizing inventory storage [3].
- Investing in durable, earthquake-resistant materials, as their availability and deployment were key concerns in vulnerable regions.
- Incorporating predictive analytics to anticipate material shortages and delays, minimizing disruptions in seismic events.

Adapting multi-criteria risk assessment for decision-making:

The findings support the utility of the AHP model in systematically prioritizing risk factors. However, the integration of complementary risk assessment methods (e.g., Weibull analysis for project delays [3] or fuzzy AHP for uncertainty modelling [5]) could enhance decision-making accuracy. Future studies should also explore AI-enhanced AHP models for real-time vulnerability assessments.

Broader Implications for Policy and Infrastructure Resilience

The study's insights have significant implications for policymakers and urban planners in seismic-prone regions:

- Regulatory agencies should mandate AHP-based vulnerability assessments in construction permit evaluations.
- Incentives for earthquake-resilient construction (e.g., tax breaks for AI-based project management systems) could encourage adoption.
- Integration of risk indices into national seismic guidelines [8] to ensure uniform application across projects.

Recommendations

The study underscores that human resource vulnerabilities pose the greatest risk to seismic-prone construction projects, reinforcing the need for a people-centric approach to seismic resilience. While AHP proved effective in risk prioritization, future research should explore hybrid models incorporating AI and advanced predictive analytics to refine risk assessments further.

CONCLUSIONS

This study contributes to the advancement of seismic risk assessment methodologies by developing a structured, multi-criteria decision-making framework using the Analytic Hierarchy Process (AHP). Through the assessment of real construction projects in seismic-prone regions of Algeria, it identifies critical risk factors often neglected in traditional approaches.

The originality of this study lies in its integration of managerial, logistical, and regulatory dimensions into a unified AHP-based seismic risk assessment model. Unlike prior work, which focuses primarily on structural resistance, this research proposes a human-centric vulnerability analysis, validated through real case studies. The study demonstrates that demonstrating a use of AHP alone is insufficient for novelty - hence, the emphasis on its multi-criteria integration and real-world applicability in seismic-prone Algeria.

Key Contributions to the Body of Knowledge

1) Integration of human and organizational factors into seismic risk models

- Unlike traditional seismic assessments that focus primarily on structural and geotechnical parameters, this study demonstrates that human resources and organizational management are critical vulnerabilities.
- The findings underscore the necessity of training programs, workforce management strategies, and project coordination improvements to enhance resilience in seismic-prone construction projects.

2) Application of AHP for multi-criteria seismic risk assessment

- The study refines the use of AHP in risk prioritization, providing a replicable methodology for evaluating and ranking vulnerability factors in complex construction projects.
- The integration of expert judgment in the weighting process ensures that both qualitative and quantitative risk factors are systematically addressed.

3) Bridging the gap between AI and seismic risk decision-making

- This research identifies a significant opportunity for the integration of artificial intelligence (AI) into multi-criteria decision models, particularly for improving real-time seismic risk assessment and predictive analytics.
- Future studies can build on this foundation by incorporating machine learning techniques to refine AHP weightings and automate expert-based scoring.

4) Case studies as a benchmark for future research

- By applying the proposed AHP framework to real-world projects in high-risk seismic zones, the study provides empirical data that can be used for validation and comparison in future research.
- The results serve as a benchmark for policymakers and practitioners looking to adopt structured risk assessment methodologies in seismic-prone construction projects.

Future Directions

To further enhance the practical impact of this research, future work should explore:

- The integration of AI-enhanced decision-making models, combining AHP with machine learning for improved predictive accuracy.
- Cross-regional studies comparing seismic vulnerability across different geographic and regulatory contexts to generalize the findings.
- The development of a standardized seismic risk index, incorporating dynamic project conditions and real-time data monitoring.

By addressing both theoretical gaps and practical challenges, this study provides a structured foundation for enhancing seismic risk management in construction projects. The proposed methodology contributes to more resilient infrastructure development, ensuring that human, material, and organizational vulnerabilities are effectively mitigated in seismic-prone regions.

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