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Research Article

Quantitative Evaluation of the Adaptability of the Shield Machine Based on the Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (FAHP)

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Tunnel engineering based on the shield method is an extremely complex project. During the construction process, many uncertain factors are often faced, which makes it difficult to effectively and quantitatively evaluate the effectiveness of the shield machine. To solve this problem, this paper proposes an adaptability evaluation method for shield machines based on the fuzzy analytic hierarchy process (FAHP) and analytic hierarchy process (AHP). First, the selection and equipment matching of Earth pressure balance shield machines in the shield interval between Tashuiqiao Station and Erxianqiao Station of Chengdu Metro Line 17 are introduced. Then, using APH for screening, the final evaluation indices of the adaptability of the shield machines in this project are determined. Next, referring to the existing research results and fuzzy mathematics method, the membership function of the evaluation indices and adaptability evaluation model of the shield machine are constructed. Finally, the rationality and accuracy of the fuzzy comprehensive evaluation model of shield adaptability are verified through onsite shield construction, and the evaluation results are consistent with the actual situation.

1. Introduction

In recent years, with the growth of the urban population and continuous expansion of the urban scale, urban development has gradually shifted to underground space development [1–5]. The forms of underground space utilization include underground parking lots, underground shopping malls, underground drainage pipelines, underground railways, etc [6–8]. As an emerging public transportation mode, subways have the advantages of large transportation capacity and fast speed. Since subways can effectively relieve the pressure of ground transportation, they have been incorporated into the construction planning of increasingly many cities. The construction methods of subway tunnels mainly include the open-cut method, sallow buried-tunnelling method, and shield method [9]. Due to its safety, efficiency, convenient construction, and low impact on the surrounding strata and the environment, the shield method has become the main method to build urban subway tunnels. Selecting a suitable shield machine is a key step in shield construction. If the machine type is not suitable, it can cause major delays and injury to shield drivers and ultimately may stop the project. In addition, it is necessary to analyse the adaptability of shield machines by adopting a reasonable method to ensure safe and smooth construction [10, 11].

Adaptability refers to the ability to adapt to different internal and external environments and objective conditions [12–14]. The system is composed of several different and related factors and can realize an organic collection with certain functions. When an important factor in the system changes, it will be directly affected and restricted by other factors in the system and affect other factors. Therefore, to maintain the overall function of the system, important factors must adapt to one another. To perform the adaptability evaluation, the evaluation index system must be determined first. The evaluation index system depends on the evaluation object. Generally, when establishing an index system that can be used for adaptability evaluation, the principles of hierarchy, validity, and simplicity should be followed.

The selection of an inappropriate shield machine will lead to low construction efficiency and abnormal phenomena such as downtime during construction and difficulty in excavation. Many scholars have performed a series of studies on the qualitative evaluation of shield machines. Rengshausen et al. [15] discussed the advantages and disadvantages of a TBM-S with Earth pressure balanced face support (EPB-TBM) and a TBM-S with slurry face support (Mix-Shield TBM) for the C310 Thames Tunnels after the contract award and a comparative risk assessment. Song et al. [16] studied the adaptability of the soil pressure balance shield in the expansive clay stratum for Xuzhou metro urban rail transit line 2, and they proposed the targeted design of the shield selection and the selection of excavation parameters. Edalat et al. [17] introduced the process of choosing tunnel boring machines for Tabriz urban railway line 2 using the multicriteria analysis method and identified some technical, economical, and environmental parameters that affected the tunnel boring machines type. Considering the disintegration of fines from cohesive soil within free water, such as slurry, Hollmann et al. [18] proposed an assessment method of logging in mechanised tunneling. Hyun et al. [19] discussed the potential risk of undesirable events that occurred during tunneling with the application of a shield tunnel boring machine. Based on the numerical computations results, Ramoni and Anagnostou [20] investigated the problem of shield jamming and analysed the effects of possible countermeasures. Based on the TOPSIS method, Wu et al. [21] carried out a study on the shield selection for subway construction and selected Wuhan Rail Transit Line 2 for example analysis to verify the feasibility of the method. Huang et al. [22] applied the statistical analysis method to the shield selection for Chengdu Metro Line 18. However, these studies mostly use qualitative methods for analysis. The adaptability analysis of a shield machine does not the link one phenomenon to another but comprehensively considers various uncertainty indices. Therefore, it is urgent to seek a quantitative evaluation method of the adaptability of the shield machine.

In this paper, the adaptability of the shield machine in the shield interval between Tashuiqiao Station and Erxianqiao Station of Chengdu Metro Line 17 is analysed by combining the fuzzy analytic hierarchy process (FAHP) and the analytic hierarchy process (AHP). Based on the analysis of the adaptability evaluation indices of the shield machine and the determination of the membership function of the evaluation indices, a quantitative evaluation model for the adaptability of the shield machine is constructed. The quantitative evaluation method of the proposed shield machine adaptability in this paper can improve the reliability and scientificity of evaluation results.

2. Project Overview

2.1. Project Introduction. The shield interval between Tashuiqiao Station and Erxianqiao Station (TS-ES) of Chengdu Rail Transit Line 17 is located in the third section of Jianshe North Road, Chenghua District, Chengdu, between the Second Ring Road and the Middle Ring Road. Figure 1 shows the plane position of the tunnels in the TS-ES section. The TS-ES section contains two shield tunnels: the left and right lines from Tashuiqiao Station to Erxianqiao Station. The demarcation mileage of the right-line tunnel in the TS-ES section is YDK92 + 649.748~YDK94 + 345.700, with a total length of 1696.391 m (the long chain is 0.439 m). The demarcation mileage of the left-line tunnel in the TS-ES section is ZDK92 + 649.749~ZDK94 + 345.700, with a total length of 1691.308 m (the short chain is 4.643 m). The buried depth of the interval tunnel is 19.9~30 m, and the minimum horizontal curve radius and vertical curve radius of the line are 450 m and 5000 m, respectively. The TS-ES shield section starts by airlifting in the undercut section of the tunnel and traverses many major risk sources, including the existing buildings and pipelines. Due to the poor geological self-stability of shield tunnels, the excavation surface easily overdig, which results in excessive surface settlement, cracks, and even ground collapse. The shield construction of this project has great risk.

The TS-ES shield section adopts prefabricated circular reinforced concrete segments. The inner diameter and outer diameter of the circular segment are 7500 mm and 8300 mm, respectively, and the circular segment is 400 mm thick. The concrete strength grade for circular segments is C50, and the impermeability grade is P12. The circular segment adopts a three-part staggered assembly mode of a standard lining ring, a left-turning wedge ring, and a right-turning wedge ring. The staggered assembly of the circular segment is connected by M30 bolts. The joints of the circular segment adopt the waterproof form of a composite elastic water-swellable rubber water stop belt.

2.2. Geological and Hydrogeological Survey. The area along the shield track in the TS-ES shield section is mainly located in dense pebbly soil and moderately weathered mudstone, stratum, and it partially passes through fully weathered mudstone strata and strongly weathered mudstone strata, including lenticular fine sand strata. The geological structure of the shield section is simple. The bad geology is mainly the sand and gravel layer contaminated by the leakage of the sewage pipe. The geological composition of the TS-ES interval is shown in Figure 2.

The TS-ES shield section belongs to the hydrogeological unit of the plain area. Quaternary loose deposits are widely distributed, with good water permeability and water abundance. According to the types of water-bearing media and characteristics of water-bearing voids, the ground water in the site is mainly divided into three types: upper stagnant water deposited above the clay layer, pore water of the Quaternary loose soil layer, and fissure water of the bedrock.

3. Selection and Matching of the Shield Machine

3.1. Selection of the Shield Machine. The type selection of the shield machine is generally based on the geological conditions of the tunnel passing through the stratum,

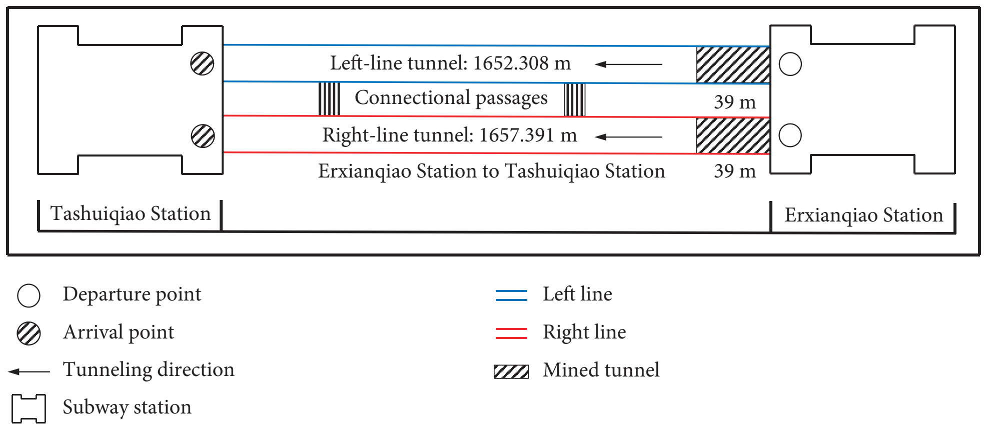


Figure 1: Plane position of the tunnels in the TS-ES section.

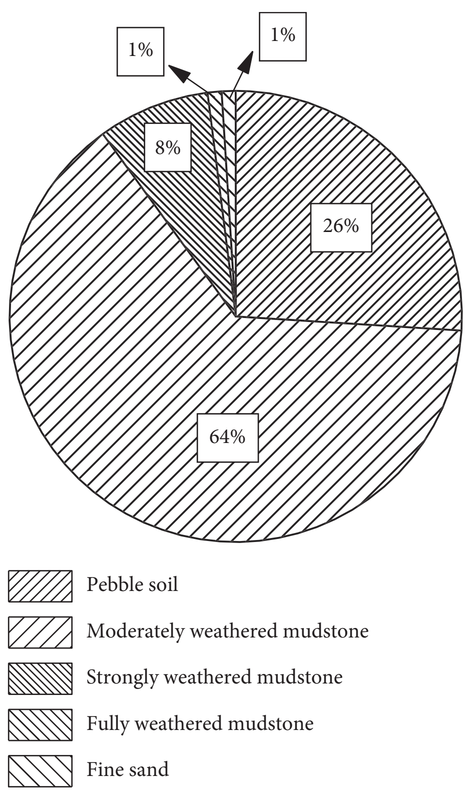


Figure 2: Geological composition of the tunnels in the TS-ES section.

environmental conditions, equipment reliability, construction period requirements, economic benefits, and engineering and technical experience. Combined with similar geological construction experience in the Chengdu area, two ZTE8600 large-diameter composite Earth pressure balance shield machines manufactured by the China Railway Construction Heavy Industry Corporation were selected to construct this shield tunnel. The crossing strata are dense cobble strata and moderately weathered mudstone strata. During the construction process, improper operation or abnormal tunneling parameters can easily make the tunnel structure float up and the road surface settle and collapse, which will affect the surrounding buildings, pipelines, and traffic safety. A single shield machine is equipped with two train groups, which adopt a single-group transportation mode; i.e., one train group will complete all transportation in a cycle to ensure the continuity of propulsion. The main performance parameters of the shield machine are shown in Table 1. The optimal parameters for the trial excavation of the shield tunnel in this project are as follows: the thrust range is 8440~10750 kN, the cutter head torque range is 1284~2440 kN m, the excavation speed is 48~65 mm/min, and the grouting pressure is 0.2~0.3.

3.2. Main System of the Shield Machine. The main system of the shield machine selected for this project is introduced as follows.

3.2.1. Configuration of the Cutter Head and Cutting Tools. The cutter head with a compound design adopts the structure form of spokes and panels. The excavation diameter and opening ratio of the cutter head are 8630 mm and 36%, respectively. The cutter head is equipped with knives, including hobs, cutting knives, shell knives, and edge scrapers. Among them, there are 6 double hobs with a knife height of 180 mm and a knife spacing of 101.5 mm; 34 front hobs with a knife height of 180 mm and a knife spacing of 78 mm; 12 edge hobs; 1 supercut tooth knife with a maximum over-xcavation of 50 mm; 52 cutting knives with a knife height of 115 mm and a knife spacing of 200 mm; 6 shell knives with a knife height of 140 mm high; and 12 pairs of edge scrapers with a knife height of 115 mm. According to different geological conditions, the hobs can be completely or partially replaced by the tooth knife. All detachable cutters can be replaced from the back of the cutter head. When the tunnel is excavated in the full section, the shield machine can realize the forward and reverse rotations of the ballast.

3.2.2. Main Drive. The main drive is a high-torque variable frequency drive composed of 14 drive units, and a single motor has a drive power of 250 kW. The relationship between rotation speed and torque is shown in Figure 3. The

Table 1: Performance parameters of the shield machine.

Serial number	Technical parameters	Parameter configuration	Unit
1	Model number of shield machine	ZTE8600	—
2	Excavation diameter	8630	mm
3	Opening ratio of cutter head	≈37	%
4	Maximum excavation speed	80	mm/min
5	Maximum thrust	81895	kN
6	Segment size (outside diameter/inside diameter – width)	8300/7500–1500	mm
7	Length of main machine of shield machine	≈11	m
8	Total length of shield machine	≈106	m
9	Total weight of shield machine	≈1200	t
10	Installed power	≈5050	kW
11	Horizontal turning radius	350	m
12	Longitudinal climbing ability	±50	‰

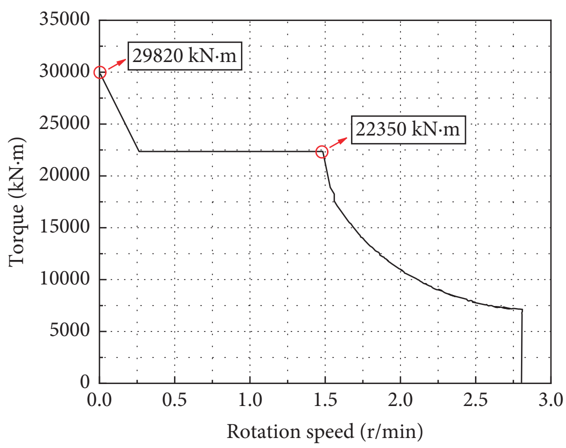


Figure 3: Relationship between rotation speed and torque.

nominal torque of the main drive can reach 22350 kN m, and the relief torque can reach 29820 kN m. It has sufficient torque reserve to achieve long-term overload and is more suitable for the geological conditions of mudstone and pebble soil in this section. To improve the pressure-bearing capacity of the main drive, polyurethane is used to seal the main drive system. After sealing, the pressure-bearing capacity of the main drive system can reach 10 bar.

3.2.3. Shield Body System. The shield machine is composed of a front shield, a middle shield, and a tail shield. The main structure of the shield machine is made of Q345 B carbon alloy steel. The outer diameter of the front shield is designed to be 8600 mm, and the notch is welded with a 5-mm wear-resistant layer to increase the wear resistance. To improve the fluidity of the muck, 4 passive stirring arms are installed on the pressure-resistant partition of the soil bin. A mud injection system is added to the middle shield to inject improved materials around to prevent the shield body from being wrapped. The designed diameter of the tail shield is 8570 mm. The connection between middle shield and tail shield adopts a passive articulation design, and the articulation adopts two rubber seals, which can satisfy the tunneling requirements of the $R = 400$ m turning radius.

3.2.4. Propulsion system. The propulsion system is divided into six groups, including 38 propulsion cylinders. The maximum thrust of the propulsion system is 81895 kN. The cylinder diameter, rod diameter, and stroke specifications of the propulsion cylinder are 280 mm, 240 mm, and 2600 mm, respectively. The pressure of the six groups of cylinders can be independently adjusted. The propulsion speed is regulated by a flow control valve, and the actual maximum excavation speed of the propulsion system is limited to 80 mm/min. By adjusting the propulsive pressure and speed of each cylinder, the excavation direction of the shield machine can be corrected and adjusted.

3.2.5. Screw Conveyor. The shield machine adopts a shaft-type screw conveyor with an inner diameter of 1020 mm. The installation angle of the screw conveyor is 22°, and it is fixed on the sleeve flange at the bottom of the front shield, which can realize the functions of forward and backward telescoping. The maximum capacity of the screw conveyor to transport muck is 581 m^3/h. When the shield machine is tunneling at the maximum excavation speed, the required capacity to transport muck is 421 m^3/h. Thus, the capacity of the screw conveyor to transport muck can satisfy the requirements of shield construction.

3.2.6. Installation system of shield segments. First, the full-ring segment is transported by the segment-transport vehicle from outside the tunnel to the unloading work area. After the unloading operation is completed, the segment-transport vehicle exits the unloading work area. The segment crane transports the segments to the storage area. Then, the segments are sent to the segment-assembly machine by the segment feeder. The segment-assembly machine is installed on the tail shield and consists of a pair of heavy lifting cylinders, a large swing mechanism, a grasping mechanism, and a translation mechanism. The segment-assembly machine has two control methods: remote control and wire control, both of which can be individually and flexibly controlled for each action. The segment-assembly machine has 6 degrees of freedom. Its rotation speed is 0~1.3 r/min and can be fine-tuned. The longitudinal movement stroke of the segment-assembly machine is 3200 mm, and the rotation angle is ±200°. Using these equipment, the segments can be installed in an accurate position.

3.2.7. Muck improvement system. The shield is equipped with a 9-way single-tube foam injection system, which is sprayed to the spout in front of the cutter head through a rotary joint. The foaming method is changed from direct foaming in the original pipeline to foaming pumped by the foam pump after the mixing box has been fully mixed. Thus, the foaming effect can be enhanced, and the foam consumption can be reduced. The bentonite system uses two hoses as injection pumps. Generally, two pumps are separately injected, one of which is used for muck improvement and the other for lubrication outside the shield shell. When a large flow is required under special circumstances, two pumps can also be used together for muck improvement. The equipped bentonite injection system can inject bentonite or clay from the outside of the shield shell, which can effectively reduce the friction resistance of the shield body and prevent the shield from jamming.

3.2.8. Grout injection system. The shield machine is equipped with 3 sets of hydraulically SCHWING grouting pumps, which inject the mortar into the annular gap between the excavation diameter and the outer diameter of the segment through the grouting pipe at the tail shield. The grouting pressure and pumping frequency of the grouting pump can be continuously adjusted within the adjustable range, and the pressure change is monitored by the pressure sensor. The shield tail is equipped with 12 grouting pipes, and the grouting capacity is 30 m^3/h.

3.2.9. Guidance system. A set of automatic guidance systems is installed on the shield machine, which can accurately measure and display various postures of the shield machine in tunneling and the line and position relationship. The angle-measuring precision of the automatic guidance system is 2 seconds, and the effective working distance is 200 m. The operator can adjust the tunneling direction and posture of the shield machine in a timely manner based on the information provided by the guidance system.

4. Adaptability Evaluation

4.1. Evaluation Methodology. The fuzzy analytic hierarchy process (FAHP) is a type of systematic analysis method that combines qualitative analysis and quantitative analysis based on a fuzzy number or fuzzy judgement matrix [23, 24]. The analytic hierarchy process (AHP) has certain limitations for testing the judgement matrix, while FAHP overcomes this defect and is a more effective comprehensive evaluation method. The analytical process of the FAHP is shown in Figure 4.

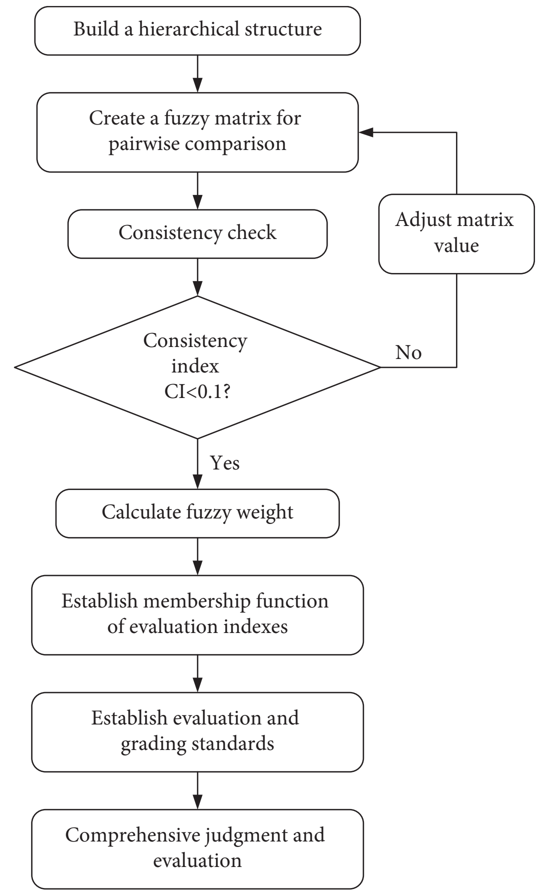


Figure 4: Analytical process of FAHP.

4.2. Evaluation Process

4.2.1. Evaluation Index. By analysing the application status of the shield machine, the evaluation of its adaptability can be divided into four grades, as shown in Table 2.

According to the FAHP, basic requirements, and basic elements of the shield-type selection, the evaluation indices for the adaptability of shield-type selection are initially formed, as shown in Table 3. The evaluation indices include 4 major categories and 24 subcategories. The primary evaluation indices for the adaptability evaluation are relatively complicated, and the factors considered involve all aspects of the project. However, the factors that have a decisive influence on the adaptability evaluation of shield selection are limited. If all primary evaluation indices are considered, it likely negatively affects the comprehensive evaluation and increase unnecessary influencing factors. Eventually, the evaluation results lose their theoretical significance and practical value.

To objectively and accurately evaluate the adaptability of the shield selection of this project, the AHP is used to screen the primary evaluation indices. The weight of each index is arranged to form a reasonable evaluation index system. The calculation results and scores of AHP for primary evaluation indices are shown in Tables 4–7, where $\lambda_{\max}$ is the largest eigenvalue of the weight matrix for the evaluation index, CI is the random consistency index, and CR is the consistency

Table 2: Evaluation grade of the adaptability of the shield machine.

Evaluation grade	Fitness value	Adaptability evaluation	Supplementary instruction
I	(0.9, 1.0]	High degree of adaptability	The shield machine selected can satisfy the engineering requirements.
II	(0.8, 0.9]	Moderate degree of adaptability	The shield machine selected basically satisfies the engineering requirements. Engineers should do a good job in equipment maintenance, ground measurement and other related work.
III	(0.7, 0.8]	Low degree of adaptability	The follow-up risk of the selected shield machine is relatively large. It is necessary to pay attention to the performance status of the shield machine every day and to monitor the tunnelling of the shield machine at all times.
IV	≤0.70	Inadaptation	The selected shield machine is not feasible.

Table 3: Primary evaluation indices.

Target layer	Rule layer	Scheme layer
Evaluation method of shield-type selection (T)	Geological conditions (C_1)	Stratigraphic characteristics (u_{11})
		Distribution of groundwater (u_{12})
		Distribution of harmful gases (u_{13})
		Bad geology and geological disasters (u_{14})
		Specific rock and soil (u_{15})
	Environmental conditions (C_2)	Existing building (u_{21})
		Underground pipelines (u_{22})
		Existing urban rail transit and railways (u_{23})
		Surface water body (u_{24})
		Urban planning land (u_{25})
		Vibration and noise (u_{26})
		Ground traffic (u_{27})
		Disposal of sludge and soil (u_{28})
	Shield construction (C_3)	Propulsion speed (u_{31})
		Rotation speed of the cutter head (u_{32})
		Grouting pressure (u_{33})
		Soil pressure (u_{34})
	Design of shield machine (C_4)	Total thrust (u_{41})
		Main drive torque (u_{42})
		Grouting ability (u_{43})
		Number of muck improvement openings (u_{44})
		Type of cutting tools (u_{45})
		Slagging quantity of screw conveyor (u_{46})
		Spacing design of cutting tool (u_{47})

Table 4: Weights and rank of the adaptability evaluation indices.

Evaluation indices	C_1	C_2	C_3	C_4
C_1	1	1/2	1/3	1/5
C_2	2	1	1/3	1/4
C_3	3	3	1	1/3
C_4	5	4	3	1
Weight	8.333%	12.777%	12.777%	12.777%
Rank	4	3	2	1

$\lambda_{max} = 4.109$; CI = 0.036; CR = 0.041 < 0.1.

ratio. The specific calculation methods and calculation steps of these parameters can be found in the literature [25, 26].

In general, a smaller CR value corresponds to better consistency of the judgement matrix. If the CR value is less than 0.1, the judgement matrix satisfies the consistency test. Conversely, if the CR value is greater than 0.1, there is no consistency, and the judgement matrix should be appropriately adjusted and analysed again. Taking Table 4 as an example, the calculated CR value is 0.041 < 0.1, which implies that the judgement matrix in this study satisfies the consistency test, and the calculated weights are consistent. According to the calculation results in Tables 4–7, if all primary evaluation indices are used, the evaluation index system appears too complicated, and the advantages of the FAHP cannot be fully utilized. The indices with a greater impact on the evaluation results, i.e., a weight value greater than 10%, are selected as the final evaluation indices, as shown in Table 8.

4.2.2. Membership Function. There is incommensurability in the indices of shield adaptability. To solve the problem of commensurability for the evaluation indices, it is necessary to quantify the evaluation indices. The degree of adaptation between each evaluation index and the shield selection is represented by a certain value in [0, 1]. When a certain evaluation index does not satisfy the shield adaptation

Table 5: Weights and rank of the environmental conditions.

Evaluation indices	u_{21}	u_{22}	u_{23}	u_{24}	u_{25}	u_{26}	u_{27}	u_{28}
u_{21}	1	1/3	2	2	2	2	2	2
u_{22}	3	1	2	2	2	2	2	2
u_{23}	1/2	1/2	1	1	1	1	1	1
u_{24}	1/2	1/2	1	1	1	1	1	1
u_{25}	1/2	1/2	1	1	1	1	1	1
u_{26}	1/2	1/2	1	1	1	1	1	1
u_{27}	1/2	1/2	1	1	1	1	1	1
u_{28}	1/2	1/2	1	1	1	1	1	1
Weight	17.747%	23.242%	9.835%	9.835%	9.835%	9.835%	9.835%	9.835%
Rank	2	1	3	3	3	3	3	3

$\lambda max = 8.120$; $CI = 0.017$; $CR = 0.012 < 0.1$.

Table 6: Weights and rank of the shield construction.

Evaluation indices	u_{31}	u_{32}	u_{33}	u_{34}
u_{31}	1	1/3	1/3	3
u_{32}	3	1	1/2	3
u_{33}	3	2	1	3
u_{34}	1/3	1/3	1/3	1
Weight	17.028%	30.315%	42.902%	9.755%
Rank	3	2	1	4

$\lambda_{\max} = 4.220$; $\mathrm{CI} = 0.073$; $\mathrm{CR} = 0.082 < 0.1$.

Table 7: Weights and rank of the shield machine design.

Evaluation indices	u_{41}	u_{42}	u_{43}	u_{44}	u_{45}	u_{46}	u_{47}
u_{41}	1	1	2	3	3	3	5
u_{42}	1	1	2	2	2	3	5
u_{43}	1/2	1/2	1	1	1	1	2
u_{44}	1/3	1/2	1	1	1	1	2
u_{45}	1/3	1/2	1	1	1	1	2
u_{46}	1/3	1/3	1	1	1	1	2
u_{47}	1/5	1/5	1/2	1/2	1/2	1/2	1
Weight	27.628%	24.620%	11.254%	10.610%	10.610%	10.020%	5.257%
Rank	1	2	3	4	4	5	6

Table 8: Final evaluation indices.

Target layer	Rule layer	Scheme layer
Evaluation method of shield-type selection (T)	Environmental conditions (C_2)	Existing building (u_{21})
		Underground pipelines (u_{22})
	Shield construction (C_3)	Propulsion speed (u_{31})
		Rotation speed of the cutter head (u_{32})
		Grouting pressure (u_{33})
	Design of shield machine (C_4)	Total thrust (u_{41})
		Main drive torque (u_{42})
		Grouting ability (u_{43})
		Number of muck improvement openings (u_{44})
		Type of cutting tools (u_{45})
		Slagging quantity of screw conveyor (u_{46})

standard, the weight of the evaluation index is quantified as 0, i.e., the membership degree is set to 0. Conversely, when a certain evaluation index fully satisfies the shield adaptation standard, the weight of the evaluation index is 1. The linear relationship is used to determine the specific membership degree of each evaluation index. The evaluation standard for each index is shown in Table 9, and its membership function is shown in Figure 5. In Table 9, v represents the propulsion speed, q represents the flow rate of the propulsion system, A represents the total area of the propulsion cylinder, F represents the total thrust, n represents the number of cylinders, p represents the thrust of the cylinder, d represents the

Table 9: Evaluation standard for the evaluation indices.

Scheme layer	Calculation basis	Evaluation standard: Low degree of adaptability	Moderate degree of adaptability	High degree of adaptability
Existing building (u21)	Based on expert experience	≥20	10~20	≤10
Underground pipelines (u22)	Based on expert experience	≥10	5~10	≤5
Propulsion speed (u31)/(mm/min)	$v = q/A$	≤40 or ≥80	40~45 or 70~80	45~70
Rotation speed of the cutter head (u32)/(r/min)	Based on expert experience	≤0.25 or ≥2.75	0.25~0.5 or 1.5~2.75	0.5~1.5
Grouting pressure (u33)/(MPa)	Based on expert experience	≤0.10 or ≥0.55	0.10~0.25 or 0.50~0.55	0.25~0.50
Total thrust (u41)/kN	$F = np\pi d^2/4$	≤69520	69520~81895	≥81895
Main drive torque (u42)/(kN·m)	$T = \alpha D^3$	≤10000	10000~22350	≥22350
Grouting ability (u43)/(m3/h)	Based on expert experience	≤15	15~25	≥25
Number of muck improvement openings (u44)/(pcs)	Based on expert experience	≤1	1~3	≥3
Type of cutting tools (u45)/(pcs)	Based on expert experience	≤1	1~4	≥4
Slagging quantity of screw conveyor (u46)/(m3/h)	$Q = 15\pi\psi n_{sc}S_{sc}(D_{sc}^2 - d_{sc}^2)$	≤350	350~421	≥421

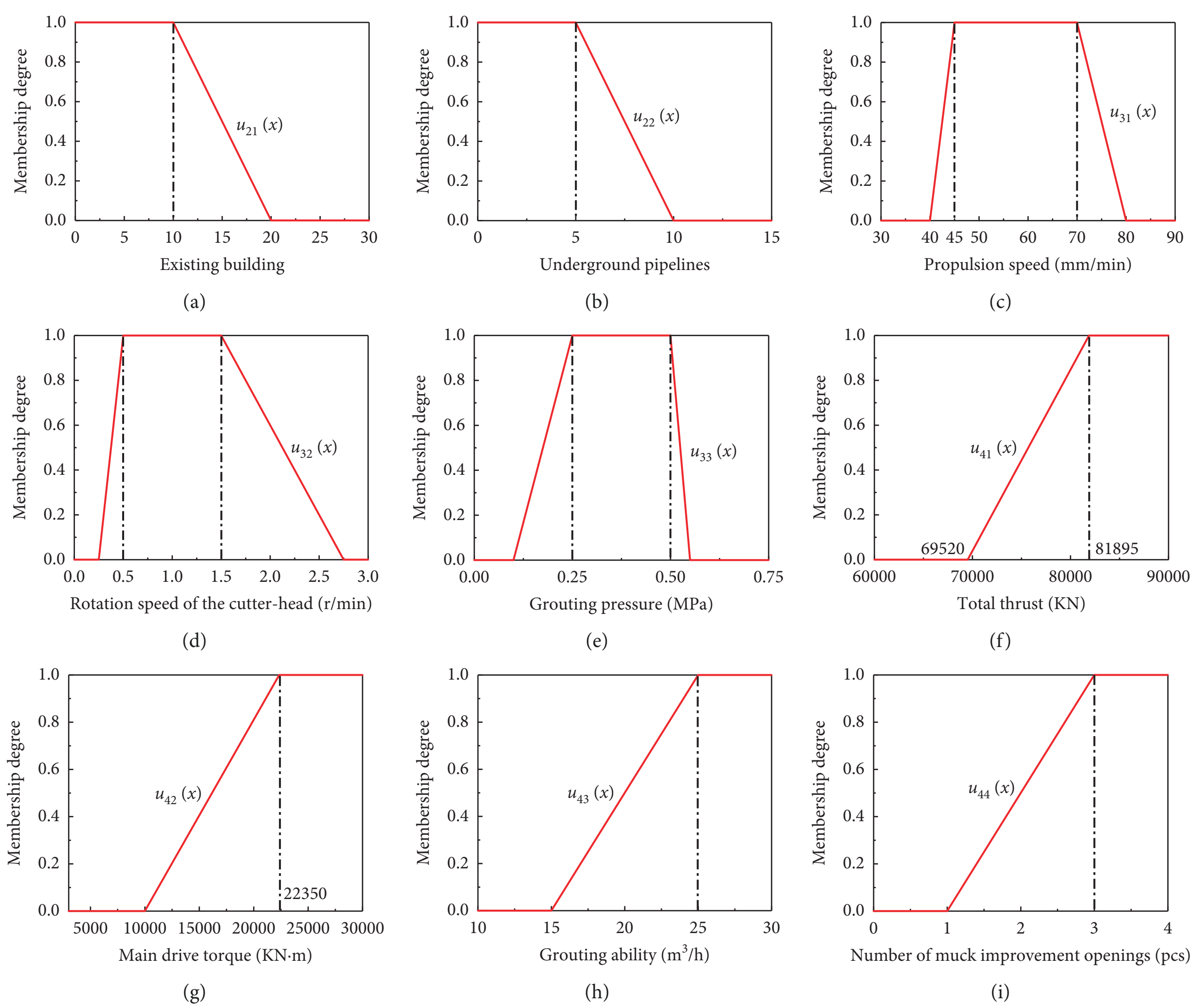
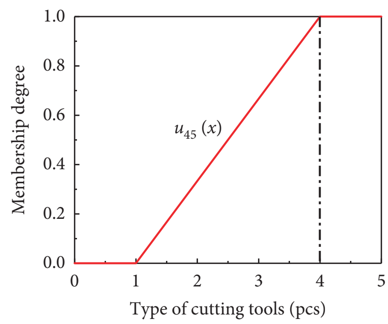
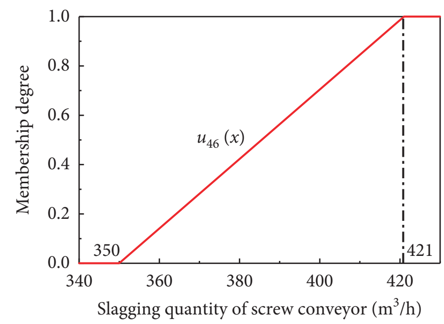


Figure 5: Continued.



(j)



(k)

Figure 5: Membership function for the evaluation indices. (a) Existing building. (b) Underground pipelines. (c) Propulsion speed. (d) Rotation speed of the cutter head. (e) Grouting pressure. (f) Total thrust. (g) Main drive torque. (h) Grouting ability. (i) Number of muck improvement openings. (j) Slagging quantity of the screw conveyor.

diameter of the cylinder piston, T represents the main drive torque, α represents the torque coefficient, D represents the outer diameter of the shield machine, Q represents slagging quantity of screw conveyor, n_{sc} represents the rotation speed of the screw conveyor, S_{sc} represents the screw pitch, D_{sc} represents the barrel inner diameter of the screw conveyor, d_{sc} represents the screw diameter of the screw conveyor, and ψ represents the filling coefficient.

4.2.3. Evaluation Results. The evaluation indices are scored according to the methods of consulting experts in the industry and conducting seminars; then, the judgement matrices of each evaluation index areobtained. Tables 10–13 show the corresponding weights calculated by the judgement matrices. These tables show that the CR value of each judgement matrix is less than 0.1, so the single-level comparison of the evaluation index passes the consistency test, and the weights of the judgement matrices are reasonably set.

The weight of each evaluation index at the scheme layer is ranked in total, and the results are shown in Table 14. From this table, the total rank of the final 11 evaluation indices that affect the adaptability of the Earth pressure balance shield machine in this project is the total thrust, main drive torque, grouting pressure, rotation speed of the cutter head, underground pipelines, grouting ability, number of muck improvement openings, type of cutting tools, slagging quantity of screw conveyor, existing building, and propulsion speed.

The combined weight set A of each index from Table 14 is

$$A = [0.0400, 0.0800, 0.0385, 0.0908, 0.1428, 0.1787, 0.1561, 0.0730, 0.0682, 0.0682, 0.0638]. \quad (1)$$

According to the engineering data of this project, the evaluation matrix R of the shield machine is established:

$$R = [0.7, 0.8, 1, 1, 0.9, 0.9, 1, 1, 0.5, 1, 1]^T. \quad (2)$$

The adaptability evaluation indices of the shield machine and the corresponding evaluation system have been determined in a previous article. Based on the above content, the adaptability of the Earth pressure balance shield machine in the shield interval between Tashuiqiao Station and Erxianqiao Station of Chengdu Metro Line 17 is evaluated, and the type-selection judgement value S of the shield machine is obtained:

Table 10: Judgement matrix of the target layer to the rule layer (T-C).

T-C	C_2	C_3	C_4
C_2	1	1/3	1/4
C_3	3	1	1/3
C_4	4	3	1
Weight	11.994%	27.210%	60.796%

λmax = 3.074; CI = 0.037; CR = 0.071 < 0.1.

Table 11: Judgement matrix of the rule layer to the environmental conditions (C_2-u).

C_2-u	u_{21}	u_{22}
u_{21}	1	1/2
u_{22}	2	1
Weight	33.333%	66.667%

$\lambda_{max} = 2.000$; CI = 0.000; CR = 0.000 < 0.1.

$$\begin{aligned} S &= A \cdot R \\ &= [0.0400, 0.0800, 0.0385, 0.0908, 0.1428, 0.1787, 0.1561, 0.0730, 0.0682, 0.0682, 0.0638] \\ &\quad \cdot [0.7, 0.8, 1, 1, 0.9, 0.9, 1, 1, 0.5, 1, 1]^T \\ &= 0.91. \end{aligned} \quad (3)$$

Based on the FAHP, the fitness value of the Earth pressure balance shield machine in this project is 0.91, i.e., the evaluation grade is I. The selected shield machine can satisfy the requirements of the current project.

The shield construction effect is evaluated by monitoring the land subsidence, the shield tunneling attitude, and the stability of the tunnel face. In the section where the tunnel passes through the house, a measuring point is arranged every 3 m along the direction of shield tunneling, and the monitoring results are shown in Figure 6. It can be seen from Figure 6 that

Table 12: Judgement matrix of the rule layer to the shield construction (C_3-u).

C_3-u	u_{31}	u_{32}	u_{33}
u_{31}	1	1/3	1/3
u_{32}	3	1	1/2
u_{33}	3	2	1
Weight	14.156%	33.377%	52.468%

$\lambda_{max} = 3.054$; CI = 0.027; CR = 0.052 < 0.1.

Table 13: Judgement matrix of the rule layer to the design of the shield machine (C_4-u).

C_4-u	u_{41}	u_{42}	u_{43}	u_{44}	u_{45}	u_{46}
u_{41}	1	1	2	3	3	3
u_{42}	1	1	2	2	2	3
u_{43}	1/2	1/2	1	1	1	1
u_{44}	1/3	1/2	1	1	1	1
u_{45}	1/3	1/2	1	1	1	1
u_{46}	1/3	1/3	1	1	1	1
Weight	29.388%	25.684%	12.009%	11.215%	11.215%	10.490%

$\lambda_{max} = 6.037$; CI = 0.007; CR = 0.006 < 0.1.

Table 14: Total rank of the evaluation index weight.

u	C_2 11.994%	C_3 27.210%	C_4 60.796%	Total weight of rule layer to scheme layer	Rank
u_{21}	33.333%	0	0	0.0400	9
u_{22}	66.667%	0	0	0.0800	5
u_{31}	0	14.156%	0	0.0385	10
u_{32}	0	33.377%	0	0.0908	4
u_{33}	0	52.468%	0	0.1428	3
u_{41}	0	0	29.388%	0.1787	1
u_{42}	0	0	25.684%	0.1561	2
u_{43}	0	0	12.009%	0.0730	6
u_{44}	0	0	11.215%	0.0682	7
u_{45}	0	0	11.215%	0.0682	7
u_{46}	0	0	10.490%	0.0638	8

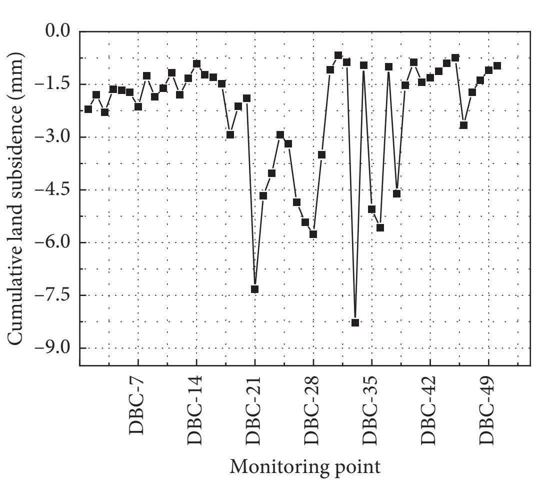


Figure 6: Monitoring value of cumulative land subsidence.

the cumulative land subsidence of each monitoring point meets the requirement that the cumulative land subsidence is less than or equal to 20 mm. To date, the shield machine has been driving steadily with good attitude control, and no engineering accidents have occurred. The shield tunneling project of Chengdu Rail Transit Line 17 has been smoothly performed, and the onsite shield construction matches well with the evaluation results of the proposed evaluation method.

5. Conclusions

A quantitative adaptability evaluation method of shield machines based on the fuzzy analytic hierarchy process (FAHP) and analytic hierarchy process (AHP) is proposed in this paper, and it is applied to the selection evaluation of shield machines in the shield interval between Tashuiqiao Station and Erxianqiao Station of Chengdu Metro Line 17. From this study, the following conclusions are drawn:

(1) The total rank of the final 11 evaluation indices that affect the adaptability of the Earth pressure balance shield machine in Chengdu Metro Line 17 is as follows: total thrust, main drive torque, grouting pressure, rotation speed of the cutter head, underground pipelines, grouting ability, number of muck improvement openings, type of cutting tools, slagging quantity of screw conveyor, existing building, and propulsion speed.

(2) The fitness value of the Earth pressure balance shield machine used in Chengdu Metro Line 17 is 0.88, i.e., the evaluation grade is I. The rationality and accuracy of the fuzzy comprehensive evaluation model of shield adaptability are verified through onsite shield construction, and the evaluation results are consistent with the actual situation.

The proposed quantitative evaluation method of the shield machine adaptability based on AHP and FAHP in this paper can provide a reference for similar projects. When analysing a specific project case, the evaluation indices and weights of specific projects should be determined again to satisfy the new analytical problem.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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