Article

A Comprehensive Assessment Approach for Water-Soil Environmental Risk during Railway Construction in Ecological Fragile Region Based on AHP and MEA

Huihua Chen ¹ , Hujun Li ¹ , Yige Wang ² and Baoquan Cheng ^{1,*}

¹ Department of Engineering Management, School of Civil Engineering, Central South University, Changsha 410075, China; chh@csu.edu.cn (H.C.); lihujunsr@csu.edu.cn (H.L.)

² Guangdong International Engineering Consulting Co. Ltd., Guangzhou 510095, China; wangyige123@outlook.com

* Correspondence: curtis_ch@csu.edu.cn

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Abstract: With China's government facilitating railway projects, more railway lines inevitably pass through ecological fragile regions (EFRs). Railway construction activities in EFRs might cause detrimental impacts on the local water-soil environment (WSE), which is the basis of the local ecological system that if destroyed can induce secondary disasters. Studies on the WSE risk (WSER) during railway construction in EFRs are limited. As such, this study aims to offer preliminary insight into the WSER assessment of railway construction in EFRs. WSERs were identified firstly based on the literature review and field surveys, and thus a risk index framework for WSER assessment including 5 categories of WSERs and 16 second-order risks was established. Then a comprehensive quantitative assessment method was developed by integrating analytic hierarchy process (AHP) and matter-element analysis (MEA) to assess the overall WSERs of railway construction in EFRs. A case (i.e., the Mingan subproject of Hefei-Fuzhou railway) was selected to demonstrate and validate the developed approach. Results show that the proposed assessment approach can be applied to evaluate the WSERs during railway construction. In addition, the case study demonstrates that the risk of construction methods should be the key focus. Findings from this study enrich the knowledge body of sustainable railways and guide the project managers to conduct practical WSER assessment of railway construction.

Keywords: water-soil environment risks; risk assessment; railway construction; ecological fragile region; analytic hierarchy process; matter-element analysis

1. Introduction

Since the successful delivery of the first high-speed railway (HSR), i.e., Beijing-Tianjin Intercity Railway in 2008, China's HSR has entered into a new stage of comprehensive and rapid development. More financial funds were invested into HSR projects. By the end of 2015, the national railway network with four vertical and four horizontal arteries had been established, and the total mileage of HSR had reached 19,000 km [1]. It was validated that the implementation of HSR can substantially improve the regional accessibility, reduce transit cost, facilitate the local economic development, and decrease regional inequality [2–4]. Thus, in 2016, the Chinese Central Government further issued a new framework of the national railway network, i.e., the national railway network with eight vertical and eight horizontal arteries [5], which indicated that more railway lines would be planned, designed, and constructed in the near future in China.

Ecological fragile region (EFR) refers to an area where the distribution unbalances of matter and energy make the area vulnerable to external disturbances and lacking in adaptability [6,7]. China has a vast landscape, and its geological structure and topography are complex and diverse, which cultivate different ecosystems and EFRs [7]. From the statistics of MEE [8], EFRs in China could be mainly divided into eight parts: (1) Water-land EFR along the coast; (2) agro-pastoral EFR in the north; (3) forest-steppe EFR in the northeast; (4) oasis-desert EFR in the northwest; (5) mountain-agro-pastoral EFR in the southwestern mountains; (6) karst-mountain EFR in the southwest; (7) compound-eroding EFR in the Tibet; and (8) red-soil hill-mountain EFR in the south. This means some railway lines have to cross the EFRs to establish the national railway networks. For instance, the Sichuan-Tibet railway must cross the karst-mountain EFR and compound-eroding EFR in the southwest of China [9]. The impacts of constructing railway in EFRs are bidirectional: The complicated soil-water environmental conditions cause more difficulties during construction; and on the contrary, construction activities would destroy the local water-soil environment (WSE) in EFRs [10,11]. The improper design and construction schemes tend to cause water and soil losses. The construction wastewater discharge is also likely to cause the contamination of underground water [12–14]. Meanwhile, large scales of earthworks further decrease the stability of local mountains and hills, which may induce geological hazards such as landslides and debris flows. [15]. In summary, railway construction is likely to further strengthen the vulnerability of local WSE in EFRs. Thus, it is necessary to take measures in advance to minimize the detrimental impacts of construction activities on the local WSE; a comprehensive assessment of the water-soil environmental risks (WSERs) during railway construction is the precondition of designing appropriate management strategies.

With the raising of environmental awareness of the whole society, the concept of environmental risk assessment (ERA) gradually draws more researchers' attention [16,17]. According to Jozi et al. [18], environmental risks (ER) can be divided into anthropogenic-event ERs, biophysical-event ERs, and natural-event ERs. Of the three ERs, anthropogenic-event related ERs include socio-economic-culture ERs, health-safety ERs, and technical ERs; biophysical-event ERs include soil ERs, water ERs, air ERs, and habitat and wildlife ERs. WSE is more vulnerable to construction activities compared with other environmental elements. If the WSE is damaged, secondary disasters such as underwater contamination, landslides, or debris flows may occur. Identifying, assessing, and minimizing WSERs is thus important in railway engineering. WSERs refer to the potential factors harmful to local WSE that are involved in design schemes, construction technologies, adopted materials and equipment, organization and management, etc. Literature review finds that there exist a few studies pertaining to ERA during dam construction [18,19]. For instance, Jozi et al. [18] identified that cut and fill, explosion, and drilling were more crucial environmental risks; Rezaian et al. [19] reported that habitat fragmentation, water pollution, and impacts on aquatics were three top priority flooding risks. However, there exists no research specifically focusing on WSER assessment during railway construction, and we still lack a systematic and comprehensive method to assess the WSER during railway construction in EFRs.

A comprehensive risk assessment approach includes a risk index framework (a list of identified risks and hierarchical structure of the risks) and corresponding quantitative methods (measurement method for each risk and its weight). Although no existing studies specifically focus on WSER assessment during railway construction, previous literature can identify many quantitative methods in railway construction risk analyses that can provide a methods pool for establishing quantitative methods of this study, such as analytic hierarchy process (AHP), experts' judgment, Monte Carlo (MC) simulation, fuzzy mathematics, machine learning (ML), structural equation model (SEM), etc. [20–24]. For instance, Cho et al. [22] established a probabilistic assessment for prestressed concrete box girder railway bridges by applying AHP; Macciotta et al. [23] applied MC simulation to determine the probability distribution of the estimated risks; Leśniak and Janowiec [25] evaluated the railway construction investments' risk of additional works using Bayes network; Chang et al. [20] employed SEM to examine the political risk paths in international high-speed railway projects. MC simulation can be a useful method to determine the occurrence possibility of a risk by taking randomness into consideration, but the realistic occurrence

probability of a risk can be difficult to determine, which the evaluation errors. The application of ML model relies on large-scale data, which are actually hard to obtain in construction projects. Additionally, SEM provides a way to analyze the risk path rather than risk measurement method. Besides, all three methods do not offer algorithms for assessing the overall risk of the evaluated project.

AHP is a widely accepted method to determine the weights based on multiple criteria decision-making. The method was proposed by Saaty (1980) and first introduced into project risks assessment by Mustafa and Al-Bahar [26]. The merit of this method is that it can help to check and decrease the inconsistency of experts' judgment and provide an algorithm for integrating individual decision-making results into group decision-making [27,28]. As such, many researchers have applied or modified AHP in different ways to increase its practicality [29–31]. Matter-element analysis (MEA) is a more objective method to determine the risk rating by calculating the correlation between the risk and its risk criteria. The method was initially proposed by Cai [32] based on the extended set aiming at addressing incompatible problems [33]. Since then, the method has been widely exploited as an assessment method in many research areas, such as ecological evaluation [34–36], risk assessment [37–39], safety and health assessment [40,41], etc. The reason is that assessments can be viewed as a group multi-rule decision-making problem, and the core processes of the decision-making are incompatible [42]. By using systematic and structural computation processes of matter-elements, the incompatible problems can be converted into compatible ones [33,43]. AHP can be combined with MEA to construct a synthetic method for multi-tier assessment, i.e., AHP-MEA, and this method integrates the advantages of AHP and MEA and was successfully used in the risk assessment by some researchers [36,44,45].

Based on literature review, this paper focuses on the WSER assessment during railway construction in EFRs. The objectives of this study are: (1) To establish a systematic and comprehensive risk index framework for the WSER assessment of railway construction in EFRs through literature review and field surveys; (2) to develop a quantitative method for the proposed risk index frameworks using AHP-MEA; (3) to demonstrate and validate the developed method through a case study. The study can enrich the risk assessment theory of WSER during railway construction in EFRs by providing a comprehensive risk index framework and corresponding quantitative methods. Besides, from the practice point of view, this study can help to deepen governments', designers', contractors', and other related stakeholders' understanding of the WSER during railway construction in EFRs. The developed method can help project managers to identify the key WSERs when conducting works in EFRs and serve as a powerful decision-making tool for design and construction scheme optimization of railway engineering to protect the WSE in EFRs.

2. Research Methodology

2.1. Identification of WSERs

A comprehensive and rational risk index framework is the basis for accurate assessment of WSERs of railway construction. Main WSER indexes are collected and identified through two approaches in this study: (1) Literature review and (2) field research on a practical engineering (i.e., Yunnan subproject of the Yunan-Guanxi railway). The coding processes can be referred to Tables A1 and A2, respectively. Then, an index framework of WSER of railway construction was developed as shown in Figure 1. The established framework includes three tiers: Target-tier, criteria-tier, and index-tier. The index-tier consists of 16 risk indexes; the criteria-tier refers to the five risk categories; and the target-tier is the overall WSERs of the evaluated railway project.

Figure 1. Index framework of water-soil environment risk (WSER) of railway construction.

2.2. Quantitative Method for Risk Index Framework

The study integrated AHP and MEA to evaluate the overall WSER of railway construction in EFR (see Figure 2). Detailed procedures of the assessment method are explained in the follow-up subsections.

Figure 2. Flowchart of the quantitative methods for WSERs.

2.2.1. Construct Matter-Element Basis for Risk Assessment

A matter-element (ME) is a mathematical description of a concerned object in an ordered triad, which can be illustrated in Equation (1), where N denotes the interested matter-element; C denotes the attribute of N ; and V denotes the value of C .

$$R = (N, C, V) \quad (1)$$

In this study, the risk categories at criteria-tier were viewed as MEs, including the risks under it at the index-tier. We use N^n to denote the n -th risk category, and then the classic domain of the ME R_c^n is expressed in Equation (2).

$$R_c^n(N^n, C_i^n, V_{ij}^n) = \begin{bmatrix} L_1 & L_2 & \dots & L_j \\ C_1^n & V_{11}^n & V_{12}^n & \dots & V_{1j}^n \\ C_2^n & V_{21}^n & V_{22}^n & \dots & V_{2j}^n \\ \vdots & \vdots & \vdots & \dots & \vdots \\ C_i^n & V_{i1}^n & V_{i2}^n & \dots & V_{ij}^n \end{bmatrix} = \begin{bmatrix} L_1 & L_2 & \dots & L_j \\ C_1^n & \langle a_{11}^n, b_{11}^n \rangle & \langle a_{12}^n, b_{12}^n \rangle & \dots & \langle a_{1j}^n, b_{1j}^n \rangle \\ C_2^n & \langle a_{21}^n, b_{21}^n \rangle & \langle a_{22}^n, b_{22}^n \rangle & \dots & \langle a_{2j}^n, b_{2j}^n \rangle \\ \vdots & \vdots & \vdots & \dots & \vdots \\ C_i^n & \langle a_{i1}^n, b_{i1}^n \rangle & \langle a_{i2}^n, b_{i2}^n \rangle & \dots & \langle a_{ij}^n, b_{ij}^n \rangle \end{bmatrix} \quad (2)$$

where C_i^n represents the i -th risk under the n -th risk category, L_j represents the j -th rating criteria, and $\langle a_{ij}^n, b_{ij}^n \rangle$ denotes the value interval of the rating criteria.

The joint domain of the ME R_p is the total value domain of all ratings. It can be expressed in the Equation (3).

$$R_p(N^n, C_i^n, V_{pi}^n) = \begin{bmatrix} N^n & C_1^n & V_{p1}^n \\ & C_2^n & V_{p2}^n \\ & \vdots & \vdots \\ & C_i^n & V_{pi}^n \end{bmatrix} \quad (3)$$

where V_{pi}^n represents the joint domain of the i -th risk C_i^n and $V_{pi}^n = \langle a_{pi}^n, b_{pi}^n \rangle$ denotes the value interval of joint domain.

The evaluated ME (overall WSER of railway project construction) R_0 can be delineated by Equation (4).

$$R_0(N_0^n, C_i^n, V_{0i}^n) = \begin{bmatrix} N^n & C_1^n & v_{01}^n \\ & C_2^n & v_{02}^n \\ & \vdots & \vdots \\ & C_i^n & v_{0i}^n \end{bmatrix} \quad (4)$$

where the v_{0i}^n is the case value of the corresponding C_i^n .

2.2.2. Determine the Weights of the Risks and Risk Categories

AHP was adopted to determine the weights of risks and risk categories because this method can transform qualitative data of experts' judgment into quantitative data [46,47]. The process of AHP is presented in the follow-up steps.

Step 1. Establish the judgment matrices

The judgment matrix Q of a set of risks are constituted by the average comparative importance of each two risks q_{ij} to the upper tier (i.e., risk categories) (see Equation (5)). q_{ij} denotes the average

importance of the i -th risk to the upper tier when compared to the j -th risk and it is the mean of q_{ij}^k (see Equation (6)), which was evaluated by the experts based on 1–9 scale (see Table 1).

$$Q = [q_{ij}]_{n \times n} = \begin{bmatrix} q_{11} & q_{12} & \dots & q_{1n} \\ q_{21} & q_{22} & \dots & q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ q_{n1} & q_{n2} & \dots & q_{nn} \end{bmatrix} \quad (5)$$

$$q_{ij} = \frac{1}{k} \sum_k^m q_{ij}^k \quad (6)$$

where n denotes the number of the risks and m refers to the number of experts.

Table 1. Definitions of the scale.

Scale of q_{ij}	Numerical Rating	Reciprocal
Equally important.	1	1
Equally to moderately	2	1/2
Moderately important	3	1/3
Moderately to strongly	4	1/4
Strongly important	5	1/5
Strongly to very strongly	6	1/6
Very strongly important	7	1/7
Very strongly to extremely	8	1/8
Extremely important	9	1/9

Step 2. Calculate the eigenvectors and eigenvalue of the judgment matrix

The eigenvectors w_i (i.e., weights of the risks) and eigenvalue λ_{max} can be calculated based on Equations (7) and (8) respectively.

$$w_i = \frac{\sqrt[n]{\prod_{j=1}^n q_{ij}}}{\sum_{i=1}^n \sqrt[n]{\prod_{j=1}^n q_{ij}}} \quad (7)$$

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(QW)_i}{w_i} \quad (8)$$

where i and j mean the number of rank and column of Q respectively.

Step 3. Consistency test

Two consistency indicators (CI and CR) were used to test the consistency of the judgment matrix (see Equations (9) and (10)). If the number of the risk is < 3 , we accepted the w_i when $CI < 0.1$; and if the number of the lower indexes is ≥ 3 , both CI and CR should be pass the test.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (9)$$

$$CR = \frac{CI}{RI} \quad (10)$$

where the value of RI can be referred to the Table 2, which were adapted from the study conducted by Wang, Yang, Lu, Wu, and Xu [45].

Table 2. Value of RI when order of judgment matrix ≥ 3 .

Order	3	4	5	6	7	8	9
RI	0.52	0.89	1.12	1.26	1.36	1.41	1.39

In applying the abovementioned procedure (Equations (5)–(8)), the weights of risk categories can also be generated.

2.2.3. Calculate the Correlation Matrix

The correlation matrix measures the correlations between the evaluated ME and each rating criteria. The correlation matrix of each risk at the index-tier can be computed using Equation (11).

$$K_j(v_{0i}^n) = \begin{cases} -\frac{\rho(v_{0i}^n, V_{ij}^n)}{|V_{ij}^n|}, & v_{0i}^n \in V_{ij}^n \\ \frac{\rho(v_{0i}^n, V_{ij}^n)}{\rho(v_{0i}^n, V_{pi}^n) - \rho(v_{0i}^n, V_{ij}^n)}, & v_{0i}^n \notin V_{ij}^n \end{cases} \quad (11)$$

where $\rho(v_{0i}^n, V_{ij}^n) = \left| v_{0i}^n - \frac{a_{ij}^n + b_{ij}^n}{2} \right| - \frac{1}{2}(b_{ij}^n - a_{ij}^n)$, $\rho(v_{0i}^n, V_{pi}^n) = \left| v_{0i}^n - \frac{a_{pi}^n + b_{pi}^n}{2} \right| - \frac{1}{2}(b_{pi}^n - a_{pi}^n)$, and $|V_{ij}^n| = |a_{ij}^n - b_{ij}^n|$; a_{ij}^n and b_{ij}^n denote the minimum value and maximum value of the classical domain of n -th risk category respectively; a_{pi}^n and b_{pi}^n refer to the minimum value and maximum value of the joint domain of n -th risk category, respectively.

Then the correlation matrix of each risk category $K_j(v_0^n)$ and the overall risk of the project can be calculated using Equations (12) and (13), respectively.

$$K_j(v_0^n) = \sum_{i=1}^m w_i^n \cdot K_j(v_{0i}^n) \quad (12)$$

$$K_j(v_0) = \sum_{i=1}^n w^n \cdot K_j(v_0^n) \quad (13)$$

where w_i^n refers to the weight of the i -th risk under n -th risk category; m denotes the number of the risks under n -th risk category; and w^n refers to the weight of the n -th risk category.

2.2.4. Determining the Ratings of the WSERs.

Based on $K_j(v_{0i}^n)$, $K_j(v_0^n)$ and $K_j(v_0)$, we can determine the rating of the evaluated risks. The calculating processes are the same, and we exemplified the calculation by determining the rating of the overall risk of the project $\bar{s}$. It can be gained after the normalization using Equations (14) and (15).

$$\bar{K}_j(v_0) = \frac{K_j(v_0) - \min K_j(v_0)}{\max K_j(v_0) - \min K_j(v_0)} \quad (14)$$

$$\bar{s} = \frac{\sum_{s=1}^j s \cdot \bar{K}_j(v_0)}{\sum_{s=1}^j \bar{K}_j(v_0)} \quad (15)$$

where $\bar{K}_j(v_0)$ refers to the normalized value of $K_j(v_0)$; $\min K_j(v_0)$ and $\max K_j(v_0)$ denote the minimum value and maximum value of all the $K_j(v_0)$; and j refers to the number of rating criteria.

The rating of an evaluated risk denotes the severity of the risk. Lower-rating WSER indicates it can cause more destruction of local WSE in EFRs. In this study, each of the identified WSER are divided into five ratings, and detailed descriptions of the rating can be seen in Table 3.

The proposed comprehensive assessment approach of WSER during railway construction includes abovementioned risk index framework and quantitative methods of the risks. This approach can be widely used in the procedures of WSER assessment by designers, contractors, consultants, government administrators, worksite managers, and researchers. It determines the risk rating by calculating the correlations between the risk and its rating criteria, which makes the assessment process more objective.

Besides, the proposed assessment approach not only can calculate the overall WSER rating of the evaluated project, but also can calculate the rating of each evaluated risk and risk category. This means that we can further identify the key WSERs or WSER categories of the evaluated project, and based on which, some more practical countermeasures can be gained by analyzing these key WSERs.

Table 3. Risk ratings and their descriptions.

Rating	Severity of Risk	Descriptions
I	Extremely high risk	The risk cannot be accepted and it will cause serious impacts on local WSE. Some control measures are needed degrade the risk to the feasible but reduction-needed zone.
II	High risk	The risk is situated in a feasible but reduction-needed zone and the detrimental impacts on local WSE caused by the risk can be controlled. Some specific measures can be taken based on the risk rating. Besides, the control cost should be less than losses the risk caused.
III	Medium risk	
IV	Lower risk	
V	Low risk	The risk can be accepted and under the normal risk monitoring.

3. Case Study

3.1. Case Description

The Mingan (MG) subproject of Hefei-Fuzhou railway is located in the red-soil hilly and mountainous EFR, and the total length of the mainline is 285.229 km. The ecosystem along the MG subproject is mainly the forest ecosystem, except for the farmland ecosystem and water ecosystem at some river-crossing sections. The MG subproject crosses 13 natural rivers and three surface sources for drinking water. The main types of groundwater are pore water, bedrock fissure water, and karst water. Along the MG subproject, there exist the Jiangnanshen Fault Zone and Fengcheng-Wuyuan Fault Zone, and geological structure is characterized by syncline, anticline, and arc. Besides, MG subproject inevitably passes through four special areas, including Damaoshan Scenic Spot, Yunbifeng Forest Park, Anshan Forest Park, and Huangchulin Nature Reserve (see Figure 3).

Figure 3. The Mingan subproject of Hefei-Fuzhou railway.

3.2. Calculate the Weights and Determine the Rating Criteria

In this step, 20 experts were invited to evaluate the comparative importance of each two risks to the risk categories, and the judgment matrices were established based on the evaluation results. Then,

according to Equation (7), the weights of each risk can be calculated. We constructed the judgment matrices of the risks at the index-tier and the risk categories at the criteria-tier and calculated their weights. The results are presented in Tables 4–9. Then the rating criteria of the risks were determined based on experts' suggestions (Table 10).

Table 4. The judgment matrix and weights of risks under u_1 .

u_1	u_{11}	u_{12}	u_{13}	u_{14}	Weights	Consistency Test
u_{11}	5/5	6/4	6.5/3.5	5.5/4.5	0.3242	$\lambda_{max} = 4.0555$ $CR = 0.0208 < 0.1$
u_{12}	4/6	5/5	7/3	4/6	0.2408	
u_{13}	3.5/6.5	3/7	5/5	3.5/6.5	0.1417	
u_{14}	4.5/5.5	6/4	6.5/3.5	5/5	0.2933	

Table 5. The judgment matrix and weights of the risks under u_2 .

u_2	u_{21}	u_{22}	u_{23}	Weights	Consistency Test
u_{21}	5/5	3.5/6.5	5.5/4.5	0.2811	$\lambda_{max} = 3.0191$ $CR = 0.0184 < 0.1$
u_{22}	6.5/3.5	5/5	6/4	0.4548	
u_{23}	4.5/5.5	4/6	5/5	0.2641	

Table 6. The judgment matrix and weights of the risks under u_3 .

u_3	u_{31}	u_{32}	Weights	Consistency Test
u_{31}	5/5	5.5/4.5	0.5500	$\lambda_{max} = 2.0000$ $CR = 0.0 < 0.1$
u_{32}	4.5/5.5	5/5	0.4500	

Table 7. The judgment matrix and weights of risks under u_4 .

u_4	u_{41}	u_{42}	u_{43}	u_{44}	Weights	Consistency Test
u_{41}	5/5	6/4	4.5/5.5	3/7	0.2033	$\lambda_{max} = 4.0628$ $CR = 0.0235 < 0.1$
u_{42}	4/6	5/5	4/6	4/6	0.1761	
u_{43}	5.5/4.5	6/4	5/5	4.5/5.5	0.2641	
u_{44}	7/3	6/4	5.5/4.5	5/5	0.3432	

Table 8. The judgment matrix and weights of the risks under u_5 .

u_5	u_{51}	u_{52}	u_{53}	Weights	Consistency Test
u_{51}	5/5	4.5/5.5	6/4	0.3460	$\lambda_{max} = 3.0045$ $CR = 0.0043 < 0.1$
u_{52}	5.5/4.5	5/5	6/4	0.3956	
u_{53}	4/6	4/6	5/5	0.2467	

Table 9. The judgment matrix and weights of risk categories.

u	u_1	u_2	u_3	u_4	u_5	Weights	Consistency Test
u_1	5/5	4/6	6.5/3.5	4/6	4.5/5.5	0.2027	$\lambda_{max} = 5.3582$ $CR = 0.0799 < 0.1$
u_2	6/4	5/5	7/3	5.5/4.5	7/3	0.2213	
u_3	3.5/6.5	3/7	5/5	3.5/6.5	4.5/5.5	0.1732	
u_4	6/4	4.5/5.5	6.5/3.5	5/5	6.5/3.5	0.2167	
u_5	5.5/4.5	3/7	5.5/4.5	3.5/6.5	5/5	0.1861	

Table 10. The rating criteria of the WSERs.

Risk Categories	Risks	Rating Criteria				
		I	II	III	IV	V
u ₁ . Risk of design scheme	u ₁₁ —Risk of slag disposal design	[0,80]	[80,85]	[85,90]	[90,95]	[95,100]
	u ₁₂ —Risk of drainage design	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₁₃ —Risk of greening design	[0,25]	[25,40]	[40,50]	[50,60]	[60,100]
	u ₁₄ —Risk of slope protection design	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
u ₂ . Risk of construction method	u ₂₁ —Risk of site Cleaning	[0,10]	[10,15]	[15,20]	[20,30]	[30,100]
	u ₂₂ —Risk of piling	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₂₃ —Risk of earthwork	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
u ₃ . Risk of materials and equipment	u ₃₁ —Risk of material quality	[0,35]	[35,50]	[50,65]	[65,80]	[80,100]
	u ₃₂ —Risk of mechanical equipment	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
u ₄ . Risk of construction management	u ₄₁ —Risk of construction waste	[0,65]	[65,75]	[75,85]	[85,95]	[95,100]
	u ₄₂ —Risk of stacking and transport for materials and wastes	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₄₃ —Risk of construction planning	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₄₄ —Risk of precautions and monitoring	[0,5]	[5,10]	[10,20]	[20,40]	[40,100]
u ₅ . Risk of personnel competency	u ₅₁ —Risk of designers' competency	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₅₂ —Risk of managers' competency	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]
	u ₅₃ —Risk of workers' competency	[0,25]	[25,50]	[50,70]	[70,85]	[85,100]

3.3. Determine the Classic Domain, Joint Domain and the Evaluated Matter-Element

Based on the rating criteria in Table 10, the classic domain $R_i(u_i)$ and joint domain $R_p(u_i)$ of risk categories can be determined. Results of risk of design scheme (u_1), construction method (u_2), materials and equipment (u_3), construction management (u_4), and personnel competency (u_5) were presented in Equations (16)–(20) respectively. According to experts' evaluation of each WSER of the MG subproject, the evaluated ME $R(u_i)$ can be generated (see Equation (21)).

$$\begin{aligned}
 R_1(u_1) &= \begin{bmatrix} N_1 & u_{11} & [0, 80] \\ & u_{12} & [0, 25] \\ & u_{13} & [0, 25] \\ & u_{14} & [0, 25] \end{bmatrix} & R_2(u_1) &= \begin{bmatrix} N_2 & u_{11} & [80, 85] \\ & u_{12} & [25, 50] \\ & u_{13} & [25, 40] \\ & u_{14} & [25, 50] \end{bmatrix} & R_3(u_1) &= \begin{bmatrix} N_3 & u_{11} & [85, 90] \\ & u_{12} & [50, 70] \\ & u_{13} & [40, 50] \\ & u_{14} & [50, 70] \end{bmatrix} \\
 R_4(u_1) &= \begin{bmatrix} N_4 & u_{11} & [90, 95] \\ & u_{12} & [70, 85] \\ & u_{13} & [50, 60] \\ & u_{14} & [70, 85] \end{bmatrix} & R_5(u_1) &= \begin{bmatrix} N_5 & u_{11} & [95, 100] \\ & u_{12} & [85, 100] \\ & u_{13} & [60, 100] \\ & u_{14} & [85, 100] \end{bmatrix} & R_p(u_1) &= \begin{bmatrix} N_p & u_{11} & [0, 100] \\ & u_{12} & [0, 100] \\ & u_{13} & [0, 100] \\ & u_{14} & [0, 100] \end{bmatrix}
 \end{aligned} \quad (16)$$

$$\begin{aligned}
 R_1(u_2) &= \begin{bmatrix} N_1 & u_{21} & [0, 10] \\ & u_{22} & [0, 25] \\ & u_{23} & [0, 25] \end{bmatrix} & R_2(u_2) &= \begin{bmatrix} N_2 & u_{21} & [10, 15] \\ & u_{22} & [25, 50] \\ & u_{23} & [25, 50] \end{bmatrix} & R_3(u_2) &= \begin{bmatrix} N_3 & u_{21} & [15, 20] \\ & u_{22} & [50, 70] \\ & u_{23} & [50, 70] \end{bmatrix} \\
 R_4(u_2) &= \begin{bmatrix} N_4 & u_{21} & [20, 30] \\ & u_{22} & [70, 85] \\ & u_{23} & [70, 85] \end{bmatrix} & R_5(u_2) &= \begin{bmatrix} N_5 & u_{21} & [30, 100] \\ & u_{22} & [85, 100] \\ & u_{23} & [85, 100] \end{bmatrix} & R_p(u_2) &= \begin{bmatrix} N_p & u_{21} & [0, 100] \\ & u_{22} & [5, 100] \\ & u_{23} & [5, 100] \end{bmatrix}
 \end{aligned} \quad (17)$$

$$\begin{aligned}
 R_1(u_3) &= \begin{bmatrix} N_1 & u_{31} & [0, 35] \\ & u_{32} & [0, 25] \end{bmatrix} & R_2(u_3) &= \begin{bmatrix} N_2 & u_{31} & [35, 50] \\ & u_{32} & [25, 50] \end{bmatrix} & R_3(u_3) &= \begin{bmatrix} N_3 & u_{31} & [50, 65] \\ & u_{32} & [50, 75] \end{bmatrix} \\
 R_4(u_3) &= \begin{bmatrix} N_4 & u_{31} & [65, 80] \\ & u_{32} & [70, 85] \end{bmatrix} & R_5(u_3) &= \begin{bmatrix} N_5 & u_{31} & [80, 100] \\ & u_{32} & [85, 100] \end{bmatrix} & R_p(u_3) &= \begin{bmatrix} N_p & u_{31} & [0, 100] \\ & u_{32} & [0, 100] \end{bmatrix}
 \end{aligned} \quad (18)$$

$$\begin{aligned}
 R_1(u_4) &= \begin{bmatrix} N_1 & u_{41} & [0, 65) \\ & u_{42} & [0, 25) \\ & u_{43} & [0, 25) \\ & u_{44} & [0, 5) \end{bmatrix} & R_2(u_4) &= \begin{bmatrix} N_2 & u_{41} & [65, 75) \\ & u_{42} & [25, 50) \\ & u_{43} & [25, 50) \\ & u_{44} & [5, 10) \end{bmatrix} & R_3(u_4) &= \begin{bmatrix} N_3 & u_{41} & [75, 85) \\ & u_{42} & [50, 70) \\ & u_{43} & [50, 70) \\ & u_{44} & [10, 20) \end{bmatrix} \\
 R_4(u_4) &= \begin{bmatrix} N_4 & u_{41} & [85, 95) \\ & u_{42} & [70, 85) \\ & u_{43} & [70, 85) \\ & u_{44} & [20, 40) \end{bmatrix} & R_5(u_4) &= \begin{bmatrix} N_5 & u_{41} & [95, 100) \\ & u_{42} & [85, 100) \\ & u_{43} & [85, 100) \\ & u_{44} & [40, 100) \end{bmatrix} & R_p(u_4) &= \begin{bmatrix} N_p & u_{41} & [0, 100) \\ & u_{42} & [0, 100) \\ & u_{43} & [0, 100) \\ & u_{44} & [0, 100) \end{bmatrix}
 \end{aligned} \tag{19}$$

$$\begin{aligned}
 R_1(u_5) &= \begin{bmatrix} N_1 & u_{51} & [0, 25) \\ & u_{52} & [0, 25) \\ & u_{53} & [0, 25) \end{bmatrix} & R_2(u_5) &= \begin{bmatrix} N_2 & u_{51} & [25, 50) \\ & u_{52} & [25, 50) \\ & u_{53} & [25, 50) \end{bmatrix} & R_3(u_5) &= \begin{bmatrix} N_{31} & u_{51} & [50, 70) \\ & u_{52} & [50, 70) \\ & u_{53} & [50, 70) \end{bmatrix} \\
 R_4(u_5) &= \begin{bmatrix} N_4 & u_{51} & [70, 85) \\ & u_{52} & [70, 85) \\ & u_{53} & [70, 85) \end{bmatrix} & R_5(u_5) &= \begin{bmatrix} N_5 & u_{51} & [85, 100) \\ & u_{52} & [85, 100) \\ & u_{53} & [85, 100) \end{bmatrix} & R_p(u_5) &= \begin{bmatrix} N_p & u_{51} & [0, 100) \\ & u_{52} & [0, 100) \\ & u_{53} & [0, 100) \end{bmatrix}
 \end{aligned} \tag{20}$$

$$\begin{aligned}
 R(u_1) &= \begin{bmatrix} N & u_{11} & 80 \\ & u_{12} & 67 \\ & u_{13} & 55 \\ & u_{14} & 80 \end{bmatrix} & R(u_2) &= \begin{bmatrix} N & u_{21} & 16 \\ & u_{22} & 51 \\ & u_{23} & 48 \end{bmatrix} & R(u_3) &= \begin{bmatrix} N & u_{31} & 70 \\ & u_{32} & 78 \end{bmatrix} \\
 R(u_4) &= \begin{bmatrix} N & u_{41} & 80 \\ & u_{42} & 52 \\ & u_{43} & 65 \\ & u_{44} & 12 \end{bmatrix} & R(u_5) &= \begin{bmatrix} N & u_{51} & 72 \\ & u_{52} & 65 \\ & u_{53} & 47 \end{bmatrix}
 \end{aligned} \tag{21}$$

3.4. Calculate the Correlation Matrix and Determine the Rating of WSER of the Overall Subproject

According to Equation (9), we calculated the correlation matrix of each WSER at the index-tier (Table 11). Using the Equation (11) and index weights in Tables 3–7, the correlation matrix of each risk category can be generated (Table 12). In applying the above computation, the correlation matrix of risk of the overall MG subproject can be produced (Table 13).

Table 11. Correlation matrix of each risks at index tier and its rating.

Risks	Correlations					Ratings
	I	II	III	IV	V	
u ₁₁	−0.400	−0.200	0.400	−0.143	−0.368	III
u ₁₂	−0.560	−0.340	0.150	−0.083	−0.353	III
u ₁₃	−0.400	−0.250	−0.100	0.500	−0.100	IV
u ₁₄	−0.733	−0.600	−0.333	0.333	−0.200	IV
u ₂₁	−0.188	0.400	−0.133	−0.350	−0.567	II
u ₂₂	−0.347	−0.020	0.050	−0.279	−0.410	III
u ₂₃	−0.324	0.080	−0.040	−0.314	−0.435	II
u ₃₁	−0.538	−0.400	−0.143	0.333	−0.250	IV
u ₃₂	−0.707	−0.560	−0.267	0.467	−0.241	IV
u ₄₁	−0.429	−0.200	0.500	−0.200	−0.429	III
u ₄₂	−0.360	−0.040	0.100	−0.273	−0.407	III
u ₄₃	−0.533	−0.300	0.250	−0.125	−0.364	III
u ₄₄	−0.368	−0.143	0.200	−0.400	−0.700	III
u ₅₁	−0.627	−0.440	−0.067	0.133	−0.317	IV
u ₅₂	−0.533	−0.300	0.250	−0.125	−0.364	III
u ₅₃	−0.319	0.120	−0.060	−0.329	−0.447	II

Table 12. Correlation matrix of each risk category and its rating.

Criteria	Correlations					Ratings
	I	II	III	IV	V	
u_1	−0.109	−0.073	0.011	0.021	−0.056	III
u_2	−0.065	0.028	−0.006	−0.068	−0.102	II
u_3	−0.106	−0.082	−0.034	0.068	−0.043	IV
u_4	−0.091	−0.038	0.055	−0.056	−0.107	III
u_5	−0.094	−0.045	0.011	−0.016	−0.068	III

Table 13. Correlation matrix of risk of the overall Mingan (MG) subproject.

Criteria	Correlations				
	I	II	III	IV	V
u	−0.092	−0.039	0.009	−0.014	−0.077

Utilizing Equations (14) and (15), we calculated the normalized rating value of risk of the overall subproject: $\bar{s} = 3.223$. As such, the rating of WSER of the overall MG subproject is at the third level.

3.5. Results Analysis and Practice Implications

The rating of the WSER of MG subproject is III, which indicates the overall WSER is situated in a feasible but reduction-needed zone, which indicates the detrimental impacts on local WSE caused by the WSERs can be controlled, and some specific measures can be taken based on the risk rating. Among the WSER categories at criteria-tier, the risk level of construction method (u_2) is the highest, followed by the risk of design schema (u_1), the risk of personnel competency (u_5), the risk of construction management (u_4), and the risk of material and equipment (u_3).

In terms of risk of construction method (u_2), the risk of site clearing (u_{21}) and the risk of earthwork (u_{23}) are higher than other risks under this WSER category. This can be explained by the fact that the subproject is located in an EFR and impractical construction method has a greater impact on the WSE. As such, optimization and improvement of construction method and programs should be strengthened. In terms of the risk of design schema (u_1), the risk of greening design (u_{13}) and the risk of slope protection design (u_{14}) are lower. The risk of slag disposal design (u_{11}) and the risk of drainage design (u_{12}) are relatively higher. Thus, the designers should optimize these two designs. As for the risk of personnel competency (u_5), the risk of workers' competency (u_{53}) is highest, followed by the risk of managers' competency (u_{52}) and the risk of designers' competency (u_{51}). Workers are the direct operators, and they exert more impacts on the WSE. In this subproject, the workers' competency and the managers' competency should be improved. All four risks under the risk of construction management (u_4) are in the same rating. The overall WSER level of construct management is modest. Therefore, it is necessary to strengthen the organization management of the project, develop more practical construction plans, and effectively reduce the overall risk. The risk of materials and equipment (u_3) is the least salient among the five risk categories. However, daily management and monitoring should be strengthened to prevent the risks from being transformed into negative contexts.

4. Conclusions and Recommendations

This paper proposed a novel approach for WSER assessment of railway project construction in the EFR. A new risk index framework for WSER analysis of railway construction in the EFR was established based on the previous literature and coding of one project case. The risks can be integrated into five categories: The risk of design schema, the risk of construction method, the risk of materials and equipment, the risk of construction management, and the risk of personnel competency. Additionally, there are 16 second-ordered WSERs under the five WSER categories. A quantitative method for

assessing the WSERs of railway construction corresponding to the index framework was also proposed by synthesizing the AHP and MEA.

We utilized the MG subproject to exemplify the practical applicability of the developed approach. The case study indicated that the overall WSER level of the MG subproject is at the third level, which means that the project participants should take more measures to reduce the detrimental impacts on local WSE. Furthermore, at the risk category level, the risk of construction method was identified as the key risk category. In detail, at the risk index level, the risk of site cleaning, the risk of earthwork, and the risk of workers' competency were identified as key WSER of this subproject. Besides, some measures aiming to decrease the impacts on local WSE in EFRs were suggested.

The constructions of this study are as follows: (1) This study enriches the risk assessment theory of railway project construction, especially on water-soil environment risk assessment; (2) a novel assessment approach for water-soil environment risk assessment was proposed for the first time for railway project construction in EFR by providing a risk index framework and corresponding quantitative methods; and (3) the proposed approach can guide designers, contractors, consultants, government administrators, worksite managers, and researchers to assess the WSERs of railway construction and help them to identify the key WSERs, according to which they can design and optimize effective risk control measures.

However, there are two limitations about this study: (1) The proposed approach did not take into account the railway project WSER in operation stage; (2) we only applied the approach into one railway project, and new WSERs can be identified in more complicated construction context. Thus, we suggest future research can be focused on the above-mentioned aspects.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Risks identification based on previous studies.

Risks	Previous Studies
Risk of slag disposal design	Tong [48]; Yu [49]; Wang [50]; Bao et al. [51].
Risk of drainage design	Zhang et al. [52]; Tong [48]; Yu [49]; Wang [50]; Qu [53].
Risk of greening design	Gao [54]; Tong [48]; Yu [49].
Risk of slope protection design	Zhou and Ma [14].
Risk of site Cleaning	Yu [49]; Qu [53]; Bao et al. [51].
Risk of piling	Jozi et al. [18]; Rezaian et al. [19]; Zhou and Ma [14]; Wang [50]; Qu [53]; Bao et al. [51].
Risk of earthwork	Jozi et al. [18]; Rezaian et al. [19]; Liao [55]; Zhou and Ma [14]; Tong [48]; Zhang [56]; Yu [49]; Wang [50]; Bao et al. [51].
Risk of material quality	Weideborg et al. [57]; Carpenter et al. [58]; Zhou and Ma [14].
Risk of mechanical equipment	Rezaian et al. [19]; Luo et al. [59]; Liao [55]; Yu [49].
Risk of construction waste	Luo et al. [59]; Lv [60]; Liao [55]; Zhou and Ma [14]; Tong [48]; Yu [49]; Wang [50]; Qu [53]; Bao et al. [51].
Risk of stacking and transport for materials and wastes	Zhou and Ma [14]; Liu et al. [61]; Wang [50]; Qu [53].
Risk of construction planning	Lv [60]; Zhang et al. [52]; Bao et al. [51].
Risk of precautions and monitoring	Yu [49].
Risk of designers' competency	Lv [60].
Risk of managers' competency	Lv [60]; Wang [50].
Risk of workers' competency	Lv [60]; Zhang et al. [52].

Table A2. Risks identification based on case coding.

Risks	Text Coding
Slope and greening design	The slope around the subgrade and tunnel entrance is protected by vegetation measures such as spraying, planting, and grass. Improper slop protection and greening designs will not be conducive to the restoration of vegetation along the railway.
Waste slag disposal design	The disposal scheme of the slags tries to avoid the ecological and water-source sensitive areas. Improper design of slag disposal scheme may easily induce soil and water loss.
Pile foundation construction	Pile foundation construction will produce a large number of high turbidity mud drilling wastewater. Cofferdam installation and demolition will exert big disturbances to water bodies and cause suspended sediment concentration in the upstream and downstream.
Earthworks	The excavation of earth or rock will change the original form of the water-soil environment. Water-soil environment problems such as stability decreasing, groundwater level changing, and water pollution occur in the disturbed area.
Site leveling	Site leveling will destroy the vegetation and bare the surface, which will lead to the reduction of soil water fixation and conservation ability.
Material quality	This project mostly adopts green materials. The quality of materials satisfies relevant green regulations.
Ground traffic control	The slags are piled up randomly without protection, and they are washed by rainwater and flowed into the nearby river, causing soil erosion or pollution.
Construction wastewater discharge	The construction wastewater includes construction washing wastewater and construction mud sewage. Construction washing wastewater mainly is produced from concrete production and maintenance process, washing and maintenance of equipment and transport vehicles, and site cleaning. The construction mud sewage is mainly produced in the process of tunnel drilling and bridge pile foundation construction. In this project, this part of waste water is discharged after precipitation.
Guarantee and monitoring	Comprehensive and scientific environmental supervision shall be carried out during project construction to effectively protect the ecological environment, maximize the conservation of water and soil resources, restore the damaged vegetation, and effectively control the pollution of water and soil environment. However, there are some imperfections in regulation.
Managing ability of managers	This project strengthens the management ability of managers, such as monitoring of drinking water and irrigation water sources for residents, and reserving the compensation for leaking water resources. Timely level the construction site, plant trees and green, and restore of the affected vegetation near the excavation.
Ability of construction personnel	This project strengthens the education and forbids the construction personnel to destroy the vegetation of the protected area. The ability of construction personnel is one of the risks of water-soil environment damage.

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