Prediction Model for Deformation Risk Grade of the Soft Rock Tunnel Based on GRA - Extension

Xinmin Ma, Yiguo Xue*, Chenghao Bai, Haiting Liu and Yuehao Yu

Geotechnical and Structural Engineering Research Center, Shandong University, Jinan, Shandong, China

*Corresponding author e-mail: xieagle@sdu.edu.cn, maxmkzx@126.com, baichenghao1112@gmail.com, lht0106@163.com, yyh19971010@163.com

Abstract. The soft rock tunnel is affected by geological factors and construction factors and it is easy to produce large deformation, which leads to cracking and spalling of the primary support, distorting the steel frame, uplifting the tunnel bottom, and cracking of the secondary lining, and has a serious impact on the safety of tunnel construction and operation. In this paper, the surrounding rock strength, rock mass integrity, groundwater condition, tunnel depth, excavation method, support strength and primary support closure time were chosen as the main factors affecting the deformation of soft rock tunnels. According to the actual monitoring and measurement data of the tunnel, the factor weights were calculated using GRA. Extension theory is used to establish the prediction model for the soft rock tunnel deformation risk. According to the comparison between actual deformation and model prediction deformation, the prediction model of tunnel deformation risk grade has high applicable performance in tunnel deformation risk assessment, which provides a reference for construction optimization of soft rock tunnel.

1. Introduction

The surrounding rock of the soft rock tunnel has low strength and poor integrity, and it is prone to large deformation of surrounding rock during tunnel construction, which has a serious impact on the safe construction and construction progress of the tunnel [1]. At present, New Austrian Tunneling Method (NATM) is often used in the construction of the mountain tunnel. NATM is to monitor the deformation and stress of the surrounding rock during the tunnel construction and optimize the tunnel excavation and support according to the monitoring information [2]. The tunnel monitoring measurement has a certain hysteresis, and it is difficult to provide a timely optimization plan for the construction of soft rock tunnels. According to the monitoring data, the nonlinear algorithm can be used to obtain the inherent law between the soft rock tunnel deformation and engineering geological conditions, and the risk grade of soft rock tunnel deformation can be predicted according to the acquired geological information and construction information.

The deformation of the soft rock tunnel is affected by many factors and is a typical multivariate nonlinear problem. Due to the inaccuracy of the prediction model and the parameter selection, the prediction results of the traditional deformation prediction methods, such as empirical models [3-4], numerical simulations [5] differ significantly from the actual measured values. In recent years,
nonlinear methods such as artificial neural network, grey theory, attribute mathematics and extenics theory have been widely used in geotechnical engineering, which provides a new idea for prediction of tunnel deformation risk grade. For example, Xue et al. established a deformation prediction model of the tunnel surrounding rock using rough set-extension [6]. Chen et al. predicted the collapse depth in the thin and extremely thin layered rock of the tunnel using geological strength index, attitude of rock, minor-major principal stress ratio, tunnel depth, excavation method and support strength as input parameters of an improved artificial neural network model [7]. Xu et al. predicted the large deformation of the tunnel surrounding rock using AHP–FUZZY method [8]. This study uses the grey theory to obtain the weight of the influence factors of the soft rock tunnel deformation and uses the extension to construct the prediction model of tunnel deformation risk grade. This study has great guiding significance for the safe construction of tunnels.

2. Methodology

2.1. Gray relational analysis

Gray relational analysis (GRA) is a nonlinear mathematical method for solving factor weights [9]. The most striking difference between this method and other weighting methods is that it does not need to provide any prior information beyond the data set of the research object, so its analysis of the uncertainty of the problem is very objective.

2.1.1. Establish the parameter matrix. \( C \) is the factors matrix. \( C_0 \) is the reference sequence and is the result sequence of deformation risk grade in this study. \( n \) is the number of factors and \( m \) is the number of objects and is the number of engineering samples.

\[
C = \begin{bmatrix}
C_1 \\
C_2 \\
\vdots \\
C_i \\
\vdots \\
C_n
\end{bmatrix} =
\begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1m} \\
c_{21} & c_{22} & \cdots & c_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
c_{ni} & c_{n2} & \cdots & c_{nm}
\end{bmatrix}
\tag{1}
\]

\[
C_0 = (c_{01}, c_{02}, \ldots, c_{0i}, \ldots, c_{0m})
\tag{2}
\]

2.1.2. Data normalization. \( E \) is the normalized parameter matrix.

\[
e_y = \frac{c_y - \min(C_y)}{\max(C_y) - \min(C_y)}
\tag{3}
\]

\[
E = \begin{bmatrix}
E_0 \\
E_1 \\
\vdots \\
E_i \\
\vdots \\
E_n
\end{bmatrix} =
\begin{bmatrix}
e_{01} & e_{02} & \cdots & e_{0m} \\
e_{11} & e_{12} & \cdots & e_{1m} \\
\vdots & \vdots & \ddots & \vdots \\
e_{ni} & e_{n2} & \cdots & e_{nm}
\end{bmatrix}
\tag{4}
\]
2.1.3. Calculate the gray relation coefficient ($\xi_y$). $\eta$ ($0 < \eta < 1$) is the resolution coefficient and usually assigned a value of 0.5.

$$|E_i - E_0| = |e_{ij} - e_{0j}| (i = 1, 2, \cdots, n, j = 1, 2, \cdots, m)$$

$$\xi_y = \frac{\min \{\min |e_{ij} - e_{0j}|\} + \eta \cdot \max \{\max |e_{ij} - e_{0j}|\}}{|e_{ij} - e_{0j}| + \eta \cdot \max \{\max |e_{ij} - e_{0j}|\}}$$

2.1.4. Calculate the gray relation degree ($q_i$).

$$q_i = \frac{1}{m} \sum_{j=1}^{m} \xi_y (j), i = 1, 2, \cdots, n, j = 1, 2, \cdots, m$$

2.1.5. Calculate the weight of the factors ($\omega_i$).

$$\omega_i = q_i / \sum_{i=1}^{n} q_i, i = 1, 2, \cdots, n$$

2.2. Extenics theory

Extenics theory is a mathematical method that can transform multiple evaluation indicators into a compatible problem [10]. It establishes the matter-element model and draws the conclusion of the extenics evaluation of the research object. After many scholars’ engineering verification, the extenics evaluation model has reliability in engineering evaluation [11-12].

The n-dimensional matter element ($R$):

$$R = \begin{bmatrix} N & c_1 & v_1 \\ c_2 & v_2 \\ \vdots \\ c_n & v_n \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix}$$

where $N$ is the name of the object, $c$ is the factor of the object, and $v$ is the value of the factor.

2.2.1. Establish a classical matter-element matrix ($R_{0w}$).

$$R_{0w} = \begin{bmatrix} N_{0w} & c_1 & < a_{0w1}, b_{0w1} > \\ c_2 & < a_{0w2}, b_{0w2} > \\ \vdots \\ c_n & < a_{0wn}, b_{0wn} > \end{bmatrix}$$

where $N_{0w}$ is the standard object, $c_j$ is the factor of $N_{0w}$, and $< a_{0wj}, b_{0wj} >$ is the value range of factor ($j = 1, 2, 3, \cdots, n$).
2.2.2. Establish a matter-element matrix of the controlled field \((R_p)\).

\[
R_p = \begin{bmatrix}
N_p & c_1 & < a_{p1}, b_{p1} > \\
& c_2 & < a_{p2}, b_{p2} > \\
& \vdots & \vdots \\
& c_n & < a_{pn}, b_{pn} >
\end{bmatrix}
\tag{11}
\]

where \(c_j\) is the factor of \(N_p\), and \(< a_{pj}, b_{pj} >\) is the largest value range of factor \((j = 1, 2, 3, \ldots, n)\).

2.2.3. Establish a matter-element matrix to be evaluated \((R_i)\).

\[
R_i = \begin{bmatrix}
N_i & c_i & v_{i1} \\
& c_i & v_{i2} \\
& \vdots & \vdots \\
& c_n & v_{in}
\end{bmatrix}
\tag{12}
\]

where \(N_i\) is the matter element to be evaluated \((i = 1, 2, 3, \ldots, m)\), \(c_i\) is the factor, and \(v_{ij}\) is the value of factor \((j = 1, 2, 3, \ldots, n)\).

2.2.4. Calculate the factor attribution degree \((k_{ij})\).

\[
k_{ij} = \begin{cases}
-1 & \rho(v_{ij}, v_{0ij}) - \rho(v_{ij}, v_{0ij}) = 0 \\
\frac{\rho(v_{ij}, v_{0ij}) - \rho(v_{ij}, v_{0ij})}{\rho(v_{ij}, v_{0ij}) - \rho(v_{ij}, v_{0ij})} & \rho(v_{ij}, v_{0ij}) - \rho(v_{ij}, v_{0ij}) \neq 0
\end{cases}
\tag{13}
\]

\[
\rho(v_{ij}, v_{0ij}) = \frac{1}{2}(a_{0ij} + b_{0ij}) - \frac{1}{2}(b_{0ij} - a_{0ij})
\tag{14}
\]

\[
\rho(v_{ij}, v_{pj}) = \frac{1}{2}(a_{0ij} + b_{0ij}) - \frac{1}{2}(b_{0ij} - a_{0ij})
\tag{15}
\]

\[
k_{i}(N_i) = \sum_{j=1}^{n} \omega_j k_{ij}(v_{ij})
\tag{16}
\]

where \(k_{ij}\) is the attribution degree of the number \(j\) factor of \(N_i\) about grade \(t\); \(k_{i}(N_i)\) is the attribution degree of \(N_i\); and \(\omega_j\) is the factor weight \((i = 1, 2, 3, \ldots, m; j = 1, 2, 3, \ldots, n; t = 1, 2, 3, \ldots, s)\).

2.2.5. Evaluation of the grades. If \(k_{i}(N_i) = \max\{k_{i}(N_i)\}_{i=1,2,\ldots,m} \), then, the grade of \(N_i\) is \(q\).

3. Engineering application

3.1. Overview of the research area

The tunnel project in this study area is an essential part of the Zheng-Wan high-speed railway and is located in Xiangyang City, Hubei Province, China. The total length of the tunnel in the study area is
4428m, and the maximum depth is 337m. It is a medium-cutting landform in the mountainous area of structural erosion. The tunnel is located in the fold belt of the Upper Yangtze Block, and the tunnel area is in the south wing of the inverted anticline.

Figure 1. Deformation of the surrounding. (a) Vault cracking. (b) A collapse in the tunnel.

The water elevation near the line is about 317m, which is about 30m lower than the elevation of the rail surface. The main types of groundwater are Quaternary pore diving, bedrock fissure water. The surrounding rock of the tunnel is mainly the sandy shale of the Silurian Xintan Formation and its uniaxial compressive strength is generally less than 25MPa. The surrounding rock mass is broken and is a typical weak surrounding rock. The tunnel is constructed by the bench method and is supported by a composite lining. During the tunnel construction process, significant deformation of the surrounding rock occurred, as shown in Figure 1.

3.2. Tunnel deformation risk classification

The deformation of the tunnel construction stage is mainly reflected by the deformation monitoring data, including the vertical deformation (Figure.1a) and horizontal convergence deformation (Figure.1b). According to the monitoring measurement data, this study selects the larger deformation grade in the vertical deformation and horizontal convergence deformation before the second lining as the tunnel deformation risk grade. The tunnel deformation risk grade is divided into five levels: I \((0<d\leq15)\), II \((15<d\leq30)\), III \((30<d\leq50)\), IV \((50<d\leq80)\), V \((d>80)\) and \(d\) (mm) is the maximum deformation of the tunnel.

3.3. Classification of factor indicators

The tunnel deformation is affected by many factors. According to the engineering geological conditions, surrounding rock strength \((R)\), rock mass integrity \((I)\), groundwater condition \((W)\), tunnel depth \((H)\), excavation method \((M)\), support strength \((S)\) and primary support closure time \((T)\) are selected as the main influencing factors of tunnel deformation. The tunnels in the study area are constructed by the bench method (Figure.2b) and the excavation methods are divided into five levels \((M_1: \text{full-face excavation}; M_2: \text{two-bench method}; M_3: \text{three-bench method}; M_4: \text{the three-bench and temporary inverted arch method}; M_5: \text{the three-bench seven-step method})\). The primary support of the tunnel is mainly composed of the composite lining (Figure.2d) and its strength is determined by the grade of surrounding rock. The grades of surrounding rock in the study area are IV and V, so the primary support strength is categorized into five grades \((I: V_2 \text{ composite lining}; II: V_1 \text{ composite lining}; III: IV_3 \text{ composite lining}; IV: IV_2 \text{ composite lining}; V: IV_1 \text{ composite lining})\). The factor grading standards are shown in Table 1.
Figure 2. Photographs of the construction sites. (a) Tunnel surrounding rock. (b) The construction of the bench method. (c) Groundwater status. (d) Composite lining.

Table 1. The factor grading standards.

| Grade | R   | I       | W       | H (m) | M | S       | T (d) |
|-------|-----|---------|---------|-------|---|---------|-------|
| 1     | Hard| Intact  | Dry     | 0-50  | M₁| I       | 0-25  |
| 2     | Slightly hard | Slightly intact | Slightly wet | 50-100 | M₂| II      | 25-50 |
| 3     | Medium | Medium  | Wet     | 100-150 | M₃| III     | 50-75 |
| 4     | Slightly weak | Slightly broken | Dripping | 150-200 | M₄| IV      | 75-100|
| 5     | weak | broken  | Linear water | 200-400 | M₅| V       | 100-150|

3.4. Weights calculation of factors

The GRA was used to calculate the weights of factors. Assign values to some factors according to Table 2. Data samples of the excavated section of the study area are selected, as shown in Table 3. The calculation result of factor weights is shown in Figure 3.

Table 2. Quantification of factors.

| Grade | R      | I       | W       | M   | S     | Assign range | Assign value |
|-------|--------|---------|---------|-----|-------|--------------|--------------|
| 1     | Hard   | Intact  | Dry     | M₃  | I     | 0–0.2       | 0.1          |
| 2     | Slightly hard | Slightly intact | Slightly wet | M₄  | II    | 0.2–0.4     | 0.3          |
| 3     | Medium | Medium  | Wet     | M₃  | III   | 0.4–0.6     | 0.5          |
| 4     | Slightly weak | Slightly broken | Dripping | M₃  | IV    | 0.6–0.8     | 0.7          |
| 5     | weak   | broken  | Linear water | M₃  | V     | 0.8–1       | 0.9          |
### Table 3. Sample data of the excavated section of the tunnel.

| No. | R  | I  | W  | H (m) | M  | S  | T (d) | D  |
|-----|----|----|----|-------|----|----|-------|----|
| 1   | 0.3| 0.3| 0.1| 240   | 0.3| 0.9| 27    | 1  |
| 2   | 0.5| 0.3| 0.1| 242   | 0.3| 0.9| 43    | 1  |
| 3   | 0.5| 0.3| 0.1| 244   | 0.3| 0.7| 38    | 1  |
| 4   | 0.5| 0.3| 0.1| 242.4 | 0.3| 0.7| 22    | 1  |
| 5   | 0.3| 0.3| 0.1| 240.8 | 0.3| 0.7| 26    | 1  |
| 6   | 0.5| 0.3| 0.5| 240   | 0.3| 0.7| 24    | 2  |
| 7   | 0.5| 0.5| 0.5| 236   | 0.7| 0.9| 49    | 2  |
| 8   | 0.5| 0.7| 0.7| 101.5 | 0.1| 0.7| 45    | 3  |
| 9   | 0.7| 0.7| 0.7| 96.5  | 0.1| 0.7| 41    | 3  |
| 10  | 0.5| 0.7| 0.7| 90.5  | 0.1| 0.7| 49    | 3  |
| 11  | 0.5| 0.5| 0.3| 93    | 0.1| 0.9| 59    | 1  |
| 12  | 0.7| 0.7| 0.7| 81.5  | 0.1| 0.7| 75    | 3  |
| 13  | 0.5| 0.7| 0.3| 88.5  | 0.1| 0.9| 40    | 2  |
| 14  | 0.5| 0.7| 0.3| 84    | 0.1| 0.9| 83    | 3  |
| 15  | 0.7| 0.7| 0.5| 75    | 0.1| 0.9| 81    | 5  |
| 16  | 0.7| 0.7| 0.5| 73.5  | 0.1| 0.5| 79    | 3  |
| 17  | 0.7| 0.5| 0.5| 70.5  | 0.1| 0.5| 77    | 3  |
| 18  | 0.7| 0.9| 0.5| 68    | 0.1| 0.5| 30    | 3  |
| 19  | 0.7| 0.7| 0.7| 78.5  | 0.1| 0.9| 96    | 3  |
| 20  | 0.7| 0.9| 0.5| 65.5  | 0.1| 0.5| 100   | 4  |
| 21  | 0.7| 0.9| 0.5| 63    | 0.1| 0.5| 101   | 5  |
| 22  | 0.7| 0.9| 0.5| 63    | 0.1| 0.3| 68    | 5  |
| 23  | 0.7| 0.9| 0.5| 63    | 0.1| 0.3| 106   | 5  |
| 24  | 0.7| 0.9| 0.5| 63.5  | 0.1| 0.3| 59    | 5  |
| 25  | 0.7| 0.7| 0.7| 75.5  | 0.1| 0.9| 60    | 3  |
| 26  | 0.5| 0.7| 0.3| 69.5  | 0.1| 0.9| 73    | 2  |
| 27  | 0.5| 0.7| 0.7| 93.5  | 0.1| 0.7| 49    | 2  |
| 28  | 0.5| 0.7| 0.7| 66    | 0.1| 0.9| 38    | 4  |
| 29  | 0.5| 0.7| 0.5| 66    | 0.1| 0.9| 81    | 3  |
| 30  | 0.5| 0.5| 0.3| 181.5 | 0.1| 0.7| 23    | 1  |
| 31  | 0.5| 0.5| 0.3| 182.5 | 0.1| 0.7| 26    | 1  |
| 32  | 0.3| 0.5| 0.3| 183   | 0.1| 0.7| 20    | 1  |
| 33  | 0.5| 0.5| 0.3| 181.5 | 0.1| 0.7| 28    | 1  |
| 34  | 0.5| 0.5| 0.3| 171   | 0.1| 0.7| 33    | 2  |
| 35  | 0.3| 0.3| 0.1| 152.5 | 0.1| 0.9| 27    | 1  |
| 36  | 0.5| 0.3| 0.1| 150   | 0.1| 0.9| 22    | 1  |
| 37  | 0.5| 0.3| 0.1| 148   | 0.1| 0.9| 28    | 1  |
| 38  | 0.3| 0.3| 0.1| 143   | 0.3| 0.7| 26    | 1  |

Note: *D*- The deformation risk grade of the soft rock tunnel.

![Figure 3. The calculation result of factor weights.](image-url)
3.5. *Extensive prediction model for tunnel deformation*

The classical domain of the factors of the tunnel deformation risk grade is shown in Table 4.

**Table 4.** The classical domain of the factors of the tunnel deformation risk grade.

| Factors | Range | I  | II | III | IV | V  | ω (%) |
|---------|-------|----|----|-----|----|----|-------|
| R       | 0~1   | 0~0.2 | 0.2~0.4 | 0.4~0.6 | 0.6~0.8 | 0.8~1 | 15.16  |
| I       | 0~1   | 0~0.2 | 0.2~0.4 | 0.4~0.6 | 0.6~0.8 | 0.8~1 | 16.72  |
| W       | 0~1   | 0~0.2 | 0.2~0.4 | 0.4~0.6 | 0.6~0.8 | 0.8~1 | 16.17  |
| H (m)   | 0~400 | 0~50 | 50~100 | 100~150 | 150~200 | 200~400 | 10.33  |
| M       | 0~1   | 0~0.2 | 0.2~0.4 | 0.4~0.6 | 0.6~0.8 | 0.8~1 | 11.03  |
| S       | 0~1   | 0~0.2 | 0.2~0.4 | 0.4~0.6 | 0.6~0.8 | 0.8~1 | 15.43  |
| T (d)   | 0~150 | 0~25 | 25~50 | 50~75 | 75~100 | 100~150 | 16.17  |

Note: ω - The factor weights calculated by GRA.

3.6. *Engineering verification*

The prediction model of the tunnel deformation risk was used to predict the deformation risk grade of the six tunnel sections of the study area. The predicted results are compared with the actual deformation risk grades, as shown in Eq. 17 and Table 5.

\[
\begin{align*}
\text{Grade} & = \begin{cases} 
2 & \text{if } 0.6942 > 1 \text{ or } 0.3901 > 1 \text{ or } 0.1397 > 1 \\
2 & \text{if } 0.2538 > 1 \text{ or } 0.9682 > 1 \text{ or } 0.5066 > 1 \\
3 & \text{if } 0.3721 > 1 \text{ or } 0.6941 > 1 \text{ or } 0.8539 > 1 \\
2 & \text{if } 0.1828 > 1 \text{ or } 0.4383 > 1 \text{ or } 0.0415 > 1 \\
4 & \text{if } 0.0675 > 1 \text{ or } 0.2613 > 1 \text{ or } 0.2305 > 1 \\
5 & \text{if } 0.569 > 1 \text{ or } 0.1995 > 1 \text{ or } 0.3757 > 1 
\end{cases}
\end{align*}
\]

**Table 5.** Comprehensive evaluation results.

| Samples | R | I | W | H(m) | M | S | T(d) | Q | Q* |
|---------|---|---|---|------|---|---|------|---|----|
| 1       | 0.3 | 0.3 | 0.1 | 141  | 0.3 | 0.3 | 21   | 2 | 2  |
| 2       | 0.5 | 0.5 | 0.3 | 238.4| 0.3 | 0.7 | 24   | 2 | 2  |
| 3       | 0.5 | 0.5 | 0.7 | 87.5 | 0.1 | 0.7 | 32   | 3 | 3  |
| 4       | 0.5 | 0.3 | 0.3 | 79.5 | 0.1 | 0.9 | 80   | 2 | 2  |
| 5       | 0.9 | 0.7 | 0.5 | 64.5 | 0.1 | 0.3 | 52   | 4 | 4  |
| 6       | 0.9 | 0.9 | 0.7 | 64.5 | 0.1 | 0.3 | 57   | 5 | 5  |

Note: Q - Actual grade. Q* - Prediction grade.

4. **Conclusion**

This study used the tunnel engineering geological information and monitoring measurement data to comprehensively analyze the subjective and objective factors affecting the soft rock tunnel deformation and used the GRA to calculate the factor weights. Rock mass integrity and primary support closure time have a significant influence on the tunnel deformation risk grade, and their weights are 16.72% and 16.17%, respectively. It can be seen that during tunnel construction, the primary support should be closed as soon as possible which is very important for controlling tunnel deformation. For the surrounding rock with poor integrity, the primary support strength should be enhanced. The prediction model for deformation risk grade of soft rock tunnel was established using extensive theory and successfully predicted the tunnel deformation risk grade with high accuracy. This
study has important guiding significance for the treatment of large deformation of tunnels and the optimization of construction support technology.

Acknowledgments
Much of the work presented in this paper was supported by the National Natural Science Foundations of China (grant numbers 40902084, 41772298, 51379112 and 51422904) and the program for Outstanding Ph.D. candidate of Shandong University (Grant 201413170). The authors would like to express appreciation to the reviewers for their valuable comments and suggestions that helped improve the quality of our paper.

References
[1] Bian K., Liu J., Liu Z., Liu S., Ai F., Zheng, X., Ni, S., Zhang, W. Mechanisms of large deformation in soft rock tunnels: a case study of huangjiazhai tunnel. Bulletin of Engineering Geology and the Environment, 2017, 78(1): 431–444.
[2] Hu D., Huang X.L., He J. Prediction of deformation of tunnel surrounding rock based on improved Grey Theory Model. Highway Engineering, 2017, 42(5), 72-75.
[3] Wang H. J., Dyskin A.V., Hsieh A., Doght P. The mechanism of the deformation memory effect and the deformation rate analysis in layered rock in the low stress region. Computers and Geotechnics, 2012, 44: 83–92.
[4] Lee Y.K., Pietruszczak S. Application of critical plane approach to the prediction of strength anisotropy in transversely isotropic rock masses. International Journal of Rock Mechanics and Mining Sciences, 2008, 45: 513–523.
[5] Cui Z.D., Liu D.A., Wu F.Q. Influence of dip directions on the main deformation region of layered rock around tunnels. Bulletin of Engineering Geology and the Environment, 2014,73(2): 441-450.
[6] Xue Y., Zhang X., Li S., Qiu D., Su M., Li L., Li Z., Tao Y. Analysis of factors influencing tunnel deformation in loess deposits by data mining: a deformation prediction model. Engineering Geology, 2018, 232: 94-103.
[7] Chen D.F., Feng X.T., Xu D.P., Jiang Q., Yang C.X., Yao P.P. Use of an improved ANN model to predict collapse depth of thin and extremely thin layered rock strata during tunnelling. Tunnelling and Underground Space Technology, 2016, 51: 372-386.
[8] Xu J.B., Chen J.P., Wu S.L., Pan Y.H., Wang W., Luo Q.Q. Prediction of Large Deformation Behavior in Tunnels Based on AHP–FUZZY Method and Numerical Simulation Method. Geotechnical and Geological Engineering, 2018, 36(1): 151-163.
[9] Deng J.L. Control Problems of Grey Systems. Systems Control Letters, 1982, 1(5): 288-294.
[10] Cai W., 1999. The extension theories and their application. Science Bulletin, 44 (7), 673-682.
[11] Wang M., Xu X., Li J., Jin J., Shen F. A novel model of set pair analysis coupled with extenics for evaluation of surrounding rock stability. Mathematical Problems in Engineering, 2015, 1: 1-9.
[12] Tu W.F., Li L.P., Li S.C., Shi S.S., Zhou Z.Q., Chen D.Y. Research on the application of dynamic weighting on the rock mass quality rating. Arabian Journal of Geosciences, 2019, 12 (87): 1-9.