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ARTICLE

Dynamic Risk-Warning of Center Diaphragm and Bench Composite Method During Construction

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ABSTRACT

During the construction of subway tunnels, safety issues should not be ignored, so it is necessary to prevent and resolve the risk in time and accurately. However, there are some shortcomings in the research of risk assessment, such as the subjectivity of initial data or the lack of scientific evaluation model, in order to solve the problem, this paper relies on the Changping section of the Guanhui Intercity Metro, in order to establish a dynamic risk-warning model for the construction process of subway tunnel with the CD-Bench composite method. First, a monitoring plan was equationted according to the specification requirements and the actual situation of the project, and based on this, an evaluation index system was established from five aspects: geological and support conditions, crown settlement, clearance convergence, and ground settlement and building settlement. Secondly, according to the established risk evaluation standards, the risk level of the index is determined by introducing extension theory and determining the combined weight of the index based on the distance function. Finally, feedback the corresponding risk-warning signals and take control measures. Through the application analysis shows that the model can alarm the risks during the tunnel construction process directly and timely, so the model is feasible and practical, and it is worthy of popularization and application in similar projects.

KEYWORDS

Risk-warning; monitoring; extension theory; combination empowerment; metro tunnel

1 Introduction

As a very complex system engineering, subway has the characteristics of large investment, large number of project participants, complex technology, long period, strong concealment and various geological conditions and so on, which brings great risks to construction. Therefore, scholars at home and abroad have carried out a lot of research on tunnel construction safety. There are many factors affecting construction safety and their contribution to risk value is different, so, in order to evaluate the construction safety scientifically and systematically, scholars like Wang et al. [1] To solve the randomness and fuzziness of water inrush risk evaluation, a comprehensive evaluation model was established based on normal cloud theory; Yuan et al. [2] established a Catastrophe theory model of tunnel collapse risk assessment based on the analysis of risk pregnancy environment and inducement of Hongyansi tunnel; Alireza et al. [3] and others combined the game theory with the interactive decision structure model of the hierarchical process of fuzzy analysis for risk management in tunnel engineering design, construction and operation; Sousa et al. [4] proposed a systematic approach to assess and manage tunnel construction-related risks based on Bayesian network; Ye et al. [5] developed an intelligent risk assessment system for deep-base pit precipitation; Abdolreza [6] proposed a risk assessment model based on fuzzy set theory to assess risk events during tunnel construction; Bai et al. [7] proposed a multi-stage risk management approach to better carry out risk management and optimize risk mitigation; Cagatay [8] selected event tree analysis method to analyze the operating risk of tunnel construction TBM (tunnel tunneling machine); Han et al. [9] proposed a risk assessment method to evaluate the pre-existing circumferential cracks of shield tunnel in order to ensure the safety of deep-digging tunnel during construction; Xia et al. [10] based on fuzzy set theory and similarity measurement theory, proposed a risk assessment model which is difficult to quantify fuzzy characteristics; Lin et al. [11] applied the improved cloud model to tunnel construction risk assessment; Xue et al. [12] rediction model for subway tunnel collapse risk based on Delphi-Ideal point method and geological forecast. Some scholars use monitoring techniques to predict the possibility of risk occurrence, scholars like Mahdi et al. [13] combined monitoring with mathematical evaluation methods according to the safety impacts of subway construction on adjacent existing bridges, and established the safety risk assessment and control system of the existing bridges including four aspects: pre-work detection, pre-work assessment, in-work dynamic control, post-work evaluation and recovery; Su et al. [14] used PSO-ANN model to predict the feasibility of surface settlement caused by tunnel excavation; Liu et al. [15] introduced microseismic monitoring and risk management theory in tunnel blasting excavation, which can obtain the probability of occurrence, potential consequences and risk grade of rock burst in real time; Liu et al. [16] proposed the reliability analysis of subway tunnel operation based on dynamic bayesian Copula model; Li et al. [17] evaluated the safety of slope with efficient Bayesian network on the strength of monitoring technology including sensors and wireless; Kang et al. [18] based on the real-time monitoring data of water inrush in Zoumaling tunnel excavation section, used fuzzy data analysis method to analyze and predict the content of water inrush.

In summary, in the aspect of risk research, on the one hand, some scholars can comprehensively identify the risk evaluation index and use scientific mathematical model to calculate risk values. However, the qualitative index is mostly and difficult to quantify, and their value are subjective only based on expert scoring. On the other hand, some scholars also use monitoring technology to carry out risk warning according to deformation value, but do not consider the different contribution of each index deformation to the overall risk. In this paper combines these two methods, it will rely on the Changping section tunnel of Guanhui Intercity Metro, and establish a dynamic risk-warning model for the construction process of subway tunnel with the CD-Bench composite method. Not only does the each risk evaluation index adopt a combination weighting method to give different weights, and uses scientific mathematical models to calculate their risk value, but also greatly reduces the difficulty of quantifying indicators.

The rest of this paper is organized as follows. In Section 2, the monitoring scheme is descripted. In Section 3, the construction risk evaluation is presented in detail. In Section 4 the information feedback of early-warning is descripted. In Section 5, a case analysis is performed to demonstrate the effectiveness of the proposed method. Conclusions and future work of the research are discussed in Section 6.

2 Monitoring Scheme

2.1 Engineering Situation

The Guanhui Intercity Rail Transit runs from Hongmei Station in Dongguan City to Huizhou Railway Station, This article mainly focuses on the Changping section of the tunnel as the research object. This part of the tunnel has such characteristics: the surrounding environment is complex, close to factory buildings, residential areas, etc., and it needs to pass through the artificial lake of the railway park, the HanViRiver, and cross the broken zone; and its ground elevation of this section is 7.31~14.32 m, and its buried depth is about 22–36 m. The engineering geological conditions are poor, mainly quaternary strata and broken zones; and need to pass through the artificial lake and HanViRiver in the railway park, so the surface water is abundant, and the groundwater is mainly bedrock fissure water and pour water, which has a greater impact on construction and is locally corrosive. In order to control tunnel deformation and ensure the safety of the construction, it is particularly important to establish a risk warning model.

In order to effectively prevent surface subsidence and large deformation of surrounding rock, the Changping section of the Guanhui intercity adopts the CD-Bench composite construction method, which means that the tunnel section is divided into two parts for excavation: The upper part is constructed by the CD method and the lower part is constructed by the bench method. This makes full use of the respective advantages of these two construction methods: the upper part is provided with vertical support by the partition wall, which effectively controls the settlement of the surrounding rock vault; and the lower part adopts the bench cut method for construction and facilitates the access of large machinery. In addition, due to the addition of temporary inverted arches, closed steel arches and other measures, the tunnel is less deformed during construction than the traditional single construction method, so has higher safety. At the same time, the construction period is shortened due to staggered construction. Although the construction cost of this method is high, compared with other treatment measures, the "performance-to-price ratio" is still the highest. The on-site construction drawing is shown in Fig. 1.

Figure 1: Site construction drawings

2.2 Monitoring Content and Frequency

The surface of this section of subway tunnel is roads with high traffic volume, HanViRiver Bridge, residential houses and levees, etc., and it needs to pass through the broken zone. Therefore, accurate and timely monitoring and measurement play an important role in the protection of ground buildings (structures) and the safety of tunnel construction. According to the Technical Specification for Monitoring and Measurement of Railway Tunnels (Q/CR 9218-2015) [19] stipulate the important and selective items for monitoring and measurement of railway tunnel construction, as shown in Table 1.

To sum up, with reference to the scale, characteristics and design requirements of this project, the monitoring content and frequency are shown in Table 2.

Table 1: Important and selection monitoring items for railway tunnel construction

	Serial number	Monitoring measurement Project	Common instruments
Important monitoring items	1	Observation inside and outside	Domainobservation, compass, digital camera
	2	Vault crown sinking	Total station, steel gauge, level
	3	Clear height variations	Convergence or total station
	4	Grand subsidence	Level, total station, indium steel ruler
Selection monitoring items	1	Surrounding rock pressure	Pressure cell
	2	Steel frame pressure	Steel gauge, strain gauge
	3	Internal forces of secondary lining	Concrete steel gauge, strain gauge
	4	Internal displacement of surrounding rock	Multi-point extensometer
	5	Tunnel floor heave	Total station, indium steel ruler and level
	6	Axial force of anchor bolt	Steel bar meter
	7	Blasting vibration	Vibration recorder, sensor

Table 2: Monitoring measurement content and frequency

	Crown settlement	Clearance convergence	Ground settlement	Building settlement
General	1/1d	1/2d	1/1d	1/1d
Big deformation	2/1d	1/1d	2/1d	2/1d

2.3 Point Layout

2.3.1 Point Layout Principles

(1) The measurement points are arranged in accordance with the construction monitoring measurement plan. If the actual terrain does not allow, the measuring points can be set near the design points, but the surface points, the convergence points and the settlement points of the vault should corresponding to the mileage of the same section, which should be stable, obvious and simple, which can reflect the actual state and development trend of the monitoring object;

(2) The measuring points should be arranged a certain time in advance, and the initial value should be read early;

(3) Arrange the points for verifying the design parameters at the most unfavorable position of the section and the design. the point is set up for guiding the construction to be arranged at the first construction position under the same working condition, which purpose is to feedback information in time to facilitate the modification of the design and guide the construction;

(4) In the course of construction, the measuring points should avoid the influence of the construction. Once damaged, the measuring point should be added as soon as possible in the original position or as close as possible to the original position to ensure the continuity of the monitoring data of the measuring point;

(5) Three points should be taken into consideration for the location of the measuring points of surface deformation and building settlement: firstly, it can fully reflect the deformation characteristics of the target object; secondly, it is easy to use instruments to monitor and measure; thirdly, it is necessary to ensure that the measuring points are not easily damaged as much as possible, the measuring points of surrounding buildings are mainly arranged at the corners;

(6) Select representative crack monitoring, with at least 2 measuring points for each crack.

2.3.2 Layout of Measuring Points

According to the principle of measuring point arrangement, the arrangement of measuring points for crown settlement and clearance convergence of this project is shown in Fig. 2, in which measuring points 1 and 4 are used to measure crown settlement, and the measuring lines A, B, C are used to measure the horizontal convergence of measuring clearance.

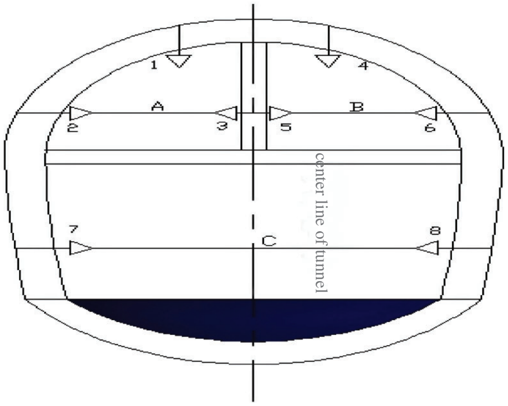
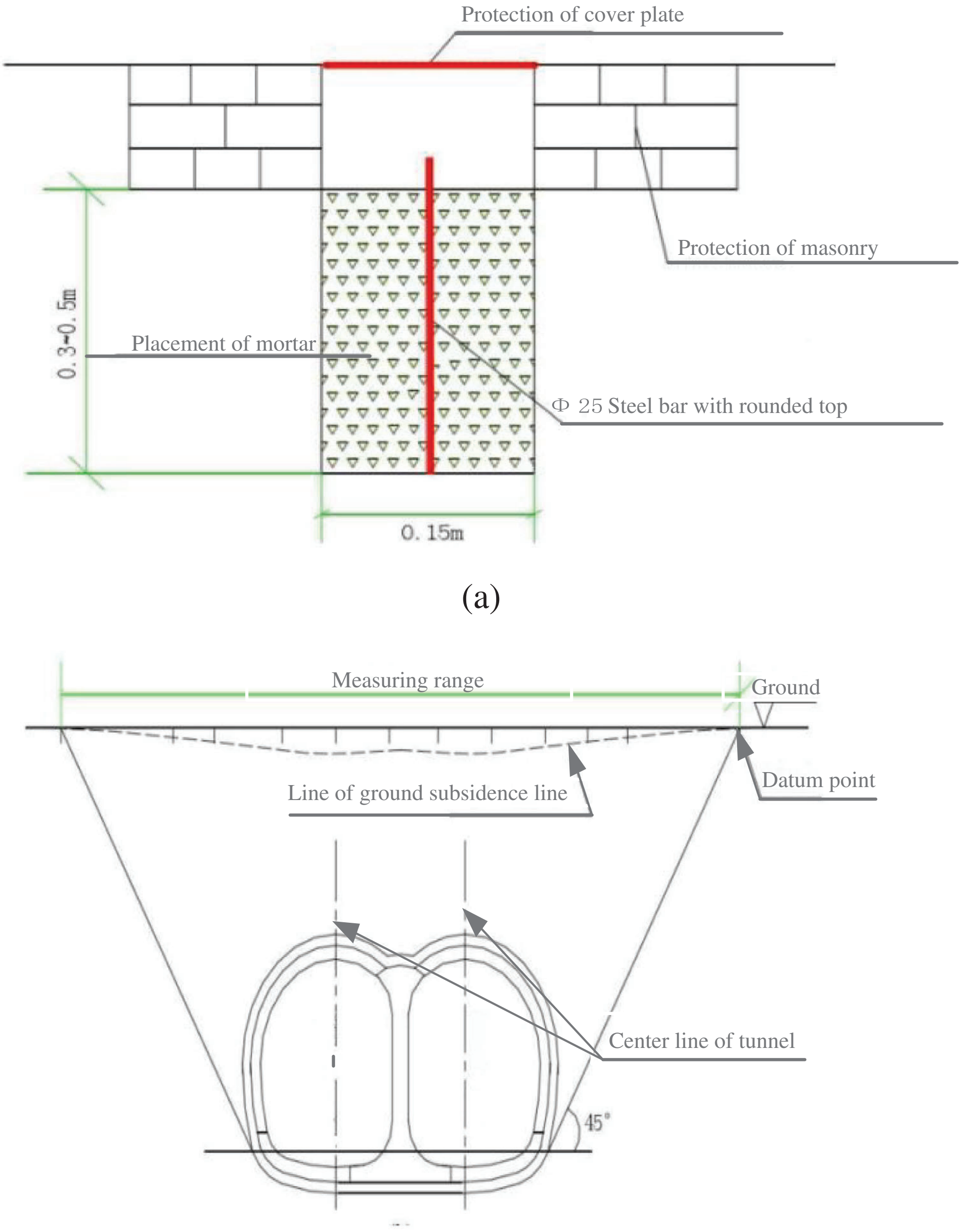


Figure 2: Point layout

Embedment of surface settlement measurement points: Before the tunnel excavation, the surface settlement observation points are buried in time. The specific measurement point arrangement rules are: the ground surface is set up a section every 20 meters along the longitudinal direction, each section is arranged for 10 measurement points, which are set on the tunnel axis and both sides and can be properly encrypted according to the needs. When burying, 20~50 cm deep hole is drilled on the surface by using the core-drilling machine, and the steel bar Φ 22~25 is vertically placed, and cement mortar can be filled between the steel bar and the hole wall, and the steel bars should be about 1 cm above the ground. As shown in Figs. 3a, 3b.

2.4 Setting of Alarm Value for Tunnel Construction

For the setting of the alarm value, according to the “Technical Regulations for Monitoring and Measurement of Railway Tunnels” (QCR 9218-2015) and the research results of Zhang et al. [20], combined with the actual situation of the site, he modified control value of the surrounding rock deformation is obtained, as shown in Table 3.



(a)

(b)

Figure 3: Survey points of surface subsidence

Table 3: Modified control value of surrounding rock deformation

Surrounding rock grade	III	IV	V-VI
Cumulative deformation/mm	60	80	100
Deformation rate/(mm/d)	5	5	10

2.5 Safeguard Measures

(1) Organizational preparation. Organizational preparation refers to the organizational safeguard activities for the implementation of risk early warning activities, which includes not only aquatinting emergency countermeasures for construction risk accidents, but also establishing and improving corresponding safety rules, regulations and standards to provide a secure organizational environment for the entire early warning management.

(2) Daily monitoring. The management activity of special third-party personnel monitoring the indicator system determined by the early warning analysis activity, which is the core of the early warning activities. These indicators are dangerous. Once a safety risk accident is induced, other disasters associated with it are likely to quickly cause uncontrollable dangerous situations, causing huge casualties and property losses. In addition, In addition, in daily monitoring, it is necessary to predict the possible outcome of the crisis and the severity of the accident after the spread of the accident as much as possible, so as to prevent problems before they occur.

(3) Emergency plan. The emergency plan mainly involves the emergency leading group, emergency plan, special rescue plan and emergency response measures, etc., which are the key to early warning activities. Once a risk accident occurs during tunnel construction and can be restored to a controllable state as soon as possible, the task of emergency management plan will be declared to be accomplished.

3 Construction Risk Evaluation

3.1 Risk Evaluation Index System

Based on the Technical Specification for Monitoring and Measurement of Railway Tunnels, and combined with the construction monitoring and measurement design plan of this project, the construction risk evaluation index system of CD-Bench composite method based on the monitoring method rely on the Changping section tunnel of Guanhui Intercity Subwayrisk warning indicator system for the CD-bench composite construction method in the Changping section of the Guanhui intercity is equationted, it contains the following five first-level indicators: geological and supporting condition, crown settlement, clearance convergence, ground settlement and building settlement, The complete index system is shown in Fig. 4. From Fig. 4, the following observations can be stated as:

(1) The geological and supporting conditions will seriously affect the construction safety. By monitoring the risk factors such as groundwater, initial branch cracks, surrounding rock characteristics, state of seepage and fault fracture zone, and their quantitative values are determined according to the quantitative rules of qualitative indicators, in order to the risk level of geological and supporting condition can be evaluated.

(2) Crown settlement, refers to the absolute settlement (quantity) of the tunnel crown measuring point, is a key indicator that characterizes the level of risk during the construction phase. Through the measurement of the absolute settlement and settlement rate of the vault measurement points, it will pave the way for the overall risk assessment.

(3) The change of the relative position between two points in the tunnel is characterized by the clearance convergence value. Therefore, by measuring the absolute convergence value and convergence rate of this indicator, which also is a key indicator to evaluate the risk status.

(4) As urban subway tunnel construction generally causes surface settlement, the measurement of the absolute settlement and settlement rate of the surface measurement points, which can reflect the level of surrounding rock, the quality of the construction level, and the magnitude of the risk to a certain extent.

(5) During underground construction, it is inevitable that the displacement and settlement of the building (construction) within a certain range, which may cause danger to existing buildings (structures), so by measuring their absolute settlement and settlement rate can also reflect the risks in the construction phase.

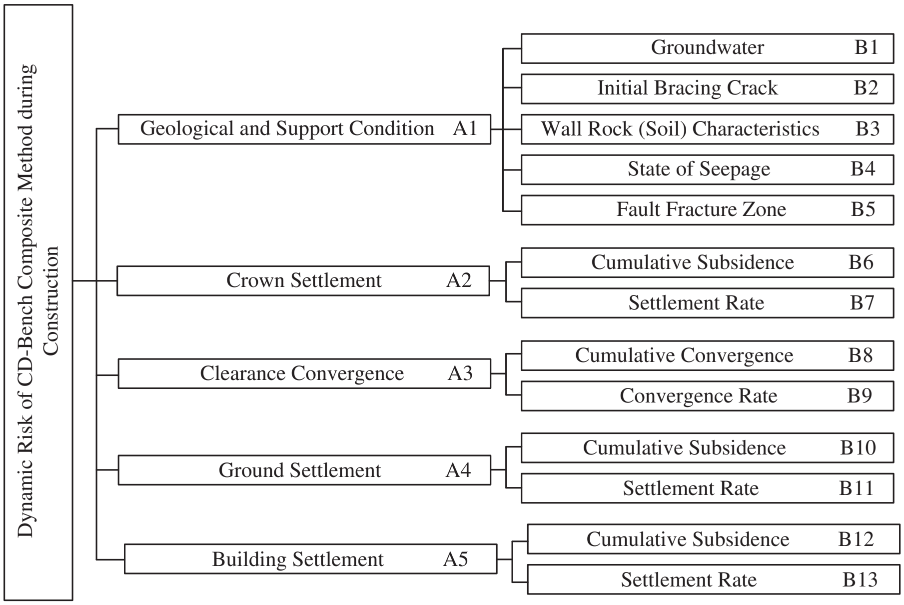


Figure 4: Construction risk-warning index system of CD-bench composite method

3.2 Extension Theory

Researcher Cai Wen, a Chinese scholar, created a new subject—Extension, which assumes that the name of the thing is denoted as N, the feature is denoted as C, and the value is denoted as V, and the ordered triple group $R = (N, C, V)$ is used to describe the basic matter element of things, the specific calculation steps [21] are as follows.

3.2.1 Determine of Classical Domain

According to the extension theory, classical domain is expressed as in Eq. (1):

$$
\begin{aligned}
R_j = (N_j,\ C_i,\ V_{ij}) &= \begin{bmatrix} N_j & C_1 & v_{1j} \\ & C_2 & v_{2j} \\ & \vdots & \vdots \\ & C_n & v_{nj} \end{bmatrix} \\
&= \begin{bmatrix} N_{0j} & C_1 & (a_{1j},\ b_{1j}) \\ & C_2 & (a_{2j},\ b_{2j}) \\ & \vdots & \vdots \\ & C_n & (a_{nj},\ b_{nj}) \end{bmatrix}
\end{aligned} \tag{1}
$$

where: R_j represents an matter element, N_j represents the jth evaluation index, namely the event described in the classical domain, C_i represents the i th discriminant index, and $V_{ij} = (a_{ij},\ b_{ij})$ represents the classical domain, that is, the range of values specified by the category N_j on the discriminant index C_i.

3.2.2 Determine the Controlled Domain

The controlled domain is expressed as in Eq. (2):

$$R_p = (P,\ C_i,\ V_{pi}) = \begin{bmatrix} P & C_1 & v_{p1} \\ & C_2 & v_{p2} \\ & \vdots & \vdots \\ & C_n & v_{pn} \end{bmatrix} = \begin{bmatrix} P & C_1 & (a_{p1},\ b_{p1}) \\ & C_2 & (a_{p2},\ b_{p2}) \\ & \vdots & \vdots \\ & C_n & (a_{pn},\ b_{pn}) \end{bmatrix} \tag{2}$$

where: P represents the whole of the evaluation category; V_{pi} represents the controlled domain of P, that is, the range of all values of P with respect to its discriminant index C_i.

3.2.3 Determine of Matter Element to be Evaluated

For things T to be evaluated, the collected data is expressed in the form of objects, that is, the matter element to be evaluated R, which is expressed as:

$$R = (T,\ C_i,\ X_i) = \begin{bmatrix} T & C_1 & X_1 \\ & C_2 & X_2 \\ & \vdots & \vdots \\ & C_n & X_n \end{bmatrix} \tag{3}$$

where: The X_i is the value of the evaluation index T on the discrimination index the C_i, that is, the actual data of the matter element to be evaluated.

3.2.4 Determination of Correlation Degree

The correlation degree of the i-th single evaluation index to the j-th category level of the matter element to be evaluated can be expressed as:

$$K_j(X_i) = \begin{cases} \dfrac{-\rho(X_i,\ V_{ij})}{|V_{ij}|},\ X_i \in V_{ij} \\ \dfrac{\rho(X_i,\ V_{ij})}{\rho(X_i,\ V_{pi}) - \rho(X_i,\ V_{ij})},\ X_i \notin V_{ij} \end{cases} \tag{4}$$

where:

$$\rho(X_i,\ V_{ij}) = \left| x_i - \frac{a_{ij}+b_{ij}}{2} \right| - \frac{b_{ij}-a_{ij}}{2};\ \ \rho(X_i,\ V_{pi}) = \left| x_i - \frac{a_{pi}+b_{pi}}{2} \right| - \frac{b_{pi}-a_{pi}}{2} \tag{5}$$

3.3 Determination of Weights

The scientific level of weight directly affects the objectivity of the calculation results of the whole evaluation model. At present, the method of subjective and objective combination weighting is channeled into solving the weight problem, which leads to the favorable results have been achieved in practical applications. Therefore, this paper uses entropy method and improved analytic hierarchy process to determine the subjective and objective weight separately, and then introduce the distance function to combine the subjective and objective weights, and then determine the weight value of each evaluation index.

3.3.1 Entropy Method

Set m evaluation grade and n evaluation index to form a matrix $R = (K_j(X_i))_{m\times n}$, where the $K_j(X_i)$ is the correlation degree of the i-th evaluation index under the j-th evaluation grade, and the weight of each index as follows:

$$w_i = \frac{1 - k\sum_{j=1}^{m} P_j(X_i)\cdot \ln P_j(X_i)}{\sum\left(1 - k\sum_{i=1}^{m} P_j(X_i)\cdot \ln P_j(X_i)\right)} \tag{6}$$

where:

$$k = \frac{1}{\ln m};\ \ P_j(X_i) = \frac{1 - K_j(X_i)}{\sum_{j=1}^{m}\left(1 + K_j(X_i)\right)} \tag{7}$$

3.3.2 Improved Analytic Hierarchy Process (IAHP)

In order to facilitate the comparison of indicators, this paper selects the improved three-scale analytic hierarchical process [22].

(1) Establishment of a cluster judgment matrix

Based on the construction risk-warning index system of CD-Bench composite method which has been established, First, according to the “0”, “1”, and “2” three-level scale method, the relevant experts are asked to compare the importance of the same level indicators in pairs, and the feedback situation is handled by the cluster method; Secondly, To report back the processed results to the experts and ask the experts to re-mark. Finally, we re-feedback the index importance scale to the experts. After three rounds of consultation, if the opinions of the experts tend to be unified, we will take the last round group judgment matrix as the final result of the evaluation index system and enter the next analysis process.

Where, the cluster judgement matrix is to process the scores of the experts on the same index according to the following mathematical treatment:

$$x_{ij} = \frac{H + 4m + L}{6} \tag{8}$$

where: m is the average value of all experts’ scores for a certain evaluation index; and H is the average value of scores higher than m; and L is the average value of scores lower than m.

Finally, after mathematical processing, the group judgment matrix A can be obtained:

$$\begin{array}{ccccc} A & C_1 & C_2 & C_3 & C_m \\ C_1 & x_{11} & x_{12} & \cdots & x_{1m} \\ C_2 & x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_m & x_{m1} & x_{m2} & \cdots & x_{mm} \end{array} \tag{9}$$

(2) Converting comparison matrix A into judgement matrix D

$$d_{ij} = 9^{(r_i - r_j)/R} \tag{10}$$

$$R = \max\{r_1, r_2, \ldots, r_n\} - \min\{r_1, r_2 \ldots r_n\} \tag{11}$$

$$r_i = \sum_{j=1}^{n} x_{ij}\, i = 1, 2, \ldots, n \tag{12}$$

where: the r_i is the importance coefficient of each element of the matrix A.

(3) Calculate the arithmetic mean of all elements in each row of the judgment matrix D and normalize to obtain the weight

$$\overline{w_i} = \frac{1}{m}\sum_{j=1}^{m} d_{ij} \tag{13}$$

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{m} \overline{w_i}} \tag{14}$$

(4) Consistency testing

1) Calculate the consistency index *CI*:

$$CI = \frac{\lambda_{\max} - m}{m - 1} \tag{15}$$

$$\lambda_{\max} = \sum_{i=1}^{m} \frac{(Dw)_i}{m w_i} \tag{16}$$

where: $(Dw)_i$ is the ith index of vector DW, and m is the order of the judgment matrix.

2) Find the corresponding average random consistency index RI (Table 4)

3) Calculation consistency ratio

$$CR = \frac{CI}{RI} \tag{17}$$

Table 4: The average random consistency index RI

n	1	2	3	4	5	6
RI	0	0	0.52	0.89	1.12	1.26

When $CR \leqq 0.10$, the judgment matrix has satisfactory consistency; Otherwise, the judgment matrix needs to be re-calculated until the consistency requirement is met.

3.3.3 Combined Weight

Suppose the subjective weight is w_{sj}, the objective weight is w_{oj}, the combined weight is w_{zj}, its expression [23] as:

$$w_{zj} = \alpha w_{sj} + \beta w_{oj} \tag{18}$$

where: α, β represent the distribution coefficients of the two weights, respectively, which can be obtained from Eq. (19):

$$\begin{cases} d(w_{sj},\ w_{oj}) = \left[\dfrac{1}{2} \sum_{j=1}^{n} (w_{sj} - w_{oj})^2 \right]^{\frac{1}{2}} \\ d(w_{sj},\ w_{oj})^2 = (\alpha - \beta)^2 \\ \alpha + \beta = 1 \end{cases} \tag{19}$$

3.4 Comprehensive Evaluation

3.4.1 Membership Matrix of First-Degree Indicators

By multiplying the comprehensive weight vector w_{ij} of the second level index with the correlation degree $K_j(X_i)$ of each risk grade, and it can be obtained the membership degree matrix A_k of the k th first-degree index for each risk grade, as shown in Eq. (20):

$$A_{kj} = \sum_{i=1}^{n} w_{ij} K_j(X_i) \tag{20}$$

where

$$\sum_{i=1}^{n} w_{ij} = 1 \tag{21}$$

3.4.2 Membership Matrix of Target Layer

Same as solving the first-level index risk membership matrix, the membership matrix of the target layer is shown as below:

$$A_j = \sum w_k \cdot A_{kj},\ \sum_{k=1}^{n} w_k = 1 \tag{22}$$

3.4.3 Identification of Risk Levels

If $K_j = \max{}_{j\in(1,2,\cdots,m)} K_j(T)$, then the warning level of the warning object is j, So Then, let j be the characteristic value of the risk level, as shown in the following equation:

$$K_j^*(T) = \frac{K_j(T) - \min_{j\in(1,2,\cdots,m)} K_j(T)}{\max_{j\in(1,2,\cdots,m)} K_j(T) - \min_{j\in(1,2,\cdots,m)} K_j(T)} \tag{23}$$

$$j^* = \frac{\sum_{j=1}^{m} j \cdot K_j^*(T)}{\sum_{j=1}^{m} K_j^*(T)} \tag{24}$$

4 Information Feedback of Early-Warning

4.1 Classification of Risk Levels

According to the principle of setting the alarm level and the construction risk characteristics of this type of weak surrounding rock section, the construction risk of this project is divided into five levels, which are shown in Table 5.

Table 5: Risk level table

Risk grade	Risk status	Treatment measures
5	High risk	Stop construction and take special control measures
4	Higher risk	Stop construction, reinforced support and measurement
3	Medium risk	Support should be reinforced
2	Low risk	Normal construction, pay more attention
1	Security	Normal construction

4.2 Five-Color Risk-Warning System

The five-color method is applied to set the alarm signal [24], as shown in Table 6.

Table 6: Five-color risk-warning system

Risk-warning grade	Definition	Indicator control
Red pre-warning	Especially urgent, it is suitable for large-scale roof collapse or mud burst, which will lead to a fatal safety accident and bring consequences of disaster	Both the rate and the cumulative absolute values of the measured deformation have reached the limit. And one of the following two situations occurs: the measured rate of settlement (or displacement) has increased rapidly, or cracks have appeared on the surface of the concrete of initial support, and started to seep water
Orange pre-warning	Emergency, suitable for local roof collapse or mud burst, which will cause major safety accidents and affect tunnel construction seriously	Both the rate and the accumulative absolute value of the measured deformation reach 85% ~100% of the limit value. Or one of the dual control indicators has reached the limit value and the other has not; Or the dual control indicators both reach the limit value, but the whole project has yet to show no signs of insecurity
Yellow pre-warning	More urgent, it is suitable for rock falling, water bursting, mud bursting or partial collapse. Although it will not cause major safety accidents, it will still affect the tunnel construction	Both the rate and the accumulative absolute value of the measured deformation reach 70% ~85% of the limit value, Or one of the dual control indicators reaches between 85%~ 100% of the limit value, and the other index has not yet reached
Blue pre-warning	General emergency, suitable for areas with a small amount of water flow or large deformation risk, which can induce collapse, but generally will not cause safety accidents and affect the tunnel construction	One of the rate and the accumulative absolute value of the measured deformation exceeds 70% of the control value, but the curve has no unstable trend yet
Green pre-warning	No need for measures	Security

4.3 Mapping Relationship

Let the value range of the dynamic risk index and risk-warning signal be the Ux and Uy respectively, f(x) represents a mapping from Ux to Uy, recorded as Y = f (x), and the mapping relationship between dynamic risk index and risk-warning signal is shown in Eq. (25).

5 Case Analysis

5.1 Criteria of Construction Risk Assessment

Refer to the research results of Zhang et al. [20], Liu et al. [25] and others, as well as *the Technical Specification for Monitoring and Measurement of Railway Tunnels*, and in order to facilitate the evaluation, the indicators are dimensionless processed: Crown settlement, clearance convergence, ground settlement, building settlement on the basis of domain measured data, and the cumulative value is the ratio of the cumulative measured value to the allowable value, and the rate is the ratio of the rate change value to the allowable value. The specific risk evaluation standards for each indicator are shown in Table 7. Then According to the actual situation of the project and consulting relevant experts with Site construction management personnel, the evaluation value of each indicator is shown in the last column of Table 7.

$$\begin{array}{ccc} U_x & & U_y \\ \begin{pmatrix} [4,\ 5] \\ [3,\ 4) \\ [2,\ 3) \\ [1,\ 2) \\ [0,\ 1) \end{pmatrix} & \xrightarrow{f(x)} & \begin{pmatrix} \text{Red pre} - \text{warning} \\ \text{Orange pre} - \text{warning} \\ \text{Yellow pre} - \text{warning} \\ \text{Blue pre} - \text{warning} \\ \text{Green pre} - \text{warning} \end{pmatrix} \end{array} \tag{25}$$

5.2 Determine the Extension Evaluation Matrix

(1) Taking the secondary index of the A_1 as an example, the classical domain R_1-R_5, the controlled domain R_P, and the matter element to be evaluated X_i be obtained by Eqs. (1) and (3), as shown in the following matrix:

$$\begin{bmatrix} C_i & R_1 & R_2 & R_3 & R_4 & R_5 & R_P & X_i \\ B_1 & (0,\ 0.15) & (0.15,\ 0.35) & (0.35,\ 0.55) & (0.55,\ 0.75) & (0.75,\ 1) & (0,\ 1) & 0.32 \\ B_2 & (0,\ 0.15) & (0.15,\ 0.35) & (0.35,\ 0.55) & (0.55,\ 0.75) & (0.75,\ 1) & (0,\ 1) & 0.34 \\ B_3 & (0,\ 0.15) & (0.15,\ 0.35) & (0.35,\ 0.55) & (0.55,\ 0.75) & (0.75,\ 1) & (0,\ 1) & 0.17 \\ B_4 & (0,\ 0.15) & (0.15,\ 0.35) & (0.35,\ 0.55) & (0.55,\ 0.75) & (0.75,\ 1) & (0,\ 1) & 0.30 \\ B_5 & (0,\ 0.15) & (0.15,\ 0.35) & (0.35,\ 0.55) & 0.55,\ 0.75 & (0.75,\ 1) & (0,\ 1) & 0.14 \end{bmatrix} \tag{26}$$

(2) Determine the degree of risk association

According to Eq. (4), the risk correlation degree of index B1-B5 is shown in matrix A1:

$$A_1 = \begin{bmatrix} -0.35 & 0.10 & -0.09 & -0.42 & -0.57 \\ -0.36 & 0.03 & -0.03 & -0.38 & -0.55 \\ -0.11 & 0.13 & -0.51 & -0.69 & -0.77 \\ -0.33 & 0.20 & -0.14 & -0.45 & -0.60 \\ 0.08 & -0.07 & -0.60 & -0.75 & -0.81 \end{bmatrix} \tag{27}$$

Table 7: Criteria of construction risk assessment

Indicators		Construction risk evaluation grade						X_i
			1	2	3	4	5	
A1	B1	Description	waterless	Leakage	Dripping water	Gushing water	Flowing water	
		Rating values	0~0.15	0.15~0.35	0.35~0.55	0.55~0.75	0.75~1	0.32
	B2	Description	None	Microstructure	Weaknesses	Strong	Drama	
		Rating values	0~0.15	0.15~0.35	0.35~0.55	0.55~0.75	0.75~1	0.34
	B3	Description	Stability	basically stable	Poor local stability	Instability	Extremely unstable	
		Rating values	0~0.15	0.15~0.35	0.35~0.55	0.55~0.75	0.75~1	0.17
	B4	Description	waterless	mild	Medium	Severe	overall water gushing	
		Rating values	0~0.15	0.15~0.35	0.35~0.55	0.55~0.75	0.75~1	0.30
	B5	Description	None	Tensional	Less	More	Broken	
		Rating values	0~0.15	0.15~0.35	0.35~0.55	0.55~0.75	0.75~1	0.14
A2	B6 (%)	Measured values	0~60	60~70	70~80	80~90	90~100	
		Dimensionless processing	0~0.60	0.60~0.70	0.70~0.80	0.80~0.90	0.90~1	0.78
	B7 (mm/d)	Measured values	0~1	1~2	2~3	3~5	5~10	
		Dimensionless processing	0~0.10	0.10~0.20	0.20~0.30	0.30~0.50	0.50~1	0.31
A3	B8 (%)	Measured values	0~60	60~70	70~80	80~90	90~100	
		Dimensionless processing	0~0.60	0.60~0.70	0.70~0.80	0.80~0.90	0.90~1	0.81
	B9 (mm/d)	Measured values	0~1	1~2	2~3	3~5	5~10	
		Dimensionless processing	0~0.10	0.10~0.20	0.20~0.30	0.30~0.50	0.50~1	0.25
A4	B10 (%)	Measured values	0~60	60~70	70~80	80~90	90~100	
		Dimensionless processing	0~0.60	0.60~0.70	0.70~0.80	0.80~0.90	0.90~1	0.85
	B11 (mm/d)	Measured values	0~1	1~2	2~3	3~5	5~10	
		Dimensionless processing	0~0.10	0.10~0.20	0.20~0.30	0.30~0.50	0.50~1	0.22
A5	B12 (%)	Measured values	0~60	60~70	70~80	80~90	90~100	
		Dimensionless processing	0~0.60	0.60~0.70	0.70~0.80	0.80~0.90	0.90~1	0.77
	B13 (mm/d)	Measured values	0~1	1~2	2~3	3~5	5~10	
		Dimensionless processing	0~0.10	0.10~0.20	0.20~0.30	0.30~0.50	0.50~1	0.13

5.3 Determine the Index Weight

5.3.1 Determination of Objective Weight Based on Entropy Weight

It can be obtain according to Eq. (5):

m = 5, *k = 0.621*, *R* = A_1 (as above)

Then the objective weight of B1–B5 is calculated as:

Table 8: Weight of risk early warning indicators

Index	A1	A2	A3	A4	A5	B1	B2	B3	B4
Subjective weight	0.49	0.14	0.26	0.05	0.06	0.20	0.21	0.24	0.15
Objective weight	0.42	0.20	0.21	0.07	0.10	0.20	0.22	0.20	0.20
Combination weight	0.46	0.17	0.24	0.06	0.08	0.20	0.21	0.22	0.17
Index	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**
Subjective weight	0.20	0.25	0.75	0.25	0.75	0.25	0.75	0.25	0.75
Objective weight	0.19	0.40	0.60	0.40	0.60	0.40	0.60	0.40	0.60
Combination weight	0.20	0.32	0.68	0.32	0.68	0.32	0.68	0.32	0.68

$W_1 = 0.20 \ldots W_5 = 0.19$. The specific calculation results are shown in Table 8.

5.3.2 Determination of Subjective Weights Based on IAHP

$$A = \begin{bmatrix} A_1 & B_1 & B_2 & B_3 & B_4 & B_5 \\ B_1 & 1 & 2 & 2 & 2 & 2 \\ B_2 & 0 & 1 & 0 & 2 & 2 \\ B_3 & 0 & 2 & 1 & 2 & 2 \\ B_4 & 0 & 0 & 0 & 1 & 1 \\ B_5 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{28}$$

Take the first-level indicator layer as an example, according to Eqs. (8)–(17), its comparison matrix A is shown above, and the judgment matrix D is as follows:

$$D = \begin{bmatrix} A_1 & B_1 & B_2 & B_3 & B_4 & B_5 & \overline{w_i} & w_i \\ B_1 & 1 & 3.510 & 1.873 & 9 & 9 & 4.877 & 0.49 \\ B_2 & 0.285 & 1 & 0.534 & 2.564 & 2.564 & 1.389 & 0.14 \\ B_3 & 0.534 & 1.873 & 1 & 4.804 & 4.804 & 2.603 & 0.26 \\ B_4 & 0.111 & 0.390 & 0.208 & 1 & 1 & 0.542 & 0.05 \\ B_5 & 0.111 & 0.390 & 0.208 & 1 & 1 & 0.542 & 0.06 \end{bmatrix} \tag{29}$$

Find out $\lambda_{\max} = 5.461$, $CI = 0.115$, $CR = 0.100$, so it meets the consistency check requirements.

5.3.3 Determining the Combination Weight

The obtained objective weight and subjective weight are brought into Eq. (19), get $\alpha = 0.523$, $\beta = 0.477$, and then take these two combination coefficient into Eq. (18) to obtain the combined weight of each indicator, as shown in Table 8.

It can be observed from Table 8 that the weight values of the five first-order indicators affecting construction risk of CD-Bench composite method are as follows: geological and supporting condition observation > clearance convergence > Crown settlement > building settlement > ground settlement, and the contribution to the overall risk decreases sequentially. In the secondary indicators, the weight values of groundwater, initial bracing crack, wall rock (soil) Characteristics, state of seepage and fault fracture zone are approximately equal, which indicates that their contribution to the risk of its upper level indicator is equal. And their second-level index, the weight value of rate value is much larger than the accumulative value, which indicates that it is essential to increase the monitoring frequency appropriately. It also show that the calculation results of weight value is consistent with objective reality.

5.4 Identification of Risk Grade

5.4.1 Determine the Membership Degree of the First-Level Indicators

According to Eq. (20), the membership matrix is:

$$\begin{aligned} A_1 &= \sum_{i=1}^{5} W_{1j} K_j(X_i) \\ &= (0.20,\ 0.21,\ 0.22,\ 0.17,\ 0.20) \\ &\quad \cdot \begin{bmatrix} -0.35 & 0.1 & -0.09 & -0.42 & -0.57 \\ -0.36 & 0.03 & -0.03 & -0.38 & -0.55 \\ -0.11 & 0.13 & -0.51 & -0.69 & -0.77 \\ -0.33 & 0.20 & -0.14 & -0.45 & -0.60 \\ 0.08 & -0.07 & -0.60 & -0.75 & -0.81 \end{bmatrix} \\ &= (-0.2099,\ 0.0749,\ -0.2803,\ -0.5421,\ -0.6629) \end{aligned} \tag{30}$$

The membership degree of other first-level indicators can be obtained in the same method.

5.4.2 Determine the Membership Degree of the Target Layer

According to Eq. (22), the membership matrix of the target layer is:

$$\begin{aligned} A &= (0.46,\ 0.17,\ 0.24,\ 0.06,\ 0.08) \\ &\quad \cdot \begin{bmatrix} -0.2099 & 0.0749 & -0.2803 & -0.5421 & -0.6629 \\ -0.4150 & -0.2630 & 0.0090 & -0.0030 & -0.3710 \\ -0.4280 & -0.2340 & 0.1540 & -0.0964 & -0.4424 \\ -0.4396 & -0.2144 & -0.0120 & -0.0236 & -0.4608 \\ -0.2668 & 0.1304 & -0.1900 & -0.4260 & -0.6184 \end{bmatrix} \\ &= (-0.3175,\ 0.0688,\ -0.1064,\ -0.3085,\ -0.5513) \end{aligned} \tag{31}$$

Get: K1(T) = −0.3175; K2(T) = −0.0688; K3(T) = −0.1064; K4(T) = −0.3085; K5(T) = −0.5513.

5.4.3 Identification of Risk Grade

It can be get accord to Eq. (23):

$$K_1^*(T) = \frac{-0.3175 - (-0.5513)}{-0.0688 - (-0.5513)} = 0.4846 \quad \begin{matrix} K_2^*(T) = 1.0000; & K_3^*(T) = 0.9221; \\ K_4^*(T) = 0.5032; & K_5^*(T) = 0; \end{matrix} \tag{32}$$

The risk grade characteristic value (j^*):

$$\begin{aligned} j^* &= \frac{1 \times 0.4846 + 2 \times 1 + 3 \times 0.9221 + 4 \times 0.5032 + 5 \times 0}{0.4846 + 1 + 0.9221 + 0.5032 + 0} \\ &= 2.50 \end{aligned} \tag{33}$$

By substituting the daily measurement data into the construction risk-warning model established in this paper, it can be getting that risk grade characteristic value which reflects the construction risks at this stage was 2.50. Thus the risk-warning signal of this evaluation is “yellow”, namely the construction risk is level 3, indicating that the phenomenon of local collapse and water and mud inrush have occurred at this time, which will affect the tunnel construction, but will not cause major accidents. Among the crown settlement rate, clearance convergence accumulation and ground subsidence accumulation are the higher risk sources, which are classified grade 4. And the vault settlement accumulation, clearance convergence rate, ground subsidence rate and building settlement accumulation are medium risks, which are classified grade 3. Therefore, the construction party should take corresponding emergency measures and safety schemes based on the above judgment.

5.5 Control Measures

According to the risk-warning results, the relevant units negotiated to change the original design and construction plan, as follows:

(1) Long anchors are added to the crown. Due to the relatively complex construction force at the crown, and the phenomenon of deformation exceeding the alarm value is particularly frequent. In order to control the further development of the risk unit at this location, it is recommended to add long anchors to the top of the tunnel arch in time.

(2) Increase the amount of deformation reserved. On the one hand, it can offset the large displacement generated by the initial support, release the in-situ stress to a large extent, and effectively prevent the problem of the exceeding the limit of initial support after the large deformation. On the other hand, it can reduce the load acting on the secondary lining, which is beneficial to the safety and stability of the tunnel structure. Therefore, it is recommended to adjust the reserved deformation of individual dangerous areas to 30–40 cm.

(3) Improve the rigidity of the supporting structure. According to the characteristics of deeper plastic zone and large damage range of soft rock tunnel, Measures should be taken to enlarge the steel frame, such as: the enlarged steel frame is adopted, the I-beam is adjusted from I20b to H175, longitudinal spacing is adjusted from the current 0.6 m to 0.5 m, and the large stiffness support system is sprayed with 30 cm-thick C25 concrete.

6 Conclusions

This paper relies on the Changping section tunnel of Guanhui Intercity Metro, a dynamic risk-warning model is established for the construction process of subway tunnel with the CD-Bench composite method. The following conclusions can be drawn:

(1) Due to the particularity and complexity of subway tunnel construction, most of the index systems established in previous studies are qualitative indexes and difficult to quantify. In the actual construction process, the deformation value can reflect the construction risk simply and directly. Therefore, based on this feature, this article equationtes a monitoring plan based on the monitoring specifications and the project characteristics, and establishes a risk evaluation index system on this basis, avoiding the difficulty of quantifying qualitative indicators. In addition, assigning different combination weights to each indicator and the mathematical model is used to calculate the risk value, which improves the one-sidedness and irrationality of evaluating construction risks based on deformation alone, and promotes scientific research on dynamic risk control.

(2) Among the four indexes of crown settlement, clearance convergence, ground settlement, and building settlement, clearance convergence has the greatest impact on construction safety risks. For their two secondary indicators, the rate of change is much greater than the cumulative change value contributing to the risk value of the upper indicator. Therefore, in actual construction, it is

necessary to appropriately increase the frequency of monitoring for poor geological conditions or abnormalities in monitoring data, and focus on the settlement value of clearance convergence.

(3) Through analysis and calculation, the initial construction risk characteristic value of this stage is 2.50, and the early warning signal is yellow, indicating that a major accident may occur at present, and control or rectification measures must be taken. For this reason, the construction unit recommends measures such as long anchors are added to the vault, increase the amount of deformation reserved and the stiffness of supporting structures and so on. After the calculation is performed again, the warning signal turns green, showing that the construction risk status at this stage is safe after taking these measures, indicating that these technologies can reduce the construction risk value and provide technical reference for similar projects.

In the future, we will continue to explore the applicability of dynamic risk-warning; the comparative analysis will also be conducted on different theoretical methods to achieve higher prediction accuracy.

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