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Risk Assessment of Metro Project Construction based on AHP-Cloud Model

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ABSTRACT

To address the fuzziness and randomness inherent in construction risk assessment for metro projects, this study proposes a risk assessment method integrating the cloud model with the analytic hierarchy process (AHP). The study establishes a construction risk assessment index system comprising 20 indicators across five dimensions: organizational, management, technical, economic, and social. AHP determines the indicator weights. The method then constructs standard clouds for different risk levels and uses an inverse cloud generator to transform expert scores into evaluation clouds. The cloud similarity algorithm calculates similarities between the evaluation clouds and the standard clouds to construct a similarity matrix, which is then integrated with the indicator weights to obtain the final assessment results. An empirical analysis of a metro project in Southwest China shows that overall construction risk is relatively high, with technical and management risks identified as the primary areas requiring control. The results demonstrate that the proposed method can comprehensively characterize the fuzziness and randomness inherent in expert evaluations and provide a reference for risk identification, risk-level determination, and hierarchical risk control in metro construction projects.

KEYWORDS

Metro Construction; Risk Assessment; Cloud Model; Analytic Hierarchy Process.

1. INTRODUCTION

With the rapid development of urban rail transit in China, the construction scale of metro projects continues to expand. Complex construction environments, numerous uncertainties, and significant risk concealment characterize metro projects. Once safety accidents occur, they not only affect project progress and investment returns but may also cause significant casualties and social impacts. Therefore, establishing a scientific and effective construction risk assessment system is highly practical for improving the safety management level of metro projects.

Metro projects feature long construction cycles, complex construction environments, constrained underground space, and interrelated risk factors, making risk identification and assessment an important component of engineering safety management research. Early studies primarily focused on risk factor identification, index system construction, and risk level determination. Zou et al. [1] constructed a risk checklist for metro projects based on accident data, literature analysis, and expert surveys, and introduced the fuzzy analytic hierarchy process into risk assessment for the Nanjing Metro project, providing an early framework for systematic identification and multi-indicator evaluation of metro construction risks. With advances in information technology and engineering management methods, research on metro construction risks has gradually shifted from experience-based judgment to model-based and data-driven approaches. Li et al. [2] established a safety risk identification and early warning system for metro construction based on BIM, integrating a risk

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knowledge base, information fusion, and construction process monitoring; Liu et al. [3] employed AHP and expert scoring methods to identify and comprehensively evaluate metro construction risks, further demonstrating the applicability of multi-level indicator systems in construction risk assessment. Overall, related research has progressed from identifying risk sources and constructing indicators to comprehensive evaluation and early risk warning.

Regarding risk assessment methods, existing studies have mainly adopted approaches such as the Analytic Hierarchy Process, fuzzy comprehensive evaluation, grey clustering, Bayesian networks, and data mining. Zhao et al. [4] conducted a grey clustering risk assessment of metro shield construction using PCA-Shapley values to reduce indicator redundancy and characterize risk levels; Lu et al. [5], addressing the time-varying characteristics of metro tunnel construction risks, combined dynamic Bayesian networks with fuzzy comprehensive evaluation and dynamically updated risk probabilities using settlement monitoring data; Shen et al. [6] further applied fuzzy theory and dynamic Bayesian networks to the risk evolution analysis of deep foundation pit construction, strengthening the characterization of causal relationships and dynamic evolution processes among risk factors. These methods have enhanced the scientific rigor of risk assessment for metro and underground projects from different perspectives, but each has its own applicable conditions: AHP can effectively reflect the hierarchical structure among risk indicators and expert experience; fuzzy evaluation is suitable for handling problems with unclear risk level boundaries; and Bayesian networks excel in expressing causal relationships and dynamic updating of risk factors. Meanwhile, many indicators in metro construction derive from expert judgment and qualitative descriptions, and their evaluation information often contains both fuzziness and randomness. Using only deterministic membership degrees, scoring values, or probability parameters cannot fully reflect the uncertainty inherent in the evaluation information itself.

The cloud model offers a new methodological approach to address these issues. The cloud model proposed by Li et al. [7] establishes a mapping relationship between qualitative concepts and quantitative values through three numerical characteristics—expectation (Ex), entropy (En), and hyper-entropy (He)—enabling the description of both fuzziness and randomness within a unified framework. Subsequently, researchers have gradually applied the cloud model to engineering safety and risk assessment. Lee et al. [8] applied the cloud model to multi-period comprehensive evaluation of construction safety risks to handle the uncertainty of expert evaluation information at different stages; Lin et al. [9] improved the normal cloud model for tunnel construction risk assessment, incorporating both the fuzziness and randomness of risk factors into risk level determination; Shen et al. [10] constructed reference clouds and identification clouds for foundation pit excavation engineering, processing multi-source risk information through the cloud model to determine the risk state of the excavation system. In recent years, cloud model research has further evolved toward dynamic approaches. Sun [11] et al. developed a two-dimensional cloud model-based dynamic risk early warning method, incorporating changes in construction environment information into tunnel construction risk assessment; Zhou [12] et al. combined the improved CRITIC method with the cloud model to conduct safety risk assessment at different construction stages of deep foundation pits for metro stations. These studies show that the cloud model is well suited to represent engineering risk uncertainty and risk-level transformation.

Although existing research has achieved relatively rich results, there remains room for further deepening. First, in terms of research objects, existing cloud model studies have predominantly focused on specific construction scenarios such as shield tunnels, deep foundation pits, excavation systems, and adjacent buildings. In contrast, research that comprehensively evaluates multidimensional risk factors, including organizational, management, technical, economic, and social aspects, throughout the project construction process remains relatively insufficient. Second, regarding risk information processing, some studies still primarily use deterministic scores, membership degrees, or single probability results to represent expert judgments; the characterization of random fluctuations within the same risk level and the fuzzy boundaries between different risk levels can be

further strengthened. Third, matching the risk clouds formed by expert evaluation with standard risk-level clouds based on indicator weights to improve the interpretability and intuitiveness of risk-level discrimination still warrants further investigation. Accordingly, this study integrates literature review, WBS-RBS cross-analysis, and expert surveys to identify construction risk factors for metro projects, constructs an evaluation indicator system encompassing organizational risk, management risk, technical risk, economic risk, and social risk, employs AHP to determine indicator weights, and subsequently utilizes the inverse cloud generator to transform expert evaluation data into evaluation clouds. The construction risk level is then determined through cloud similarity between evaluation clouds and standard clouds, thereby providing methodological support for comprehensive evaluation and hierarchical risk control of metro construction projects.

2. RISK IDENTIFICATION AND INDEX SYSTEM CONSTRUCTION FOR METRO CONSTRUCTION

2.1. Risk Identification Method

This study identifies metro construction risk factors following the approach of "literature preliminary screening – structured identification – expert correction." First, the study systematically reviewed metro construction risk-related studies, summarized high-frequency risk factors, and developed an initial risk factor checklist. Second, the WBS-RBS cross-analysis approach matched the Work Breakdown Structure with risk sources, identifying risk factors that may arise in different construction phases. Finally, experts with experience in metro project construction and management were invited to conduct two rounds of consultation on the initial risk factors, supplementing, merging, and correcting the indicators, ultimately forming the construction risk evaluation indicator system.

2.2. Risk Evaluation Indicator System

Table 1. Metro construction risk evaluation indicator system

Indicator Level	First-level Indicators	Second-level Indicators
Construction Risk Evaluation Indicator System	Organizational Risk	Project management team competence risk
		Engineering personnel competence risk
		Stakeholder coordination risk
	Management Risk	Schedule management risk
		Quality management risk
		Cost management risk
		Safety management risk
		Management system risk
		On-site construction deployment risk
	Technical Risk	Geological survey risk
		Engineering design risk
		Material and equipment installation quality risk
		New technology promotion and application risk
	Economic Risk	Interest rate risk
		Market price fluctuation risk
		Related resource allocation risk
		Stakeholder contract performance risk
	Social Risk	Policy risk
		Laws and regulations risk
		Nearby resident obstruction risk

Based on the aforementioned risk identification results and considering the characteristics of metro project construction processes and risk sources, and in accordance with the principles of systematic representation, representativeness, and evaluability of indicators, metro construction risks are classified into five first-level indicators—organizational risk, management risk, technical risk, economic risk, and social risk—which are further subdivided into 20 second-level indicators, forming the metro construction risk evaluation indicator system, as shown in Table 1.

2.3. Risk Assessment Level Classification

Metro construction risks are classified into five levels: $G = \{g_1, g_2, g_3, g_4, g_5\}$, corresponding to low risk, relatively low risk, moderate risk, relatively high risk, and high risk, respectively. The author uses a 100-point scoring system, where higher scores indicate greater risk. The score intervals corresponding to each level are as follows: low risk [0, 20), relatively low risk [20, 40), moderate risk [40, 60), relatively high risk [60, 80), and high risk [80, 100]. This classification scheme maintains continuity of level intervals while facilitating the subsequent construction of standard clouds for each risk level.

3. CONSTRUCTION OF RISK ASSESSMENT MODEL BASED ON CLOUD MODEL

3.1. Cloud Model Theory

The cloud model, proposed by Academician Li Deyi in 1995, is an uncertainty transformation model that can achieve natural mapping between qualitative concepts and quantitative descriptions. The cloud model employs three numerical characteristics—expectation (Ex), entropy (En), and hyper-entropy (He)—to comprehensively represent a qualitative concept. Ex is the expected distribution of cloud drops in the domain space and serves as the typical representative of the qualitative concept; En is the uncertainty measure of the qualitative concept, reflecting the fuzziness of the concept, i.e., the width of the cloud; He is the uncertainty measure of entropy, reflecting the degree of dispersion of cloud drops, i.e., the thickness of the cloud.

The cloud model enables bidirectional transformation between qualitative concepts and quantitative data through the forward and backward cloud generators. The forward cloud generator generates cloud drops conforming to a normal distribution based on the numerical characteristics of the cloud (Ex, En, He), realizing the transformation from qualitative to quantitative; the backward cloud generator calculates the three numerical characteristics of the cloud from a certain number of precise data samples, achieving the transformation from quantitative to qualitative. Compared with single deterministic values or traditional membership degree expressions, the cloud model can jointly characterize the central position, degree of fuzziness, and random dispersion characteristics of evaluation concepts using expectation, entropy, and hyper-entropy, and is therefore applicable to handling the fuzziness and randomness inherent in expert judgments in metro construction risk assessment.

3.2. Determination of Indicator Weights

The Analytic Hierarchy Process is used to calculate the weights of important risk factors during the project construction process. The structural hierarchy model is constructed by decomposing the project risks into three levels:

(1) Objective layer: the overall project risk objective, containing only one element.

(2) Criteria layer: the overall construction risk is divided into five categories: organizational, management, technical, economic, and social risks.

(3) Indicator layer: decomposition of each major risk category into individual risk elements.

The nine-point scale method (see Table 2) compares the relative importance of two factors and establishes the judgment matrix.

Table 2. Evaluation criteria for risk indicators

Factor i Compared with Factor j	Quantified Value
Equal importance	1
Slightly more important	3
Moderately more important	5
Strongly more important	7
Extremely more important	9
Intermediate values between adjacent judgments	2, 4, 6, 8
Reciprocal	Ratio of importance of j compared to i

The indicator weights are calculated by normalizing the geometric means of the rows of the pairwise comparison matrix:

$$g_i = (\prod_{j=1}^{n} a_{ij})^{1/n}$$

$$w_i = g_i / (\sum_{k=1}^{n} g_k), i = 1, \dots, n \quad (1)$$

Here, a_{ij} is the importance of factor i relative to factor j, g_i is the geometric mean of row i, w_i is the normalized weight of factor i, and n is the number of factors in the comparison matrix.

Step 1: Establish the risk comment levels. Set the comment values for project risks at five levels, with the corresponding comment set Y = {y_1, y_2, y_3, y_4, y_5} = (low risk, relatively low risk, moderate risk, relatively high risk, high risk).

Step 2: Construct the standard risk-level clouds. The expectation, entropy, and hyper-entropy of each standard cloud are calculated as follows:

$$Ex_y = (y_{max} + y_{min})/2 \quad (2)$$

$$En_y = (y_{max} - y_{min})/6 \quad (3)$$

$$He_y = k \quad (4)$$

where y = y_1, y_2, y_3, y_4, y_5; y_{max} and y_{min} represent the upper and lower bounds of the project risk-score interval, respectively; and k is a constant determined by comprehensively considering various factors.

Step 3: Calculate the cloud parameters. Experts are invited to score the project risk factors. Calculate parameters for each indicator level. The calculation formulas are as follows:

Sample mean of second-level indicators:

$$\overline{X} = \frac{1}{m} \sum_{j=1}^{m} x_{ij} \quad (5)$$

Sample variance of second-level indicators:

$$S_i^2 = \frac{1}{m-1} \sum_{j=1}^{m} (x_{ij} - Ex_i)^2 \quad (6)$$

Three cloud parameters of second-level indicators:

$$\begin{cases} Ex_i = \frac{1}{m} \sum_{j=1}^{m} x_{ij} \\ En_i = \sqrt{\frac{\pi}{2}} \times \frac{1}{m} \sum_{j=1}^{m} |x_{ij} - Ex_i| \\ He_i = \sqrt{|S_i^2 - En_i^2|} \end{cases} \quad (7)$$

Three cloud parameters of first-level indicators:

$$\begin{cases} Ex = \frac{\sum_{i=1}^{n} Ex_i \times En_i \times w_i}{\sum_{i=1}^{n} En_i \times w_i} \\ En = \sum_{i=1}^{n} E\,n_i \times w_i \\ He = \frac{\sum_{i=1}^{n} He_i \times En_i \times w_i}{\sum_{i=1}^{n} En_i \times w_i} \end{cases} \tag{8}$$

Step 4: Draw the risk cloud diagram. Using MATLAB, compare the generated risk cloud diagram with the standard cloud diagram to determine the risk status of each risk indicator level.

Step 5: Calculate cloud similarity and determine risk levels. Calculate the similarities between each indicator evaluation cloud and the five standard risk clouds to construct the cloud similarity matrix. For indicators at the same level, the similarities are weighted and synthesized according to the indicator weights to obtain the comprehensive similarity vector, and the risk level of the evaluation object is determined based on the maximum similarity principle. This process converts expert scores into risk-level results.

4. ENGINEERING CASE STUDY

4.1. Project Overview

A metro line in Southwest China is taken as the research object. The line runs through the central urban area of a provincial capital city, crossing water-rich sandy cobble strata with complex geological conditions, dense surrounding buildings, and numerous underground pipelines. The line is approximately 16 km long and has 12 stations. The shield tunneling method is predominantly used for construction, with certain local sections employing the cut-and-cover method and the mining method (NATM). The construction difficulty and risk level are both at a high level.

4.2. Calculation of Indicator Weights

Eight metro construction management experts were invited to score the relative importance of each indicator using the 1–9 scale method, construct the judgment matrix, and calculate the weights. The first-level indicator weights are: organizational risk 0.10, management risk 0.28, technical risk 0.35, economic risk 0.15, and social risk 0.12, with CR = 0.038 < 0.1, satisfying the consistency requirement. Table 3 presents the weights of each second-level indicator. The second-level indicator weights in Table 3 are local weights relative to the corresponding first-level indicator; for the overall risk evaluation, the composite weight of a second-level indicator is obtained by multiplying the first-level indicator weight by the corresponding second-level indicator local weight.

4.3. Evaluation Results and Analysis

Eight experts scored each second-level indicator on a 100-point scale. The author used the inverse cloud algorithm to obtain the evaluation cloud parameters for each indicator. The author calculated the similarity between each indicator and the five standard risk-level clouds using the cloud similarity algorithm. By synthesizing the weights with the similarity matrix, we obtained the comprehensive evaluation results, as shown in Table 4.

As shown in Table 4, the overall construction risk level of this metro project is classified as relatively high. Among the first-level indicators, technical risk and management risk are ranked highest, both at the relatively high risk level, and thus constitute the primary targets for risk management control. Specifically, organizational risk, economic risk, and social risk are all at the moderate risk level. Further comparison across levels shows that the similarity between technical risk and the relatively high-risk standard cloud is 0.59, while that for management risk is 0.52, indicating that technical and

management factors in the construction process require priority attention. From the perspective of the actual project conditions, the project crosses water-rich sandy cobble strata with dense buildings and underground pipelines along the route, creating significant challenges for construction technology and organizational coordination, consistent with the evaluation results.

Table 3. Indicator weights

First-level Indicators	Weight	Second-level Indicators	Weight
Organizational Risk	0.10	Project management team competence risk	0.38
		Engineering personnel competence risk	0.35
		Stakeholder coordination risk	0.27
Management Risk	0.28	Schedule management risk	0.15
		Quality management risk	0.20
		Cost management risk	0.15
		Safety management risk	0.25
		Management system risk	0.13
		On-site construction deployment risk	0.12
Technical Risk	0.35	Geological survey risk	0.30
		Engineering design risk	0.28
		Material and equipment installation quality risk	0.24
		New technology promotion and application risk	0.18
Economic Risk	0.15	Interest rate risk	0.20
		Market price fluctuation risk	0.32
		Related resource allocation risk	0.25
		Stakeholder contract performance risk	0.23
Social Risk	0.12	Policy risk	0.35
		Laws and regulations risk	0.33
		Nearby resident obstruction risk	0.32

Table 4. Comprehensive evaluation results

Evaluation Object	Low Risk	Rel. Low Risk	Moderate Risk	Rel. High Risk	High Risk	Risk Level
Organizational Risk	0.00	0.15	0.58	0.24	0.01	Moderate
Management Risk	0.00	0.06	0.36	0.52	0.04	Rel. High
Technical Risk	0.00	0.03	0.30	0.59	0.06	Rel. High
Economic Risk	0.01	0.25	0.51	0.20	0.00	Moderate
Social Risk	0.01	0.22	0.55	0.20	0.00	Moderate
Overall Assessment	0.00	0.11	0.41	0.43	0.03	Rel. High

5. RISK CONTROL COUNTERMEASURES

Based on the evaluation results, risk control countermeasures are proposed from five dimensions following the principle of "focused control and hierarchical implementation".

5.1. Technical Risk Control Countermeasures

The similarity between technical risk and the relatively high-risk standard cloud reaches 0.59, the highest among all first-level risks, and it should be treated as the priority control target. First, strengthen geological surveys and advance prediction; for complex strata, use multiple exploration methods, and during construction, use advanced horizontal drilling, geological radar, and other techniques for prediction, with tunneling parameters adjusted dynamically. Second, optimize construction plans and key process controls by improving deep foundation pit support design and deformation monitoring, and develop specialized protection plans for adjacent buildings and pipelines. Third, reinforce material and equipment quality control with strict acceptance inspections, full-process quality traceability, and standardized installation operations.

5.2. Management Risk Control Countermeasures

Management risk is also classified as relatively high risk, with a similarity of 0.52 to the relatively high-risk standard cloud. It should be treated as another key focus of construction risk control. First, strengthen the safety management system by implementing the safety production responsibility system and establishing a dual prevention mechanism that integrates hierarchical risk control with hidden-danger investigation and remediation. Second, the company should rigorously enforce quality management by establishing a quality assurance system covering the entire process, implementing the "three-inspection system," and conducting on-site supervision for key processes. Third, enhance schedule and cost control through scientific planning, strict management of change orders and visas, and a dynamic cost early-warning mechanism. Fourth, improve emergency response plans with regular drills to strengthen emergency response capabilities.

5.3. Organizational Risk Control Countermeasures

Regarding organizational risk, efforts should focus on both project management team capacity building and improving coordination mechanisms. First, enhance the project department's management level by improving the organizational structure and job responsibilities and selecting experienced core management personnel. Second, strengthen personnel capacity building through tiered, categorized training, and require special operations personnel to hold valid certifications. Third, establish a coordination mechanism among all participating parties, with regular coordination meetings to promptly resolve issues related to design changes, cross-operation, and other interface matters.

5.4. Economic Risk Control Countermeasures

Although economic risk is moderate, poor management may trigger cascading effects, requiring stronger prevention and control in the following areas. First, enhance market price monitoring by establishing early-warning mechanisms for major materials such as steel and cement, and implement timely countermeasures. Second, optimize resource allocation by properly arranging procurement and mobilization schedules to reduce inventory backlog and capital occupation. Third, reinforce contract performance management through standardized contract terms, strengthened process tracking, and timely dispute resolution.

5.5. Social Risk Control Countermeasures

Social risk is directly related to the external environment and the project's construction order, and should be proactively prevented and resolved. First,closely monitor changes in policies and regulations to ensure compliant project progress and prevent compliance risks. Second, strengthen communication with nearby residents through effective publicity and explanation, accessible complaint channels, and timely response to and remediation of issues raised by residents. Third, implement civilized construction measures, with strict control of noise and dust emissions, to minimize the impact of construction on the surrounding environment.

6. CONCLUSION

(1) Addressing the characteristics of fuzziness and randomness in expert judgments in metro construction risk assessment, this study constructs an AHP–cloud model-based construction risk assessment method. The method uses AHP to determine indicator weights, transforms expert scores into evaluation clouds through the inverse cloud generator, and determines risk levels through cloud similarity. It can simultaneously characterize the fuzziness and randomness inherent in expert

evaluation information, providing a quantitative method for addressing uncertainty in construction risk assessment.

(2) Multiple methods are comprehensively employed to identify metro construction risk factors systematically, and a risk evaluation indicator system is established comprising 5 first-level indicators (organizational, management, technical, economic, and social risks) and 20 second-level indicators.

(3) The engineering case study results show that the overall construction risk of the project is at a relatively high level, with technical risk and management risk identified as the primary risk sources. The evaluation results are consistent with the project's complex geological conditions and significant organizational challenges, preliminarily indicating that the construction method has certain engineering applicability.

(4) Based on the evaluation results, risk control countermeasures are proposed from five aspects: technical, management, organizational, economic, and social dimensions, providing practical reference for metro construction risk management. This study primarily relies on static risk assessment using expert evaluation data, and the number of engineering case studies is limited; the evaluation results remain subject to expert experience and sample scope. Future research could incorporate multi-source dynamic data from construction monitoring, BIM, and Internet of Things technologies to update model parameters in real time, and conduct multi-project comparative studies and dynamic risk early-warning research.

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