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Research on an Evaluation Method for the Adaptability of TBM Tunnelling

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Abstract: When a TBM carries out tunnelling in complex strata, there is often low tunnelling efficiency and an increase in tunnelling costs due to the improper selection of tunnelling parameters, the wrong estimation of geological conditions, or adverse geology, so it is necessary to evaluate the tunnelling adaptability of TBM construction. In this paper, based on hydraulic engineering in Xinjiang, 11 evaluation indexes of TBM tunnelling adaptability are determined by comprehensively considering the influence of tunnelling parameters, geological conditions, and adverse geological factors on TBM tunnelling adaptability. After that, the membership function of each evaluation index is determined by referring to the existing research results and fuzzy mathematics method, and the weight of each evaluation index is determined and adjusted by the analytic hierarchy process (AHP)–entropy weight (EW) method. Finally, the adaptability evaluation method and evaluation model of TBM tunnelling are put forward. The TBM tunnelling adaptability evaluation model proposed in this paper is verified by relying on the actual situation of three interval tunnels in the project, and good effects are obtained. This study can provide a reference for the evaluation of TBM tunnelling adaptability in similar strata.

Keywords: TBM; tunnelling adaptability; AHP–EW method; evaluation method; evaluation model

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1. Introduction

Due to the requirements of infrastructure construction and the implementation of the "One Belt, One Road" strategy, large-scale water diversion, railway, and highway tunnel projects are becoming more and more common in China. With the increase in buried depth, longer tunnelling distances, and more complex geological conditions, the larger section size, more-demanding construction period, and cost requirements are becoming the development direction of tunnel construction in China. For example, the open TBM used in hydraulic engineering in Xinjiang caused large fault fracture zones, rock bursts and water inrushes during tunnelling, resulting in equipment jamming and delaying the construction period for up to half a year. Another example is the Gaoligongshan tunnel project in Yunnan, China, which adopts the open-TBM construction method; due to poor geological conditions, there are a large number of fault fracture zones with different scales, and the problem of high geotemperature is prominent, resulting in extremely poor TBM construction conditions and slow excavation [1]. An open TBM was used in the construction of an S tunnel during hydraulic engineering in Japan. Due to insufficient geological surveying in the early stage and wrong judgments on the tunnelling adaptability of the TBM, the TBM was affected by the large deformations of the surrounding rock in the tunnelling process, and machine jams occurred frequently. Finally, a TBM can only be removed and used for the shield tunnelling of the remaining projects [2].

The main reason for the serious construction consequences outlined above is the lack of systematic and quantifiable TBM tunnelling adaptability evaluation methods and theories. Therefore, the research on an evaluation method of TBM tunnelling adaptability under complex geological conditions has become a large problem that needs to be overcome in the construction of long tunnels in the fields of water conservancy, railways, and highways. TBM tunnelling involves massive amounts of data, such as on the surrounding rock deformations, electromechanical control, cutter rock breaking, geological disasters, and construction safety, from advanced exploration to design to tunnelling, which provide a stage for the application of fuzzy comprehensive evaluation. The fuzzy mathematics theory can describe and model a large number of fuzzy concepts and fuzzy phenomena in the real world with precise mathematical means, so as to achieve the purpose of proper processing [3]. In order to solve the uncertainties of geological and geotechnical parameters, Hamidi et al. have adopted the method of fuzzy hierarchy analysis to pre-judge the selection adaptability of different TBMs under adverse geological conditions [4]. In order to predict the specific energy demand of a TBM, Acaroglu constructed a TBM-specific energy prediction method based on a fuzzy logic model [5]. Min built a new resource model based on the tunnel-assisted decision-making system DAT, which optimizes the allocation and planning of tunnel resources [6]. In addition, in order to identify the risks of TBM tunnelling and provide a clear roadmap for possible measures, Sharafat et al. proposed a new risk analysis method, which is based on a generic bow-tie method and integrates fault tree and event tree analysis methods, which can be used to systematically assess and manage TBM-related risks under difficult ground conditions [7]. Therefore, the application of the fuzzy theory to TBM tunnelling adaptability evaluation is the current development trend. This can not only improve the construction level of TBM tunnel engineering but also avoid engineering accidents caused by unsuitable TBM tunnelling to a certain extent, as well as promote more efficient, scientific, and systematic decision-making evaluations of TBM tunnelling adaptability.

Based on hydraulic engineering in Xinjiang, this paper comprehensively analyzed geological conditions, adverse geology, tunnelling parameters, and other factors affecting the tunnelling adaptability of a TBM, and evaluated the tunnelling adaptability of a TBM based on the fuzzy comprehensive evaluation method and analytic hierarchy process (AHP)–entropy weight (EW) method. The research results provide a new quantitative analysis method for the TBM tunnelling adaptability evaluation of similar tunnels.

2. TBM Adaptability Evaluation Method and Project Overview

For an open TBM, tunnelling adaptability refers to the adaptability of the tunnelling machine to various factors affecting tunnel tunnelling such as geological conditions and adverse geology.

As TBM tunnelling is affected by a variety of factors, we chose the AHP–EW method and fuzzy membership function method to evaluate TBM tunnelling adaptability, and proposed a TBM tunnelling adaptability standard, forming a complete TBM tunnelling adaptability evaluation system; the specific operation process is shown in Figure 1.

2.1. Evaluation Index and Index System

There are many factors affecting the tunnelling adaptability of an open TBM, and the relationship is complex. Therefore, the most important factors should be selected as evaluation indexes based on actual engineering, relevant scientific research results, expert opinions, and mathematical evaluations. Then, each evaluation index is described quantitatively by the method of fuzzy mathematics to accurately reflect its influence on the adaptability of TBM tunnelling.

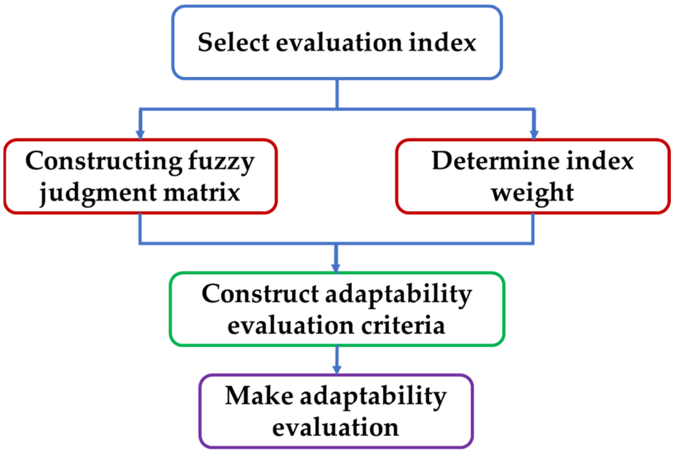

Figure 1. TBM tunnelling adaptability evaluation process.

When selecting evaluation indexes, in order to avoid the influence of excessive correlation between indexes on the evaluation results, the evaluation indexes should be guaranteed to have strong independence and representativeness. At the same time, in order to ensure the logic and practicability of the evaluation, it is necessary to classify the evaluation indexes by constructing a hierarchical structure.

2.2. Fuzzy Evaluation Model and Fuzzy Membership Function

2.2.1. Fuzzy Evaluation Model

Suppose that the evaluation target set is $D = \{O_1, O_2, \cdots, O_n\}$; the evaluation index set is $U = \{U_1, U_2, \cdots, U_n\}$; and R is the subordination matrix of U to D. The basic model of fuzzy comprehensive evaluation is shown in Equation (1):

$$D = U \times R \tag{1}$$

In the equation above, D is the set of the comprehensive evaluation values of O. The range of D is 0–1: 1 means perfect fit and 0 means complete unsuitability.

$D = U \times R$ is expanded as follows, shown in Equation (2):

$$\{D_1, D_2, \cdots, D_n\} = \{U_1, U_2, \cdots, U_n\} \times \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix} \tag{2}$$

2.2.2. Fuzzy Membership Function

There are many factors influencing the adaptability of TBM tunnelling, and the units, characteristics, and impacts of each index are quite different. The measurement standards are different. This problem can only be solved by relying on expert experience, site investigation, and construction data, in addition to strict mathematical logic reasoning.

In this paper, a membership function is established by using the method of fuzzy mathematics. When an influencing factor makes TBM tunnelling completely unsuitable, its membership function is set to 0, otherwise its membership function is set to 1. When evaluating the quantitative value of the indexes, the scope of action of each index and the size of its interval should be displayed as much as possible.

2.3. The Method of Determining the Weight of the Evaluation Index

At present, there are many methods for determining the weight of indexes. According to the different data sources when calculating the weight, they can be roughly divided into three categories: the subjective weighting method, the objective weighting method, and the subjective and objective comprehensive weighting method. The subjective weighting method can provide a corresponding weight according to the importance of the index; the theory is mature and the operation is convenient. However, it is difficult to rule out the interference of human factors in the weight of indexes. The objective weighting method includes the EW method and principal component analysis. The calculation results are relatively objective based on the actual data of the scheme, avoiding the influence of subjective factors on the index weights. However, the index weights obtained only represent the relative intensity of competition among the indexes, rather than the actual importance of each index [8].

Neither subjective nor objective weighting can fully consider the tunnelling adaptability evaluation of a TBM. The commonly used subjective weighting methods include the AHP method and Delphi method. The AHP method can clearly show the relationship between each layer, each criterion, and each element. Even if there are omissions or deficiencies in the research data, the importance of each element can still be obtained. However, the judgment matrix is completely determined by expert experience, it is difficult to exclude the influence of personal factors on the index weight, the solution process is relatively rough, the analysis, comparison, and decision-making steps are not quantitative enough and the solution to the problem with high precision may not be consistent with the actual situation. Therefore, we combine the AHP method with the EW method, which not only gives play to the advantages of the clear logic as well as convenient and simple operation of the AHP method, but also combines the advantages of EW to avoid weighting results that are too subjective.

2.3.1. Analysis and Determination of Hierarchy

The AHP method is applied, firstly to sort out the orderliness and hierarchy of the problem and then to construct an AHP structure model. When structuring the hierarchical analysis structure, it is generally divided into three layers: the target layer above, the criterion layer in the middle, and the index layer below. The target layer represents the purpose of problem solving, i.e., the goal to be achieved by applying the AHP method. The criteria layer represents the intermediate links involved in achieving the intended objectives; the index layer represents specific indexes to solve problems.

2.3.2. Construct a Judgment Matrix

In order to divide the degree of the influence of different elements in the same layer on the previous layer, all of the elements in the layer are compared pairwise to construct a judgment matrix. The elements in the matrix should meet the requirements of Equation (3):

$$\left.\begin{array}{l} a_{ij} > 0 \\ a_{ij} = \frac{1}{a_{ji}}(i \neq j) \\ a_{ij} = 1(i = j) \end{array}\right\} \tag{3}$$

Accordingly, the judgment matrix is obtained as shown in Equation (4):

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots & & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nj} & \cdots & a_{nn} \end{pmatrix} \tag{4}$$

2.3.3. Error Correction by the Entropy Weight Method

In order to reduce the errors among the indexes, it is necessary to use the entropy weight method to correct them.

Firstly, the judgment matrix passing the consistency test is standardized to obtain the standardized judgment matrix, R, as shown in Equation (5):

$$R = \{r_{ij}\}_{n\times n} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2j} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots & & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nj} & \cdots & r_{nn} \end{pmatrix} \tag{5}$$

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{6}$$

Use Equation (7) to calculate the entropy, E_j, of each index:

$$E_j = -\frac{\sum_{i=1}^{n} r_{ij} \ln r_{ij}}{\ln n} \tag{7}$$

Use Equation (8) to calculate the correction coefficient, μ_j, for each index:

$$\mu_j = \frac{1 - E_j}{\sum_{j=1}^{n} (1 - E_j)} \tag{8}$$

The correction coefficient, μ_j, of each index is used to modify the initial weight coefficient, α_j, calculated by the AHP method, and the weight coefficient, θ_j, modified by the EW method is obtained, as shown in Equation (9):

$$\theta_j = \frac{\mu_j \alpha_j}{\sum_{j=1}^{n} \mu_j \alpha_j} \tag{9}$$

Finally, the initial weight coefficient, α_j, obtained by the AHP method, and the weight coefficient, θ_j, modified by the EW method, are calculated according to Equation (10), and the more reasonable weight coefficient, ω_j, obtained by AHP–EW method is obtained:

$$\omega_j = 0.5\alpha_j + 0.5\theta_j \tag{10}$$

2.3.4. Consistency Test of the Judgment Matrix

In order to verify the correctness of the judgment matrix, it is necessary to check the consistency of the constructed judgment matrix during the evaluation process as follows:

Normalize the product of each row elements of the matrix via Equation (11):

$$\left.\begin{aligned} \delta_i &= (\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}} \\ \alpha_j &= \frac{\delta_j}{\sum_{i=1}^{n} \delta_i} \end{aligned}\right\} \tag{11}$$

Based on Equation (11): α = [α_1, α_2, ⋯, α_n]T is the eigenvector of the judgment matrix. The maximum eigenvalue of the judgment matrix is calculated by Equation (12):

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} a_{ij}\alpha_j}{\alpha_i} \tag{12}$$

Use Equation (13) to calculate the consistency index CI:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{13}$$

Look up Table 1 to find the average random consistency index *RI*. *RI* is obtained by repeatedly calculating the eigenvalues of random judgment matrix for many times (at least 500 times). To a certain extent, the introduction of *CI* can overcome the disadvantage that the consistency index of judgment matrix increases significantly with the increase in order *n*. Table 1 lists the *RI* values of the judgment matrix of order *n* = 1 to 9.

Table 1. Classification standard of TBM tunnelling adaptability.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The random consistency ratio, *CR*, is used to judge whether the judgment matrix has satisfactory consistency. If the condition of Equation (14) is satisfied, it is proven that the judgment matrix meets the requirement of consistency.

$$CR = \frac{CI}{RI} < 0.1 \tag{14}$$

2.4. Adaptability Evaluation Criteria

Through the comprehensive fuzzy mathematics theory and the construction characteristics of the TBM, the tunnelling adaptability of the TBM is graded, as shown in Table 2.

Table 2. Classification standard of TBM tunnelling adaptability.

Degree of Adaptability	>0.9	0.9~0.7	0.7~0.4	<0.4
Adaptation criteria	Completely adaptable	Adaptable	Slightly adaptable	Inadaptable

2.5. Project Overview

A hydraulic engineering project in Xinjiang, with a total length of 540 km, consists mainly of the XE tunnel (139.04 km), the KS tunnel (283.27 km) and the SS tunnel (92.15 km). The tunnels account for 95.6% of the total length and are all deep-buried superlong tunnels. The tunnels are constructed mainly by the TBM method and supplemented by the mining method. According to a geological investigation, the TBM passes through eight regional faults and 129 secondary fault fracture zones. In general, the faults and fissures near the tunnel body are not well-developed, and the fissure faces are mostly filled with quartz veins. The basic regional earthquake intensity is the VII degree zone. The lithology of the tunnel is mainly late Variscan intrusive rocks with Permian, Triassic, Jurassic, Cretaceous mudstone, and sandstone.

Due to the limitation of site conditions, it is difficult to obtain all of the geological conditions and TBM tunnelling conditions of the XE tunnel, KS tunnel and SS tunnel, so the typical interval K112+000-K114+000 in the XE tunnel, the typical interval K2+310-K4+310 in the KS tunnel and the typical interval K18+500-K20+500 in the SS tunnel are selected to study the TBM tunnelling conditions. The geological profiles of the interval tunnels K112+000-K114+000, K2+310-K4+310, and K18+500-K20+500 are shown in Figure 2. The specific parameters of the interval tunnels are shown in Table 3.

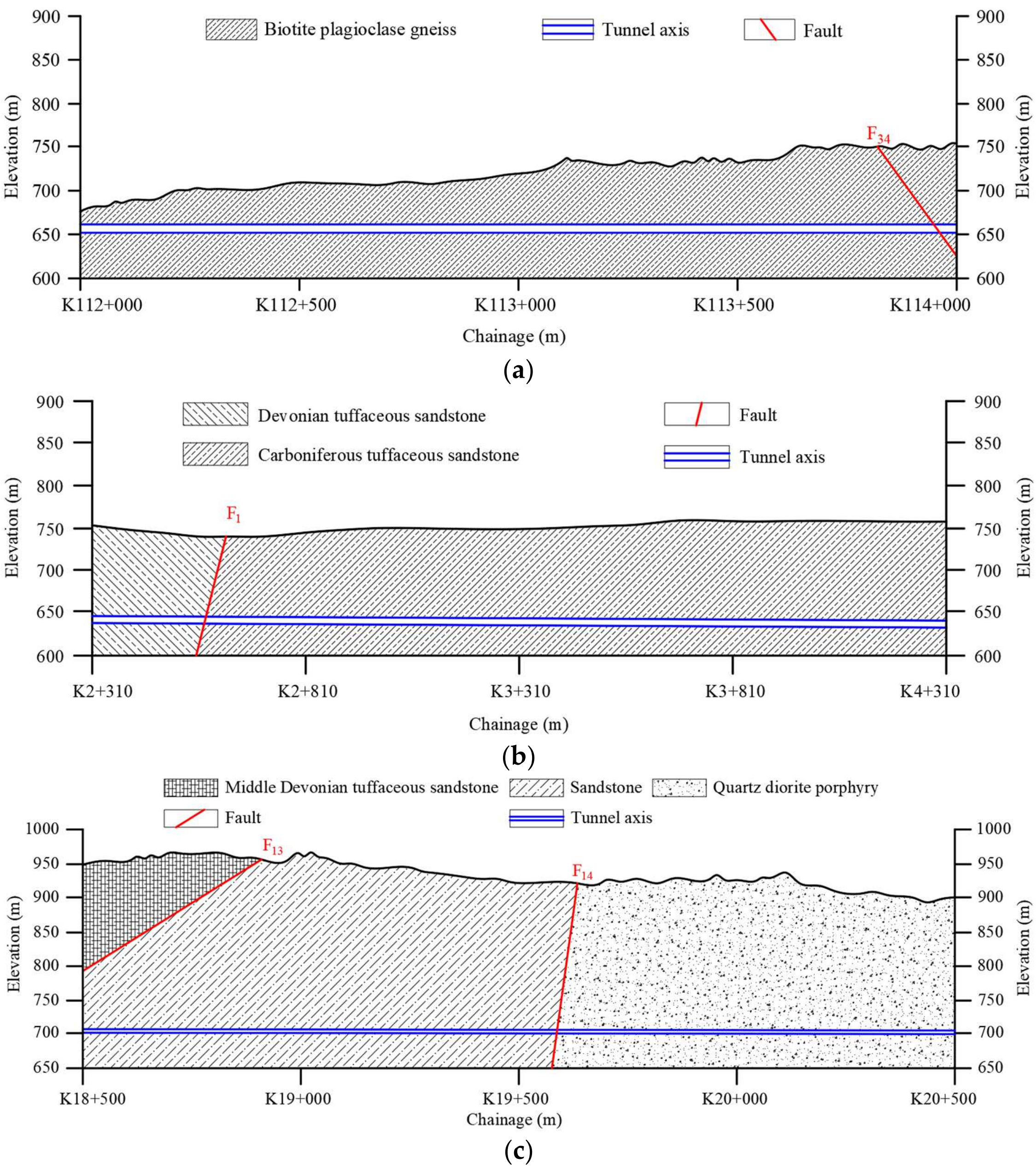

Figure 2. The geological profile of the interval tunnel; (**a**) K112+000-K114+000, (**b**) K2+310-K4+310, (**c**) K18+500-K20+500.

Table 3. Interval tunnel parameter statistics.

Section	Tunnel Length (m)	Tunnel Diameter (m)	Buried Depth (m)	Uniaxial Compressive Strength of Rock (MPa)	Rock Mass Integrity Coefficient
K112+000-K114+000	2000	7.8	15–92	92–96	0.78–0.84
K2+310-K4+310	2000	7.0	95–119	65–71	0.52–0.58
K18+500-K20+500	2000	5.5	193–239	67–73	0.40–0.44

3. Selection of Evaluation Index and Establishment of Fuzzy Function

3.1. Selection of Evaluation Index

The factors affecting open-TBM tunnelling include TBM tunnelling parameters, geological conditions, and adverse geology. After data analysis and summary, we found that there are 19 influencing indexes, including the following: 1. penetration rate, 2. thrust,

3. rotations per minute (RPM), 4. torque, 5. penetrations per revolution (Prev), 6. uniaxial compressive strength, 7. rock mass integrity coefficient, 8. crustal stress, 9. Cerchar abrasivity index (CAI), 10. number of rock mass joints, 11. fault fracture zone, 12. large deformations of the surrounding rock, 13. water inrush, 14. rock burst, 15. high geotemperature, 16. harmful gases, and 17. weak and uneven stratum. These 17 indexes can be divided into three categories, in which indexes 1–5 belong to tunnelling parameters, indexes 6–10 belong to geological conditions, and indexes 11–17 belong to adverse geology.

In order to strengthen the operability of the method proposed in this paper and the weight of subsequent evaluation indexes, we use the expert scoring method to score and screen the 17 indexes.

The nine-scale method is selected as the scoring method. The nine-scale method comes from the principle of psychology. It is possible for people to judge the relative difference between two objects through a sensory thinking comparison. At the same time, the psychological limit that can distinguish the difference is 7 ± 2. Therefore, when using the nine-scale method, if the expert scores eight or nine, we will round off this index to improve the accuracy of the evaluation.

The key to the expert scoring method is to select appropriate experts for the scoring and evaluation; therefore, these experts must have a solid professional foundation, rich on-site work experience, and a fair and rigorous scientific attitude. Based on the above requirements, four professors engaged in TBM and tunnel engineering research for many years and three project chief engineers with rich experience in TBM tunnel engineering were selected. Combined with the specific conditions of Xinjiang hydraulic engineering, they were asked to use the nine-scale method to score the 17 indexes proposed above to judge the influence of different indexes on the adaptability of TBM tunnelling.

The scoring results of the 17 indexes in the three categories by seven experts are shown in Tables 4–6. Based on the scoring results, 11 indexes with the greatest influence on TBM tunnelling adaptability are selected, which are the following: 1. RPM, 2. torque, 3. thrust, 4. uniaxial compressive strength, 5. rock mass integrity coefficient, 6. crustal stress, 7. CAI, 8. fracture zone, 9. large deformations of the surrounding rock, 10. water inrush, and 11. rock burst. On this basis, the evaluation index system of the TBM tunnelling adaptability of Xinjiang hydraulic engineering is constructed, as shown in Figure 3.

Table 4. Scoring of tunnelling parameters.

	1	**2**	**3**	**4**	**5**
1	1	1/2	1/3	8	9
2	2	1	2/3	9	9
3	3	3/2	1	9	9
4	1/8	1/9	1/9	1	9/8
5	1/9	1/9	1/9	8/9	1

1. RPM, 2. torque, 3. thrust, 4. penetration rate, and 5. Prev.

Table 5. Scoring of geological conditions.

	6	**7**	**8**	**9**	**10**
6	1	1	3	3	8
7	1	1	3	3	8
8	1/3	1/3	1	1	8/3
9	1/3	1/3	1	1	8/3
10	1/8	1/8	3/8	3/8	1

6. Uniaxial compressive strength, 7. rock mass integrity coefficient, 8. crustal stress, 9. CAI, and 10. number of rock mass joints.

Table 6. Scoring of adverse geology.

	11	12	13	14	15	16	17
11	1	2	1/2	4	8	9	8
12	1/2	1	1/4	2	4	4.5	4
13	2	4	1	1/8	9	9	9
14	1/4	1/2	8	1	2	9/4	2
15	1/8	1/4	1/9	1/2	1	9/8	1
16	1/9	2/9	1/9	4/9	8/9	1	8/9
17	1/8	1/4	1/9	1/2	1	9/8	1

11. Fault fracture zone, 12. large deformations of the surrounding rock, 13. Water inrush, 14. rock burst, 15. high geotemperature, 16. harmful gases, and 17. weak and uneven stratum.

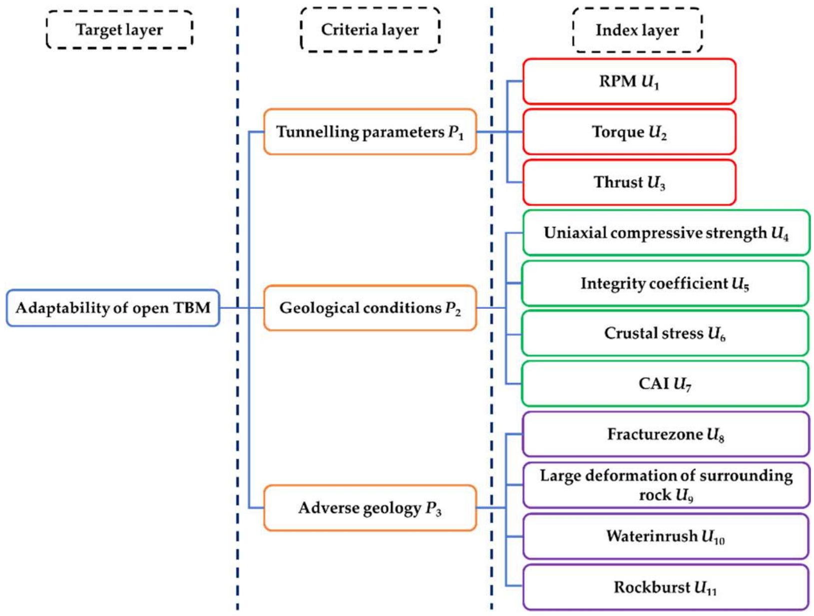

Figure 3. Evaluation index system of the TBM tunnelling adaptability of Xinjiang hydraulic engineering.

3.2. Establishment of the Fuzzy Function

3.2.1. Membership Function of the Tunnelling Parameters

(1) Membership function of the RPM

The main working parameters of the TBM cutting mechanism are the RPM (rotations per minute), torque and thrust. Gong et al. [9] carried out a statistical study on the RPM and TBM diameter based on the HC surrounding rock classification method for hydraulic and hydropower projects in China [10], and obtained Equation (15):

$$\text{RPM} = \frac{v_{\text{cutter}}}{\pi D} \times \alpha \tag{15}$$

In the equation, v_{cutter} is the limit linear speed of the cutter. For the cutter of this project, its range is 120~165 m/min, D is the diameter of the TBM cutter head and α is the reduction coefficient, which can be determined by the following Equation (16):

$$\alpha = 0.1417 \times T^{0.4463} \tag{16}$$

In the above equation, T is the comprehensive index in the HC surrounding rock classification method, which is composed of the uniaxial compressive strength, rock mass integrity coefficient, groundwater conditions, structural plane conditions, and structural plane orientation. If $T \geq 80$, α takes 1.

The RPM has different values in hard rock, soft rock, and the hard–soft rock transition section. It is about two r/min for soft rock and about six r/min for hard rock.

Since most of the surrounding rocks exposed in the project are hard rocks, the membership function is as follows in Equation (17):

$$U_1(x) = \begin{cases} \frac{x}{6}(0 < x \leq 6) \\ 1(x > 6) \end{cases} \quad (17)$$

(2) Membership function of the torque

The design of the torque mainly depends on the type of TBM, the cutter head form and the type and quantity of cutters. Under normal conditions, the torque should be controlled within a reasonable range to reflect the adaptability of TBM construction and formation. Improper torque control of the cutter head will not only affect the tunnelling efficiency of the TBM construction, but also cause engineering accidents in serious cases [11,12].

Ates et al. studied the design parameters of 265 TBMs after 1895. Based on Rostami's torque equation [13], they proposed Equation (18) [14]:

$$T_{open} = F_R \cdot N_c \cdot \frac{D}{4} F_l \quad (18)$$

where T_{open} is the minimum torque, F_R is the average rolling force of the cutter, N_c is the number of props, D is the radius of the TBM cutter head and F_l is the friction loss constant; F_l is 1.2 for the cutter.

Cao summarized the value of the TBM torque and considered that the torque of the TBM is composed of T_{open}, the rock slag mixing resistance moment, T_2, and the cutter head self-weight resistance moment, T_3, as shown in Equation (19):

$$\left. \begin{aligned} T_2 &= Q\pi R^3 P\eta \\ T_3 &= W\eta R \\ T_{total} &= T_{open} + T_2 + T_3 \end{aligned} \right\} \quad (19)$$

In general, the actual torque of the TBM is between T_{open} and T_{total}. Therefore, the membership function of the torque is constructed as follows in Equation (20):

$$U_2(x) = \begin{cases} 0(x < T_{open}) \\ \frac{x - T_{open}}{T_{total} - T_{open}}(T_{open} < x \leq T_{total}) \\ 1(x \geq T_{total}) \end{cases} \quad (20)$$

(3) Membership function of the thrust

The thrust of the TBM is the main performance index of the equipment, which is closely related to other tunnelling parameters. Based on the known parameters, calculating the thrust plays a key role in TBM tunnelling. Bilgin believes that, when tunnelling in hard rock, the required thrust force comes from the propulsion force of the cutter head and the frictional resistance of the shield bottom [15]. Most of the tunnelling interval of this project is hard rock; therefore, it should be paid attention to when determining the membership function [11,12].

The thrust, F_1, is determined by Equation (21):

$$F_1 = nP \quad (21)$$

where n is the number of cutters and P is the rated bearing capacity of the cutters.

The friction, F_{U1}, between the shield and tunnel wall is determined by Equation (22):

$$F_{U1} = \mu W \quad (22)$$

where μ is the friction coefficient and W is the shield gravity.

The thrust of the TBM is between F_1 and $F_1 + F_{U1}$, as shown in Equation (23):

$$\left.\begin{array}{l} F_{low} = F_{U1} \\ F_{hign} = F_1 + F_{U1} \end{array}\right\} \tag{23}$$

Therefore, the membership function of the thrust is constructed as follows in Equation (24):

$$U_3(x) = \begin{cases} 0(x < F_{low}) \\ \frac{x - F_{low}}{F_{hign} - F_{low}}(F_{low} \le x < F_{hign}) \\ 1(x \ge F_{hign}) \end{cases} \tag{24}$$

3.2.2. Geological Condition Membership Functions

(1) Membership function of the rock uniaxial compressive strength

The uniaxial compressive strength of rock is an important index for predicting the TBM evaluation model. The lower the R_c the higher the TBM's penetration rate, and the faster the tunnelling. The higher the R_c the lower the TBM's penetration rate, and the slower the tunnelling. With the increase in the uniaxial compressive strength of the rock, the TBM's penetration rate efficiency gradually declines. However, when the R_c is too low, the self-stabilizing time of the surrounding rock after TBM tunnelling is extremely short, or even cannot be stabilized. When the R_c value is within a certain range, the tunnelling of the TBM can not only maintain a certain speed but also keep the surrounding rock of the tunnel self-stabilizing for a certain period of time. It is generally believed that when the rock uniaxial compressive strength, R_c, is between 40 and 75 MPa, the TBM has strong adaptability; however, when the rock uniaxial compressive strength, R_c, exceeds 180 MPa or is lower than 15 MPa, it is not conducive to TBM construction [16].

To sum up, combined with the existing research results and actual engineering conditions, construct the membership function of the rock uniaxial compressive strength, R_c, as shown in Equation (25):

$$U_4(x) = \begin{cases} 0(x < 15) \\ \frac{x-15}{40-15}(15 \le x < 40) \\ 1(40 \le x < 75) \\ \frac{180-x}{180-75}(75 \le x < 180) \\ 0(x \ge 180) \end{cases} \tag{25}$$

(2) Membership function of the rock mass integrity coefficient

The rock mass integrity coefficient, K_v, is an index reflecting the integrity of the rock mass. The integrity coefficient of the rock mass is the square of the ratio of the longitudinal wave velocity between the rock mass and the rock. The integrity coefficient can be measured by the dynamic method. According to the integrity coefficient of the rock mass, the integrity degree of the rock mass can be classified into five categories: complete, relatively complete, relatively broken, broken, and extremely broken. The development degree of the structural planes (joints, bedding, schistosity, and faults) in the rock mass (i.e., rock mass integrity) is an important geological factor affecting the TBM tunnelling efficiency. Generally, when the rock mass is very complete, if the strength of the surrounding rock is high, it is not conducive to TBM tunnelling, and when the integrity of the rock mass is low, the TBM penetration rate is fast and its efficiency is high; however, when the structural plane is particularly developed and the rock mass integrity is very poor, the rock mass has been broken or loose, and the overall strength is very low. As the surrounding rock of the project, it has no self-stability. At this time, the TBM tunnelling speed is very slow and the efficiency is very low. Therefore, when the rock mass structural plane is especially developed or undeveloped, it is not conducive to TBM tunnelling.

Judging from the tunnelling situation of the TBM construction tunnel, when $K_v \geq 0.85$ the rock mass is very intact; if the rock compressive strength of the corresponding rock mass $R_c > 150$ MPa, the TBM tunnelling efficiency is very low. When $0.45 \leq K_v \leq 0.75$, the rock mass is relatively complete; if the corresponding R_c = 30~60 MPa, the TBM tunnelling efficiency is the highest. When $K_v < 0.35$, the rock mass is very broken and mostly located in the fault influence zone, the engineering geological conditions are very poor and the surrounding rock of the tunnel is prone to collapse and instability, which seriously affects the normal tunnelling of the TBM, and the tunnelling efficiency is very low [16].

To sum up, combined with the existing research results and actual engineering conditions, construct the membership function of the rock mass integrity coefficient, K_v, as shown in Equation (26):

$$U_5(x) = \begin{cases} 0(x < 0.35) \\ \frac{x-0.35}{0.45-0.35}(0.35 \leq x < 0.45) \\ 1(0.45 \leq x < 0.75) \\ \frac{0.85-x}{0.85-0.75}(0.75 \leq x < 0.85) \\ 0(x \geq 0.85) \end{cases} \quad (26)$$

(3) Membership function of the crustal stress

In a TBM project of deep buried long tunnels, the problem of large deformations and rock bursts caused by high crustal stress is very prominent. For deep-buried composite bottoms, high ground stress is the leading factor that endangers engineering safety. At present, crustal stress cannot be measured directly [17]. According to the field data and borehole measured data, the in situ stress level can be analyzed by linear regression within different depth ranges. The crustal stress level is generally divided by the strength stress ratio of the surrounding rock, as shown in Equation (27):

$$T_s = \frac{\sigma_{max}}{R_c} \quad (27)$$

σ_{max} is the maximum stress of a tunnel section; R_c is the uniaxial compressive strength of the rock.

According to the research at home and abroad, it can be found that a T_S greater than 0.4 will have a great impact on TBM tunnelling, and the impact of T_S on TBM tunnelling can be ignored when the T_S is less than 0.15 [17,18]. Combined with the engineering experience at home and abroad, the working conditions of a TBM are divided into the following four levels according to the crustal stress level, as shown in Table 7.

Table 7. Evaluation criteria for the adaptability of the crustal stress level.

Evaluating Indicator	TBM Operating Conditions			
	Good	Secondary	Commonly	Worse
Crustal stress level	<0.15	0.15~0.2	0.2~0.4	≥0.4

To sum up, combined with the existing research results and actual engineering conditions, construct the membership function of the crustal stress level, as shown in Equation (28):

$$U_6(x) = \begin{cases} 1(x < 0.15) \\ \frac{0.4-x}{0.4-0.15}(0.15 \leq x < 0.4) \\ 0(x \geq 0.4) \end{cases} \quad (28)$$

(4) Membership function of the CAI

The CAI is an important evaluation index that reflects the TBM cutter wear and tunnelling efficiency. In general, the higher the wear resistance of the rock the more serious the wear of the TBM cutter, cutter ring and bearing, and the higher the prop loss and construction costs. In serious cases, it even causes an increase in the number of downtime and cutter change, which affects the normal tunnelling of a TBM. Its value is measured by the Cerchar rock machine abrasion test. The Cerchar rock machine abrasion tester consists of an abrasion test device part and a measurement part. According to the calibration conversion of microscope measurements, take 0.1 mm as the basic unit, convert the measured value into the steel needle abrasion value and compare the steel needle abrasion value experience table to judge whether the measurement is reasonable. Calculate the average value of the abrasion values measured at three angles [19] and record it as a single test value. Each sample is tested three times on the surface, and the arithmetic mean of the three test values is the final CAI value of the sample.

According to a large number of TBM construction engineering examples at home and abroad, the efficiency of a TBM is the highest when tunnelling in the surrounding rock with low–medium wear resistance, while the tunnelling efficiency in the surrounding rock with strong–extra strong wear resistance is greatly reduced [20]. Therefore, the working conditions of a TBM are divided into five grades according to the size of the wear resistance index, as shown in Table 8.

Table 8. Corresponding relationship between the TBM working conditions and the CAI.

Evaluating Indicator	TBM Operating Conditions				
	Good	**Preferably**	**Secondary**	**Commonly**	**Worse**
CAI (0.1 mm)	<0.5	0.5~1	1~4	4~5	≥5

To sum up, combined with the existing research results and actual engineering conditions, the membership function of the CAI is constructed Equation (29):

$$U_7(x) = \begin{cases} 1(x < 0.5) \\ \frac{5-x}{5-0.5}(0.5 \le x < 5) \\ 0(x \ge 5) \end{cases} \tag{29}$$

3.2.3. Adverse Geology Membership Functions

(1) Membership function of a fracture zone

A fault fracture zone, especially a large-scale fault zone, is a bad geological condition encountered in most tunnel tunnelling. The main problem encountered by a TBM entering a weak and broken surrounding rock section is collapse. The rock mass fissures in the fault fracture zone are developed, the groundwater is rich, and the hardness of the rock and soil layers is different, which easily cause cutter head damage as well as water inrush accidents and even endanger the safety of construction personnel and equipment. The wider the fault fracture zone the greater the possibility of collapse during construction. Therefore, the width of a fracture zone is an important evaluation index to characterize the geological adaptability of TBM construction [21].

Gong divided the width of fault fracture zones into five levels. When the width of a fracture zone is less than 0.1 m, it has little impact on tunnel construction. When the width of a fracture zone is in the range of 0.1–0.5 m, the fault fracture zone has a small impact on the TBM. When the width of a fracture zone is in the range of 0.5–2 m, the fault fracture zone has an impact on TBM tunnelling. When the width of a fracture zone is in the range of 2–8 m, it has a great impact on TBM tunnelling. When the width of a fracture zone is greater than 8 m, a TBM jams and is unable to tunnel normally [22,23].

Therefore, the working conditions of a TBM are divided into five levels according to the width of the fracture zone, as shown in Table 9.

Table 9. Evaluation criteria for the adaptability of the fracture zone width.

Evaluating Indicator	TBM Operating Conditions				
	Worse	Commonly	Secondary	Preferably	Good
Fracture zone width (m)	≥8	2~8	0.5~2	0.1~0.5	<0.1

To sum up, combined with the existing research results and actual engineering conditions, the membership function of the width of the fracture zone is constructed as shown in Equation (30):

$$U_8(x) = \begin{cases} 1(x < 0.1) \\ \frac{8-x}{8-0.1}(0.1 \le x < 8) \\ 0(x \ge 8) \end{cases} \quad (30)$$

(2) Membership function of large deformations of the surrounding rock

Scholars have much in the way of research on the prediction of large deformations of the surrounding rock. Although some results have been achieved, it is still a weak aspect. Muirwood put forward the concept of a firmness coefficient, which was accepted by Chinese scholars. In China, a similar stress strength ratio is mostly used to characterize the deformation mechanism of the surrounding rock, that is, the ratio between the maximum principal stress, shear stress or vertical principal stress of the surrounding rock and the uniaxial compressive strength. Hoke proposed a judgment index of extrusion deformation, shown in Equation (31), based on the above theory, which establishes the relationship between the convergent strain value of the surrounding rock and the ratio of the rock strength to in situ stress. It is commonly used in predicting soft rock deformations [24]:

$$\xi = \frac{\omega}{D} \times 100\% \quad (31)$$

where, ξ is the deformation of the surrounding rock; ω is taken as the convergence deformation value of the surrounding rock; and D is the tunnel diameter.

Due to the insufficient amount of data collected in the project, Hoke's method is more convenient to use. Based on this, a judgment standard of soft rock deformations, as shown in Table 10, is obtained.

Table 10. Hoke's soft rock deformation judgment standard.

Evaluating Indicator	TBM Operating Conditions			
	Extremely Strong Deformation	Strong Deformation	Medium Deformation	Weak Conjugation
Deformation	>0.1	0.1~0.05	0.05~0.025	≤0.025

According to Wang's research on the large deformations of TBMs, it can be concluded that when the large deformations of the surrounding rock reach the strong deformation standard in Table 10 they will have a greater impact on the tunnelling of the TBM [25].

To sum up, combined with the existing research results and actual engineering conditions, the membership function of large deformations of the surrounding rock is shown in Equation (32):

$$U_9(x) = \begin{cases} 1(x < 0.025) \\ \frac{5-x}{5-0.025}(0.025 \le x < 0.05) \\ 0(x \ge 0.05) \end{cases} \quad (32)$$

(3) Membership function of water inrushes

Tunnel water inrushes is often encountered in the process of TBM construction. There are many factors affecting water inrush in tunnels. Due to the complexity and variability of tunnel water inrushes, the prediction of water inrushes is not accurate enough. Tunnel water inflow is an important index to evaluate the adaptability of TBM construction to water inrushes.

According to the field-measured data, the greater the unit maximum water inflow the higher the risk of water inrush disasters in the tunnel and the worse the adaptability of TBM construction to geology. Hamidi JK et al. used the RME evaluation standard for evaluation, while Jean Paul Dudt and others used the "penalty factors" method to predict the performance of a TBM. The reduction factor of water inflow less than 2 0 L/S is 1, the reduction factor of 20 to 50 L/S is 0.8 and the reduction factor of more than 50 L/S is 0.5.

Both the code for the hydrogeological and engineering geological exploration of mining areas (GB12719-1991) and the provisions of water prevention and control in coal mines (2009) require that the aquifers be divided into weak, medium, strong, and extremely strong according to the unit water inflow, Q, of the borehole. Based on this, the adaptability evaluation criteria of the maximum water inflow are shown in the following Table 11.

Table 11. Water yield grade of aquifers.

Evaluating Indicator	TBM Operating Conditions			
	Extremely Water Rich	Strong Water Richness	Medium Water Rich	Weak Water Rich Property
Unit water inflow (L/(s·m))	>5.0	1.0~5.0	0.1~1.0	≤0.1

To sum up, combined with the existing research results and actual engineering conditions, the membership function of water inflow is constructed, as shown in Equation (33):

$$U_{10}(x) = \begin{cases} 1(x < 0.1) \\ \frac{5-x}{5-0.1}(0.1 \leq x < 5) \\ 0(x \geq 5) \end{cases} \tag{33}$$

(4) Membership function of rock bursts

The common rock burst criterion includes rock brittleness coefficient, σ_c/σ_t, the rock stress coefficient, σ_θ/σ_c, the elastic energy index, W_{et}, the initial stress level, σ_1/σ_c, and the rock brittleness index. Among them, σ_θ is the maximum shear stress, σ_c is the uniaxial compressive strength of rocks, σ_t is the uniaxial tensile strength of rocks and σ_1 is the maximum principal stress. See Table 12 for a rock burst evaluation index and intensity classification. For the convenience of parameter acquisition, the initial stress level, σ_1/σ_c, is selected in this paper as the evaluation object of rock bursts [26].

Table 12. Rockburst evaluation index and intensity classification.

Rock Burst Grade	TBM Operating Conditions			
	Hign Rock Burst	Medium Rock Burst	Low Rock Burst	No Rock Burst
σ_1/σ_c	≥0.55	[0.3, 0.55)	[0.2, 0.3)	<0.2

To sum up, combined with the existing research results and actual engineering conditions, the membership function of rock burst is constructed, as shown in Equation (34):

$$U_{11}(x) = \begin{cases} 1(x < 0.2) \\ \frac{0.55-x}{0.55-0.2}(0.2 \leq x < 0.55) \\ 0(x \geq 0.55) \end{cases} \tag{34}$$

4. Case Study

4.1. Determination of Index Weight

Through the method introduced in Section 2.3, based on the scores of experts, we used the AHP–EW method to obtain the weight correction coefficient, ω, of each level and each index, as shown in Tables 13–16.

Table 13. Weight correction coefficient of the criteria layer to the target layer.

D	P_3	P_2	P_1
P_3	1	1	2
P_2	1	1	2
P_1	1/2	1/2	1
ω	0.394	0.394	0.212

Table 14. Weight correction coefficient of tunnelling parameters.

P_1	U_1	U_2	U_3
U_1	1	1/2	1/3
U_2	2	1	2/3
U_3	3	3/2	1
ω	0.1803	0.3359	0.4838

Table 15. Weight correction coefficient of geological conditions.

P_2	U_4	U_5	U_6	U_7
U_4	1	1	3	3
U_5	1	1	3	3
U_6	1/3	1/3	1	1
U_7	1/3	1/3	1	1
ω	0.3987	0.3987	0.1027	0.0998

Table 16. Weight correction coefficient of adverse geology.

P_3	U_8	U_9	U_{10}	U_{11}
U_8	1	2	1/2	4
U_9	1/2	1	1/4	2
U_{10}	2	4	1	1/8
U_{11}	1/4	1/2	8	1
ω	0.3647	0.1538	0.2401	0.2414

Through the weight correction coefficient, ω, of each level and each evaluation index obtained from Tables 13–16, the weight coefficients, ω', of each evaluation index on TBM tunnelling adaptability can be calculated, as shown in Table 17.

Table 17. Weight coefficients of each evaluation index on TBM tunnelling adaptability.

D	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}
$\omega'(\times 10^{-2})$	3.82	7.12	10.25	15.71	15.71	4.05	4.02	14.37	6.06	9.46	9.51

4.2. TBM Tunnelling Adaptability Evaluation

The AHP–EW method and fuzzy comprehensive evaluation method have the characteristics of clear logic and easy quantification. We only need to obtain the corresponding data from the selected section and bring them into the fuzzy membership function mentioned above to obtain the adaptability of each index. After the adaptability of each index is formed into the adaptability vector in order and multiplied by the weight vector, we can obtain the tunnelling adaptability score of a TBM in the selected section. Finally, corresponding to the adaptability standard, the tunnelling adaptability evaluation results of a TBM can be obtained.

We selected three typical interval tunnels (K112+000-K114+000, K2+310-K4+310, and K18+500-K20+500) from hydraulic engineering in Xinjiang, which, combined with the fuzzy membership function mentioned in Section 3 and the weight coefficient in Section 4.1, as well as with the project data shown in Table 18, evaluated the TBM tunnelling adaptability of three typical interval tunnels of Xinjiang hydraulic engineering.

Table 18. Parameters required for evaluation.

Section	1	2	3	4	5	6	7	8	9	10	11	12	13
K112+000-K114+000	7.1	2224	17,000	18,500	16,320	94	17.3	7.8	0.81	2.4	0.033	0.6	3.6
K2+310-K4+310	6.0	1770	8877	9950	8400	68	14.2	7.0	0.55	1.1	0.022	0.1	1.9
K18+500-K20+500	6.2	840	7840	9300	7400	70	15.5	5.5	0.42	7.2	0.170	5.5	3.1

1. RPM; 2. torque; 3. thrust; 4. maximum thrust; 5. minimum thrust; 6. rock uniaxial compressive strength; 7. maximum stress of the tunnel section; 8. tunnel diameter; 9. rock mass integrity coefficient; 10. width of fracture zones; 11. deformation of the surrounding rock; 12. unit water inflow; and 13. CAI.

The RPM, torque, and thrust come from the TBM's own tunnelling parameter recording system; the rock mass integrity coefficient is obtained by measuring the wave velocity of the rock mass through drilling; the uniaxial compressive strength is measured by a coring test in the tunnel; the crustal stress is obtained by the hydraulic fracturing method; the width of fault fracture zones and unit water inflow are obtained by geological exploration reports and on site construction records; the CAI is measured by the Cerchar abrasion test; and the deformation of the surrounding rock is obtained by total station and reflective film.

We bring the obtained data into the membership function to obtain the adaptability value of each evaluation index, as shown in Table 19.

Table 19. Adaptability value of each evaluation index.

Section	1	2	3	4	5	6	7	8	9	10	11
K112+000-K114+000	1	0.85	0.688	0.819	0.4	0.2	0.311	0.709	1	0.9	1
K2+310-K4+310	1	0.91	0.692	1	1	0	0.689	0.873	1	0.8	1
K18+500-K20+500	1	0.88	0.79	1	0.7	0	0.422	0.07	1	0	1

1. RPM; 2. torque; 3. thrust; 4. rock uniaxial compressive strength; 5. rock mass integrity coefficient; 6. crustal stress; 7. CAI; 8. fracture zones; 9. large deformation of surrounding rock; 10. water inrush; and 11. rock bursts.

Based on this, the adaptability evaluation results are as follows in Equations (35)–(37):
K112+000-K114+000 section:

$$\begin{pmatrix} 1 \\ 0.85 \\ 0.688 \\ 0.819 \\ 0.4 \\ 0.2 \\ 0.311 \\ 0.709 \\ 1 \\ 0.9 \\ 1 \end{pmatrix}^T \times \begin{pmatrix} 0.0382 \\ 0.0712 \\ 0.1025 \\ 0.1571 \\ 0.1571 \\ 0.0405 \\ 0.0402 \\ 0.1437 \\ 0.0606 \\ 0.0946 \\ 0.0951 \end{pmatrix} = 0.72 \quad (35)$$

After calculation, the TBM tunnelling adaptability value of a section of K112+000-K114+000 is 0.72, which belongs to being adaptable. From the actual excavation situation, the surrounding rock of the K112+000-K114+000 section has good stability and is relatively hard, with less adverse geological conditions and less faults during TBM excavation, but the cutter wear is serious and the penetration rate is slow.

K2+310-K4+310 section:

$$\begin{pmatrix} 1 \\ 0.91 \\ 0.692 \\ 1 \\ 1 \\ 0 \\ 0.689 \\ 0.873 \\ 1 \\ 0.8 \\ 1 \end{pmatrix}^T \times \begin{pmatrix} 0.0382 \\ 0.0712 \\ 0.1025 \\ 0.1571 \\ 0.1571 \\ 0.0405 \\ 0.0402 \\ 0.1437 \\ 0.0606 \\ 0.0946 \\ 0.0951 \end{pmatrix} = 0.87 \tag{36}$$

After calculation, the TBM tunnelling adaptability value of a section of K2+310-K4+310 is 0.87, which belongs to being adaptable. The surrounding rock of the K2+310-K4+310 section has good stability, moderate rock hardness, less adverse geological conditions, and less faults during TBM excavation, while the cutter wear is within the normal range, and the penetration rate is fast.

K18+500-K20+500 section:

$$\begin{pmatrix} 1 \\ 0.88 \\ 0.79 \\ 1 \\ 0.7 \\ 0 \\ 0.422 \\ 0.07 \\ 1 \\ 0 \\ 1 \end{pmatrix}^T \times \begin{pmatrix} 0.0382 \\ 0.0712 \\ 0.1025 \\ 0.1571 \\ 0.1571 \\ 0.0405 \\ 0.0402 \\ 0.1437 \\ 0.0606 \\ 0.0946 \\ 0.0951 \end{pmatrix} = 0.63 \tag{37}$$

After calculation, the TBM tunnelling adaptability value of a section of K18+500-K20+500 is 0.63, which belongs to being slightly adaptable. The surrounding rock of the K18+500-K20+500 section has poor stability and high rock hardness, and there are large faults, water inrushes, and large deformations of the surrounding rock during excavation. In order to prevent the influence of adverse geological conditions, more support measures are taken during TBM excavation, but the shutdown time is long, and the penetration rate is slow due to excessive water inrushes.

Through comparative analysis, the method proposed in this paper can be used to evaluate the TBM tunnelling adaptability of three interval tunnels in Xinjiang hydraulic engineering, and the evaluation results are consistent with the actual situation.

5. Conclusions

According to the weight analysis and adaptability evaluation results, the following conclusions can be drawn:

(1) The adaptability evaluation method adopted in this paper selects the factors that have the greatest impact on the adaptability of TBM tunnelling through expert scoring and comprehensive investigation, quantifies various factors affecting TBM tunnelling based on fuzzy mathematics theory, establishes the weight of various indexes by using the AHP and EW method and the suggested value of the evaluation standard of TBM tunnelling

adaptability is given. In the practical application of three interval tunnels, the evaluation results of this method are more consistent with the actual situation, so this method can provide a reference for the TBM tunnelling adaptability evaluation of similar projects.

(2) The tunnelling adaptability of a TBM is mainly restricted by geological conditions and adverse geology, and the influence of tunnelling parameters on it is relatively small, but the reasonable selection of TBM tunnelling parameters still greatly improve the tunnelling adaptability of TBMs.

(3) The uniaxial compressive strength of rock, the integrity coefficient of rock masses and the width of fault fracture zones play a key role in the tunnelling adaptability of TBMs. Therefore, these three indexes should be fully investigated in the investigation stage, which plays a key role in the selection of a tunnel construction method.

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