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Study on Resilience Evaluation for Construction Management of Major Railway Projects

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Abstract: The construction of major railway projects poses significant risks, which present considerable challenges to construction management. To accurately assess the level of construction management for these projects, this study incorporated resilience theory into the field. The grounded theory method was utilized to establish a resilience evaluation indicator system for managing a major railway project construction. Additionally, a resilience evaluation model based on the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation method was proposed. This model was applied to evaluate the construction management resilience of a major railway project located in the mountainous region of southwest China. The results indicated that the project exhibits a very high overall level of construction management resilience. Specifically, it demonstrates high levels of ability to monitor and warn, an ability to resist absorption, and an ability to respond to emergencies. Additionally, it showcases high levels of ability to recover and rebuild, and an ability to learn to adapt. The evaluation results were consistent with the actual situation and verified the correctness and reliability of the method. Based on the aforementioned research findings, this paper puts forward recommendations on material redundancy and resource security from a resource perspective, and suggestions on organizational optimization and personnel capacity improvement from a subject perspective, thus indicating directions for enhancing the management level of major engineering railway constructions.

Keywords: construction management resilience; major railway; evaluation model; empirical study

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1. Introduction

The construction and management of major railway projects face significant challenges due to the complex environmental characteristics [1]. Firstly, the geological environment's complexity not only increases the construction difficulty but also demands higher levels of stability and safety for the project [2]. Secondly, the extreme harshness of the climate environment poses another problem in railway engineering construction [3]. For instance, under extreme climatic conditions, such as high temperatures, low temperatures, and strong winds, railway equipment and structures are susceptible to damage, compromising the safety and stability of railway operations. Thirdly, the vulnerability of the ecological environment requires sufficient attention during railway project construction. Additionally, a variety of disaster risks, including climatic disasters, geological disasters, engineering disasters, and plateau disasters, can significantly impact railway projects [4].

Currently, most studies on major railway engineering construction rely on traditional risk prevention and control methods [5–7]. These studies primarily focus on risk management, emphasizing a pre-construction analysis of explicit risk sources, predicting the probability and impact of risks, and formulating risk plans and contingency measures in advance to control and mitigate damage caused by disasters within an acceptable range. However, major railway projects differ significantly from general engineering and construction projects. The natural environment in which major railway projects are undertaken possesses multiple high-energy characteristics, and our understanding of it is still not comprehensive enough [8,9]. This implies that further improvement is needed in our comprehension of natural environmental conditions, potential risk factors, and interactions faced by the project. Particularly, interactions with construction activities may give rise to various hidden hazards that are difficult to accurately portray and predict using traditional risk management methods.

In contrast to the traditional risk management concept, crisis management under the resilience perspective emphasizes the adaptability and sustainable development of the engineering construction system during crises. The objective is to enhance the system's resilience capabilities in the face of shocks, ensuring uninterrupted and stable engineering and construction activities without breaching the system's resilience threshold [10]. As shown in Table 1. Therefore, this study aims to introduce resilience theory into the construction management of significant railway projects, facilitating the shift in project management philosophy from risk control to risk adaptation. Building upon an analysis of the composition of construction management for major railway projects and a comprehensive understanding of resilience management in existing projects, the study proposes that the core concept of resilience in construction management is the system's ability to prevent, absorb, adapt to, and recover from risk impacts. This allows the construction management system to maintain its characteristics, functions, and operational modes, even exceeding its pre-impact state. Furthermore, this paper integrates the Analytic Hierarchy Process (AHP) and the fuzzy comprehensive evaluation (FCE) method to develop a systematic and comprehensive resilience assessment system for major railway construction project management. It also proposes targeted recommendations for improvement, enhancing the adaptability and sustainability of the construction project system in dealing with explicit and implicit risk impacts. This aligns with the management needs of major railway construction project systems and bears significant theoretical research significance and practical application value.

Table 1. The difference between traditional risk management and resilience management.

Approaches	Advantages	Disadvantages
Traditional Risk Management	When engineering project uncertainty is low, engineering construction risks can often be accurately identified, controlled, and even avoided.	When engineering project uncertainty is high, engineering construction risks often exceed cognition and are difficult to accurately identify.
Resilience Management	When engineering project uncertainty is high, the improvement of system resilience can help it adapt, recover, and even surpass its own steady state during the shock of unknown risks.	When engineering project uncertainty is low, the system may not suffer shocks, and excessive resilience will cause a large waste of resources.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 proposes a resilience evaluation indicator system for the construction management of major railway projects. Section 4 constructs a resilience evaluation model for major railway construction management. Section 5 conducts an empirical analysis based on the model. Section 6 discusses the results. Finally, Section 7 presents the conclusions, recommendations for resilience enhancement, and the limitations of this study.

2. Literature Review

2.1. Engineering Resilience

The concept of engineering resilience has its origins in ecological resilience [11], and has since been adopted by scholars in the field of engineering construction management. In this context, robustness can be seen as synonymous with engineering resilience [12]. The core principle of engineering resilience is to enable major engineering or infrastructure systems to maintain their core functions in the face of internal or external shocks or conflicts, and to recover quickly from unforeseen crises [13,14]. Key elements of engineering resilience include monitoring and warning capabilities, resistance to absorption, recovery and reconstruction, and adaptive learning in major projects [15]. Bruneau et al. developed a framework for resilience capabilities that includes robustness, resourcefulness, redundancy, and rapidity [16]. Li and Lence highlighted the importance of engineering resilience in the context of water resource systems, specifically the ability to recover from failure and return to a safe state [17]. Building on the 4R framework of resilience developed by Bruneau et al., a resilience capacity triangle model was proposed that consists of absorptive capacity, adaptive capacity, and recoverability [12]. Vugrin et al. focused on the ability to restore engineering resilience after a disturbance, acknowledging that certain crises cannot be avoided in the current environment [18]. Therefore, resilience emphasizes the development of flexibility and adaptability in critical engineering and infrastructure systems in order to maintain minimal functionality during crises, and to recover as quickly as possible afterwards. The introduction of this concept has led to a shift in the critical infrastructure industry, moving from an attitude of simply protecting critical infrastructure to actively improving its resilience [19,20].

2.2. Resilience Evaluation

With the increasing research on the meaning and conceptual framework of resilience in major infrastructure engineering, quantifying engineering resilience and evaluating the level of system engineering resilience has become a focal point for researchers. Resilience evaluation research stems from well-established risk assessment research, but there are clear differences between the two. Risk assessment is a common method for quantifying potential risks and reducing their occurrence, focusing on measuring the potential losses to the system [21]. In contrast, resilience evaluation emphasizes measuring the system's ability to withstand and recover from adaptive disturbances [22–24]. Major infrastructure projects, as complex adaptive systems, are characterized by significant complexity and uncertainty. Under the influence of internal and external disturbances, system losses are difficult to avoid, which is precisely the challenge that resilience evaluation addresses. In terms of the time dimension, resilience evaluation focuses more on the timing of resilience activities rather than analyzing the entire process of risk occurrence as in risk assessment studies. For example, it involves reconfiguring the organizational structure and resources to cope with the impact of internal and external disturbances within the system. Additionally, conducting regular internal vulnerability analyses of the system is crucial for cultivating the system's adaptive capacity and enhancing its resilience [25–28].

Existing resilience evaluations of major infrastructure projects have mainly been conducted from two perspectives: the single dimension and the network dimension. Evaluations from a unidimensional perspective focus on a specific major infrastructure project, identifying weak points within the system to improve reliability and reduce vulnerability by assessing the resilience level of that particular infrastructure [29,30]. Resilience evaluations from a network dimension perspective are concentrated in the field of urban resilience. The research primarily focuses on evaluating the importance and interconnectivity of each infrastructure node within the resilience network composed of multiple lifeline infrastructure projects. This provides a basis for enhancing the resilience of the infrastructure network and proposing strategies to improve the resilience of lifeline infrastructure systems [31,32].

Regarding resilience assessment methods, existing mainstream methods can be categorized into three types: qualitative, quantitative, and a combination of both. Qualitative research mainly employs conceptual framework modeling, constructing models based on relevant literature and works in the field of resilience. This approach effectively elucidates the correlation and relationship between system resilience and key internal elements at a macro level [33]. The data involved in this method are typically textual, and are thus less costly. However, due to the lack of data information, it is challenging to accurately describe the changes in internal parameters of technical systems. Empirical analysis is another popular qualitative assessment method, constructing qualitative indicators based on the practical experience of typical engineering projects to evaluate the resilience of infrastructure [34,35]. Researchers using this method often have close cooperation with the construction and construction units of the engineering projects they study, allowing them to accurately refine resilience indicators and effectively and realistically assess the resilience level of projects. However, this method tends to focus on a specific engineering project, and its evaluation results may lack universality. Quantitative research on resilience assessment mainly utilizes tools such as Bayesian networks [36,37], Monte Carlo simulation [38,39], machine learning, and nonlinear dynamic analysis based on the OpenSees platform [40–42]. These tools are used to simulate the characteristics and behavior of the system for nonlinear dynamic analysis to assess the system resilience [43,44]. Quantitative research methods significantly improve the accuracy and reliability of resilience assessments by conducting various predictive simulation experiments based on a large dataset of infrastructure system structural properties and impact actions and selecting the most effective models. The main challenges of this approach lie in the complexity of the models, the time-consuming model construction and simulation processes, and the demand for a large amount of technical, managerial, and organizational data. Finally, the method combining qualitative and quantitative assessments of resilience has become increasingly popular in recent years. These methods involve assigning indicators representing resilience based on the nature of the system and its operating conditions and calculating the resilience index using a weighted average [45]. This approach combines a large amount of objective data and expert experience from relevant fields, yielding scientifically reasonable results with moderate implementation difficulty, but it also has its limitations. Indicator construction may be limited by historical data, and expert assessments as a significant source of data may introduce considerable subjectivity.

3. Resilience Evaluation Indicator System for Major Railway Project Construction Management

3.1. Methodology for the Selection of Evaluation Indicators

The resilience of major railway project construction management is a comprehensive and complex concept characterized by dynamism and evolution. Relying solely on statistical research techniques can lead to the exclusion of qualitative data and overlook hidden details. To address this, this study employed the semi-structured field interview method to collect qualitative data from various stakeholders involved in major railway projects, including owners, constructors, designers, and supervisors. Grounded theory research was then utilized to analyze the qualitative material, aiming to clarify, illustrate, and systematize the resilience of construction management iteratively and deductively in major railway projects. The objective was to enhance the evaluation system for resilience in major railway construction management based on the field-collected data.

The data collection process spanned 17 months and involved multiple symposiums with each respondent from major railway project owners, construction units, and scientific research units. These symposiums addressed the topics outlined in the interview guide, as well as the actual situation of the projects. Following the completion of the interviews, audio and video recordings were transcribed into written materials, resulting in a total of 40 interview memos. A random selection of 30 memos was chosen for coding analysis, while the remaining 10 were used to test theoretical saturation.

3.2. Determination of Evaluation Indicators

This research was based on the analysis of 40 interview transcripts and incorporates existing literature resources, such as journals, dissertations, newspapers, and monographs, from both domestic and international sources. The objective was to identify the key factors that influence major railway project construction management or construction management resilience. During the coding process, relevant literature was consulted to assign names and definitions to these factors [46–49]. The interview records, totaling 50,000 words, were analyzed using Nvivo 11 software, which employed open coding, axial coding, and selective coding techniques. Initially, initial concepts were extracted and refined from the organized interview records, resulting in 23 categories. Subsequently, utilizing the coding feature of Nvivo 11, these 23 concept categories were classified based on their inherent connections, leading to the identification of 12 main categories. Through repeated discussions and debates, employing the steps of selective coding, including outlining storylines, describing primary and secondary categories along with their relevant dimensional attributes, and establishing connections between core and other categories, five core categories were ultimately determined. Table 2 summarizes these core categories and their definitions regarding the influential factors of major railway project construction management resilience. Subsequently, the remaining 10 interview records underwent independent coding, which did not introduce any new concepts or categories, thereby satisfying the requirements for theoretical saturation testing.

Table 2. Encoding of factors influencing resilience of major railway construction management.

Core Categories	Concept Description	Main Category	Category
Ability to monitor early warning	During the construction of major railway projects, advanced and reliable technological methods, such as big data, cloud computing, sensors, and intelligent terminals, are employed to gather information on construction safety, ecological environment, geological hazards, and occupational health risks and hazards. Dynamic tracking and monitoring activities are conducted to proactively identify and monitor potential risks before they have a significant impact, thereby providing valuable support for risk analysis. Additionally, a well-established risk assessment system is implemented, utilizing the monitoring data collected on-site to conduct comprehensive analysis and evaluation. With the aid of a risk warning platform, modern information technology is utilized to intelligently disseminate safety warnings.	Shock Monitoring	Natural and geological Hazards monitoring
			Production safety inspection
			Occupational health and safety management
			Construction environment and water protection monitoring and inspection
			Material security monitoring and inspection
		Information Processing	Processing and analysis of various types of monitoring data
		Shock Warning	Early warning platforms and mechanisms

Table 2. *Cont.*

Core Categories	Concept Description	Main Category	Category
Ability to resist absorption	On one hand, the ability to resist absorption refers to the system's capacity to promptly develop emergency plans and issue command instructions upon the occurrence of major internal or external risks. This involves mobilizing all departments to respond to the emergency, coordinating the deployment of personnel and resources, and collaborating with external organizations to collectively address the situation. On the other hand, it pertains to the capability of ongoing construction activities, as well as the equipment and facilities on-site, to withstand risk impacts and prevent or minimize casualties and property damage. It also encompasses the system's ability to sustain its construction functions and mitigate losses in the face of regular risk events.	Shock Resistance	Rapid decision-making response and organizational mechanisms
		Shock Absorption	Occupational health protection facilities and medical personnel
			On-site redundancy of key construction equipment
			Repair and maintenance of large machinery and equipment
			Redundant stockpiles of important key materials
Ability to respond to emergencies	In order to cope with the extremely high-risk challenges faced by the construction management of major railway projects, the construction site and rescue bases are strengthened through the construction of hardware and software rescue facilities and equipment, with the ability to enter, rescue, transport, and treat after a disaster occurs.	Emergency organization	Emergency rescue leadership team and rescue team
		Emergency Management	Emergency plan and emergency response
			Three-tier emergency medical treatment and transportation systems
		Emergency Facilities and Materials	Emergency rescue equipment configuration
Ability to recover and rebuild	After the occurrence of risk impact, the ability to quickly mobilize engineering machinery and equipment and materials to arrive at the construction site, quickly clean up the construction site, and quickly restore the damaged engineering entity.	Resource Recovery	Rapid restoration of key equipment or rapid arrival at the site
			Rapid restoration of construction roads, power and communication networks
		Engineering Recovery	Rapid cleanup of the site
			Rapid resumption of normal construction activities
Ability to adapt to learning	After a shock occurs, through summarizing, refining, and reflecting on the practical experience of coping with risky shocks, and drawing on the lessons learned from other risky shock coping experiences and relevant theories, it optimizes the organizational structure and operational mechanism, and trains field staff in crisis cognition and shock-handling ability, so as to enhance the system's overall ability to cope with shocks and adapt to changes in the external environment.	Lessons Learned	Summarizing and improving experience and learning exchange
			Organization and performance of emergency drills
		Adaptation	Plateau acclimatization and technical training

3.3. Indicator System for Resilience Evaluation

By summarizing and refining the influencing factors of construction management resilience through grounded theoretical research methods, the resilience evaluation indicator system of major railway project construction management was formed as shown in Figure 1.

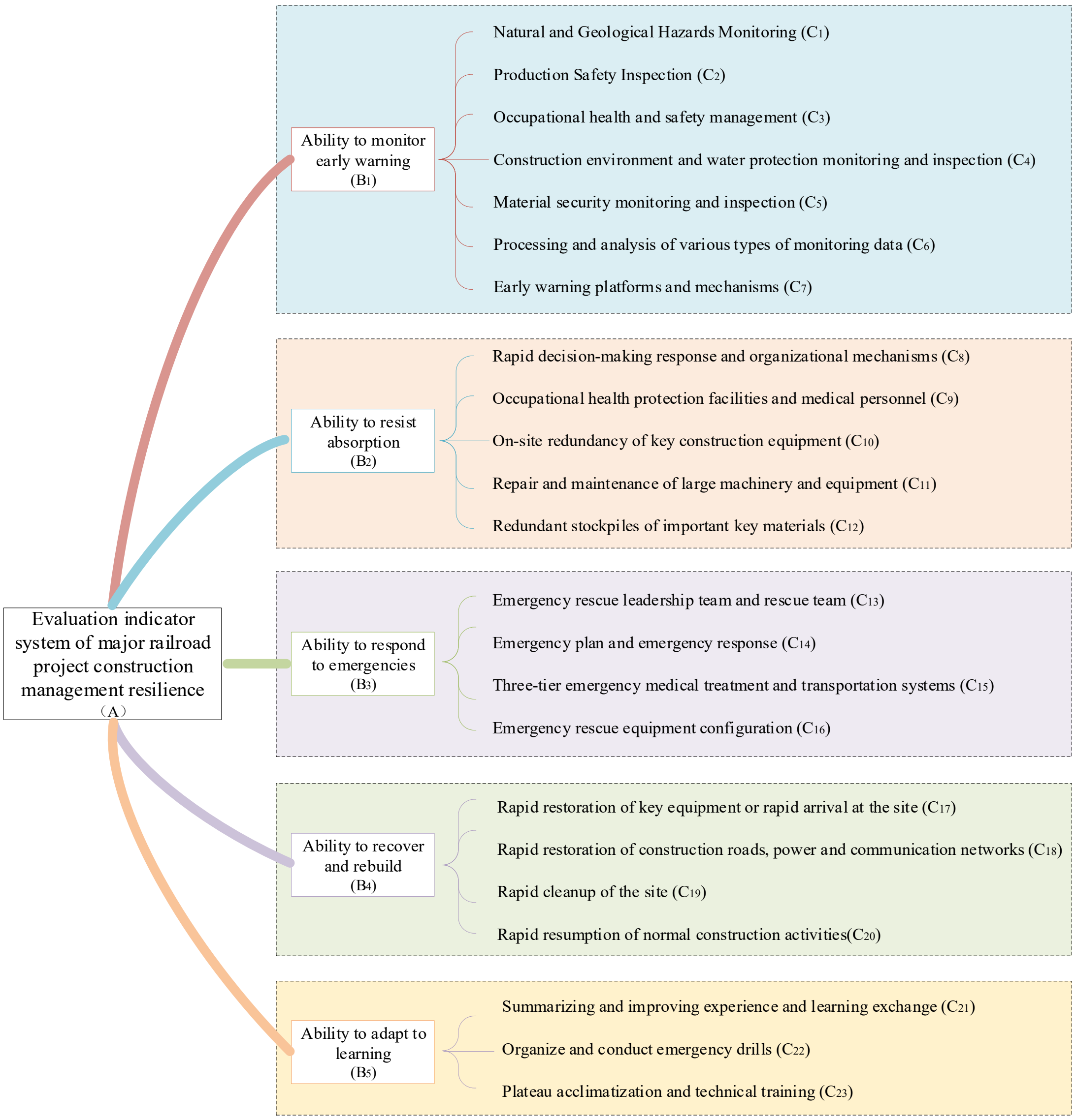

Figure 1. Resilience evaluation indicator system of major railway project construction management.

4. Resilience Evaluation Model for Major Railway Construction Management

4.1. Calculation of Evaluation Indicator Weights

This study used the AHP to determine the weights of indicators. AHP first hierarchizes a problem, decomposes it into different constituent factors according to the nature of the problem and the overall goal to be achieved, and forms different levels of aggregation combinations in accordance with the interrelated influences and affiliations among the factors, so as to constitute a multilevel analytical structural model [50,51]. The scale method of a 1 to 9 scale was used to judge the importance of two elements in the matrix for two-by-two comparison, and to assign a value to the degree of importance. From the quantitative results of the scale-constructed two-by-two comparison of the judgment matrix, the judgment matrix for single sorting calculation to determine the weight of each indicator was created. The weight calculation was firstly normalized, and the number of indicators in the group was set to be n.

Step 1: Compute the product M_i of the elements of each row of the matrix.

$$M_i = \prod_{j=1}^{n} a_{ij} \quad i = 1, 2, \cdots, n \tag{1}$$

Step 2: Calculate the nth root $\overline{W}_i$ of M_i.

$$\overline{W}_i = \sqrt[n]{M_i} \quad i = 1, 2, \cdots, n \tag{2}$$

Step 3: Normalize the vector $\overline{W} = [\overline{W}_1, \overline{W}_2, \cdots, \overline{W}_n]^T$.

$$\overline{W}_i = \frac{\overline{W}_i}{\sum\limits_{i=1}^{n} \overline{W}_i} \quad i = 1, 2, \cdots, n \tag{3}$$

$W = [W_1, W_2, \cdots, W_n]^T$ is the desired weight vector.

Step 4: In order to ensure the scientific and reliability of the calculation results, the judgment matrix must be tested for consistency.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

where $\lambda_{\max}$ is the largest eigen value of the judgment matrix, n is the judgment matrix order, and RI is the average random consistency value corresponding to n. When $CR < 0.1$, it was considered that the judgment matrix had good consistency. Otherwise, the judgment matrix elements should be adjusted.

This study utilized the expert scoring method to collect questionnaires from experienced experts in the field of construction management for major railway projects. The purpose was to determine the relative importance of each rating indicator. A total of 40 questionnaires were collected, and a rigorous screening process was employed to ensure the scientific validity and applicability of the Analytic Hierarchy Process (AHP) method, resulting in the exclusion of invalid questionnaires that exhibited inconsistencies in two-by-two comparisons, had excessively short response times, or consecutively selected the same options. Ultimately, 30 valid questionnaires were retained for the AHP analysis. By employing the AHP method, the significance of each group of indicators was compared and scored by the 30 participating experts. Calculation resulted in obtaining 30 weight vectors for each group of indicators, and the average values were utilized to determine the weights of technical indicators at all levels within the construction management resilience system for major railway projects. The significance attributed to the ability to monitor early warning (B_1) was quantified at 28.41 percent, with its subordinate indicators (C_1 through C_7) assigned weights of 4.18 percent, 5.00 percent, 3.32 percent, 3.31 percent, 3.34 percent, 3.33 percent, and 3.33 percent, respectively. The ability to resist absorption (B2) was evaluated at 24.88 percent, with its secondary indicators (C_8 through C_{12}) having weights of 8.35 percent, 3.33 percent, 3.31 percent, 3.32 percent, and 3.33 percent, respectively. The ability to respond to emergencies (B_3) held a weight of 28.41 percent, with its associated indicators (C_{13} through C_{16}) weighted at 6.67 percent, 5.83 percent, 3.33 percent, and 7.50 percent, respectively. The ability to recover and rebuild (B_4) was determined to be 11.29 percent, with the weights for its secondary indicators (C_{17} through C_{20}) set at 4.18 percent, 4.17 percent, 4.17 percent, and 4.19 percent, respectively. The ability to adapt to learning (B_5) was assessed at 7.01 percent, with each of its secondary indicators

(C_{21}, C_{22}, and C_{23}) uniformly weighted at 4.17 percent. The obtained weights are presented in Table 3.

Table 3. Weights of resilience indicators for major railway construction management.

First Level Indicator	First Level Indicator Weight	Second Level Indicator	Second Level Indicator Weight
B_1	28.41%	C_1	4.18%
		C_2	5.00%
		C_3	3.32%
		C_4	3.31%
		C_5	3.34%
		C_6	3.33%
		C_7	3.33%
B_2	24.88%	C_8	8.35%
		C_9	3.33%
		C_{10}	3.31%
		C_{11}	3.32%
		C_{12}	3.33%
B_3	28.41%	C_{13}	6.67%
		C_{14}	5.83%
		C_{15}	3.33%
		C_{16}	7.50%
B_4	11.29%	C_{17}	4.18%
		C_{18}	4.17%
		C_{19}	4.17%
		C_{20}	4.19%
B_5	7.01%	C_{21}	4.17%
		C_{22}	4.17%
		C_{23}	4.17%

4.2. Fuzzy Integrated Evaluation

Fuzzy comprehensive evaluation method was used for the resilience evaluation for construction management of major railway projects [52,53], and its main steps are shown in Figure 2.

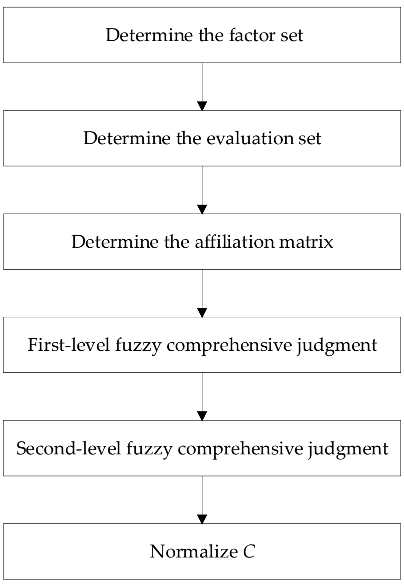

Figure 2. Step of fuzzy integrated evaluation.

Step 1: Determine the factor set. Divide the factor set of fuzzy comprehensive judgment of resilience of major railway project construction management into n sub-factor sets to obtain the resilience factor set U, $U = \{U_1, U_2, \cdots, U_n\}$.

Step 2: Determine the evaluation set. Due to the different levels of major railway project construction management resilience, the evaluation set is composed of all possible judgments. Define the evaluation level of major railway project construction management resilience as {very low, low, average, high, very high} five levels, and perform one comprehensive fuzzy judgment V for each U_i denoted as $V = \{v_1, v_2, v_3, v_4, v_5\}$. In order to facilitate the statistical calculation, we quantify the semantics scale of subjective evaluation and assign the values of 5, 4, 3, 2, and 1 in turn.

Step 3: Determine the affiliation matrix. The fuzzy relationship between the set of resilience factors U and the evaluation set V is represented, and the matrix element representing U_n evaluates its affiliation vector belonging to the mth rubric of V as $R_n = \{r_{n1}, r_{n2}, \cdots, r_{nm}\}$, to obtain the affiliation matrix R.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{6}$$

Step 4: First-level fuzzy comprehensive judgment. Calculate the affiliation matrix R_1 of the seven influencing factors of ability to monitor early warning (B_1), the affiliation matrix R_2 of the five influencing factors of ability to resist absorption (B_2), the affiliation matrix R_3 of the four influencing factors of ability to respond to emergencies (B_3), the affiliation matrix R_4 of the four influencing factors of ability to recover and rebuild (B_4), and the affiliation matrix R_5 of the three influencing factors of ability to adapt to learning (B_5). Then, perform the synthesis operation with the relative weights of the second-level indicators W_i to obtain the first-level fuzzy comprehensive evaluation matrix.

$$B = W_i * \mathrm{R}_i \tag{7}$$

Step 5: Second-level fuzzy comprehensive judgment. According to Equation (7), the first-level fuzzy comprehensive judgment matrix B is obtained, and the importance weights of the first-level indicators W are synthesized to obtain the second-level fuzzy comprehensive judgment vector.

$$C = W * B \tag{8}$$

Step 6: Normalize C to obtain the comprehensive evaluation results of the construction management resilience of major railway projects.

5. Empirical Research

5.1. Data Collection

This study focused on a major railway project located in the mountainous region of southwest China. It involved the participation of 80 senior managers and experts directly involved in the construction of this project. Their task was to rate the resilience indicators using a 1–5 scoring method. The respondents included 50 experts in the field of engineering construction management, accounting for 62.5%, and 30 individuals in engineering risk management, representing 37.50%. Among them, there were 4 project managers (5%), 10 department heads (12.5%), 36 project engineers (45%), and 30 supervising engineers (37.5%). Over half of the respondents had a working experience of more than 5 years. For more details, see Table 4. To ensure the scientific rigor and accuracy of the fuzzy comprehensive evaluation results, stringent measures were taken to obtain high-quality data. The 80 collected questionnaires underwent a thorough screening, eliminating invalid ones that had short response times or consecutively selected the same options. Consequently, 78 valid questionnaires were retained for the subsequent fuzzy comprehensive evaluation.

The reliability test conducted on the questionnaire data yielded a result of 0.997, surpassing the required threshold with exceptional standards. This high level of reliability not only validates the research findings from a mathematical analysis perspective but also attests to the validity of the research results.

Table 4. Information on respondents.

Basic Information on Experts	Category	Number of Persons	Percentage
Years of work/research	Less than 5 years	22	27.50%
	5–10 years	28	35.00%
	More than 10 years	30	37.50%
Work unit	Project Owner	5	6.25%
	Design Unit	26	32.50%
	Construction Contractor	45	56.25%
	Research Institutes	4	5.00%
Research Field	Engineering Construction Management	50	62.50%
	Engineering Risk Management	30	37.50%
Position/Title	Project Manager	4	5.00%
	Department Heads	10	12.50%
	Project Engineer	36	45.00%
	Engineer-in-Charge	30	37.50%

5.2. Fuzzy Comprehensive Evaluation for Construction Management Resilience of Major Railway Projects

Based on the evaluation results of the single-factor indicators, the judgment matrix of the three-level indicators for ability to monitor early warning (B_1) was collated.

$$R_{B_1} = \begin{bmatrix} 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0 & 0.4 & 0.6 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0 & 0 & 0.2 & 0.2 & 0.6 \\ 0 & 0 & 0.2 & 0.4 & 0.4 \\ 0 & 0 & 0.2 & 0.4 & 0.4 \\ 0 & 0.2 & 0.4 & 0.4 & 0 \end{bmatrix}$$

Similarly, the same method was used to process the data for the tertiary indicators of B_2, B_3, B_4, and B_5, resulting in the following judgment matrix.

$$R_{B_2} = \begin{bmatrix} 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.4 & 0.6 & 0 \\ 0 & 0.1 & 0.4 & 0.5 & 0 \\ 0 & 0.1 & 0.3 & 0.6 & 0 \\ 0 & 0 & 0.1 & 0.3 & 0.6 \end{bmatrix}$$

$$R_{B_3} = \begin{bmatrix} 0 & 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0 & 0 & 0 & 0.4 & 0.6 \end{bmatrix}$$

$$R_{B_4} = \begin{bmatrix} 0 & 0 & 0.2 & 0.6 & 0.2 \\ 0 & 0.2 & 0.2 & 0.4 & 0.2 \\ 0 & 0 & 0.2 & 0.6 & 0.2 \\ 0 & 0 & 0.2 & 0.6 & 0.2 \end{bmatrix}$$

$$R_{B_5} = \begin{bmatrix} 0 & 0.2 & 0.4 & 0.4 & 0 \\ 0 & 0.1 & 0.5 & 0.4 & 0 \\ 0 & 0.1 & 0.3 & 0.6 & 0 \end{bmatrix}$$

The fuzzy comprehensive evaluation results were obtained from the indicator weight vector A and the fuzzy relationship matrix R using the fuzzy operation, and the commonly used fuzzy operators were the Zadeh operator, weighted average type $M(\cdot, +)$, the Einstein operator, the Hamacher operator, and the Yager operator. In this study, the weighted average operator was used to calculate the results of five toughness capacity evaluations using the matrix multiplication operator in MATLAB R2023a software.

In order to presume the evaluation results more finely and intuitively, fuzzy vector singularization can be implemented, combining the value assigned to each grade rubric, $V = \{V_\mathrm{k}\} = \{V_1, V_2, V_3, V_4, V_5\}$ = {very low, low, average, high, very high}, where the score for V_1 is 1, the score for V_2 is 2, the score for V_3 is 3, the score for V_4 is 4, and the score for V_5 has a score of 5, constructed as column vector V^T = (1, 2, 3, 4, 5). Then, we calculated $G = U \times V^\mathrm{T}$, which finally resulted in the fuzzy comprehensive evaluation scores of the five toughness abilities. The specific process was as follows.

$$\begin{aligned} B_1 &= A_1 \bullet R_{B_1} = (0.0418, 0.0500, 0.0332, 0.0331, 0.0334, 0.0333, 0.0333) \bullet \begin{bmatrix} 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0 & 0.4 & 0.6 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0 & 0 & 0.2 & 0.2 & 0.6 \\ 0 & 0 & 0.2 & 0.4 & 0.4 \\ 0 & 0 & 0.2 & 0.4 & 0.4 \\ 0 & 0.2 & 0.4 & 0.4 & 0 \end{bmatrix} \\ &= (0.000, 0.026, 0.171, 0.400, 0.403) \end{aligned}$$

$$G_{B_1} = U_{B_1} \bullet V_{B_1}^T = \begin{pmatrix} 0.000 & 0.026 & 0.171 & 0.400 & 0.403 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 4.181$$

The fuzzy comprehensive evaluation was carried out for the seven resilience tertiary level 3 indicators in the ability to monitor early warning (B_1), as well as for the five comment sets, and the $M(\cdot, +)$ operator. We then calculated $G = U \times V^\mathrm{T}$, which finally resulted in a fuzzy comprehensive evaluation score of monitoring and early warning capacity B_1 of G_{B_1} = 4.181, with an evaluation grade of "very high".

$$\begin{aligned} B_2 &= A_2 \cdot R_{B_2} = (0.0835, 0.0333, 0.0331, 0.0332, 0.0333) \bullet \begin{bmatrix} 0 & 0 & 0.1 & 0.5 & 0.4 \\ 0 & 0 & 0.4 & 0.6 & 0 \\ 0 & 0.1 & 0.4 & 0.5 & 0 \\ 0 & 0.1 & 0.3 & 0.6 & 0 \\ 0 & 0 & 0.1 & 0.3 & 0.6 \end{bmatrix} \\ &= (0.000, 0.031, 0.223, 0.247, 0.500) \end{aligned}$$

$$G_{B_2} = U_{B_2} \bullet V_{B_2}^T = \begin{pmatrix} 0.000 & 0.031 & 0.223 & 0.247 & 0.500 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 4.216$$

$$B_3 = A_3 \cdot R_{B_3} = (0.0667,\ 0.0583,\ 0.0333,\ 0.0750) \bullet \begin{bmatrix} 0 & 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0 & 0 & 0 & 0.4 & 0.6 \end{bmatrix}$$
$$= (0.000,\ 0.000,\ 0.136,\ 0.361,\ 0.504)$$

$$G_{B_3} = U_{B_3} \bullet V_{B_3}^T = \begin{pmatrix} 0.000 & 0.000 & 0.136 & 0.361 & 0.504 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 4.368$$

$$B_4 = A_4 \cdot R_{B_4} = (0.0418,\ 0.0417,\ 0.0417,\ 0.0419) \bullet \begin{bmatrix} 0 & 0 & 0.2 & 0.6 & 0.2 \\ 0 & 0.2 & 0.2 & 0.4 & 0.2 \\ 0 & 0 & 0.2 & 0.6 & 0.2 \\ 0 & 0 & 0.2 & 0.6 & 0.2 \end{bmatrix}$$
$$= (0.000,\ 0.050,\ 0.200,\ 0.550,\ 0.200)$$

$$G_{B_4} = U_{B_4} \bullet V_{B_4}^T = \begin{pmatrix} 0.000 & 0.050 & 0.200 & 0.550 & 0.200 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 3.900$$

$$B_5 = A_5 \cdot R_{B_5} = (0.0417,\ 0.0417,\ 0.0417) \bullet \begin{bmatrix} 0 & 0.2 & 0.4 & 0.4 & 0 \\ 0 & 0.1 & 0.5 & 0.4 & 0 \\ 0 & 0.1 & 0.3 & 0.6 & 0 \end{bmatrix}$$
$$= (0.000,\ 0.133,\ 0.400,\ 0.467,\ 0.000)$$

$$G_{B_5} = U_{B_5} \bullet V_{B_5}^T = \begin{pmatrix} 0.000 & 0.133 & 0.400 & 0.467 & 0.000 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 3.333$$

Similarly, the fuzzy comprehensive evaluation score G_{B2} = 4.216 for the ability to resist absorption (B_2) had an evaluation grade of "very high". The fuzzy comprehensive evaluation score G_{B3} = 4.368 for ability to respond to emergencies (B_3) had a rating of "very high". The fuzzy composite evaluation score G_{B4} = 3.900 for ability to recover and rebuild (B_4) had an evaluation grade of "high". The fuzzy composite evaluation score G_{B5} = 3.333 for ability to adapt to learning (B_5) had an evaluation rating of "high".

$$S_1 = \omega_1^* R_1 = \begin{pmatrix} 0.2841 & 0.2488 & 0.2841 & 0.1129 & 0.0701 \end{pmatrix} * \begin{bmatrix} 0.000 & 0.026 & 0.171 & 0.400 & 0.403 \\ 0.000 & 0.031 & 0.223 & 0.247 & 0.500 \\ 0.000 & 0.000 & 0.136 & 0.361 & 0.504 \\ 0.000 & 0.050 & 0.200 & 0.550 & 0.200 \\ 0.000 & 0.133 & 0.400 & 0.467 & 0.000 \end{bmatrix}$$
$$= \begin{pmatrix} 0.000 & 0.030 & 0.193 & 0.404 & 0.372 \end{pmatrix}$$

$$G_1 = U_1 \bullet V_1^T = \begin{pmatrix} 0.000 & 0.030 & 0.193 & 0.404 & 0.372 \end{pmatrix} \bullet \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 4.119$$

The fuzzy synthesis results of the indicators of B_1, B_2, B_3, B_4, and B_5 were summarized to obtain the evaluation matrix of the resilience management of a major railway project and we carried out a fuzzy synthesis evaluation of the same type, with the result being G_1 = 4.119, with a rating of very high. Therefore, the evaluation results of the construction management resilience of a major railway project in the mountainous area of southwest China could be obtained as shown in Table 5.

Table 5. Results of the management resilience evaluation.

Resilience System	Score	Evaluation Rating	Resilience Capability	Score	Evaluation Rating
Construction management system resilience (A_1)	4.119	very high	Ability to monitor early warning (B_1)	4.181	very high
			Ability to resist absorption (B_2)	4.216	very high
			Ability to respond to emergencies (B_3)	4.368	very high
			Ability to recover and rebuild (B_4)	3.900	high
			Ability to adapt to learning (B_5)	3.333	high

6. Discussion

(1) Ability to respond to emergencies

The ability to respond to emergencies scored the highest, with a very high rating. This result not only demonstrates the on-site managers' commitment to the safety of construction personnel, but also highlights the potential dangers of major railway construction activities. In fact, compared to other railway projects in plain and coastal areas in China, the mountainous areas in Southwest China are more prone to high-intensity earthquakes and active ruptures, rock bursts, large deformations, high geothermal temperatures and hot water, noxious gases, granite radioactivity, and sudden water and mud flows, which pose a very high risk to the safety of the project. The project established a "hole rapid self-help, effective self-help section, provincial and regional base professional rescue, local social linkage rescue" three-tier emergency rescue system, and equipped it with more emergency rescue equipment and small emergency rescue special tools than other railway projects in the plains and developed coastal areas, following the principle of "combining peace and war".

(2) Ability to resist absorption

The ability to resist absorption was rated second, with a very high rating. Resilience reflects the reliability and redundancy of the construction management system to cope with disasters, and is a core capability that site managers prioritize. At the hardware level, key equipment for tunnel construction has been over-equipped for management to prevent the high-altitude environment from severely impacting mechanical equipment. Additionally, the maintenance of mechanical equipment has exceeded the normal construction state. At the software level, the company provides occupational health training to improve the construction staff's understanding of plateau construction and dispel their fear of difficulties. Health monitoring files are established for the entire workforce, and a strict health checkup system is implemented, including regular personnel changes and rotations. Furthermore, project management personnel have significant experience in constructing major railway projects, enabling quick decision-making and proper accident handling, which are crucial to the reliability of the construction management system.

(3) Ability to monitor early warning

The ability to monitor early warning ranked third, with a very high rating. A major railway project in the mountainous region of Southwest China faces various geological challenges, including great uncertainty of geological conditions, extremely large depth of burial, and extremely high gestures environment. To predict geological conditions ahead of the project, various forecasting means are employed (micro seismic monitoring, physical exploration, and over-drilling), and rock burst occurrence patterns are investigated based on construction process records. Physical surveying (ultra-long geological drilling rig, TSP203, seismic wave method) is performed to detect large deformations of soft rock in combination with geological exploration, tunnel design, and construction palm surface sketch results.

For active fracture zones, geological forecasting means such as geological radar, TSP, and over-drilling are used to prejudge surrounding rock conditions. Over-drilling explores hydrogeological conditions ahead to prevent high temperature groundwater surges in high geothermal temperature warning situations. For gas and other harmful gases, the whole section of the gas section is detected in advance and the location of harmful gases is recorded. In water-rich sand layers, overrun pipe shed-grouting or overrun grouting is adopted to carry out an overrun pretreatment of the surrounding rock, combined with the overrun through the flat guide to probe the geological conditions in advance, and overrun water discharge to improve the construction conditions of the main hole.

(4) Ability to recover and rebuild

The ability to recover and rebuild scored fourth, with a high evaluation rating. For human resources recovery, a major railway project in the mountainous region of Southwest China relies on local health resources and maintains a close linkage mechanism with local medical units, highlighting medical treatment, disease prevention, and oxygen-rich construction. It establishes a targeted three-tier medical treatment and transfer system. Local military districts have jointly established post-disaster recovery teams responsible for carrying out post-rescue cleanup of the site and assisting the project in resuming normal construction activities as soon as possible. Specialized management of the construction right-of-way is set up to restore roads, electricity, communications, and other resources. Construction teams are dispatched to carry out post-disaster corrections, while local electricity and communications units join forces with the project to set up a joint team to assist with the post-disaster restoration of key resources.

(5) Ability to adapt to learning

The ability to adapt to learning was rated fifth, with a high rating. This ability was mainly reflected in all aspects of training activities for construction personnel. The project has carried out extensive publicity and education on occupational health and safety to make all employees truly realize the importance and necessity of occupational health and safety. Regular rescue and rescue training and drills for on-site emergency rescue personnel are conducted, and construction personnel are trained in rapid self-rescue skills in cave entrances.

7. Conclusions and Recommendations

7.1. Conclusions

Based on resilience theory, this study introduced the concept of construction management resilience for major railway projects. It constructed a resilience evaluation indicator system for construction management based on five dimensions: the ability to monitor early warning, the ability to resist absorption, the ability to respond to emergencies, the ability to recover and rebuild, and the ability to adapt to learning. The study proposed a resilience evaluation method for construction management using the AHP and fuzzy comprehensive evaluation approach. An empirical study was conducted on a major railway project located in the mountainous area of southwest China as an example. The validity and reliability of the research results were verified through an empirical analysis. The research results indicated that the capabilities for emergency response and early warning monitoring are paramount, both accounting for 28.41%, and are central to the resilience of large-scale railway project construction management. The empirical analysis demonstrated that the construction projects studied exhibit high resilience levels, with scores above 4 for monitoring and early warning, resistance and absorption, and emergency response capabilities. Recovery and rebuilding, along with learning and adaptation abilities, scored between 3 and 4, indicating a relatively high level of resilience. This methodology facilitated the assessment of construction management's risk resistance capabilities in major railway projects, identifying strengths and areas for improvement, thus offering necessary references and a decision-making basis for mitigating, responding to, and adapting to uncertain risk impacts.

7.2. Recommendations

(1) Advance planning of project redundant resource reserves and strengthening of on-site resource guarantee mechanism.

The project company should verify the reserve of raw materials and components required for production in advance, based on the list of material demand, and manage them in a unified manner. A designated person should be responsible for coordinating with local meteorological and road administration departments to stay updated on road flow, control, and warning information. This will ensure that materials are prepared in advance and delivered in a staggered manner, preventing road delays from affecting normal construction. Utilizing big data, artificial intelligence, and other informational tools actively can improve and optimize the existing material management digital platform, allowing for dynamic reserve and scheduling of redundant resources. This will guarantee the smooth execution of site engineering and construction activities. It is also important to strengthen the reserves of professional highland construction personnel to ensure continuous and stable progress in the construction activities. Personnel should be allocated in an organized manner according to the work schedule and echelon. Adequate feeding security and a reasonable shift rest mechanism should be in place to alleviate the hazards associated with low oxygen in plateau areas. Implementing a robust incentive mechanism is necessary to motivate site personnel to actively engage in their work.

(2) Optimize the post-disaster organizational structure and operational mechanism, and improve personnel's crisis awareness and impact management capabilities.

Establishing and improving the operation mechanism of the special work leadership organization will facilitate compliance with relevant government emergency prevention and control requirements. Establishing a contact mechanism with the Ministry of Emergency Response, the Earthquake Bureau, and other relevant units is crucial. Continuous monitoring of disaster information and smooth information reporting should be ensured. Additionally, being prepared to support local earthquake relief preparations is important. Organizing post-disaster hidden danger inspections and establishing safety and quality inspection teams will ensure the condition of buildings and equipment at each work site. Enhancing the categorized and hierarchical training model for emergency management personnel is necessary. This includes strengthening the education and training of leaders' emergency management knowledge. Organizing sharing sessions for project managers to exchange crisis response experience will improve the crisis awareness and responsibility of the project manager team. Furthermore, enhancing the overall process of crisis prevention, response, and post-disaster emergency response capabilities is crucial. Optimizing the education and training of technical personnel on emergency management knowledge and enabling them to utilize their professional expertise and technical advantages will enhance their ability to analyze sources of danger and risks. It is essential to improve the crisis awareness of all construction personnel by disseminating relevant knowledge on emergency management, disaster prevention and relief, and self-rescue and mutual assistance. Conducting disaster defense knowledge training and organizing drills and training sessions for construction personnel to handle emergencies promptly are also important measures to be implemented.

7.3. Limitations

The data in this study were obtained from the builders and managers of major railway projects in China, which is typical of major projects in China. In the future, we will expand the data of major railroad projects in many developed and developing countries, so that the results of the study can be more generalized. In addition, the construction management resilience indicators of major railroad projects identified in this study tended to be qualitative, which is difficult to describe using objective data. In the future, we will devote ourselves to constructing an objective evaluation index system for construction management resilience and researching objective assessment methods for construction management resilience of major railroad projects.

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