



# Extension prediction model of soft rock tunnel deformation grade based on entropy weight method and rough set

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## Abstract

When the tunnel passes through the soft rock area, the deformation problem is unavoidable, which affects the construction of the tunnel. In this paper, a method is proposed to predict the deformation grade of soft rock tunnel. Six influencing factors of soft rock tunnel deformation are selected as evaluation indexes, including tunnel depth, excavation method, support closure time, groundwater condition, angle of bedding, and uniaxial compressive strength of rock. Vault subsidence and clearance convergence are selected as actual grading indexes, and the deformation grade was divided into four grades. The entropy weight method is used to calculate the weight of the actual grading index, and the excavation section deformation is graded based on extension theory. Then the weight of influencing factors is calculated based on rough set theory, and the main factors controlling deformation are highlighted. Finally, an extension prediction model of soft rock tunnel deformation grade is established and applied to the prediction of deformation grade of the Huangjiagou tunnel of the Zhengwan high-speed railway. The prediction model is in good agreement with the field observation results, and the accuracy rate reaches 90%, which provides a new idea for the prediction of deformation grade of soft rock tunnel.

**Keywords** Soft rock tunnel · Rough set · Extension theory · Displacement monitoring · Deformation grade prediction

## Introduction

In recent years, with the rapid development of global traffic construction, tunnel engineering construction has also made great progress. As underground engineering, tunnel engineering is faced with complex and diverse engineering environment, among which the problem of large deformation of soft rock with high stress has always been an important factor affecting project construction (Ping et al. 2016). When the tunnel passes through the soft rock area with high stress, the initial in-situ stress of the original rock will be released due to the excavation and unloading of the tunnel, and the stress of the surrounding rock will be redistributed, resulting in the deformation of the tunnel (Luo et al. 2018; Bian et al. 2017; Lai et al. 2018). If the deformation of surrounding

rock is not effectively controlled, the deformation will continue to increase and eventually lead to tunnel instability and collapse (Hoek 2001). For example, Tauern highway tunnel in Austria (Steiner 1996), Bolu Mountain tunnel in Turkey (Brox and Hagedorn 1999; Dalgıç 2002), Chibbro-Khodri tunnel in India (Dwivedi 2013), Jieling tunnel (Wu et al. 2018), Zhegu Mountain tunnel (Meng et al. 2013), and Jiazhuqing (Zhang 2003) tunnel in China all suffered from different degrees of tunnel deformation and instability. The maximum deformation of vault subsidence and clearance convergence of the Jiazhuqing tunnel and Muzhailing tunnel is more than 1000 mm. Therefore, it is of great practical significance to study the deformation of soft rock tunnel with high stress and predict the deformation grade of the tunnel.

Many scholars at home and abroad have studied the deformation mechanism, control measures and deformation prediction of soft rock tunnel. Bian et al. (2017) studied the large deformation of soft rock in the Huangjiazhai tunnel through mineral composition monitoring, microstructure observation and in-situ stress test, and considered that the high stress and groundwater infiltration were the main reasons for the large deformation of surrounding rock. Based

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on the analysis of the soft rock characteristics and geological conditions of the Zhegu Mountain tunnel, Meng et al. (2013) concluded that the soft rock expansion was not the leading cause of the large deformation of the tunnel, and three mechanisms of large deformation of the tunnel, namely the plastic flow of the soft rock, the shear slide of the wedge and the bending of the thin layer of the soft rock, were proposed. Bizjak and Petkovek (2004) explained the development and evolution of the excavation failure zone in the surrounding rock of the tunnel by the analysis of displacement monitoring results of the Golovec tunnel. They calculated the stress field around the tunnel using the finite difference method. The results showed that the installation time and stiffness of the initial support are the essential factors affecting tunnel deformation. Based on a series of model development and experiments, Erguler and Ulusay (2009) explained that the uniaxial compressive strength and elastic modulus of rock would decrease with the increase of water content, thus proved the water is an important factor leading to tunnel deformation. Jiang et al. (2014) detected the weakening effect of water on soft rock intuitively using computerized X-ray tomography. Through real-time visual observation, the evolution mechanism of water-induced fracture was divided into three steps: water invasion, soft rock volume expansion, and fracture expansion. Li et al. (2010) used the Flac3D numerical simulation software to simulate the displacement, stress and plastic zone of soft rock tunnel after excavation, and proposed the failure mechanism of surrounding rock at the intersection of soft rock tunnel. Besides, a new support method was proposed, which can effectively restrain the deformation of surrounding rock: the Double-Bolt Control Technology (DBCT). Based on field investigation and deformation mechanics analysis, Wang et al. (2009) proposed two deformation mechanisms of soft rock tunnel: stress expansion type and structural deformation type. A rigid, flexible layer supporting technique was proposed, which successfully solved the problem of high stress and large deformation of soft rock tunnel. Anagnostou (1993) regarded the rock expansion during tunnel excavation as a process of hydraulic coupling, which can simulate the observed floor deformation in a real sense. In addition to the importance of seepage, the influence of rock strength was also explained.

The deformation prediction of soft rock tunnel has also attracted extensive attention from scholars. Guan et al. (2012) proposed a Markov geological prediction method, which uses a Bayesian method to update the geological parameters in the tunnel in real-time, to predict the deformation in front of the tunnel dynamically. Jiang (2007) proposed a nonlinear intelligent prediction method based on particle swarm optimization to predict the deformation of an underground cavern. Aydan et al. (1996) proposed a method for predicting the extrusion potential and degree of surrounding rock, which was applied to the deformation

grade prediction of the circular tunnel, and the comparison between the predicted value and the actual observed value verified the applicability and effectiveness of the proposed method. Based on the Weighted Voting method, Zhang et al. (2020a, b) proposed a new classifier integration method. Seven independent machine learning classifiers were aggregated. By classifier ensemble, the prediction accuracy of rock extrusion problems in tunnels was improved. Agan (2016) studied a new rock mass classification system: RMQR, which was used to predict the risk of rock mass extrusion. With the development of computer technology, nonlinear prediction and artificial intelligence provide new ideas for solving complex problems. Mahdevari et al. (2013) used support vector machine (SVM) to establish the dynamic prediction model of tunnel convergence. Xue et al. (2020) used artificial neural network (ANN) to predict non-uniform deformation and established a deformation prediction model. However, artificial neural network has a complex structure and takes a long time to calculate.

Previous researches on deformation prediction of soft rock tunnels have made significant contributions. However, the degree of influence of various factors on tunnel deformation is rarely studied at present, and previous nonlinear prediction methods have shortcomings. In this paper, based on rough set theory and extension theory, the influence degree of each influencing factor on tunnel deformation is quantitatively analyzed, the main factors controlling tunnel deformation are highlighted, and the deformation grade prediction model is established. A flowchart of deformation risk assessment for soft rock tunnels is shown in Fig. 1.

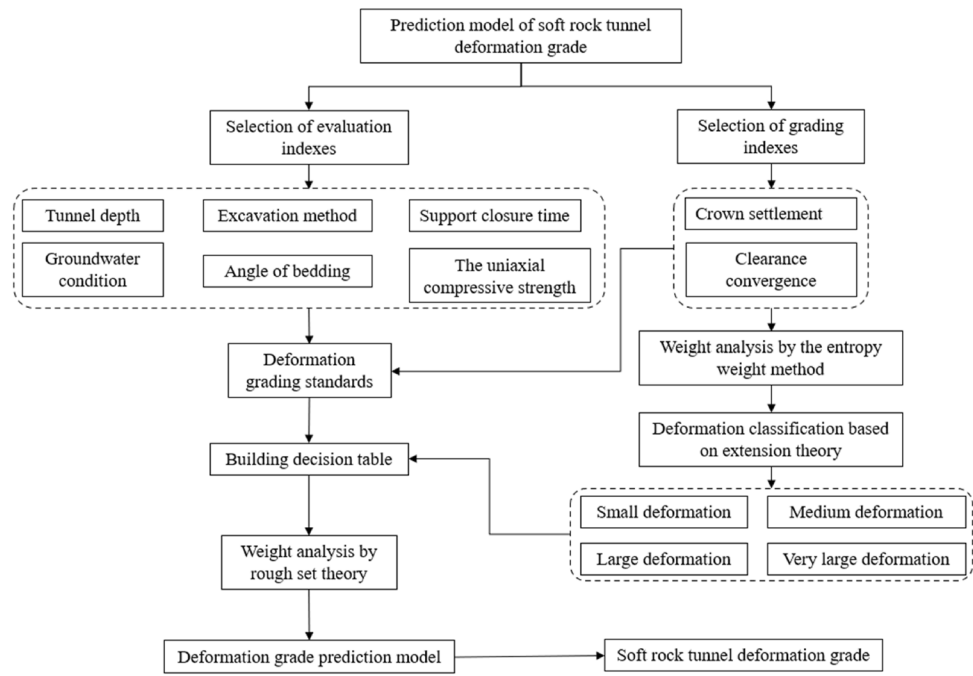
## Project overview

Huangjiagou tunnel of the Zhengwan high-speed railway is located in Hubei Province, with a total length of 7827 m and a maximum depth of 210 m. This area belongs to the low mountain landform area of tectonic erosion. The overall terrain is high in the middle and low on both sides, with an altitude of 380–859 m, and the terrain fluctuates wildly.

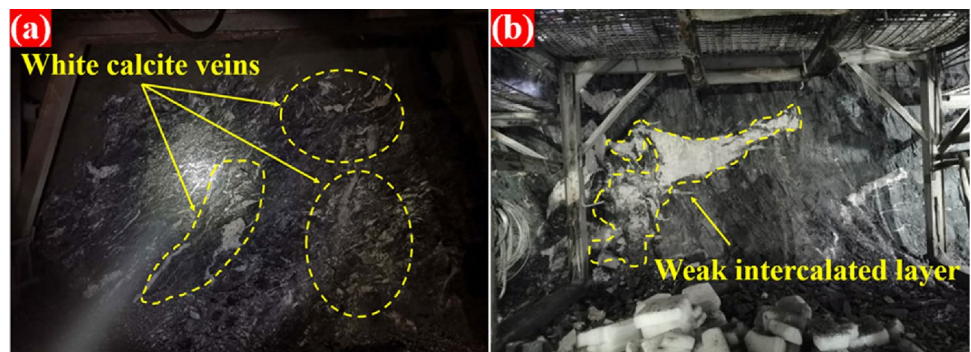
The rock stratum in the project area is sandy shale of Silurian Xintan formation ( $S_1x$ ), with argillaceous structure, bedding structure, developed joints and fissures, and relatively soft rock. The mineral composition is mainly clay minerals, with partial carbon content. Affected by the structure, the rock layer is thin-layered, with specular phenomena between layers and disordered occurrence. It contains a large amount of white calcite (Fig. 2a) and a weak intercalated layer (Fig. 2b).

The tunnel is located in the north wing of the inverted anticline of Jindou-Anzizhai and is in the fold belt of the Upper Yangtze block. It passes through the footwall of Tianjiagou reverse fault. The fault is located on the right side of

**Fig. 1** The prediction model of soft rock tunnel deformation grade



**Fig. 2** Soft surrounding rock of the Huangjiagou tunnel. **a** Contains a large amount of white calcite. **b** Contains a weak intercalated layer



the tunnel, and the line runs parallel to the tectonic fault line, 100–1000 m away from the line. Affected by the fault, the rock mass of the tunnel is broken, and the fault has a great influence on the surrounding rock of the tunnel.

The groundwater near the project area is mainly supplied by the bedrock fissure water. Bedrock fissure water occurs in the weathering and structural fissures of the shallow surface, mainly from atmospheric precipitation and surface water supply. The groundwater level changes significantly with the seasons. The rainy season is rich, while the dry season is poor. Because the sandy shale of the Silurian Xintan Formation contains carbonaceous locally, the groundwater in the tunnel body has certain erosiveness.

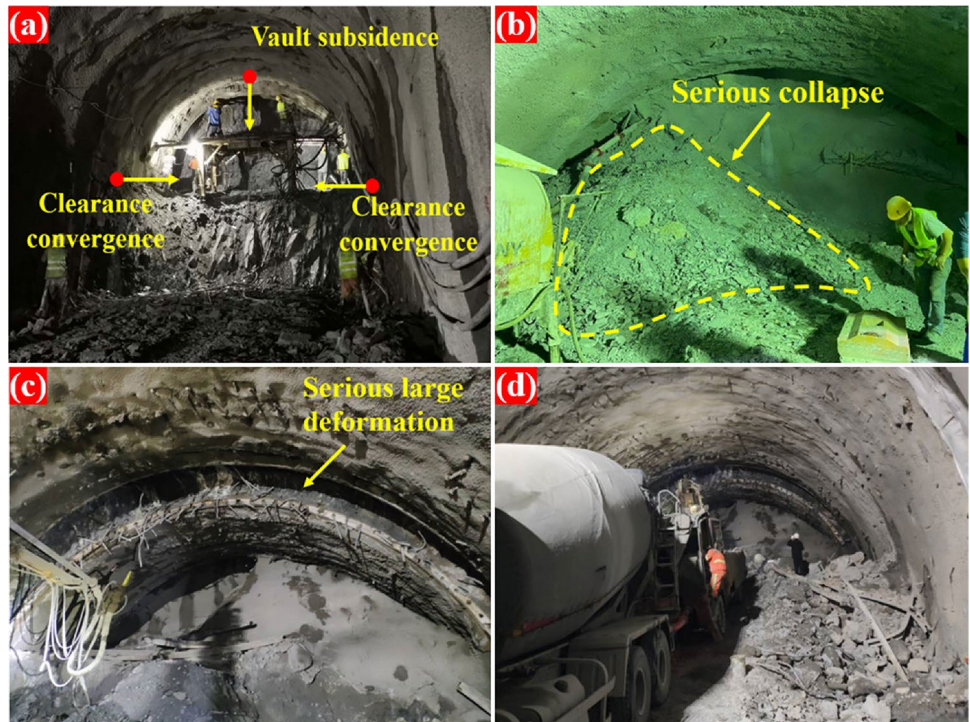
The New Austrian Tunneling Method is adopted to monitor the deformation of vault subsidence and clearance convergence (Fig. 3a) during the excavation process. The tunnel has been faced with serious collapse (Fig. 3b) and deformation (Fig. 3c) in the process of excavation. Therefore, some measures were taken to control the deformation (Fig. 3d).

### Methodology

The deformation risk assessment of soft rock tunnel is a multi-objective evaluation and decision-making problem, and each factor is contradictory and mutually restricted. The key is to establish a comprehensive evaluation system and use reasonable algorithms to assign values to evaluation indexes. Commonly used nonlinear prediction methods include analytic hierarchy process, fuzzy comprehensive evaluation method, grey correlation theory and artificial neural network, which have their shortcomings. For example, the learning speed of artificial neural networks is slow, and the optimization function may make the training process pause. Analytic hierarchy process has strong subjectivity in determining weights. The results of fuzzy comprehensive evaluation are only determined by one or several factors, which will miss a lot of information. The weight of evaluation index is calculated by entropy



**Fig. 3** Photographs are showing construction sites of the soft rock tunnel. **a** Measuring of vault subsidence and clearance convergence. **b** Collapse caused by large deformation. **c** Serious large deformation hazard. **d** Shotcrete to reduce large deformation



weight method, which can avoid the interference of subjective factors. Rough set does not need to deal with any information outside the data set, through the known data to reveal the potential law. Extension evaluation can not only evaluate the risk level of surrounding rock deformation, but also determine its degree of bias to a certain level. Therefore, using entropy weight method-extension theory can make the parameters more objective and accurate. Finally, the processed parameters are used as the input parameters of rough set-extensions to establish the deformation risk assessment model of soft rock tunnel.

**Entropy weight method**

The concept of entropy was first proposed by Shen Nong in 1951. As an objective weighting method, the entropy weighting method is not affected by subjective factors. The weight is calculated based on the degree of uncertainty of each index (Wang et al. 2018).

In this paper, the entropy weight method is used to determine the weight of two kinds of tunnel deformation: vault subsidence and clearance convergence. The steps are as follows (Fang et al. 2020; Xie et al. 2019):

(1) The deformation grades are divided into  $m$  grades, with  $n$  evaluation indexes for each grade. The original data matrix  $A = (a_{ij})_{m \times n}$  is constructed and  $A$  is standardized to obtain matrix  $B = (b_{ij})_{m \times n}$ :

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \dots & a_{ij} & \dots \\ a_{m1} & \dots & a_{mn} \end{pmatrix}_{m \times n}, \tag{1}$$

$$b_{ij} = \frac{a_{ij} - \min a_j}{\max a_j - \min a_j}, \tag{2}$$

where  $\max a_j$  and  $\min a_j$  are the maximum and minimum index values of the deformation grade under the  $j$ th evaluation index.

(2) Calculating the entropy  $e_j$

$$e_j = -(\ln m)^{-1} \sum_{i=1}^m p_{ij} \ln p_{ij}, \tag{3}$$

where  $p_{ij} = b_{ij} / \sum_{i=1}^m b_{ij}$ .

(3) Calculating the degree of variation coefficient  $d_j$ ,

$$d_j = 1 - e_j \tag{4}$$

where  $e_j$  is the entropy value of the evaluation index.

(4) Calculating the weight  $\omega_j$  of the  $j$ -th index

$$\omega_j = \frac{d_j}{\sum_{j=1}^n d_j} \tag{5}$$

### Extension theory

The theory of extensions was first proposed by Cai Wen, a famous scholar in China (Cai 1998). Based on matter-element theory and extension set theory, extension theory aims to solve incompatible problems in the real world. At present, extension theory has been widely used in the field of civil engineering (Wang et al. 2015; Shang et al. 2013).

Based on extension theory, this paper classifies excavated sections' deformation levels and predicts the deformation levels of unexcavated sections. The steps are as follows (Qiao et al. 2020):

(1) Determining the classical field  $R_{oi}$  and node field  $R_p$

$$R_{oi} = (N_i, C_i, V_i) = \begin{vmatrix} N_i & C_1 & V_{i1} \\ \dots & \dots & \dots \\ C_n & V_{in} & \end{vmatrix} = \begin{vmatrix} N_i & C_1 & (a_{i1}, b_{i1}) \\ \dots & \dots & \dots \\ C_n & (a_{in}, b_{in}) & \end{vmatrix}, \quad (6)$$

$$R_p = (N_p, C_i, V_p) = \begin{vmatrix} N_p & C_1 & V_{p1} \\ \dots & \dots & \dots \\ C_n & V_{pn} & \end{vmatrix} = \begin{vmatrix} N_p & C_1 & (a_{p1}, b_{p1}) \\ \dots & \dots & \dots \\ C_n & (a_{pn}, b_{pn}) & \end{vmatrix}, \quad (7)$$

where  $N$  is the evaluation grade,  $C$  is the evaluation index, and  $V$  is the value range of the evaluation grade.

(2) Determining the matter-element  $R_i$  to be evaluated

$$R_i = (M, C_i, V_i) = \begin{vmatrix} M & C_1 & V_1 \\ \dots & \dots & \dots \\ C_n & V_n & \end{vmatrix}, \quad (8)$$

where  $M$  is the thing to be evaluated.

(3) Calculating the correlation degree of the single index.

The correlation degree of every single index to every evaluation grade is as follows:

$$K_j(V_i) = \begin{cases} \frac{-\rho(V_i(t), V_{ij})}{|V_{ij}|} & V_i \in V_{ij} \\ \frac{\rho(V_i(t), V_{ij})}{\rho(V_i(t), V_{pi}) - \rho(V_i(t), V_{ij})} & V_i \notin V_{ij} \end{cases}, \quad (9)$$

where

$$\rho(V_i(t), V_{ij}) = \left| V_i - \frac{a_{ij} + b_{ij}}{2} \right| - \frac{b_{ij} - a_{ij}}{2}. \quad (10)$$

(4) Calculating the comprehensive correlation degree

$$K_i(M) = \sum_{i=1}^n \omega_i K_j(V_i), \quad (11)$$

where  $K_i(M)$  is the comprehensive correlation degree of the  $j$ -th level, and  $\omega_i$  is the weight of the  $i$ th evaluation index. If  $K_i = \max \{K_i(M)\}$ , then, the grade of  $M$  is level  $i$ .

### Rough set theory

Rough set theory is a nonlinear mathematical method proposed by Polish scholar Z. Pawlak, which eliminates the uncertainty of data by discretization without any prior information, and is used for quantitative analysis of inaccurate, incomplete and inconsistent information (Zhang et al. 2016). At present, rough set theory has been widely used in geotechnical engineering (Xue et al. 2018, 2020).

In this paper, rough set theory is adopted to analyze the weight of the influencing factors. The specific steps include (Huang et al. 2020):

(1) Building the decision table.

As a knowledge representation system, the decision table can be defined as the division of  $U$  belonging to all possible relation pairs in  $R$ , denoted as:  $F = (U, R)$ , If  $R = C \cup D$  and  $C \cap D \neq \phi$ ,  $S = (U, R, C, D)$  is the decision table.

Where  $F$  is the knowledge base,  $U$  and  $R$  are all non-empty finite sets,  $C$  is the conditional attribute,  $D$  is the decision attribute.

(2) Calculating the dependence of decision attribute on conditional attribute.

$$k = \gamma_c(D) = \frac{1}{|U|} \sum_{i=1}^m |\gamma_c(D_i)|, \quad (12)$$

where  $|\gamma_c(D_i)|$  is the compatibility number of samples,  $0 < k < 1$ .

(3) Calculating the weight of the influencing factors.

After the deletion of the evaluation index  $i$ , the dependence of the decision attribute on the conditional attribute is:

$$\gamma_{c-c_i}(D) = \frac{1}{|U|} \sum_{i=1}^m |\gamma_{c-c_i}(D_i)|. \quad (13)$$

The weight coefficient of the conditional attribute set  $C$  is calculated as follows:

$$\omega_i = \frac{\gamma_c(D) - \gamma_{c-c_i}(D)}{\sum_{i=1}^m [\gamma_c(D) - \gamma_{c-c_i}(D)]}, \quad (14)$$

where  $|\gamma_{c-c_i}(D_i)|$  is the sample size after the evaluation index  $i$  is deleted, and  $\omega_i$  is the weight.

### Rough set-extension prediction model

First, the weights of vault subsidence and clearance convergence were calculated by entropy weight method, and then the deformation classification of 30 tunnel sections is carried out by extension theory. Then, 30 groups of data and their deformation grades were used to establish a decision table,

and the weights of 6 input parameters were calculated by rough set theory. Finally, the extension theory was used to establish the risk assessment model, and the accuracy of the model was verified by another 20 sets of data. (All calculations were performed in MATLAB).

## Soft rock tunnel deformation risk evaluation system

### Actual classification index of soft rock tunnel

The deformation monitoring of tunnel surrounding rock is a common means to ensure the safety of tunnel excavation (Kavvasdas 2005; Zhang et al. 2020a, b), real-time deformation monitoring was carried out for the studied tunnel, and monitoring values of vault subsidence and clearance convergence were collected (Huang et al. 2017), obtain deformation information in time during excavation.

#### (1) Vault subsidence ( $A_1$ ).

The vault subsidence is the primary deformation type of soft rock tunnel, which reflects the vertical settlement of the tunnel. It is usually caused by the subsidence of the arch foot and mainly occurs before the closure of the initial support.

#### (2) Clearance convergence ( $A_2$ ).

The clearance convergence reflects the horizontal deformation of the tunnel, which will affect the stress distribution and the overall shape of the tunnel. If the convergence value is too large, it will lead to the cracking of the initial support and the collapse of the tunnel.

In summary, vault settlement and clearance convergence are selected as the actual indexes of tunnel deformation classification.

### Influencing factors of soft rock tunnel deformation

According to the existing literature and engineering experience, the tunnel depth ( $B_1$ ), excavation method ( $B_2$ ), support closure time ( $B_3$ ), groundwater conditions ( $B_4$ ), angle of bedding ( $B_5$ ), the uniaxial compressive strength of rock ( $B_6$ ) are selected as the evaluation indexes of tunnel surrounding rock deformation risk.

#### (1) Tunnel depth ( $B_1$ ).

The tunnel depth refers to the vertical distance from the top of the excavation face to the ground. With the increase of the tunnel excavation depth, the rock mechanics characteristics and stress environment become more complex; correspondingly, the tunnel surrounding rock pressure and stress also increase (Li et al. 2013a, b), leading to greater deformation hazards (Sun et al. 2018). The tunnel depth will affect the stability of the surrounding rock (Li et al. 2019).

#### (2) Excavation method ( $B_2$ ).

The selection of tunnel excavation method is usually determined by factors such as tunnel length, section size, structure form, machinery and equipment, geological conditions. Different excavation methods have different disturbance degree and deformation control effect on tunnel surrounding rock (Zhang et al. 2015). In this study, the central diaphragm method (M1), three-bench seven-step excavation method (M2), three-bench method (M3), and two-bench method (M4) are adopted in the tunnel.

#### (3) Support closure time ( $B_3$ ).

Support closure time refers to the time from excavation to initial support closure, which varies with different excavation and support methods. The initial support should form a ring structure from top to bottom as soon as possible (Chen et al. 2020), and timely seal the invert, which can effectively reduce foundation disturbance.

#### (4) Groundwater conditions ( $B_4$ ).

The effects of groundwater on surrounding rock of the tunnel mainly include softening, segmentation and lubrication. When the soft rock contacts with water, the internal clay mineral will swell, disintegrate and soften rapidly, and its self-stabilization ability decreases, which causes the instability of the surrounding rock and the deformation of the initial support.

#### (5) Angle of bedding ( $B_5$ ).

The tunnel in this study is stratified soft rock tunnel, and bedding bias is the main unfavorable geology. The tunnel has a large bedding angle and a poor adhesion force between layers, and is prone to bedding slip and deformation under the action of compressive stress. In general, the larger bedding angle will lead to worse self-stability of the surrounding rock (Bai et al. 2021). For the surrounding rock with a smaller bedding angle (Fig. 4a), the horizontal convergence deformation is small, and the sidewalls on both sides will not produce large deformation failure. For the surrounding rocks with a larger bedding angle (Fig. 4b), slippage, collapse, and over-excavation often occur at the hollow position of the arch roof, and the arch waist part causes the deformation and collapse of the initial support, which leads to the staggered (Fig. 4c) and broken deformation of the initial support arch frame that has been completed on the arch roof (Fig. 4d).

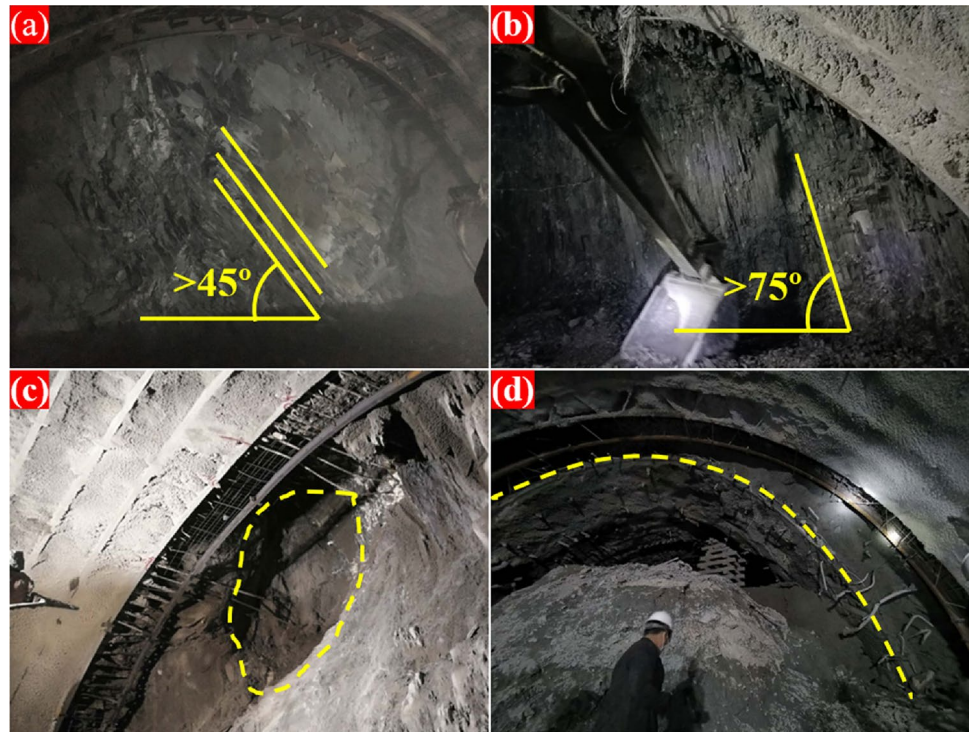
#### (6) Uniaxial compressive strength ( $B_6$ ).

The uniaxial compressive strength of rock directly represents the strength of surrounding rock (Li et al. 2019). The higher the uniaxial compressive strength of rock, the greater the deformation resistance of surrounding rock. On the contrary, the lower the strength, the more likely the tunnel deformation.

In summary, tunnel depth, excavation method, support closure time, groundwater conditions, angle of bedding and uniaxial compressive strength are considered to be important factors in the analysis of soft rock tunnel deformation.



**Fig. 4** Figure shows the different bedding angles on the tunnel face and deformation hazards caused by bias. **a** A smaller bedding angle. **b** A larger bedding angle. **c** Arch collapse due to bias. **d** Primary support invasion limit due to bias



**Table 1** Quantization of excavation method and groundwater condition

Influencing factor		Standard	Value	Deformation grade
Excavation method	Groundwater condition			
Method 1	No water	0–0.25	0.125	Small (I)
Method 2	Water seepage	0.25–0.5	0.375	Medium (II)
Method 3	Drip water	0.5–0.75	0.625	Large (III)
Method 4	Linear drop	0.75–1	0.875	Very large (IV)

Method 1 is central diaphragm method; Method 2 is three-bench seven-step excavation method; Method 3 is three-bench method; Method 4 is two-bench method

**Tunnel deformation risk classification standard**

The influencing factors of soft rock tunnel deformation are analyzed as the evaluation index of deformation grade prediction. The deformation of the soft rock tunnel is divided into four grades: small (I), medium (II), large (III), and very large (IV). Where, as a qualitative indicator, the excavation method ( $B_2$ ) and groundwater conditions ( $B_4$ ) are treated with standard discretization in Table 1, corresponding to four grades.

According to the characteristics of the tunnel and previous research (Bai et al. 2021; Xue et al. 2018), the quantitative standard is determined by sorting out the geological survey and deformation monitoring data in Table 2.

**Table 2** Classification standard of deformation index and influencing factors

Index	Deformation grade			
	Small (I)	Medium (II)	Large (III)	Very large (IV)
$A_1$ (mm)	0–100	100–200	200–400	> 400
$A_2$ (mm)	0–100	100–300	300–500	> 500
$B_1$ (m)	0–40	40–80	80–120	> 120
$B_2$	0–0.25	0.25–0.5	0.5–0.75	0.75–1
$B_3$ (d)	0–15	15–50	50–90	> 90
$B_4$	0–0.25	0.25–0.5	0.5–0.75	0.75–1
$B_5$ (°)	0–22.5	22.5–45	45–67.5	> 67.5
$B_6$ (MPa)	> 30	15–30	5–15	< 5

**Table 3** Monitoring data of excavated tunnel sections

Samples	A <sub>1</sub> (mm)	A <sub>2</sub> (mm)	Samples	A <sub>1</sub> (mm)	A <sub>2</sub> (mm)
1	91.5	168.2	16	75.5	84.2
2	189.4	214.6	17	130.4	156.5
3	158.1	215.3	18	101	144.9
4	166.6	197.8	19	118.3	236.7
5	169.8	204.6	20	183.7	315.1
6	42.6	34.8	21	279.6	501.3
7	75.4	139.1	22	273.86	487.6
8	100.6	113.4	23	120	189.4
9	453.6	521.7	24	92.1	91.9
10	162.9	202.1	25	327.5	390.6
11	228.9	216.3	26	165.5	207.1
12	246.6	273.3	27	225.5	381.2
13	231.4	356.3	28	107.8	157.3
14	447.6	489.3	29	130	151.6
15	414.7	755.1	30	97.7	182.5

**Results**

The weight coefficient of vault subsidence A<sub>1</sub> and clearance convergence A<sub>2</sub> are determined by the entropy weight method. Weights are calculated according to Eqs. (1)–(5). The results show that the weights of vault subsidence and clearance convergence are 0.4714 and 0.5286, respectively.

Monitoring data of 30 representatives excavated sections of the Huangjiagou tunnel are collected in Table 3. Based on the monitoring data, the actual deformation grades of 30 tunnels are classified using the extension method (Eqs. (6)–(11)). The results are shown in Table 4. The deformation level (Table 4) is taken as the decision attribute set, and the influencing factor (B<sub>1</sub>–B<sub>6</sub>) as a set of conditional attributes, the samples collected for rough set theoretical analysis are shown in Table 5.

Based on the grading standards of various factors in Table 2, the values (Table 5) are converted into discrete values (I:1, II:2, III:3, IV:4) to construct the decision table in Table 6. Equations (12)–(14) are used for weight analysis. The results are shown in Table 7 and Fig. 5.

Based on the division standard (Table 2) and the weight of each influencing factor (Table 7), rough set-extension model is established to predict the deformation grade of the unexcavated tunnel section, among which the influencing factors (B<sub>1</sub>–B<sub>6</sub>) as the evaluation indexes. To verify the correctness of the model, the model is used to conduct deformation grading prediction for another 20 samples, and the prediction grade is compared with the actual grade in Table 8 and Fig. 6.

Based on rough set theory, this paper conducts a weight analysis on the influencing factors of deformation. According to Table 7 and Fig. 5, tunnel depth (B<sub>1</sub>), excavation

**Table 4** Results of deformation classification for excavated tunnel sections

Samples	Correlation				Grade
	I	II	III	IV	
1	0.7060	1.0000	0.2655	0.0000	II
2	0.2607	1.0000	0.4548	0.0000	II
3	0.2734	1.0000	0.3360	0.0000	II
4	0.2824	1.0000	0.3329	0.0000	II
5	0.2739	1.0000	0.3527	0.0000	II
6	1.0000	0.2292	0.0577	0.0000	I
7	1.0000	0.9820	0.2448	0.0000	I
8	0.8805	1.0000	0.2488	0.0000	II
9	0.0000	0.1452	0.5975	1.0000	IV
10	0.2783	1.0000	0.3258	0.0000	II
11	0.2198	1.0000	0.6312	0.0000	II
12	0.0825	0.8603	1.0000	0.0000	III
13	0.0000	0.4275	1.0000	0.0667	III
14	0.0000	0.1811	0.7517	1.0000	IV
15	0.0000	0.0631	0.3400	1.0000	IV
16	1.0000	0.6092	0.1454	0.0000	I
17	0.4647	1.0000	0.2716	0.0000	II
18	0.7048	1.0000	0.2604	0.0000	II
19	0.4103	1.0000	0.3552	0.0000	II
20	0.1765	1.0000	0.9007	0.0000	II
21	0.0000	0.2524	1.0000	0.5165	III
22	0.0000	0.2593	1.0000	0.4492	III
23	0.4270	1.0000	0.2785	0.0000	II
24	1.0000	0.8153	0.1984	0.0000	I
25	0.0000	0.2233	1.0000	0.2645	III
26	0.2742	1.0000	0.3435	0.0000	II
27	0.0000	0.3770	1.0000	0.0919	III
28	0.5977	1.0000	0.2664	0.0000	II
29	0.4817	1.0000	0.2702	0.0000	II
30	0.6005	1.0000	0.2717	0.0000	II

method (B<sub>2</sub>), support closure time (B<sub>3</sub>), groundwater conditions (B<sub>4</sub>), angle of bedding (B<sub>5</sub>), the uniaxial compressive strength of rock (B<sub>6</sub>), respectively, 10%, 19%, 33%, 24%, 10%, and 4%.

The results showed that support closure time, groundwater conditions and excavation method account for a large proportion (33%, 24%, and 19%, respectively), while the tunnel depth, angle of bedding and the uniaxial compressive strength of rock account for a small proportion (10%, 10%, 4%, respectively).

The parameter of support closing time has the largest weight, account for 33% in total, which means the support closing time plays an important role in the deformation of the surrounding rock of soft rock tunnels. However, the tunnel in this study is deformed greatly and often stops and reworks, which leads to the extension of support closing



**Table 5** Samples for analyzing the weights of influencing factors using rough set theory

Samples	$B_1$ (m)	$B_2$	$B_3$ (d)	$B_4$	$B_5$ (°)	$B_6$ (MPa)	Grade
1	101.5	Method 2	45	Water seepage	82	16	II
2	81.5	Method 3	75	Water seepage	63	7	II
3	78.5	Method 3	96	Drip water	82	9	II
4	75.5	Method 3	60	Drip water	51	4	II
5	72.5	Method 3	66	Water seepage	84	11	II
6	93	Method 2	59	No water	48	20	I
7	88.5	Method 3	40	No water	20	35	I
8	77	Method 3	83	No water	84	12	II
9	75	Method 2	81	Water seepage	86	2	IV
10	73.5	Method 2	79	No water	46	20	II
11	39.5	Method 3	77	No water	49	20	II
12	68	Method 2	30	Water seepage	62	10	III
13	65	Method 1	80	Linear drop	60	2	III
14	63	Method 3	101	Drip water	65	5	IV
15	63.5	Method 3	59	Linear drop	85	1	IV
16	69.5	Method 3	73	No water	79	11	I
17	87.5	Method 3	32	Water seepage	78	17	II
18	101.5	Method 2	49	Water seepage	83	21	II
19	96.5	Method 1	41	Drip water	61	6	II
20	66	Method 3	38	Water seepage	76	31	II
21	64.5	Method 3	57	No water	59	2	III
22	64	Method 3	57	No water	44	16	III
23	84	Method 2	83	Water seepage	54	31	II
24	79.5	Method 3	80	Drip water	51	14	I
25	65.5	Method 3	100	Water seepage	60	13	III
26	66.5	Method 3	47	Water seepage	50	15	II
27	80.5	Method 2	52	Water seepage	78	20	III
28	120.5	Method 3	49	Water seepage	82	25	II
29	84.5	Method 3	58	Water seepage	76	17	II
30	66	Method 3	81	No water	80	30	II

The data are obtained by sorting out construction data such as engineering investigation reports

time. Therefore, it is necessary to determine the standard of support closure time according to the specific conditions of the tunnel. Besides, attention should be paid to shorten the support closing time, and support as soon as possible. For example, shorten the length of the footage, implement the initial support in time, and implement the secondary lining in time after the deformation is stabilized.

As shown in the results of the weight analysis, the groundwater is a factor that cannot be ignored for the deformation of the surrounding rock. To reduce the negative effect of groundwater, the method of combining drainage and water plugging can be adopted. Through advanced geological forecast to judge the position of the water body, and then advance boreholes is drilled to divert and drain groundwater and centralized to the channel. In addition, advanced pre-grouting can be used to improve the strength and compactness of the surrounding rock to achieve the purpose of water shutoff.

The surrounding rock of the tunnel in this study is layered sandy shale with low strength, broken rock mass, poor integrity, and self-stability of the surrounding rock, which results in a large amount of vault subsidence and horizontal convergence. To reduce the deformation of the vault and sidewall, grouting reinforcement can be combined with lengthening and encrypting bolts. The over-excavation part should be filled with concrete and grouted in time, and the under-excavation part should be supplemented by blasting and trimming. Besides, advanced support measures should be adjusted in time, and vault and sidewall support should also be strengthened.

Twenty typical soft rock tunnel sections were selected to verify the accuracy of the model. Except for the 1st and 7th sections, the deformation prediction results were consistent with the actual situation. The predicted grade of these two sections was large (III), but the actual grade was medium (II). Due to the instability of the tunnel face in

**Table 6** Decision table for analyzing influencing factors of tunnel deformation

Samples	$B_1$	$B_2$	$B_3$	$B_4$	$B_5$	$B_6$	Grade
1	3	2	2	2	4	2	2
2	3	3	3	2	3	3	2
3	2	3	4	3	4	3	2
4	2	3	3	2	3	4	2
5	2	3	3	2	4	3	2
6	3	2	3	1	3	2	1
7	3	3	2	1	1	1	1
8	2	3	3	1	4	3	2
9	2	2	3	2	4	4	4
10	2	2	3	1	3	2	2
11	1	3	3	1	3	2	2
12	2	2	2	2	3	3	3
13	2	1	3	4	3	4	3
14	2	3	4	3	3	3	4
15	2	3	3	4	4	4	4
16	2	3	3	1	4	3	1
17	3	3	2	2	4	3	2
18	3	2	2	2	4	2	2
19	3	1	2	3	3	2	2
20	2	3	2	2	4	3	2
21	2	3	3	1	3	4	3
22	2	3	3	1	2	2	3
23	3	2	3	2	3	1	2
24	2	3	3	3	3	3	1
25	2	3	4	2	3	3	3
26	2	3	2	2	3	3	2
27	3	2	3	2	4	2	3
28	4	3	2	2	4	2	2
29	3	3	3	2	4	2	2
30	2	3	3	1	4	1	2

**Table 7** Analysis results of influencing factors by rough set theory

Index	$B_1$	$B_2$	$B_3$	$B_4$	$B_5$	$B_6$
Dependence	0.86667	0.80000	0.70000	0.76667	0.86667	0.90000
Importance	0.06667	0.13333	0.23333	0.16667	0.06667	0.03333
Weight	10%	19%	33%	24%	10%	4%

the process of excavation, the construction personnel took measures such as grouting and strengthening advance support to control the deformation. Because these measures are not considered in the prediction model, the predicted deformation grade is higher than the actual grade.

In the construction process, the deformation risk grade can be obtained by the prediction model. If the predicted deformation grade of this section is high (III or IV), advance support, drainage, grouting reinforcement and other measures can be taken in advance. If the deformation grade is low (I or II), the support can be appropriately strengthened according to the construction site. Thus

provide a reference for tunnel construction and ensure safety.

## Discussion

### Comparison with previous prediction methods

The rough set-extension model proposed in this paper is compared with the Artificial neural networks (ANN), extreme learning machine (ELM), wavelet neural network (WNN), and other machine learning prediction models,

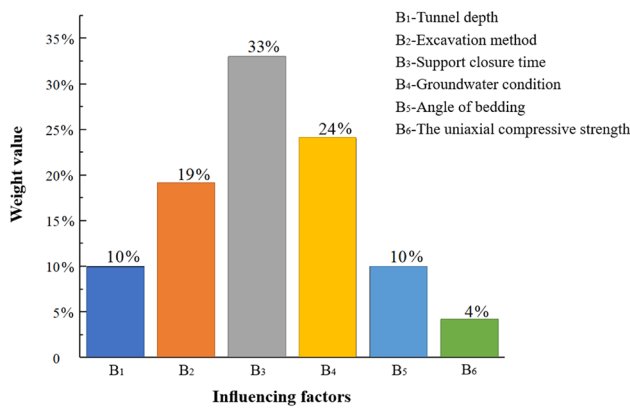


Fig. 5 The bar chart shows the weights of the different influencing factors

and the results are shown in Table 9. Compared with other machine learning models, the proposed rough set-extension prediction model achieved excellent results, with accurate predictions for 20 sets of data selected in this paper, with 90% accuracy. In the case of less samples, the accuracy of rough set-extension model is higher.

**Limitations**

Although the rough set-extension prediction model achieved satisfactory results, the model has some limitations and

needs to be further solved in future research. There are many influencing factors for the deformation risk assessment of soft rock tunnels. Six most representative influencing factors are selected for deformation analysis, and other factors need to be further considered in future research, such as blasting disturbance, drilling location, and explosive quantity. In addition, the classification standard of soft rock tunnel deformation risk assessment is established based on the actual tunnel project and previous research, which is not unalterable and needs further improvement in future research.

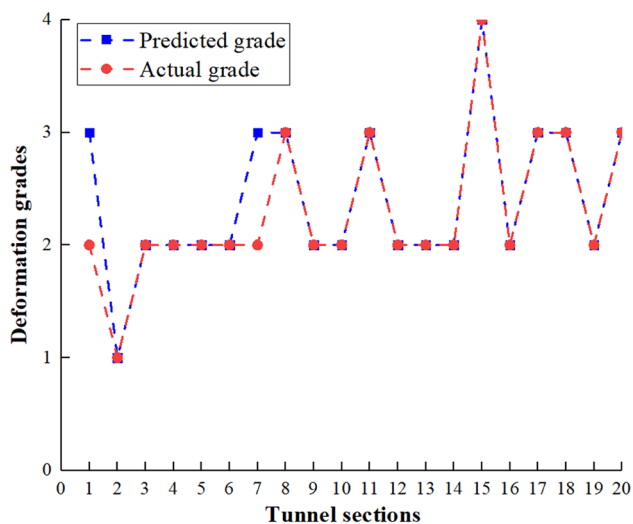
**Conclusion**

(1) In this paper, six influencing factors, including the tunnel depth, excavation method, support closure time, groundwater condition, angle of bedding, and uniaxial compressive strength of rock, are selected as the evaluation indexes of soft rock tunnel deformation grade prediction. Vault subsidence and clearance convergence are selected as the actual classification indexes of excavation section deformation grade. The entropy weight method is used to calculate the weight of the actual grading index, and the weight of six influencing factors is analyzed based on rough set theory. The results show that support closure time, groundwater condition and excavation method are the most important factors to control deformation. These results provide scientific guidance for the actual construction.

Table 8 Validation results of the extension model for predicting deformation

No.	B <sub>1</sub> (m)	B <sub>2</sub>	B <sub>3</sub> (d)	B <sub>4</sub>	B <sub>5</sub> (°)	B <sub>6</sub> (MPa)	Predicted grade	Actual grade
1	76	0.625	81	0.125	80	5	III*	II
2	78.5	0.125	79	0.125	84	16	I	I
3	80	0.375	77	0.375	80	15	II	II
4	81.5	0.125	30	0.375	75	20	II	II
5	63	0.375	45	0.125	68	25	II	II
6	84.5	0.375	32	0.125	77	24	II	II
7	83.5	0.875	60	0.375	74	11	III*	II
8	82.5	0.375	79	0.625	63	11	III	III
9	81.5	0.625	45	0.375	79	7	II	II
10	79.5	0.625	51	0.375	77	21	II	II
11	78.5	0.625	96	0.625	82	9	III	III
12	93	0.375	59	0.125	48	20	II	II
13	75	0.375	81	0.375	86	2	II	II
14	68	0.375	30	0.375	62	10	II	II
15	63.5	0.625	59	0.875	85	1	IV	IV
16	101.5	0.375	49	0.375	83	21	II	II
17	64.5	0.625	57	0.125	59	2	III	III
18	79.5	0.625	80	0.625	51	14	III	III
19	80.5	0.375	52	0.375	78	20	II	II
20	66	0.625	81	0.125	80	30	III	III

The \* indicates the tunnel sections where the predicted results are inconsistent with the actual results



**Fig. 6** A line chart comparing the predicted grade with the actual grade

**Table 9** Comparison of the rough set-extension model with other machine learning models

Model	Correct number	Wrong number	Accuracy (%)
Rough set-extension model	18	2	90
Artificial neural networks model	13	7	65
Extreme learning machine model	7	13	35
Wavelet neural network model	11	9	55

(2) In this paper, the quantitative indexes are classified continuously, and the quantitative processing methods and classification standards for qualitative indicators are proposed. Based on the weight and grading standards of the influencing factors, a deformation grade prediction model is established using an extension method, which to predict the deformation grade of the unexcavated section. The deformation grade is divided into four levels: small (I), medium (II), large (III), and very large (IV), which provided a reference for deformation classification. Different classification standards should be selected for different research tunnels.

(3) Taking the Huangjiagou tunnel of the Zhengwan high-speed railway as an example, the prediction model of soft rock tunnel deformation grade is established. The predicted deformation grade is basically consistent with the actual deformation grade, and the accuracy rate reaches 90%, which verifies the reliability of the model.

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