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Selection of Karst treatment methods based on fuzzy theory

Helin Fu[1*], Jie Li[1]

(1 Central South University , Changsha 410075 , Hunan , China)

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ABSTRACT: The complexity and variability of Karst development in China's wide range of Karst areas present significant challenges and risks for tunnel construction and safety,therefore, effective treatment of tunnel Karst is of utmost importance. In this study, the theory of fuzzy mathematics was applied to evaluate and compare Karst tunnel treatment schemes using an evaluation index system. The comparison judgment matrix and eigenvalue method were used to determine the weights of evaluation indexes, and the fuzzy comprehensive evaluation model was employed to identify the optimal or combined treatment options for Karst treatment schemes. The proposed model was then applied to the DK248+480 ~ DK248+495 section of No.2 tunnel in Wuling mountain, and the results demonstrated that the model provides reliable guidance for tunnel Karst treatment that is both safe and reasonable. This research provides valuable technical guidance and practical experience for similar engineering projects.

Key words:tunnel Karst treatment; weight; membership degree; fuzzy comprehensive evaluation model

I. INTRODUCTION

During tunnel construction in Karst areas, when encountering Karst ahead of the tunnel through advanced geological exploration, some severe catastrophes could occur, such as tunnel collapse and water inrush (Fan et al,. 2018; Li et al,. 2019; Lyu et al,. 2020), thus the engineering and hydrogeological characteristics of the Karst should be determined first. Based on these characteristics, targeted pre-treatment or post-excavation treatment strategies should be developed.

In terms of the Karst disposal, Shen et al.(2022) proposed a refined geophysical prospecting scheme to probe the Karst environment around the Nanshibi Tunnel and developed a series of treatments, including surrounding rock grouting, lining replacement and adding inverted arch.Aiming at the water inrush and ground collapse during the tunnel excavation in Karst area, some comprehensive countermeasures and waterproofing strategy was proposed by Kang et al. (2021), such as cavern filling and grouting. According to the geological conditionand position relationship between Karst caverns and tunnel, Li et al. (2021) put forward a series of support reinforcement design to prevent tunnel collapse or water inrush, such as increasing the thickness of tunnel face, second lining and reserved deformation. Similarly, Zheng et al. (2021) reported three giant Karst caverns encountered by Yujingshan tunnel, six treatments were developed, which are cavern infilling, underground river diversion and sealing, bench cut excavation, cavern roof stabilization, tunnel sidewall and floor reinforcement, in-tunnel bridge construction.In addition, the excavation speed also will affect the stability of tunnel near the Karst caverns (Liu et al., 2021).

In terms of evaluation methods, Magdalene and Alexander (1995) used weighted overlay analysis in Arcgis to analyze the related factors of karst collapse development: karst type, soil thickness, distance from geological structure and distance from surface water system.Tipping (2002) established an evaluation geographic information system (GIS) model that quantified the bedrock geological conditions, bedrock overburden thickness, karst collapse density and neighborhood effects, and evaluated the karst collapse risk in southeastern Minnesota. Katarina et al. (2008) used spatial analysis statistical methods such as K-function, weighted regression and inverse distance difference value to evaluate the impact of natural and human factors on karst collapse in Frederick Valley karst area.In summary, most of the existing literature only assesses karst risk, but there is less selection and evaluation research of karst disposal measures.

Based on the three basic principles of ensuring construction safety, structural stability and safe operation in tunnel field.This paper evaluates and selects six common schemes of karst treatment technology (A. Strengthening the lining parameters and radial pre-grouting or curtain grouting; B. Karst backfilling or enhancing drainage; C. Base pile group steel pipe reinforcement scheme; D. Advance pre-grouting and advance pipe shed; E. combination of support beam and span plate scheme; F. Bypassing the karst cavernaccording to the development of karst by using fuzzy comprehensive evaluation model, so as to find the optimal scheme for tunnel karst treatment.

II. CONSTRUCTION OF FUZZY MODEL FOR KARST TREATMENT METHOD SELECTION

2.1 Determination of evaluation index system

Based on a large number of karst engineering examples, and comprehensively referring to existing research results, the treatment of karst tunnels should meet the requirements of technical feasibility and economic rationality, and also pay attention to reducing environmental disturbance and adverse effects. According to this, the evaluation index system of tunnel karst treatment technology was determined, as shown inFig. 1, in which, u_1, u_2, u_3, u_4 are the first-level evaluation indexes, $u_{1,1}$, $u_{1,2}$,$u_{1,3}$,$u_{1,4}$,$u_{1,5}$,$u_{2,1}$,$u_{2,2}$,$u_{2,3}$,$u_{3,1}$,$u_{4,1}$ are the second-level evaluation indexes. In terms of the second-level evaluation indexes, $u_{1,1}$, $u_{1,2}$are quantitative analysis indexes, and others are qualitative analysis indexes.

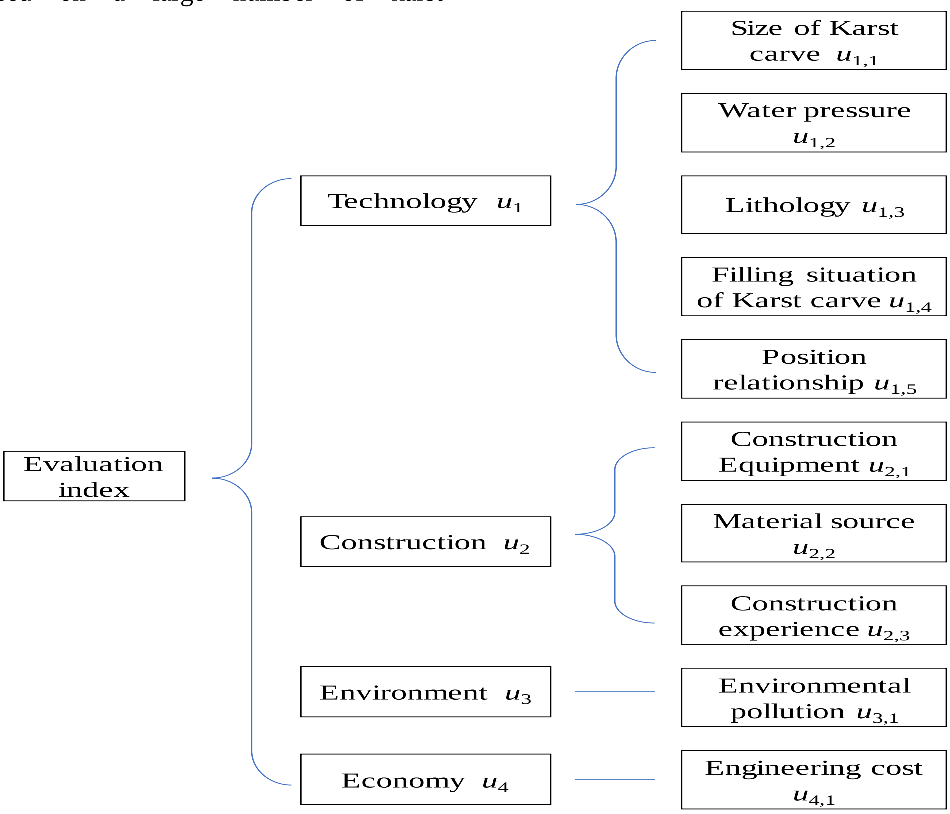

Fig. 1 The evaluation index system of tunnel Karst treatment technology

2.2 Determination of evaluation index weight

The eigenvalue method was used to determine the weights of evaluation indexes. Taking the first-level evaluation index as an example, the relative importance between indexes was determinedaccording to expert assessment and theoretical experience. u_1: u_2=1:1 means that the index one and index two are equally important for the objective; while u_1: u_2=3:1 means that index one is more important than index two. According to the reciprocal scale method, a judgment matrix A was constructed based on the scale values between pairs of evaluation indexes; where $a_{ij}=u_i: u_j$, $a_{ij}=1/a_{ji}$, $A=(a_{ij})_{n\times n}, a_{ij}>0$, as shown in

Table 1. Similarly, the judgment matrixB_1 of the second-level evaluation index regarding u_1 is shown

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in

Table 2, and judgment matrixB_2 of the second-level evaluation index regarding u_1 is shown in

Table 3.

Table 1Matrix A for the first-level evaluation index judgment

Evaluation index	u_1	u_2	u_3	u_4
u_1	1	3	5	2
u_2	1/3	1	2	1
u_3	1/5	1/2	1	1/2
u_4	1/2	1	2	1

Table 2Matrix B_1 for the second-level evaluation index judgment

Evaluation index	$u_{1,1}$	$u_{1,2}$	$u_{1,3}$	$u_{1,4}$	$u_{1,5}$
$u_{1,1}$	1	7	4	3	4
$u_{1,2}$	1/7	1	1/2	1/3	1/2
$u_{1,3}$	1/4	2	1	2	1
$u_{1,4}$	1/3	3	1/2	1	2
$u_{1,5}$	1/4	2	1	1/2	1

Table 3Matrix B_2 for the second-level evaluation index judgment

Evaluation index	$u_{2,1}$	$u_{2,2}$	$u_{2,3}$
$u_{2,1}$	1	3	5
$u_{2,2}$	1/3	1	2
$u_{2,3}$	1/5	1/2	1

Usually, the judgment matrix obtained from practice does not satisfy transitivity and consistency, so a consistency test is needed. The expression of the consistency index CI is shown in Eq. (1), where λ_{max} is the maximum eigenvalue of the judgment matrix, n is the order of the judgment matrix, and CI approaches zero as consistency improves, and vice versa. In addition, the average random consistency index RI is used to measure the consistency degree of a random judgment matrix, which depends on n. Generally, RI increases as n increases, the values are shown in

Table 4.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

Table 4 Value of the mean random consistency indexRI

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.24	1.32	1.41	1.45

By combining CI and RI, the random consistency ratio CR=CI/RI can be obtained. Generally, CR<0.1 indicates that the judgment matrix is consistent. The calculated values of CR for the three judgment matrices (A, B_1, B_2) are shown in

Table 5, in which W_i(i=1,2 3)is the weight vector, whose value is the normalized eigenvector corresponding to the maximum eigenvalue of the judgment matrix.

Table 5Value of CRwith respect to each judgment matrix

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Judgment matrix	W_i	λ_{max}	CI	RI	CR
A	(0.4965,0.1915,0.1,0.212)	4.0155	0.0052	0.89	0.006
B_1	(0.4922,0.0635,0.1649,0.1610,0.1184)	5.1854	0.04635	1.12	0.041
B_2	(0.6483,0.2297,0.122)	3.0037	0.0019	0.52	0.004

According to the data in

Table 5, the weight vector of the 10 second-level evaluation indexes is given by Eq. (2).

$$w=(0.4965W_2, 0.1915W_3, 0.1, 0.212) = (0.244, 0.032, 0.082, 0.080, 0.059, 0.124, 0.044, 0.023, 0.1, 0.212) \quad (2)$$

(2)

2.3 Determination of membership of qualitative analysis indexes

For the qualitative analysis indexes, the engineering analogy method was adopted, and the comprehensive value of the evaluation vector corresponding to the tunnel karst treatment scheme was obtained based on the scores of multiple experts.

(1) Determination of evaluation level

In this paper, the evaluation set consists of five elements, i.e., V =(V_1, V_2, V_3, V_4, V_5), which are defined as the applicability degrees (very suitable, suitable, general, unsuitable, very unsuitable). The domain of the ratingscore is in [0,1], and the ratingscore criterions of each element are 0.9，0.7，0.5，0.3，0.1, respectively.

(2) Determination of experts

In this paper, according to the requirements of the actual karst tunnel engineering example, five experts were selected. The experts were personnel who had been engaged in tunnel construction for more than 10 years and had senior titles. According to the different influences of each person on the final decision result, a weight value was assigned to each person, as shown in Eq. (3). And the sum of weight values in Eq. (3) is equal to 1.

$$W_{\exp} = (W_{\exp 1}, W_{\exp 2}, W_{\exp 3}, W_{\exp 4}, W_{\exp 5}) \quad (3)$$

(3) Determination of membership

Assuming that the rating score of the jth expert for the ith index regarding the kth tunnel karst treatment scheme is r_{ijk}, then the evaluation matrix R_i of the ith index is obtained as shown in Eq. (4).

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1k} & \cdots & r_{i16} \\ r_{i21} & r_{i22} & \cdots & r_{i2k} & \cdots & r_{i26} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{ij1} & r_{ij2} & \cdots & r_{ijk} & \cdots & r_{ij6} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{i51} & r_{i52} & \cdots & r_{i5k} & \cdots & r_{i56} \end{bmatrix} \quad (4)$$

Considering the weight coefficients of each expert, the evaluation vector Mi of index i regarding the karst treatment scheme is $M_i=W_{exp}\cdot R_i=(m_{i1},m_{i2},m_{i3},m_{i4},m_{i5},m_{i6})$. Similarly, the evaluation vectors of all second-level evaluation indexes can be obtained as shown in Eq. (5).

$$M = (M_{u1,2}^T, M_{u1,3}^T, M_{u1,4}^T, M_{u2,1}^T, M_{u2,2}^T, M_{u2,3}^T, M_{u3,1}^T, M_{u4,1}^T) \quad (5)$$

2.4 Determination of membership of quantitative analysis indexes

For the quantitative analysis indexes ($u_{1,1}$ and $u_{1,2}$), a fuzzy variable evaluation model is adopted.According to the form and scale of karst, it can be divided into four categories: cavern type, fissure type, pipe type, and large karst cavern type; according to the water pressure of karst tunnel, it also can be divided into four levels: P=0MPa, P=0~0.5MPa, P=0.5~1MPa, P>1MPa. The applicability conditions of sixtreatment techniques(A. Strengthening the lining parameters and radial pre-grouting or curtain grouting; B. Karst backfilling or enhancing drainage; C. Base pile group steel pipe reinforcement scheme; D. Advance pre-grouting and advance pipe shed; E. combination of support beam and span plate scheme; F. Bypassing the karst cavernfor different categories of karst with different sizes and water pressures are shown in

Table 6.

Table 6 Applicable conditions of Karst treatment techniques

Categories of karst	Treatment techniques	Applicability conditions	Water pressure (MPa)

		(Karst section area/m^2)	
cavern type	scheme A	<1	<0.3
fissure type	scheme B	1~3	0.3～0.5
pipe type	scheme C and D	3～10	0.5～1
large karst cavern type	scheme E and F	>10	>1

As an example of quantitative analysis index $u_{1,1}$, in the fuzzy variable evaluation model, let the $u_{1,1}$ be described by cross-sectional area of Karst, and set its domain as 0~100m^2. Then the membership degree of attractivenessfor scheme A as $\mu_A(u_{1,1})$, and the membership degree of repulsiveness for scheme A as $\mu_{AR}(u_{1,1})$ Let the difference between $\mu_A(u_{1,1})$ and $\mu_{AR}(u_{1,1})$ be the relative difference degree $D_A(u_{1,1})$, as shown in Eq. (6).

$$D_A(u_{1,1}) = \mu_A(u_{1,1}) - \mu_{AR}(u_{1,1}) \quad (6)$$

Obviously, $D_A(u_{1,1}) \in [-1,1]$, and the $\mu_A(u_{1,1})$ can be expressed as Eq. (7).

$$\mu_A(u_{1,1}) = (1 + D_A(u_{1,1}))/2 \quad (7)$$

In terms of $u_{1,1}$, the applicable condition of Scheme A is its attraction domain, and the upper or lower limit of the attraction domain extending to the applicable condition of adjacent schemes is the scope domain. $\mu_A(u_{1,1}) > \mu_{AR}(u_{1,1})$ when $u_{1,1} \in (a,b)$, thus (a, b) is regarded as the attraction domain of Scheme A. $\mu_A(u_{1,1}) < \mu_{AR}(u_{1,1})$ when $u_{1,1} \in (c,a) \cup (b,d)$, thus (c, a) and (b, d) is regarded as the repulsiveness domain; $\mu_A(u_{1,1})=0$ and $\mu_{AR}(u_{1,1})=1$ when $u_{1,1} \notin (c,d)$, thus (c, d) is the upper and lower limit interval of Scheme A, which is called the scope domain. The specific relationship is shown inFig. 2.

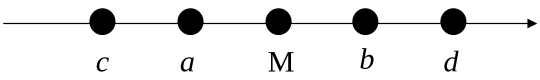

Fig. 2 Domain of Scheme A regarding a certain index

In Fig. 2, point M is the midpoint of the interval (a, b). In this paper, the applicable condition of each scheme is the respective attraction region, and the scope domain is bounded by the upper or lower limit of applicable condition of the adjacent scheme. Taking the Scheme B as an example, its attraction domain is (1, 3), and the scope domain is (0, 10). According to the relationship between the attraction domain and the repulsiveness domain, the relative difference degree$D_A(u_{1,1})$ can be obtained.

(1) When $u_{1,1}$ is on the left side of point M

$$\begin{cases} D_A(u_{1,1}) = \dfrac{u_{1,1}-a}{M-a} & u_{1,1} \in (a,\mathrm{M}) \\ D_A(u_{1,1}) = -\dfrac{u_{1,1}-a}{c-a} & u_{1,1} \in (c,a) \end{cases} \quad (8)$$

(2) When $u_{1,1}$ is on the right side of point M

$$\begin{cases} D_A(u_{1,1}) = \dfrac{u_{1,1}-b}{M-b} & u_{1,1} \in (\mathrm{M},b) \\ D_A(u_{1,1}) = -\dfrac{u_{1,1}-a}{d-b} & u_{1,1} \in (b,d) \end{cases} \quad (9)$$

(3) When $u_{1,1}$ is not in the range (c, d)

$$D_A(u_{1,1}) = -1 \qquad u_{1,1} \notin (c,d) \quad (10)$$

According to Eq. (8), Eq. (9), Eq. (10), the relative difference degree of $u_{1,1}$ for Scheme A is calculated, and then the membership degree of $u_{1,1}$ for Scheme A is achieved from formula (7). Thus, the evaluation vector$M_{u1,1}$ of $u_{1,1}$ can be obtained.

Similarly, the domain of the $u_{1,2}$ is 0~3MPa. According to the formula (7)~(10), the membership degree of $u_{1,2}$ for each scheme is achieved, and the evaluation vector $M_{u1,2}$ of the index$u_{1,2}$canalso be obtained.

2.5Fuzzy comprehensive evaluation

The weight vector wof the second-level evaluation indexesregarding the Karst treatment scheme and the evaluation vector $M=(M^T_{u1,1}, M^T_{u1,2}, M^T_{u1,3}, M^T_{u1,4}, M^T_{u1,5}, M^T_{u2,1}, M^T_{u2,2}, M^T_{u2,3}, M^T_{u3,1}, M^T_{u4,1})$ of each index are obtained. Therefore, the fuzzy relation matrix is expressed as Eq. (11).

$$B = M \cdot w^T \quad (11)$$

According to the maximum membership principle, the scheme with the maximum value in vector B is the optimal karst treatment scheme.

III. ENGINEERING CASE ANALYSIS

3.1 Overview of engineering geology

The No.2 tunnel in Wuling mountain is a double-track railway tunnel located in Changde City, Hunan Province, China. It belongs to a low mountain plateau karst depression area and Yuanjiang River system. The ground elevation is generally 390~480 m, and the tunnel site area is characterized by dense vegetation, relatively gentle natural slope. In addition, the tunnel site area has developed someKarst features, such as funnels, sinkholes, caverns, springs and conduit flows. The tunnel starts at DK248+250 and ends at DK248+495 with a total length of 245 m. The maximum burial depth is about 35 m. The entire tunnel belongs to an area with strong karst development, and the longitudinal section diagram is shown in Fig. 3.

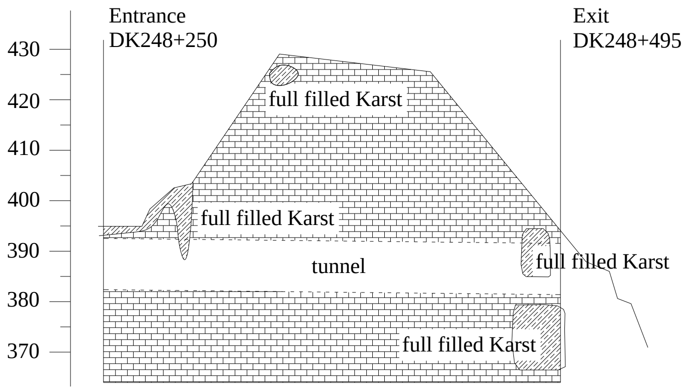

Fig. 3 longitudinal sectional profile of the No.2 tunnel in Wuling mountain

3.2 Analysis and selection of Karst treatment scheme

The section DK248+480～DK248+495 of the No.2 tunnel in Wuling mountain is selected for research regarding Karst treatment scheme. The Karst in this section is located at the base, 3~17m below the excavation surface of the middle terrace, about 15m along the tunnel axis, and about 2~8m in transverse width. The Karst is fully filled with clay mixed with gravelly soil, and the clay is mainly soft plastic soil.

5 experts are invited to evaluate the qualitative analysis indexes, the weight coefficient of each expert is equal, then the evaluation vector of index i is M_i, which is expressed as Eq. (12). 5 experts scored according to the engineering geological conditions and engineering experience of the research section, and obtained the evaluation vector group of all second-level qualitative indexes,expressed as Eq. (13).

$$M_i = \frac{1}{5}\left(\sum_{j=1}^{5} r_{ij1}, \sum_{j=1}^{5} r_{ij2}, \sum_{j=1}^{5} r_{ij3}, \sum_{j=1}^{5} r_{ij4}, \sum_{j=1}^{5} r_{ij5}, \sum_{j=1}^{5} r_{ij6},\right) \tag{12}$$

$$M = \begin{bmatrix} 0.85 & 0.72 & 0.55 & 0.63 & 0.73 & 0.75 & 0.62 & 0.65 \\ 0.92 & 0.53 & 0.52 & 0.61 & 0.65 & 0.73 & 0.52 & 0.67 \\ 0.73 & 0.82 & 0.83 & 0.56 & 0.63 & 0.57 & 0.55 & 0.53 \\ 0.75 & 0.62 & 0.53 & 0.51 & 0.65 & 0.61 & 0.55 & 0.57 \\ 0.65 & 0.53 & 0.65 & 0.41 & 0.55 & 0.32 & 0.42 & 0.32 \\ 0.55 & 0.38 & 0.28 & 0.37 & 0.53 & 0.29 & 0.35 & 0.18 \end{bmatrix} \tag{13}$$

In the evaluation of quantitative analysis indexes $u_{1,1}$ and $u_{1,2}$, the average Karst section area is taken as 5m by referring the engineering geological data of the research section,the original water pressure is 0.7MPa. According to the definition of relative difference degree and

Table 6, the upper and lower limits of the

Table 7 and

attraction domainand scope domainof each scheme are obtained, as shown in

Table 8.

Table 7 Attraction domain of each scheme in terms of $u_{1,1}$ and $u_{1,2}$

Index	Scheme A	Scheme B	Scheme C	Scheme D	Scheme E	Scheme F
$u_{1,1}$	(0,1)	(1,3)	(3,10)	(3,10)	(10,100)	(10,100)
$u_{1,2}$	(0,0.3)	(0.3,0.5)	(0.5,1)	(0.5,1)	(1,3)	(1,3)

Table 8 Scope domain of each scheme in terms of $u_{1,1}$ and $u_{1,2}$

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Index	Scheme A	Scheme B	Scheme C	Scheme D	Scheme E	Scheme F
$u_{1,1}$	(0,3)	(0,10)	(1,100)	(1,100)	(3,100)	(3,100)
$u_{1,2}$	(0,0.5)	(0,1)	(0.3,3)	(0.3,3)	(0.5,3)	(0.5,3)

According to Eq. (8), Eq. (9),Eq. (10), the relative difference degree of $u_{1,1}$ and $u_{1,2}$regarding each scheme are as follow.

$$D(u_{1,1}) = (-1, -\frac{4}{7}, \frac{4}{7}, \frac{4}{7}, -\frac{5}{7}, -\frac{5}{7}) \quad (14)$$

$$D(u_{1,2}) = (-1, -\frac{4}{5}, \frac{4}{5}, \frac{4}{5}, -\frac{3}{5}, -\frac{3}{5}) \quad (15)$$

According to Eq. (7), the evaluation vectors of indexes$u_{1,1}$ and $u_{1,2}$regarding each scheme are as follow.

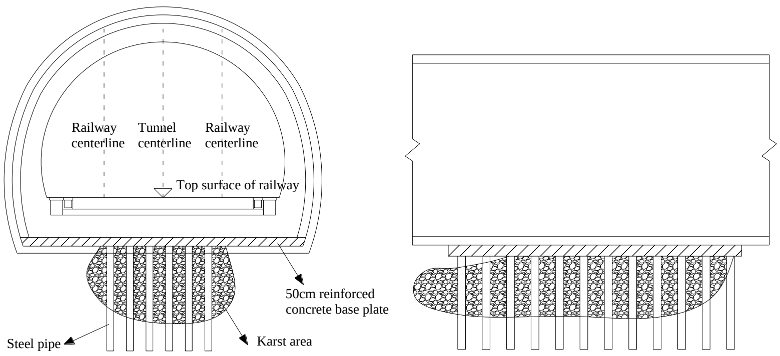
$$M_{u1,1} = (0, 0.21, 0.79, 0.79, 0.14, 0.14) \quad (16)$$

$$M_{u1,2} = (0, 0.1, 0.9, 0.9, 0.2, 0.2) \quad (17)$$

By combining Eq. (13), Eq. (16),Eq. (17), the evaluation vector group of all indexes can be achieved, and then the corresponding fuzzy relation matrixB can be deduced by Eq. (11), the results are shown in Eq. (18). According to the principle of maximum subordination, the scheme C (base pile group steel pipe reinforcement scheme) is selected as the optimalKarst treatment method for the section DK248+480～DK248+495 of the No.2 tunnel in Wuling mountain.

3.3 Karst treatment effect and construction process

For the section DK248+480～DK248+495 of No.2 tunnel in Wuling mountain. Because of the exist of Karst cavern beneath the tunnel, the rock mass under the invert is small in thickness, and the bearing capacity is less than 80kPa. The combination of Φ194 steel pipe pile and cement slurry reinforcementgroutingscheme is adopted, the reinforcement range depends on the size ofKarst cavern, the steel pipe piles is arranged in a quincunx layout with spacing of 0.6 × 0.6m, which is filled with M10 cement mortar, it should be noted that the depth of pile into bedrock shall not be less than 1m. Before the construction of inverted arch, the pile top is paved with C20 reinforced concrete with a thickness of 50cm, and the reinforcement mesh is set inside; Other supporting measures shall be implemented according to the original plan. The specific scheme layout is shown inFig. 4. After treatment, there is no basement collapse or large deformation in the section DK248+480 ～ DK248+495 of tunnel. The effect is ideal and the excavation of this section is smooth.



(a)Cross section (b) Longitudinal section

Fig. 4 Layout of base pile group steel pipe reinforcement scheme

IV. CONCLUSION

(1) In this paper, the fuzzy comprehensive evaluation model is used to evaluate and compare the treatment schemes of tunnel Karst. The evaluation index system includes quantitative analysis indexes and qualitative analysis indexes. The weight is used to describe the relationship of indexes, and the membership degree is used to describe the impact of each index on the treatment scheme selection. It not only takes into account experts and previous engineering experience, but also uses fuzzy theory to provide rational support, whichguarantees the reliability of the evaluation results.

(2) The weight of the index is determined by eigenvalue method, and the membership degree of the index is determined by the engineering analogy method and the fuzzy variable evaluation model. Then, according to the principle of maximum membership degree, the optimal karst treatment scheme or several joint treatment schemes are found, which is more scientific and reasonable than the previous subjective judgment.

(3) The proposed model has good guidance and reference significance for both the Karst treatment

and the evaluation, and it is also worthy of further study on other engineering problems.

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