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*Research article*

# Dynamic risk evaluation method of collapse in the whole construction of shallow buried tunnels and engineering application

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**Abstract:** The collapse is the most frequent and harmful geological hazard during the construction of the shallow buried tunnel, which seriously threatens the life and property safety of construction personnel. To realize the process control of collapse in the tunnel construction, a three-stage risk evaluation method of collapse in the whole construction process of shallow tunnels was put forward. Firstly, according to the engineering geology and hydrogeology information obtained in the prospecting stage, a fuzzy model of preliminary risk evaluation based on disaster-pregnant environment factors was proposed to provide a reference for the optimization design of construction and support schemes in the design stage. Secondly, the disaster-pregnant environment factors were corrected based on the obtained information, such as advanced geological forecast and geological sketch, and the disaster-causing factors were introduced. An extension theory model of secondary risk evaluation was established to guide the reasonable excavation and primary support schemes. Finally, the disaster-pregnant and disaster-causing factors were corrected according to the excavation condition, an attribute model of final risk evaluation for the collapse was constructed combined with the mechanical response index of the surrounding rock. Meanwhile, the risk acceptance criteria and construction decision-making method of the collapse in the shallow buried tunnels were formulated to efficiently implement the multi-level risk control of this hazard. The proposed method has been successfully applied to the Huangjiazhuang tunnel of the South Shandong High-Speed Railway. The comparison showed that the evaluation results are highly consistent for these practical situations, which verify the application value of this study for guiding the safe construction of shallow buried tunnels.

**Keywords:** shallow buried tunnel; collapse; dynamic evaluation; construction decision-making; application

## 1. Introduction

With the national strategies implementation of "one belt and one road", the construction of highway, railway, and other transportation facilities in China has entered a new period of development. Due to the extensive distribution of mountains and hills in China, tunnel engineering inevitably becomes an important part of transportation lines, and the increasing numbers of tunnels will be built [1]. Affected by complex geological conditions and backward investigation techniques, abrupt geological hazards often occur during tunnel construction [2]. Among them, the collapse is one of the most common geological hazards, which will lead to a series of severe results, including casualties, construction delay, and economic loss [3,4]. The collapse is particularly serious in the shallow buried tunnels.

In recent years, the risk evaluation theory and methods have been widely used in tunnels, slopes, and dams [5]. Since the risk concept was introduced into underground engineering [6], Nilsen et al. [7] adopted the Lichtenberg method to determine the occurrence probability of subsea tunnel accidents. Based on tunnel engineering, Sturk et al. [8] proposed the scheme decision procedure and risk assessment method to effectively reduce the possible security problem in the construction. Woude et al. [9] established a risk control and avoidance method in the design and construction stages based on the Betuweroute tunnel, which was applied in each construction process. The Guidelines for Tunneling Risk Management published by the International Tunneling Association provided a set of reference standards and methods for risk management of tunnel engineering [10]. Choi et al. [11] systematically studied the whole process of risk management and established a relatively complete risk assessment system of subway construction based on expert scoring method and fuzzy theory. Shin et al. [12] put forward a risk assessment model of tunnel collapse based on the measured data. Fera and Macchiraroli [13] analyzed the evolution of the temperature, the oxygen and CO concentrations, and the visibility computed by the tunnel fire CFD simulation, and proposed a fire risk evaluation method combining simulation results with experts' knowledge. Benekos and Diamantidis [14] provided a risk-cost-benefit optimization risk assessment approach based on the quantitative World Road Association's quantitative risk assessment model (QRAM) and QRAM risk acceptance criterion. The use of risk assessment in tunnel engineering projects is increasing [15].

In China, the research on risk management of tunnel engineering is relatively late [16,17]. For the construction scale and safety accidents of tunnels are greatly increased, some research achievements of risk management have been made. Considering the fuzzy uncertainty of the influencing factors of tunnel collapse, Chen et al. [18] used the fuzzy analytic hierarchy process risk evaluation model to assess the collapse risk of the Qinggangshan tunnel. On this basis, Zhai et al. [19] considered the nonlinear characteristics of influencing factors on tunnel collapse and established a nonlinear fuzzy risk evaluation method for tunnel collapse based on entropy weight. Yuan et al. [20] selected 8 main factors as risk assessment indexes through analyzing nearly 300 tunnel collapse cases and established a tunnel collapse risk assessment model based on catastrophe theory. Gao et al. [21] determined 7 controlling factors of tunnel collapse as evaluation indexes and established a comprehensive risk evaluation model based on entropy weight and grey relational degree. Because some factors are unnecessary or redundant, and the weight determination of the evaluation index relies on expert experience and subjective assignment, Chen et al. [3] proposed a risk evaluation model of mountain tunnel collapse based on rough set and conditional information entropy. Ou et al. [22] selected 11 influencing factors as risk evaluation indices after analyzing the typical tunnel collapse cases and put forward a risk assessment method of tunnel collapse based on D-S evidence theory. Li et al. [23,24] proposed an attribute recognition model of tunnel collapse based on attribute mathematical theory. Wang et al. [25,26] presented a dynamic attribute synthetic risk assessment method involving primary assessment before the excavation and second assessment between excavation and support, and developed the Mountain Tunnel Collapse Risk Assessment System. In addition, there are set pair analysis [27,28], cloud model [29,30], extension theory [31,32], efficacy coefficient method [33], machinery method [34] which has also been applied to risk evaluation of tunnel collapse.

The tunnel collapse is mainly caused by poor geological conditions, unreasonable construction and support parameters, so the risk runs through the investigation stage, design stage, and construction stage. However, the current risk assessment was used during the tunnel construction stage and conducted for the tunnel portal section or a complex geological section. There are few studies on the collapse risk evaluation of whole tunnel and multi-level risk management methods, which are conducive to the control of tunnel collapse during construction. Zhou et al. [35] established a dynamic risk assessment method of tunnel collapse including the static evaluation and dynamic evaluation based on fuzzy analytic hierarchy process. The dynamic risk assessment of tunnel collapse is only carried out in the construction stage, and the applicability of evaluation models is different in different stages. Aiming at the above limitations, a dynamic risk evaluation method of shallow tunnel collapse during the whole construction was established involving preliminary evaluation based on disaster-pregnant environment factors, secondary evaluation based on disaster-causing factors, and dynamic evaluation based on the mechanical response. This proposed method has been successfully applied to the Huangjiazhuang tunnel of the south Shandong high-speed railway.

## 2. Dynamic risk evaluation method of tunnel collapse

The collapse usually occurs after the surrounding rock excavation of construction stage. The engineering geology and hydrogeology conditions along the tunnel are explored at the prospecting stage. And the information of section size, construction scheme, and support parameters is determined at design stage. However, the unknown geological conditions and unreasonable design parameters are important influencing factors that cause the tunnel collapse. Therefore, a three-stage risk evaluation method of tunnel collapse in the whole construction cycle was proposed. At first, after the geological conditions are explored in prospecting stage, a preliminary risk evaluation model based on disaster-pregnant environment factors is presented, and its evaluation results are used to provide a reference for reasonable design parameters determination. Secondly, the disaster-pregnant environment factors are corrected and the disaster-causing factors are quantitatively analyzed according to the advanced geological exploration, the geological sketch, and the prepared excavation and support scheme before the surrounding rock excavation of working face, then a secondary risk evaluation is carried out based on the disaster-causing factors and corrected disaster-pregnant environment factors to provide a reference for improving the excavation and support parameters. Finally, the disaster-pregnant and disaster-causing factors are corrected according to the exposing geological condition and construction information, a dynamic risk evaluation model based on the mechanical response, corrected disaster-pregnant and disaster-causing factors were established to provide a reference for strengthening the support parameters. The collapse of shallow buried tunnels during the whole construction can be effectively controlled by multi-level risk management. The detailed evaluation process is shown in Figure 1.

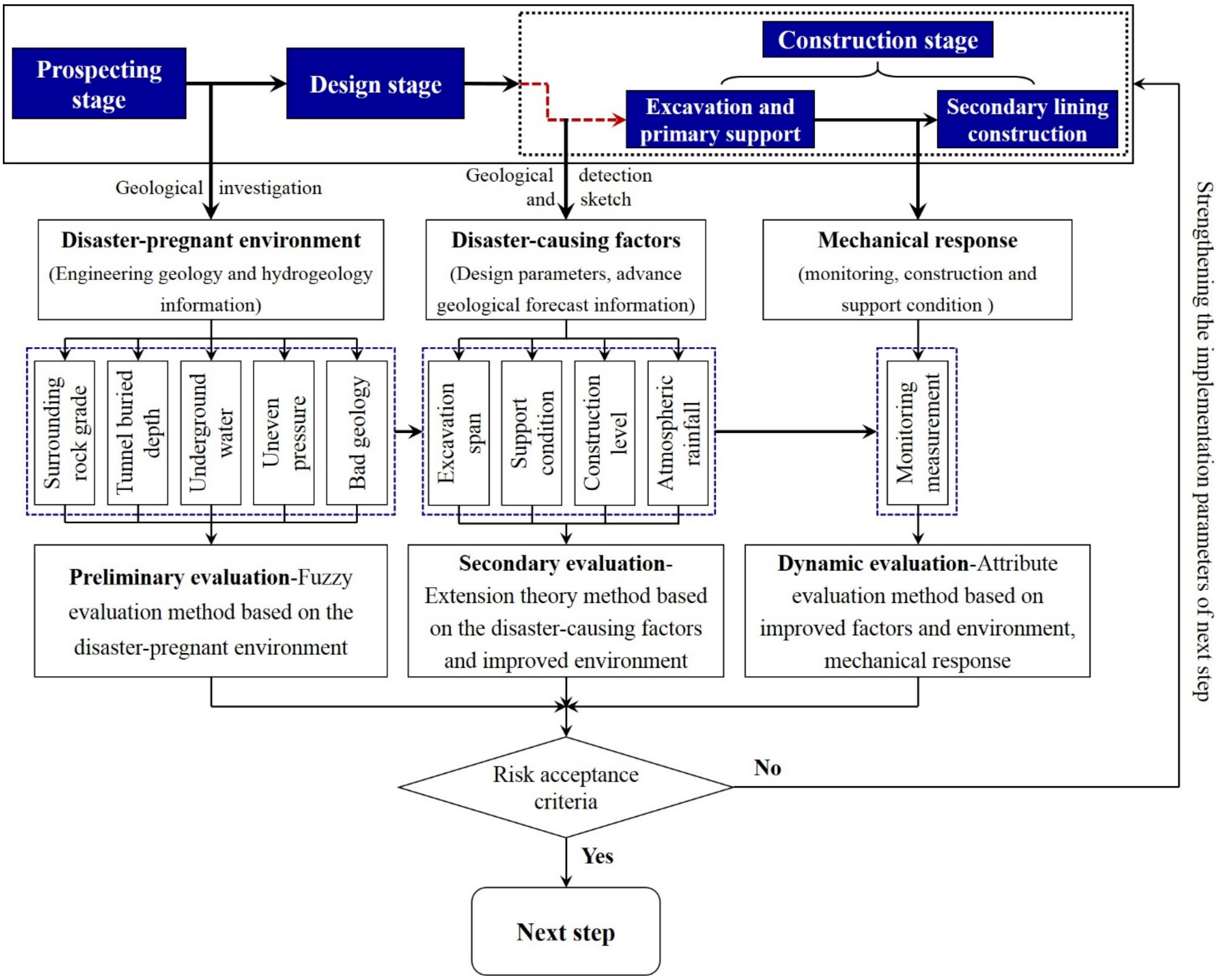


**Figure 1.** Three-stage risk evaluation of collapse in the whole construction of shallow buried tunnels.

## *2.1. Preliminary evaluation*

### 2.1.1. Index system of disaster-pregnant environment factors

The preliminary evaluation occurs between the prospecting stage and design stage. According to the statistical analysis of typical tunnel collapse cases [20,22,27], the surrounding rock grade, tunnel buried depth, underground water, uneven pressure, and bad geology were selected as the preliminary evaluation indexes. The occurrence probability and danger of tunnel collapse were analyzed, and every evaluation index was divided into very high risk ($C_1$), high risk ($C_2$), medium risk ($C_3$), and low risk ($C_4$). It is difficult to quantify the surrounding rock grade, groundwater, and bad geology, so the fuzzy language was adopted for the qualitative classification description of these three indexes. Based on the existing research results, the classification standard of disaster-pregnant environment factors was determined, as shown in Table 1.

**Table 1.** Classification standard of disaster-pregnant environment factors for tunnel collapse.

| Risk grade | Tunnel buried depth $I_1$ (m) | Surrounding rock level $I_2$ | Underground water $I_3$ | Uneven pressure angle $I_4$ (°) | Bad geology $I_5$ |
|---|---|---|---|---|---|
| $C_1$ | < 20 | V | Rich water-bearing, streamed water or gushing water in the tunnel wall | > 40 | Strong catatrophability |
| $C_2$ | 20~40 | IV | Developed groundwater, severe dripping water, or local small gushing water | 30~40 | Medium catatrophability |
| $C_3$ | 40~60 | III | Weakly developed groundwater, large amount of dripping water or linear water | 20~30 | Weak catatrophability |
| $C_4$ | > 60 | I、II | Dry tunnel wall or small amount of dripping water | < 20 | Slight catatrophability |

2.1.2. Fuzzy preliminary evaluation model

Due to the limitation of the existing investigation technology, the recognition of engineering geology and hydrogeology conditions is fuzzy and uncertain. Therefore, the fuzzy mathematics theory was used to establish the preliminary evaluation model.

(1) Fuzzy fusion operator

The fuzzy weighted averaging operator was adopted to calculate the comprehensive membership degree belonging to each risk grade. The integrated fuzzy judgment set $B$ is as follows:

$$B = W \bullet R = \left(w_1, w_2, \cdots, w_n\right) \bullet \begin{matrix} \\ I_1 \\ I_2 \\ \vdots \\ I_n \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_m \end{matrix} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \end{matrix} = \left( \sum_{i=1}^{n} r_{i1} w_i, \sum_{i=1}^{n} r_{i2} w_i, \cdots, \sum_{i=1}^{n} r_{im} w_i \right) \quad (1)$$

where $W = \{w_1, w_2, \cdots, w_n\}$ is the weight vector of evaluation indexes, $R = [r_{ij}]_{n\times m}$ is the fuzzy judgment matrix of single index determined by the membership function. $n$ and $m$ represent the number of evaluation indexes and risk grades respectively.

(2) The membership degree function

The most widely used half-trapezoidal function is used to establish the fuzzy membership relationship between the factor set and comment set based on Eqs (2)–(4).

$$r_{i1}(t)=\begin{cases}1 & t_i \le a_{i1}\\ \dfrac{a_{i2}-t_i}{a_{i2}-a_{i1}} & a_{i1}<t_i<a_{i2}\\ 0 & t_i \ge a_{i2}\end{cases} \quad (2)$$

$$r_{ij}(t_i)=\begin{cases}0 & t_i \le a_{ij-1}\\ \dfrac{t_i-a_{ij-1}}{a_{ij}-a_{ij-1}} & a_{ij-1}<t_i \le a_{ij}\\ \dfrac{a_{ij+1}-t_i}{a_{ij+1}-a_{ij}} & a_{ij}<t_i<a_{ij+1}\\ 0 & t_i \ge a_{ij+1}\end{cases} \quad (3)$$

$$r_{im}(t_i)=\begin{cases}0 & t_i \le a_{im-1}\\ \dfrac{t_i-a_{im-1}}{a_{im}-a_{im-1}} & a_{im-1}<t_i<a_{im}\\ 1 & t_i \ge a_{im}\end{cases} \quad (4)$$

where $a_{ij}$ and $r_{ij}$ represent the interval limit value and membership degree of $i$th evaluation index corresponding to $j$th risk grade respectively. $t_i$ is the measured value of $i$th evaluation index.

The membership degree functions of quantitative indexes can be obtained (Table 2). However, the Karwowski membership method (Table 3) was used to calculate the membership degree of surrounding rock $I_2$, groundwater $I_3$, and bad geology $I_5$.

**Table 2.** Membership function determination of preliminary evaluation indexes.

| Index | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| $I_1$ | $r_{11}=\begin{cases}1 & t_1\le 20\\ \frac{40-t_1}{20} & 20<t_1<40\\ 0 & t_1\ge 40\end{cases}$ | $r_{12}=\begin{cases}0 & t_1\le 20\\ \frac{t_1-20}{20} & 20<t_1\le 40\\ \frac{60-t_1}{20} & 40<t_1<60\\ 0 & t_1\ge 60\end{cases}$ | $r_{13}=\begin{cases}0 & t_1\le 40\\ \frac{t_1-40}{20} & 40<t_1\le 60\\ \frac{100-t_1}{40} & 60<t_1<100\\ 0 & t_1\ge 100\end{cases}$ | $r_{14}=\begin{cases}0 & t_1\le 60\\ \frac{t_1-60}{40} & 60<t_1<100\\ 1 & t_1\ge 100\end{cases}$ |
| $I_4$ | $r_{41}=\begin{cases}1 & t_4\ge 60\\ \frac{t_4-40}{20} & 40<t_4<60\\ 0 & t_4\le 40\end{cases}$ | $r_{42}=\begin{cases}0 & t_4\le 30\\ \frac{t_4-30}{10} & 30<t_4\le 40\\ \frac{60-t_4}{20} & 40<t_4<60\\ 0 & t_4\ge 60\end{cases}$ | $r_{43}=\begin{cases}0 & t_4\le 20\\ \frac{t_4-20}{10} & 20<t_4\le 30\\ \frac{40-t_4}{10} & 30<t_4<40\\ 0 & t_4\ge 40\end{cases}$ | $r_{44}=\begin{cases}0 & t_4\ge 30\\ \frac{30-t_4}{10} & 20<t_4<30\\ 1 & t_4\le 20\end{cases}$ |

**Table 3.** Karwowski fuzzy membership function.

| Fuzzy linguistic variable | Membership function | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Very big | 0.00 | 0.00 | 0.00 | 0.10 | 0.50 | 0.80 | 1.00 |
| Big | 0.00 | 0.00 | 0.10 | 0.30 | 0.70 | 0.90 | 1.00 |
| Average | 0.00 | 0.20 | 0.70 | 1.00 | 0.70 | 0.20 | 0.00 |
| Moderately small | 0.00 | 0.00 | 0.30 | 0.50 | 0.85 | 0.95 | 1.00 |
| Small | 1.00 | 0.90 | 0.70 | 0.30 | 0.10 | 0.00 | 0.00 |

#### 2.1.3. Determination of evaluation index weight

Whether the weights of the factors are reasonable will affect the accuracy of the evaluation results, so establishing an effective weight determination method is an important part of the evaluation model. The synthetic weighting method combining frequency statistics (FS) and analytic hierarchy process (AHP) is used to determine the evaluation index weights of tunnel collapse.

$$W = k_o W_o + k_s W_s \tag{5}$$

where $W_o$ and $W_s$ are the objective weight vector determined by FS and subjective weight vector calculated by AHP respectively. The $k_o$ and $k_s$ are the distribution coefficient of $W_o$ and $W_s$, and $k_o + k_s = 1$.

(1) Objective weight

Based on the domestic mountain tunnel collapse cases, the disaster-pregnant environment factors were counted by the FS. The $W_o$ vector was determined by normalization:

$$W_o = (I_1, I_2, I_3, I_4, I_5) = (0.078, 0.343, 0.252, 0.160, 0.167)$$

(2) Subjective weight

According to the obtained engineering geology and hydrogeology data, the relative importance among the disaster-pregnant environment factors was analyzed and the Saaty 1~9 scale method was used to construct the judgment matrix as shown in Table 4. The $W_s$ was calculated based on AHP.

**Table 4.** Judgment matrix of disaster-pregnant environment factors.

| Index | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $W_s$ |
|---|---|---|---|---|---|---|
| $I_1$ | 1 | 1/2 | 6 | 4 | 3 | 0.286 |
| $I_2$ | 2 | 1 | 8 | 6 | 5 | 0.479 |
| $I_3$ | 1/6 | 1/8 | 1 | 1/2 | 1/3 | 0.045 |
| $I_4$ | 1/4 | 1/6 | 2 | 1 | 1/2 | 0.074 |
| $I_5$ | 1/3 | 1/5 | 3 | 2 | 1 | 0.116 |

Note: meeting the consistency condition.

when $k_o = k_s = 0.5$, the comprehensive weight vector $W^1$ of the preliminary evaluation is as follows:

$$W^1 = (I_1, I_2, I_3, I_4, I_5) = (0.182, 0.411, 0.149, 0.117, 0.142)$$

### *2.2. Secondary evaluation*

#### 2.2.1. Index system of disaster-causing factors

The secondary evaluation occurs before the working face excavation of construction stage, in which the advanced geological forecast and geological sketch of the tunnel face are carried out. The understanding of disaster-pregnant environment factors is further improved and the collapse will be affected by the disaster-causing factors, such as the tunnel section size, excavation method, support parameter, and climate condition. Therefore, the excavation span, support condition, construction level, and atmospheric rainfall were selected as the disaster-causing evaluation indexes. Among them, the support condition, construction level, and atmospheric rainfall were qualitatively classified by the fuzzy language, as shown in Table 5.

**Table 5.** Classification standard of disaster-causing factors and mechanical response index for tunnel collapse.

| Risk grade | Excavation span $I_6$ (m) | Support design $I_7$ | Construction level $I_8$ | Atmospheric rainfall $I_9$ | Monitoring measurement $I_{10}$ |
|---|---|---|---|---|---|
| $C_1$ | > 15 | Extremely unreasonable | Poor construction technology and management level | Continuous heavy rain or short-term strong rainfall | Large deformation and fast deformation rate |
| $C_2$ | 12~15 | Unreasonable | Relatively poor construction technology and management level | Continuous moderate rain or short-term heavy rainfall | Relatively large deformation and fast deformation rate |
| $C_3$ | 10~12 | Reasonable | General construction technology and management level | Continuous light rain or short-term moderate rainfall | General deformation and deformation rate |
| $C_4$ | < 10 | Completely reasonable | Strong construction technology and management level | short-term light rainfall | Small deformation |

#### 2.2.2. Extension secondary evaluation model

Since the evaluation indexes have both quantitative and qualitative factors, and the factor information is between uncertainty and uncertainty, the extension theory was selected for the secondary evaluation of tunnel collapse. According to reference [36], the classical field, segment field matter elements, and the matter-element for appraising were determined.

The correlation function was introduced to represent the mapping relationship of evaluation indexes belonging to each risk level. The specific formula is as follows:

$$K_j(v_i)=\begin{cases}\dfrac{-\rho(v_i,v_{0ij})}{\left|v_{0ij}\right|}, v_i\in v_{0ij}\\ \dfrac{\rho(v_i,v_{0ij})}{\rho(v_i,v_{pi})-\rho(v_i,v_{0ij})}, v_i\notin v_{0ij}\end{cases} \tag{6}$$

$$\rho\left(v_i,v_{0ij}\right)=\left|v_i-\frac{a_{0ij}+b_{0ij}}{2}\right|-\frac{b_{0ij}-a_{0ij}}{2} \tag{7}$$

$$\left|v_{0ij}\right|=\left|b_{0ij}-a_{0ij}\right| \tag{8}$$

$$\rho\left(v_i,v_{pi}\right)=\left|v_i-\frac{a_{pi}+b_{pi}}{2}\right|-\frac{b_{pi}-a_{pi}}{2} \tag{9}$$

where $K_j(v_i)$ represents the correlation degree of evaluation index $I_i$ belonging to risk grade $C_j$. $v_{0ij}$ = [$a_{0ij}$, $b_{0ij}$] is the classical field of evaluation index $I_i$ belonging to risk grade $C_j$, $V_{pi}$ = [$a_{pi}$, $b_{pi}$] is the segment field of evaluation index $I_i$, $v_i$ is the measured value of evaluation index $I_i$. As the understanding of evaluation factors is further clarified at this stage, the qualitative indexes were quantitatively classified based on expert scoring method with 0-100 scale, which was divided into [0, 25], (25, 50], (50, 75] and (75, 100]. The higher the index score is, the greater the risk of tunnel collapse is. The correction degree functions of the secondary evaluation indexes are shown in Table 6.

The multi-index synthetic correlation degree can be calculated as follows:

$$K_j\left(N_k\right)=\sum_{i=1}^{n}w_iK_j\left(v_{ki}\right) \tag{10}$$

where $N_k$ represents $k$th evaluation object. The risk grade corresponding to the maximum correlation degree is selected as the most probable risk of tunnel collapse.

**Table 6.** Correlation function determination of secondary evaluation indexes.

| Index | $I_1$ | $I_4$ | $I_6$ | $I_2$, $I_3$, $I_5$, $I_7$~ $I_9$ |
|---|---|---|---|---|
| $\rho\left(v_i, v_{pi}\right)$ | $\lvert v_1-50\rvert-50$ | $\lvert v_1-40\rvert-40$ | $\left(\lvert v_1-10\rvert-10\right)$ | $\lvert v_1-50\rvert-50$ |
| $C_1$ | $K_{11}=\begin{cases} -\frac{\lvert v_1-10\rvert-10}{20} & v_1\in[0,20) \\ \frac{\lvert v_1-10\rvert-10}{\rho(v_1,v_{p1})-(\lvert v_1-10\rvert-10)} & v_1\notin[0,20) \end{cases}$ | $K_{41}=\begin{cases} -\frac{\lvert v_4-60\rvert-20}{40} & v_4\in(40,80] \\ \frac{\lvert v_4-60\rvert-20}{\rho(v_4,v_{p4})-(\lvert v_4-60\rvert-20)} & v_4\notin(40,80] \end{cases}$ | $K_{61}=\begin{cases} -\frac{\lvert v_6-17.5\rvert-2.5}{5} & v_6\in(15,20] \\ \frac{\lvert v_6-17.5\rvert-2.5}{\rho(v_6,v_{p6})-(\lvert v_6-17.5\rvert-2.5)} & v_6\notin(40,80] \end{cases}$ | $K_{i1}=\begin{cases} -\frac{\lvert v_i-87.5\rvert-12.5}{25} & v_i\in(75,100] \\ \frac{\lvert v_i-87.5\rvert-12.5}{\rho(v_i,v_{pi})-(\lvert v_i-87.5\rvert-12.5)} & v_i\notin(75,100] \end{cases}$ |
| $C_2$ | $K_{12}=\begin{cases} -\frac{\lvert v_1-30\rvert-10}{20} & v_1\in[20,40) \\ \frac{\lvert v_1-30\rvert-10}{\rho(v_1,v_{p1})-(\lvert v_1-30\rvert-10)} & v_1\notin[20,40) \end{cases}$ | $K_{42}=\begin{cases} -\frac{\lvert v_4-35\rvert-5}{10} & v_4\in(30,40] \\ \frac{\lvert v_4-35\rvert-5}{\rho(v_4,v_{p4})-(\lvert v_4-35\rvert-5)} & v_4\notin(30,40] \end{cases}$ | $K_{62}=\begin{cases} -\frac{\lvert v_6-13.5\rvert-1.5}{3} & v_6\in(12,15] \\ \frac{\lvert v_6-13.5\rvert-1.5}{\rho(v_6,v_{p6})-(\lvert v_6-13.5\rvert-1.5)} & v_6\notin(12,15] \end{cases}$ | $K_{i2}=\begin{cases} -\frac{\lvert v_i-62.5\rvert-12.5}{25} & v_i\in(50,75] \\ \frac{\lvert v_i-62.5\rvert-12.5}{\rho(v_i,v_{pi})-(\lvert v_i-62.5\rvert-12.5)} & v_i\notin(50,75] \end{cases}$ |
| $C_3$ | $K_{13}=\begin{cases} -\frac{\lvert v_1-50\rvert-10}{20} & v_1\in[40,60] \\ \frac{\lvert v_1-50\rvert-10}{\rho(v_1,v_{p1})-(\lvert v_1-50\rvert-10)} & v_1\notin[40,60] \end{cases}$ | $K_{43}=\begin{cases} -\frac{\lvert v_4-25\rvert-5}{10} & v_4\in[20,30] \\ \frac{\lvert v_4-25\rvert-5}{\rho(v_4,v_{p4})-(\lvert v_4-25\rvert-5)} & v_4\notin[20,30] \end{cases}$ | $K_{63}=\begin{cases} -\frac{\lvert v_6-11\rvert-1}{2} & v_6\in[10,12] \\ \frac{\lvert v_6-11\rvert-1}{\rho(v_6,v_{p6})-(\lvert v_6-11\rvert-1)} & v_6\notin[10,12] \end{cases}$ | $K_{i3}=\begin{cases} -\frac{\lvert v_i-37.5\rvert-12.5}{25} & v_i\in(25,50] \\ \frac{\lvert v_i-37.5\rvert-12.5}{\rho(v_i,v_{pi})-(\lvert v_i-37.5\rvert-12.5)} & v_i\notin(25,50] \end{cases}$ |
| $C_4$ | $K_{14}=\begin{cases} -\frac{\lvert v_1-80\rvert-20}{40} & v_1\in(60,100] \\ \frac{\lvert v_1-80\rvert-20}{\rho(v_1,v_{p1})-(\lvert v_1-80\rvert-20)} & v_1\notin(60,100] \end{cases}$ | $K_{44}=\begin{cases} -\frac{\lvert v_4-10\rvert-10}{20} & v_4\in[0,20) \\ \frac{\lvert v_4-10\rvert-10}{\rho(v_4,v_{p4})-(\lvert v_4-10\rvert-10)} & v_4\notin[0,20) \end{cases}$ | $K_{64}=\begin{cases} -\frac{\lvert v_6-5\rvert-5}{10} & v_6\in[0,10) \\ \frac{\lvert v_6-5\rvert-5}{\rho(v_6,v_{p6})-(\lvert v_6-5\rvert-5)} & v_6\notin[0,10) \end{cases}$ | $K_{i4}=\begin{cases} -\frac{\lvert v_i-12.5\rvert-12.5}{25} & v_i\in[0,25] \\ \frac{\lvert v_i-12.5\rvert-12.5}{\rho(v_i,v_{pi})-(\lvert v_i-12.5\rvert-12.5)} & v_i\notin[0,25] \end{cases}$ |

2.2.3. Weight determination of secondary evaluation

The objective weights of disaster-pregnant and disaster-causing factors were determined based on FS. Due to too many secondary evaluation indexes, the judgment matrix constructed based on AHP is prone to scale confusion. Therefore, the judgment matrix of disaster-causing factors was constructed based on AHP, and then the subjective weights of secondary evaluation indexes were calculated by proportional distribution. The comprehensive weights can be obtained (Table 7).

**Table 7.** Weight determination of secondary evaluation indexes.

| Weight type | | Value | |
|---|---|---|---|
| Objective weight | | $W_o^2$ = (0.073, 0.281, 0.182, 0.046, 0.091, 0.107, 0.031, 0.078, 0.110) | |
| Subjective weight | Judgment matrix | — | $\begin{bmatrix} 1 & 3 & 1 & 2 \\ 1/3 & 1 & 1/3 & 1/2 \\ 1 & 3 & 1 & 2 \\ 1/2 & 2 & 1/2 & 1 \end{bmatrix}$ |
| | Distribution coefficient | 0.6 | 0.4 |
| | Value | $W_s^2$ = (0.172, 0.287, 0.027, 0.044, 0.070, 0.140, 0.044, 0.140, 0.075) | |
| Comprehensive weight | | $W^2$ = (0.123, 0.284, 0.105, 0.045, 0.081, 0.124, 0.038, 0.109, 0.093) | |

*2.3. Dynamic evaluation*

2.3.1. Index system of the mechanical response

Under the combined action of excavation disturbance and stress release, the probability of tunnel collapse is very high before the secondary lining. There is the obvious mechanical response in the evolution process of collapse, the monitoring measurement is mainly used to monitor the deformation of surrounding rock. Therefore, the deformation response characteristics of surrounding rock were introduced as an index of dynamic evaluation. Meanwhile, the disaster-pregnant and disaster-causing factors are corrected again according to the exposed geological conditions, actual excavation, and support method. The classification standard of monitoring measurement was shown in Table 5. The expert scoring method with a 0~100 scale was adopted to quantify this index.

2.3.2. Attribute dynamic evaluation model

(1) Single-index attribute measure

The attribute measure function was used to establish the attribute relationship of evaluation indexes belonging to each risk level.

$$b_{ij} = \frac{a_{ij-1} + a_{ij}}{2} \tag{11}$$

$$d_{ij} = \min\left\{\left|b_{ij} - a_{ij}\right|, \left|b_{ij+1} - a_{ij}\right|\right\} \tag{12}$$

where $[a_{ij-1}, a_{ij}]$ is the attribute interval of evaluation index $I_i$ corresponding to risk grade $C_j$. The single-index attribute measure functions of $a_{i0} < a_{i1} < \cdots < a_{im}$ and $a_{i0} > a_{i1} > \cdots > a_{im}$ are referred to [26] and [36]. The functions of dynamic evaluation indexes were determined (Table 8).

(2) Multi-index synthetic attribute measure

$$\mu_j = \sum_{i=1}^{n} w_i \mu_{ij} \tag{13}$$

where $\mu_{ij}$ represents the attribute measure value of evaluation index $I_i$ corresponding to risk grade $C_j$. The risk grade is identified based on the confidence criterion, and the specific analysis method is referred to [36].

2.3.3. Weight determination of dynamic evaluation

Limited by the index number of mechanical responses, the comprehensive weight method is no longer applicable. To determine the accurate weights of evaluation indexes, the balance variable-weight function was adopted to calculate the comprehensive weights on basis of FS weights. The improved variable-weight formula is as follows:

$$w_i = w_i^{(0)} y_i^{a-1} / \sum_{i=1}^{m} (w_i^{(0)} y_i^{a-1}) \tag{14}$$

where $w_i^{(0)}$ represents the initial weight of $I_i$, $y_i$ represents the ratio of the measured value $t_i$ of $I_i$ to its upper limit value $b_{pi}$. $a$ is the control coefficient of variable weight types. When $0 \le a < 1$, $w_i$ is a punishing state variable weight; When $a > 1$, $w_i$ is an encouraging state variable weight; When $a = 1$, $w_i$ is constant. The initial weight vector was as follows:

$W^{(0)}$ = (0.067, 0.257, 0.166, 0.042, 0.084, 0.098, 0.028, 0.071, 0.101, 0.088)

*2.4. Risk regulation criteria*

The corresponding control measures were formulated to reduce the unacceptable risk to an acceptable range based on multi-stage risk evaluation results, which can realize effective risk avoidance. The risk regulation criteria are shown in Table 9.

**Table 8.** Attribute measure function determination of dynamic evaluation indexes.

| Index | $I_1$ | $I_4$ | $I_6$ | $I_2$, $I_3$, $I_5$, $I_7$~ $I_{10}$ |
|---|---|---|---|---|
| $C_1$ | $\mu_{11}=\begin{cases}1 & t_1<10\\ \frac{30-t_1}{20} & 10\le t_1\le 30\\ 0 & t_1>30\end{cases}$ | $\mu_{41}=\begin{cases}0 & t_4<35\\ \frac{t_4-35}{10} & 35\le t_4\le 45\\ 1 & t_4>45\end{cases}$ | $\mu_{61}=\begin{cases}0 & t_6<13.5\\ \frac{t_6-13.5}{3} & 13.5\le t_6\le 16.5\\ 1 & t_6>16.5\end{cases}$ | $\mu_{i1}=\begin{cases}0 & t_i<62.5\\ \frac{t_i-62.5}{25} & 62.5\le t_i\le 87.5\\ 1 & t_i>87.5\end{cases}$ |
| $C_2$ | $\mu_{12}=\begin{cases}0 & t_1<10\\ \frac{t_1-10}{20} & 10\le t_1\le 30\\ \frac{50-t_1}{20} & 30<t_1\le 50\\ 0 & t_1>50\end{cases}$ | $\mu_{42}=\begin{cases}0 & t_4<25\\ \frac{t_4-25}{10} & 25\le t_4\le 35\\ \frac{45-t_4}{10} & 35<t_4\le 45\\ 0 & t_4>45\end{cases}$ | $\mu_{62}=\begin{cases}0 & t_6<11\\ \frac{t_6-11}{2} & 11\le t_6<13\\ 1 & 13\le t_6\le 13.5\\ \frac{16.5-t_6}{3} & 13.5<t_6\le 16.5\\ 0 & t_6>16.5\end{cases}$ | $\mu_{i2}=\begin{cases}0 & t_i<37.5\\ \frac{t_i-37.5}{25} & 37.5\le t_i<62.5\\ \frac{87.5-t_i}{25} & 62.5\le t_i\le 87.5\\ 0 & t_i>87.5\end{cases}$ |
| $C_3$ | $\mu_{13}=\begin{cases}0 & t_1<30\\ \frac{t_1-30}{20} & 30\le t_1\le 50\\ \frac{70-t_1}{20} & 50<t_1\le 70\\ 0 & t_1>70\end{cases}$ | $\mu_{43}=\begin{cases}0 & t_4<15\\ \frac{t_4-15}{10} & 15\le t_4\le 25\\ \frac{35-t_4}{10} & 25<t_4\le 35\\ 0 & t_4>35\end{cases}$ | $\mu_{63}=\begin{cases}0 & t_6<9\\ \frac{t_6-9}{2} & 9\le t_6<11\\ \frac{13-t_6}{2} & 11\le t_6\le 13\\ 0 & t_6>13\end{cases}$ | $\mu_{i3}=\begin{cases}0 & t_i<12.5\\ \frac{t_i-12.5}{25} & 12.5\le t_i<37.5\\ \frac{62.5-t_i}{25} & 37.5\le t_i\le 62.5\\ 0 & t_i>62.5\end{cases}$ |
| $C_4$ | $\mu_{11}=\begin{cases}0 & t_1<50\\ \frac{t_1-50}{20} & 50\le t_1\le 70\\ 1 & t_1>70\end{cases}$ | $\mu_{44}=\begin{cases}1 & t_4<15\\ \frac{25-t_4}{10} & 15\le t_4\le 25\\ 0 & t_4>25\end{cases}$ | $\mu_{64}=\begin{cases}1 & t_6<9\\ \frac{11-t_6}{2} & 9\le t_6\le 11\\ 0 & t_6>11\end{cases}$ | $\mu_{i4}=\begin{cases}1 & t_i<12.5\\ \frac{37.5-t_i}{25} & 12.5\le t_i\le 37.5\\ 0 & t_i>37.5\end{cases}$ |

**Table 9.** Risk regulation criteria of tunnel collapse.

| Risk grade | | Acceptance criteria | Control measure | | |
|---|---|---|---|---|---|
| | | | Preliminary evaluation | Secondary evaluation | Dynamic evaluation |
| $C_1$ | Very high risk | Rejected | Strengthening support and construction design | Advanced reinforcement. Short footage, weak blasting, tough support, and early closing | Shutdown. High attention and taking strong measures based on expert judgment |
| $C_2$ | High risk | Unacceptable | Strengthening support design | Advanced reinforcement. Short footage, weak blasting, tough support, and early closing | Shutdown. Early warning and taking control measure |
| $C_3$ | Medium risk | Acceptable | — | Short footage, weak blasting, tough support, and early closing | Strengthening monitoring measurement |
| $C_4$ | Low risk | — | — | Strengthening advanced exploration | Normal construction |

### *2.5. Three-stage assessment process*

The specific calculation process of the three-stage risk assessment method for shallow buried tunnels is as follows:

(1) According to the data obtained in the investigation stage, the tunnel depth and uneven pressure are quantified, the surrounding rock grade, underground water, and bad geology are described qualitatively. The functions in Table 2 and the Karwowski function in Table 3 are used to respectively determine the membership degree of quantitative indexes and qualitative indexes. And then the single-index membership degree matrix $R$ is constructed. By substituting the matrix $R$ and the comprehensive weight vector $W^1$ into Eq (1), the synthetic membership degree can be calculated. The final risk grade for tunnel collapse is determined through the maximum membership principle. Based on the risk regulation criteria, the unacceptable risk and the rejected risk are identified, and the collapse risk is controlled by optimizing construction and support parameters during the design stage.

(2) According to the advance geological forecast, geological sketch for tunnel face, survey-design data, and other data, the evaluation indexes of the preliminary assessment are corrected, and the new evaluation indexes are quantified. The correlation functions in Table 6 are used to calculate the correlation degree $K_j(v_i)$ between the index $I_i$ and risk grade $C_j$. The $K_j(v_i)$ and the weight $W_2$ in Table 7 are substituted into the Eq (10), and the multi-index synthetic correlation degree $K_j(N)$ can be obtained. Based on the maximum correlation degree principle, the risk grade is determined. For unacceptable risk and the rejected risk judged by the risk regulation criteria, the changes should be made to the construction and support parameters before the tunnel face excavation.

(3) According to the exposed geological conditions, the actual construction, and the monitoring and measurement, the evaluation indexes of the secondary assessment are revised, and the deformation response index is quantified. The initial weight $W^{(0)}$ and the measured values of the evaluation indexes are substituted into Eq (14), and the comprehensive weight can be obtained. The single-index attribute measure functions in Table 8 are used to calculate the attribute measure value $\mu_{ij}$ of the index $I_i$

corresponding to the risk grade $C_j$. Then the multi-index synthetic attribute measure value $\mu_j$ can be obtained by the Eq (13). Based on the confidence degree principle, the risk grade can be determined, and some measures such as strengthening support should be taken to control the unacceptable risk and the rejected risk.

## 3. Engineering application

### *3.1. Engineering background*

The newly south Shandong high-speed railway is located in the south of Shandong province, which is an important connecting passage of Shandong "three vertical and five horizontals" fast railway network and Chinese "eight vertical and eight horizontals" fast railway network. Its total length is 494 km. This railway is a double-line passenger dedicated line with a design speed of 350 km/h.

**Table 10.** Geological conditions of Huangjiazhuang Tunnel shallow buried section.

| Shallow buried section | Length (m) | Surrounding rock level | Strata inclination | Geological condition |
|---|---|---|---|---|
| DK228 + 960~DK229 + 080 | 120 | Ⅴ | 45° | Fully weathered diorite with developed open joint fissures. High crushing degree, poor stability, and serious uneven pressure. Covered with artificial waste soil, grade I loosen soil |
| DK229 + 080~DK229 + 150 | 70 | Ⅴ | 45° | Strongly weathered diorite with developed joint fissures. The poor structural integrity of rock mass and developed bedrock fissure water |
| DK229 + 150~DK229 + 235 | 85 | Ⅴ | 45° | Strongly weathered diorite with developed joint fissures. Broken rock mass and poor self-stability, developed bedrock fissure water |
| DK229 + 320~DK229 + 400 | 80 | Ⅳ | 60° | Moderately weathered diorite with relative integrity of rock mass |
| DK229 + 575~DK229 + 671 | 96 | Ⅴ | 60° | Strongly weathered diorite with developed joint fissures and broken rock mass |
| DK229 + 671~DK229 + 725 | 54 | Ⅴ | 60° | Strongly weathered diorite with developed joint fissures, underneath natural gully, minimum buried depth 11m, good rainfall seepage |

Huangjiazhuang tunnel is a control project of Linyi city to Qufu county section of south Shandong high-speed railway, which is located in Sizhang town, Sishui county, Shandong province. The total length of this tunnel is 1185 m with the import mileage DK228 + 875 and the export mileage DK230 + 060. The maximum buried depth is about 65 m. Among them, the length of the shallow buried section is 910m, which accounts for about 77% of the total length. The tunnel site area is the hilly landform with hill trough and undulation terrain. The strata along the tunnel are mainly artificial waste soil (Q4q) and slope-alluvial (Q4d1 + p1) silty clay of quaternary Holocene, Fuping age diorite of late Archean (wSδβ13). In the tunnel area, the joints are developed and the surrounding rocks are fully weathered or locally strongly weathered. The micro-tensile~open joints are filled with argillaceous sand and the joint surface is rough. There is no obvious surface water, and seasonal flow occurs during the rainy season. The groundwater type is mainly bedrock fissure water which is relatively less and recharged by atmospheric rainfall. The groundwater mainly occurs in the fully weathered and strongly weathered diorite formation (wSδβ13). The atmospheric rainfall is the main recharge source of groundwater and is mainly concentrated from June to August accounting for 63.7% of the annual rainfall. The joint fissures of partial rock masses are relatively developed and their integrity is poor, which provides the migration pathway of groundwater. The groundwater migrates along the bedrock fissures and there is no obvious groundwater discharge point. In addition, this tunnel entrance section is covered with artificial waste soil which may lead to collapse and falling blocks. The geological conditions of shallow buried sections are shown in Table 10.

### *3.2. Analysis of three-stage evaluation results*

The three-stage risk evaluation method of tunnel collapse was applied to analyze the collapse risk of Huangjiazhuang Tunnel shallow buried sections. Due to space limitations, the evaluation results are shown in Table 11.

Due to the non-implementation of advanced grouting reinforcement, the collapse occurred in the section DK229 + 671~DK229 + 725of Huangjiazhuang tunnel, as shown in Figure 2.

**Figure 2.** Collapse in the section DK229 + 671~ DK229 + 725 of Huangjiazhuang tunnel.

## 4. Conclusions

(1) To realize multi-level control of tunnel collapse, a three-stage risk evaluation method of collapse in the whole construction process of shallow buried tunnels was proposed. Due to the fuzziness and uncertainty of geological information between the prospecting stage and design stage, a preliminary evaluation model based on fuzzy theory was established. According to the uncertainty and uncertainty of geology and construction information before the surrounding rock excavation of the working face, a secondary evaluation model based on extension theory was introduced. After the surrounding rock excavation, a dynamic evaluation model based on attribute mathematical theory was put forward. Aiming at the evaluation results, the risk regulation criteria was determined.

**Table 11.** Evaluation results and regulation measures of collapse in Huangjiazhuang tunnel.

| Shallow buried section | Preliminary evaluation | | Secondary evaluation | | | Dynamic evaluation | | |
|---|---|---|---|---|---|---|---|---|
| | $I_1$~ $I_5$ | Risk grade | $I_1$~ $I_9$ | Correction basis | Risk grade | $I_{10}$ | Correction basis | Risk grade |
| DK228+960~ DK229+080 | (20, V, $C_4$, 45, $C_3$) | $C_2$ | (20, 85, 30, 35, 30, 15, 80, 50, 20) | Gravel soil, seriously weathered, and extremely broken surrounding rock. Weakly developed bedrock fissure water | $C_1$↑ | 30 | Advanced grouting, three-step method, anchor reinforcement | $C_3$↓ |
| DK229+080~ DK229+150 | (23, $C_1$, $C_3$, 45, $C_4$) | $C_2$ | (23, 80, 40, 35, 30, 15, 80, 50, 20) | Soft rock. Mud and sand outflow from the boreholes, fissure water, and joint fissure development, poor rock-mass integrity | $C_1$↑ | 30 | Advanced grouting, three-step method, anchor reinforcement | $C_3$↓ |
| DK229+150~ DK229+235 | (25, $C_1$, $C_3$, 45, $C_4$) | $C_2$ | (25, 75, 40, 40, 30, 15, 80, 50, 20) | Moderately weathered diorite with weak joint fissures, good integrity, and self-stability, fissure water development | $C_2$→ | 40 | Three-step method, short footage, weak blasting, tough support | $C_3$↓ |
| DK229+575~ DK229+671 | (20, $C_1$, $C_3$, 60, $C_4$) | $C_2$ | (20, 75, 30, 35, 30, 15, 80, 50, 20) | Moderately weathered diorite with hard and complete lithology, good integrity, and self-stability. Relatively dry face and weak fissure water development | $C_3$↓ | 30 | Three-step method, short footage, weak blasting, tough support | $C_3$→ |
| DK229+671~ DK229+725 | (18, $C_1$, $C_3$, 60, $C_3$) | $C_2$ | (18, 90, 20, 40, 40, 15, 80, 50, 20) | Fully weathered, structural fissures with good coherence and weak interlayer cementation. Collapse and falling blocks are prone to occur | $C_1$↑ | 50 | Three-step method, no advanced reinforcement | $C_2$↓ |

Note: The distribution coefficients of objective and subjective weights were 0.5 and 0.5 respectively. The ↑, ↓ and → represent risk increase, risk decrease, and risk unchanged respectively.

(2) In the preliminary evaluation between the prospecting stage and design stage, the surrounding rock grade, tunnel buried depth, underground water, uneven pressure, and bad geology were selected as evaluation indexes and quantified mainly according to the geological investigation data. Based on corrected disaster-pregnant environment factors, the excavation span, support condition, construction level, and atmospheric rainfall were introduced as the secondary evaluation indexes. The disaster-pregnant and disaster-causing factors were corrected again based on the geology and construction information revealed by excavation, and the monitoring measurement was introduced as a dynamic

evaluation index. The classification standard of 10 evaluation indexes was established.

(3) The proposed three-stage risk evaluation method of tunnel collapse was applied to the Huangjiazhuang Tunnel of the South Shandong High-Speed Railway. The collapse risk of section DK229 + 671~DK229 + 725 is high and the evaluation results were consistent with the actual situation. It is proved that the proposed evaluation method has good application value and the risk regulation criteria are scientific and reasonable.

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## Conflict of interest

We declared that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript.

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