Research Article

Evaluation of the Adaptability of an EPB TBM to Tunnelling through Highly Variable Composite Strata

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Received 3 March 2021; Revised 22 June 2021; Accepted 19 July 2021; Published 28 July 2021

Academic Editor: Abdul Qadeer Khan

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The adaptability of an earth pressure balance (EPB) tunnel boring machine (TBM) to complex geological strata needs to be evaluated when a tunnel project is set up. It is helpful for better design and more suitable technical parameters of the machine. Because the factors that influence adaptability are numerous and interrelated, their effects also differ; hence, a quantitative assessment of adaptability is generally difficult. In the present study, a method for quantitatively evaluating the excavation adaptability of an EPB TBM was developed using an analytic hierarchy process (AHP) and fuzzy comprehensive evaluation. The method first involves an initial selection of factors that may influence tunnelling. Based on the expert questionnaire and their influence weights determined by AHP, the 10 evaluation indexes from 25 primary indexes were selected to establish the evaluation index system (EIS) including a target, criteria, and index level. Fuzzy membership functions are then derived one after another based on the effect of each evaluation index on the EPB TBM tunnelling process. A fuzzy mathematical method was finally presented to determine the adaptability of an EPB TBM excavation performance. The proposed method was applied to two special sections of diameter 6.98 m excavated by two EPB TBMs in the Shenzhen Metro Line 11 project. The geological exploration shows that these two tunnel sections pass through typical composite strata in Shenzhen. The determined adaptability grades of the EPB TBMs used for composite strata were confirmed by the actual tunnel excavation. It indicates that the developed method is reasonable and useful to evaluate tunnelling adaptability of EPB TBM.

1. Introduction

Composite strata are often encountered when using the shield tunnelling method to construct subway tunnels in South China. Strata of this type are characterized by a complex and highly variable composition, with large differences occurring between the strengths of different sections. Researchers in China first encountered such strata during the tunnelling of Line 1 of the Guangzhou Metro. The unique geological conditions created enormous difficulties when using ordinary earth pressure balance (EPB) shield machines for tunnel excavation [1, 2]. Composite EPB shield machines were first introduced to China to address this issue [3, 4]. Such machines combine the advantages of hard-rock tunnel boring machines (TBMs) and soft-ground shield

machines, and they are commonly referred to as EPB TBMs. Although these machines are now widely used in the region, composite strata continue to pose difficulties in tunnelling. This includes the need for frequent switching of boring modes, severe wear and tear of the cutterheads, and schedule overruns. In severe cases, the shield tunnelling method may have to be abandoned and replaced by the shallow tunnelling method [5]. There is thus an urgent need for a method for evaluating the tunnelling adaptability of an EPB TBM in composite strata. It could help to decide whether mechanical excavation should be adopted for such tunnel projects. The evaluation results would further determine the technical parameters of EPB TBM and even the tunnelling method.

There have been some research findings on the factors that affect EPB TBM excavation and the associated

construction risks. For example, Zhao et al. [6] detailed the effects of composite strata on EPB TBM tunnelling based on a case study conducted on an actual engineering project. Tokgoz et al. [7] also analysed the relationship between the geotechnical and tunnelling parameters to evaluate the capability of an EPB TBM for tunnelling through fine-grained soil strata and examine the associated risks. Hu et al. [8] and Hyun et al. [9] used fault tree analysis and the analytic hierarchy process (AHP) to examine the risks of EPB TBM construction and proposed some targeted control measures. Hong et al. [10] used event tree analysis to evaluate the risks of underwater tunnelling using an EPB TBM. More studies have, however, been conducted on the boreability and performance of hard-rock TBMs and the influencing factors. Sapigni et al. [11] used geotechnical grading standards to evaluate the performance of a TBM, while Yan et al. [12] took energy consumption during the tunnelling process as a key indicator and analysed the construction efficiency of shield tunnelling through soft deposit. Mikaeil et al. [13] applied the multifactor fuzzy method to examine the hard-rock boreability of a TBM. Lin et al. [14] proposed a novel fuzzy model for identifying high-risk factors during deep excavations in karst geological ground. Dudt and Delisio [15] used the penalty factor method to predict the performance of a TBM in highly variable strata. Furthermore, owing to the uncertainties of the various impact factors of TBM tunnelling, fuzzy mathematical methods have been widely used to predict the boreability of the machine [16–19]. Rostami [20] presented a comprehensive review and evaluation of existing models for predicting TBM's performance under difficult strata conditions and reported several new research findings. Bernados and Kaliampakos [21] introduced a vulnerability index for describing the uncertainties of the strata parameters and proposed a methodology for evaluating the probability of a geological disaster occurring during TBM tunnelling. Farrokh and Rostami [22] presented a detailed description of the impact of poor geological conditions on the performance of double-shield TBMs based on the construction of the Ghomroud Tunnel in Iran. In a recent comprehensive report, Gong et al. [23] discussed the main issues encountered during TBM tunnelling under poor geological conditions and the corresponding mitigation measures. Considering the complexity of the relevant issues, mathematical methods applicable to multifactorial analysis are used to select the appropriate TBM and shield and assess the construction risks of a project. Such methods include AHP, decision analysis, and the use of expert systems [24–29]. Recently, artificial intelligence (AI) models and related methods have been applied to some issues in shield tunnelling, for example, predicting disc cutter life and modelling performance of EPB shield tunnelling [30–34].

It can thus be seen that many efforts have been devoted to determine the various factors affecting EPB TBM tunnelling and also to evaluate the EPB TBM's performance and the construction risks in difficult ground conditions. Nevertheless, there remains a lack of a method to quantitatively evaluate the tunnelling adaptability of EPB TBMs under complex geological conditions.

The aim of the present study was to develop a viable and quantitative method for evaluating the tunnelling adaptability of EPB TBMs in composite strata. The methodology for evaluation is first presented, which is based on AHP and fuzzy comprehensive evaluation (FCE). Secondly, the factors that affect the adaptability of an EPB TBM were then described according to the study and practice of EPB TBM in Shenzhen Metro construction. AHP was then used to determine the weights of these primary factors. Based on the expert questionnaire and their influence weights determined by AHP, the evaluation indexes were selected to form the evaluation index system (EIS) comprising the target, criteria, and index layers. Fuzzy membership functions were then derived one after another based on the effect of each evaluation index on the EPB TBM tunnelling process. Thirdly, a fuzzy mathematical method was presented to determine the adaptability of an EPB TBM excavation performance. Finally, the proposed method was verified by applying it to two special sections passing through composite strata of the Shenzhen Metro Line 11. These sections were excavated using the EPB TBPs with a diameter of 6.98 m, which were applied for the first time in Shenzhen Metro construction.

2. Methodology for Evaluating Adaptability

For an EPB TBM, tunnelling adaptability refers to the ability of the machine to adapt to the various factors that affect tunnel excavation. This ensures that the machine can manifest its design effectiveness to complete the tunnelling task.

2.1. Evaluation Indexes and Evaluation Index System.

Because the adaptability of an EPB TBM is affected by numerous factors, it was necessary to first select the most important or critical factors in the present study. Each shortlisted factor was then comprehensively described using a type of quantitative index. The evaluation indexes were selected based on considerations such as project implementation, results of scientific research, expert opinion, and mathematical assessment.

Based on the selected quantitative indexes, an evaluation index system (EIS) can be established so as to accurately reflect the impact of the various factors on tunnelling adaptability. Because influencing factors are not only often numerous but also interrelated, each evaluation index in an EIS should be highly representative when used to characterize the impact of a particular factor. Moreover, the principles of hierarchy, validity, and conciseness were needed to construct an EIS [35, 36].

2.2. Fuzzy Membership Function of the Evaluation Indexes.

The evaluation indexes have different units, attributes, and degrees of importance, which causes a lack of commensurability among them. Hence, a fuzzy membership function (FMF) can be used to achieve commensurability among the indexes. The value of the function describes the relationship between an uncertain quantity x and a membership function $\nu(x)$, which is defined in the interval $[0, 1]$. The FMF may take different forms such as trigonometric, exponential, and

Gaussian. To simplify the implementation of FMF, only a straight line and trapezoid were considered in this study.

2.3. Weights of the Evaluation Indexes. The weights of the different evaluation indexes were determined using AHP [35, 36]. The process was as follows.

2.3.1. Hierarchy of Evaluation Indexes. After setting the evaluation targets, their mutual impact and membership relationships between the evaluation indexes were used as the bases for ranking them in descending order, with respect to the target, determined criteria, and index layers. The indexes at higher levels thus predominated over those at lower levels.

2.3.2. The Judgment Matrix. The relative importance of a pair of indexes can be qualitatively determined using the judgment matrix. For the comparison of evaluation indexes U_i and U_j ($i, j = 1, \dots, n$), Saaty [35] proposed the use of Table 1 for the assignment of values to a_{ij} in the judgment matrix A . A comparison of U_i and U_j defines a_{ij} , while that of U_j and U_i defines $a_{ji} = 1/a_{ij}$.

Although the judgment matrix A established using the above method may objectively reflect the different impacts between a pair of indexes, a certain degree of inconsistency is unavoidable when analysing the results of comparing all indexes. To address this problem, the elements of the matrix A should also satisfy the following equation:

$$a_{ij}a_{jk} = a_{ik}, \quad \forall i, j, k = 1, 2, 3, \dots, n. \quad (1)$$

2.3.3. Single Hierarchical Arrangement (SHA). For the matrix A , it was assumed that Ω (ω_i) is the eigenvector corresponding to the maximum eigenvalue of $\lambda_{\max}$. After normalization, Ω would represent the hierarchy of weights and the relative importance between the indexes on one level and a specific index on a higher level. The maximum eigenvalue of A and its corresponding eigenvector could be approximately determined using the root mean square method, as follows:

- (a) The product of the elements in each row of the matrix A is obtained:

$$\delta_i = \left(\prod_{j=1}^n a_{ij} \right)^{1/n}, \quad (i = 1, 2, \dots, n). \quad (2)$$

- (b) δ_i is normalized before the eigenvector Ω is calculated:

$$\omega_j = \frac{\delta_j}{\sum_{k=1}^n \delta_k}, \quad (j = 1, 2, \dots, n). \quad (3)$$

- (c) The maximum eigenvalue $\lambda_{\max}$ of the matrix A is calculated. Because $A\Omega = \lambda_{\max}\Omega$, then

TABLE 1: Method for assigning values to elements a_{ij} in the judgment matrix A .

Value assignment basis	a_{ij}
U_i and U_j are equally important	1
U_i is slightly more important than U_j	3
U_i is obviously more important than U_j	5
U_i is definitely more important than U_j	7
U_i is extremely more important than U_j	9
Intermediate judgment for the above pairs	2, 4, 6, and 8

$$\sum_{j=1}^n a_{ij}\omega_j = \lambda_{\max}\omega_i, \quad (j = 1, 2, \dots, n). \quad (4)$$

Hence,

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{\sum_{j=1}^n a_{ij}\omega_j}{\omega_i}. \quad (5)$$

The consistency testing of the SHA is conducted as follows:

- (a) The consistency index CI can be calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}. \quad (6)$$

- (b) To determine the corresponding mean random consistency index RI, the random method is used to construct 500 sample matrices. Random numbers between 1 and 9 were chosen and their respective reciprocals were used to construct a positive reciprocal matrix. The following definition would apply:

$$RI = \frac{\bar{\lambda}_{\max} - n}{n - 1}, \quad (7)$$

where $\bar{\lambda}_{\max}$ is the mean of the maximum eigenvalues of these matrices.

- (c) Consistency check: the consistency ratio is defined as $CR = CI/RI$. If $CR < 0.10$, then the matrix A meets the condition for consistency; otherwise, a revision is required.

2.3.4. Total Hierarchical Arrangement (THA). Determination of the THA of various indexes is based on the hierarchical weights, especially those at the lowest layer, with respect to the target layer. The weights of the THA could be obtained by summing the weights of the SHA from top to bottom.

For the index set $U = \{U_1, U_2, \dots, U_m\}$, its THA weights are denoted by $u_1, u_2, \dots, u_m$, respectively. Assuming that the index set one layer below U is $V = \{V_1, V_2, \dots, V_n\}$, the SHA weights of the latter set with respect to U_j would be $v_{1j}, \dots, v_{nj}$. Obviously, $v_{ij} = 0$ when V_i and U_j are unrelated. The method illustrated in Table 2 can be used to calculate the weight of the indexes in V with respect to the THA weights $v_1, v_2, \dots, v_n$.

TABLE 2: Method for calculating the THA weights of V .

U/V	U_1 u_1	U_2 u_2	$\dots$ $\dots$	U_m u_m	THA weights for index set V
V_1	v_{11}	v_{12}	$\dots$	v_{1m}	$v_1 = \sum_{j=1}^m v_{1j}u_j$
V_2	v_{21}	v_{22}	$\dots$	v_{2m}	$v_2 = \sum_{j=1}^m v_{2j}u_j$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
V_n	v_{n1}	v_{n2}	$\dots$	v_{nm}	$v_n = \sum_{j=1}^m v_{nj}u_j$

Even when all layers pass the consistency test for SHA, it is still possible for the nonuniformity of the various layers to accumulate during comprehensive analyses. To avoid this nonuniformity in the final judgment, a consistency check of the THA should be conducted as follows.

Regarding the paired comparative judgment matrices formed by the indexes in set V that are related to U_j , it is assumed that these have passed the consistency test at the SHA stage and that the corresponding CI_j and RI_j have been solved. The THA of V would thus be given by

$$CR = \frac{\sum_{j=1}^n CI_j u_j}{\sum_{j=1}^n RI_j u_j}. \quad (8)$$

The THA results are considered consistent if $CR < 0.1$.

2.4. Fuzzy Comprehensive Evaluation Model. Assuming that $U = \{U_1, U_2, \dots, U_m\}$ is the set of evaluation indexes for the evaluation target set $O = \{O_1, O_2, \dots, O_n\}$, then the basic model for FCE would be

$$D = \bar{U} \times R, \quad (9)$$

or

$$\{D_1, D_2, \dots, D_n\} = \{u_1, u_2, \dots, u_m\} \times \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}, \quad (10)$$

where D is the set of comprehensive judgment values for O and D_i is the adaptability degree of the evaluation target O_i . When $0 \leq D_i \leq 1$, “0” indicates complete inadaptability, while “1” indicates complete adaptability. $\bar{U}$ is the set of THA weights for the evaluation index U , where $u_i \geq 0$ and $\sum_{i=1}^m u_i = 1$. R is the matrix for the degree of membership between V and O . The adaptability evaluation of O_i can be performed based on the numerical value of D_i and in accordance with the classification criteria in Table 3.

3. Tunnel Construction for the Shenzhen Metro Line 11

The Shenzhen Metro Line 11 starts from Futian Station and ends at Bitou Station, with a total length of 51.681 km and 17 stations. In all the tunnel sections of Line 11, only the Chegongmiao-Hongshuwan section (Section C-H) with a length of 5477.9 m and the Nanshan-Qianhaiwan section (Section N-Q) with a length of 3582.6 m were excavated using EPB TBMs of diameter 6.98 m, while other sections

were constructed with common shield machines of diameter 6.30 m. The site location of these two sections is shown in Figure 1.

3.1. Geotechnical Investigation. To investigate the site geotechnical conditions of these two sections, geophysical method and boreholes were mainly used before tunnel construction. A seismic reflection survey was carried out to explore the thickness of the overburden layers and the subsurface structures along the tunnel alignment. A total number of 1,047 boreholes were drilled to provide the site information. The borehole spacing along the tunnel alignment is arranged as follows: 100–500 m for a simple site, 30–50 m for a moderately complex site, and less than 30 m for a complex site. The physicommechanical parameters of the main stratum have been ascertained by geotechnical tests in laboratory.

The geological cross-sections of these two sections are shown in Figures 2 and 3, respectively. The profile gives an overall image of the ground condition along the tunnel alignment. The main strata and stratigraphic distribution traversed by this tunnel section are detailed in Figure 4. The different types of strata and complex geological conditions are typical of composite strata. Some basic strength parameters of soil and rock samples are given in Table 4, which were obtained from laboratory tests such as direct and triaxial shear test. It can be seen that a large proportion of the strata comprises weathered granite strata, which is characterized by substantial strength variation.

The investigation report recognized that varied ground conditions and transitions from high strength granite to low strength weathered materials (and vice versa) would be a major challenge to EPB TBM tunnelling. The poor geological conditions encountered in Section C-H and Section N-Q during the tunnelling caused several difficulties (see Table 5).

3.2. Basic Functions of an EPB TBM. The EPB TBM of diameter 6.98 m used for tunnelling was manufactured by China Railway Engineering Equipment Group Co., Ltd. And first used in Shenzhen subway construction. Targeted designs are incorporated into a composite EPB TBM for overcoming the difficulties encountered during tunnelling through composite strata. The basic functions of the machine and the specifications of its cutterheads are detailed in Tables 6 and 7, respectively.

4. Evaluation Indexes and Fuzzy Membership Functions for EPB TBM Tunnelling

4.1. Evaluation Indexes and EIS

4.1.1. Preliminary Selection of Evaluation Indexes. The factors that affect EPB TBM tunnelling include the EPB TBM design, tunnelling method, geological conditions, and surrounding environment. A detailed analysis of the various influencing factors was conducted in this study, taking into account the geological and environmental conditions along the two aforementioned sections. Based on the study and

TABLE 3: Adaptability classification for the evaluation targets.

Grade	Description of adaptability	Degree of adaptability
I	Completely adaptable	≥ 0.9
II	Adaptable	0.6–0.9
III	Slightly adaptable	0.4–0.6
IV	Inadaptable	0.1–0.4
V	Completely inadaptable	≤ 0.1

FIGURE 1: Site location map of Section C-H and Section N-Q.

FIGURE 2: Geological profile of Section C-H of the Shenzhen Metro Line 11.

FIGURE 3: Geological profile of Section N-Q of the Shenzhen Metro Line 11.

FIGURE 4: Distribution of main ground conditions along the tunnel alignment. (a) Section C-H. (b) Section N-Q.

TABLE 4: Physical and mechanical indexes of cored samples from tunnel site.

Rock and soil type	Unit weight (kN/m ³)	Cohesion (kPa)	Inner friction angle (degree)	UCS (MPa)
Clay	19.2–19.9	20.0–25.0	20.0–22.0	
Gravel-sand	20.0–20.4		32.0–35.0	
Gravelly clay	18.3–18.7	24.0–25.0	22.0–25.0	
Fully weathered granite	18.2–18.6	28.0–30.0	25.0–28.0	
Severely weathered granite	19.0–21.5	38.0–40.0	32.0–35.0	
Moderately weathered granite	25.1–25.5			45.0–60.0
Lightly weathered granite	26.0–26.5			145.0–170.0

TABLE 5: Difficulties encountered during tunnel excavation of Section C-H and Section N-Q.

Adverse geological conditions	Difficulties during tunnelling
Silt and soft soil layer	Loss of stability at excavation surfaces; excessive strata deformation causing surface collapse
Artificial accumulation layer	Complex soil compositions and properties; uneven hardness; difficult shield tunnelling
Clay layer	Large stratigraphic disturbances; tendency for formation of mud cakes; augers tending to squirt easily
Mix ground	Difficulty in controlling TBM attitude; poor adaptability of cutterheads and cutter bits to ground conditions, necessitating frequent changing of construction method
Layer with mildly weathered granite	Severe wear and tear of cutterheads due to very strong rocks
Layer with spherical weathered granite boulders	Severe wear and tear of cutterheads and cutter bits due to very strong boulders, affecting the progress of shield tunnelling
Fractured zone of faults	High likelihood of squirting; unstable TBM attitude
Fully saturated sand layer	High likelihood of water inrush and sand boiling; risk of excavation surface collapse

TABLE 6: Technical parameters of the EPB TBM.

Parameter	Value	Unit
Excavation diameter	6,980	mm
Diameter of shield machine	6,950/6,940/6,930	mm
Rotation speed of cutterhead	0–3.6 (inflection speed = 1.37)	rev/min
Maximum advancing speed	80	mm/min
Maximum speed	49,588	kN
Main drive power	1,120	kW
Rated torque	7,806	kN·m
Torque turnaround	9,757	kN·m
Screw conveyor (diameter/power/torque)	900/315/210	mm/kW/kN·m

practice of constructing Shenzhen Metro using shield tunnelling technology [5], 25 primary evaluation indexes $W_1 \sim W_{25}$ were selected, as detailed in Table 8.

To determine the mutual impacts of these indexes, 20 experts from universities, design institutes, and construction companies were asked to complete a

TABLE 7: Specifications of the cutterhead and cutters.

Property	Specification
Structural form	Hybrid (spokes + plate)
Opening ratio (central opening rate)	33% (38%)
Cutterhead specifications (diameter × length)	6,980 mm × 1,635 mm
17-inch center hob (number/height/spacing)	6/175 mm/90 mm
17-inch single-blade hob (number/height/spacing)	38/175 mm/75–85 mm
Side scraper (number/height)	12/135 mm
Scraper (number/height/width)	49/135 mm/250 mm

TABLE 8: Primary evaluation indexes for the adaptability of an EPB TBM during tunnelling.

Target layer	Adaptability degree of EPB TBM under mixed ground conditions D			
Criteria layer	EPB TBM design U_1	Tunnelling method U_2	Geological conditions U_3	Environment conditions U_4
Index layer	Total thrust W_1		Artificial fill W_{14}	
	Cutterhead structure W_2		Soft soil stratum W_{15}	
	Cutterhead torque W_3	Advancing speed W_9	Liquefied sand layer W_{16}	
	Cutterhead opening ratio W_4	Rotating speed of cutterhead W_{10}	Residual soil layer W_{17}	Underground structures W_{23}
	Muck improvement technique W_5	Earth pressure in cutterhead chamber W_{11}	Composite strata W_{18}	Ground buildings W_{24}
	Selection and layout of cutters W_6	Shield tail void W_{12}	Microweathered granite protrusions W_{19}	Structure of existing tunnel lines W_{25}
	Cutter spacing W_7	Wall-back grouting pressure W_{13}	Hard-rock layer W_{20}	
	Muck amount of screw conveyor W_8		Fault crushed zone W_{21}	
			Spherical weathered boulders W_{22}	

questionnaire survey. Based on their judgments, values were first assigned to the judgment matrix as shown in Table 1. AHP was then used to analyse the weights and hierarchy of the indexes in each layer. Based on the analysis of weights and hierarchy, the 25 primary indexes were evaluated and reduced to 10 indexes that have strong influencing weights.

4.1.2. Evaluation Index System. As shown in Table 9, the 10 remaining indexes marked with $V_1 \sim V_{10}$ were used to form the EIS of EBP TBM according to the principles for establishing an EIS. The fuzzy membership function of these indexes and the way they are evaluated are given in the next section.

4.2. Fuzzy Membership Function of Indexes in the EIS

4.2.1. Total Thrust V_1 . The equation commonly used to predict the total thrust of an EPB TBM is

$$F = \frac{F_s \pi D_e^2}{4}, \quad (11)$$

where F_s is an empirical coefficient with a value within 700–1,200 kN/m² and D_e is the excavation diameter [37]. Based on the known value of $D_e = 6.980$ m, the adaptability range of the total thrust was determined to be 26,785–45,918 kN. According to these values, the FMF of the total thrust was established as expressed by equation (12).

$$v_1(x) = \begin{cases} 0, & x < 26785, \\ \frac{x - 26785}{45918 - 26785}, & 26785 \leq x < 45918, \\ 1, & x \geq 45918. \end{cases} \quad (12)$$

4.2.2. Cutterhead Torque V_2 . The empirical equation for calculating the cutterhead torque is

$$T = \alpha D_e^3, \quad (13)$$

where α is the torque coefficient, which ranges within 15–23 [37]. For $D_e = 6.980$ m, the adaptability range of the cutterhead torque was determined to be 5,101–7,821 kN•m. The corresponding FMF is as expressed by equation (14).

$$v_2(x) = \begin{cases} 0, & x < 5101, \\ \frac{x - 5101}{7821 - 5101}, & 5101 \leq x < 7821, \\ 1, & x \geq 7821. \end{cases} \quad (14)$$

4.2.3. Cutterhead Opening Ratio V_3 . The selection of the cutterhead opening ratio is related to the adaptability of the cutterhead to the soil layer. The ratio is defined as

TABLE 9: EIS of the EPB TBM.

Target layer	Adaptability of EPB TBM to tunnelling under mixed ground conditions D		
Criteria layer	EPB TBM design U_1	Tunnel construction U_2	Geological conditions U_3
Index layer	Total thrust V_1 (kN)	Earth pressure in cutterhead chamber V_6 (MPa)	Composite strata V_9 (%)
	Cutterhead torque V_2 (kN•m)		
	Cutterhead opening ratio V_3 (%)	Wall-back grouting pressure V_7 (kPa)	Spherical weathered boulders V_{10} (m)
	Muck amount of screw conveyor V_4 (m ³ /h)	Shield tail void V_8 (mm)	
	Cutter spacing V_5 (mm)		

$$\xi = \frac{A_s}{A_r}, \quad (15)$$

where A_s and A_r are the opening area and the full cutting area of the cutterhead, respectively. The various magnitudes of the correlation value ξ between the EPB TBM tunnelling time and the soil layer [37] are detailed in Table 10.

It can be seen from Table 11 that there is an optimal adaptability range for the cutterhead opening ratio. The corresponding FMF is expressed by equation (16).

$$v_3(x) = \begin{cases} 0, & \\ \frac{x - 15\%}{25\% - 15\%}, & 15\% \leq x < 25\%, \\ 1, & 25\% \leq x < 35\%, \\ \frac{45\% - x}{45\% - 35\%}, & 35\% \leq x < 45\%, \\ 0, & x \geq 45\%. \end{cases} \quad (16)$$

4.2.4. Slagging Ability of the Screw Conveyor V_4 . Theoretically, the maximum amount of soil cut by the cutters of an EPB TBM during continuous excavation is given by

$$Q_1 = \frac{v_{\max} \pi D_e^2}{4}, \quad (17)$$

where $v_{\max}$ is the maximum driving speed of the EPB TBM [37]. Based on the data in Table 7, Q_1 was determined to be 183.7 m³/h. The slagging ability of the screw conveyor was thus determined to be given by

$$Q_2 = \left(\frac{d}{F_z} \right)^{2.5} K_d K_\beta, \quad (18)$$

where d is the diameter of the screw, K_z is the synthetic characteristic coefficient of the muck (0.049 is generally used), K_d is the filling coefficient (0.32 is generally used), and K_β is the inclination coefficient (0.65 is generally used). For $d = 0.9$ m, $Q_2 = 300.7$ m³/h.

Because the mixing of bentonite slurry with the soil inside the chamber of the EPB TBM expands the muck

TABLE 10: Correlation between the cutterhead opening ratio and the soil layer.

Geological stratification	Soil layer	ξ (%)
Diluvium	Cohesive soil	25–30
	Sandy soil	15–20
	Gravelly soil	20–25
	Interbedding of soft and hard soil	30–35
Alluvium	Cohesive soil	20–25
	Sandy soil	10–15
	Gravelly soil	15–20
	Interbedding of soft and hard soil	20–25

TABLE 11: Cutter spacing for different rock types.

Rock type	Cutter spacing (mm)
Limestone	70–85
Granite	50–85
Gneiss	60–70
Sandstone	70–85
Shale	85–100

volume, the maximum amount of muck conveyed by the screw is given by

$$Q_{\max} = K_s Q_1, \quad (19)$$

where K_s is the expansion coefficient of the muck, with 2.1 being considered as the maximum value, based on which $Q_{\max} = 385.8$ m³/h.

Using the above calculation results, the expression of the FMF of the slagging ability of the screw conveyor was derived as

$$v_4(x) = \begin{cases} 0, & x < 300.7, \\ \frac{x - 300.7}{385.8 - 300.7}, & 300.7 \leq x < 385.8, \\ 1, & x \geq 385.8. \end{cases} \quad (20)$$

4.2.5. Cutter Spacing V_5 . The layout of the cutter spacing is significantly determined by the strength of the rock being cut. The cutter spacing used for common rocks is presented in Table 11 [2].

Based on a consideration of the rock strata of the two tunnel sections and noting that the adaptability range of the cutter spacing should be 40–100 mm, the corresponding FMF was derived as expressed by equation (21).

$$v_5(x) = \begin{cases} 0, & x < 40, \\ \frac{x - 40}{60 - 40}, & 40 \leq x < 60, \\ 1, & 60 \leq x < 80, \\ \frac{100 - x}{100 - 80}, & 80 \leq x < 100, \\ 0, & x \geq 100. \end{cases} \quad (21)$$

4.2.6. Earth Pressure in the Cutterhead Chamber V_6 . During EPB TBM tunnelling, the maximum and minimum control pressures on the excavation surface are, respectively, given by [38].

$$\begin{aligned} P_{\max} &= P_w + P_0 + P_i, \\ P_{\min} &= P_w + P_a + P_i, \end{aligned} \quad (22)$$

where P_w is the groundwater pressure, P_0 is the static earth pressure, P_a is the active earth pressure (for strata with differentially weathered granite, the loose pressure of the granite could be considered representative), and P_i is the preparatory pressure for compensating for the loss in pressure during tunnelling (0.01–0.02 MPa is generally used).

Using the known maximum depth of the tunnelling section of 30.5 m and geotechnical data, $P_{\max}$ was determined to be 0.320 MPa; using Rankine's theory, P_a was determined to be 0.170 MPa; and using Protodyakonov's theory, the loose pressure was determined to be 0.150 MPa. Based on these results, the FMF of the earth pressure in the cutterhead chamber was derived as expressed by equation (23). It should be noted that ground uplift due to excessive pressure was not considered.

$$v_6(x) = \begin{cases} 0, & x < 0.15, \\ \frac{x - 0.15}{0.32 - 0.15}, & 0.15 \leq x < 0.32, \\ 1, & x \geq 0.32. \end{cases} \quad (23)$$

4.2.7. Grouting Pressure V_7 . The grouting pressure is related to the earth and water pressures, segment strength, TBM type, and characteristics of the slurry material. It was observed during the construction of the Shenzhen Metro that the synchronous grouting pressure generally did not fall

below 200 kPa [5]. Hence, the maximum permissible grouting pressure [1] was determined to be given by

$$P_f = p_0 + (0.9 \ln \eta + 0.73)q_u, \quad (24)$$

where $\eta = (D_e + 2H)/D_e$, H is the buried depth, p_0 is the overburden pressure, and q_u is the unconfined compressive strength of the soil. Using the geotechnical data of the shallowest tunnel profile in the tunnel sections, it was determined that $P_f = 600$ kPa. Based on this result, the adaptability range of the grouting pressure was determined to be 200–660 kPa. The corresponding FMF is expressed by equation (25).

$$v_7(x) = \begin{cases} 0, & x < 200, \\ \frac{x - 200}{660 - 200}, & 200 \leq x < 660, \\ 1, & x \geq 660. \end{cases} \quad (25)$$

4.2.8. Shield Tail Void V_8 . The selected amount of shield tail impacts its sealing effect and determines the soil deformation. Statistical data from actual cases of using different tail voids are presented in Table 12 [37].

Generally, the shield tail void should not be less than 30 mm. In addition, based on observations from the construction of the Shenzhen Metro, the maximum void is approximately 65 mm [5]. Thus, the adaptability range for the void should be 30–65 mm. The corresponding FMF is

$$v_8(x) = \begin{cases} 0, & x < 30, \\ \frac{x - 30}{65 - 30}, & 30 \leq x < 65, \\ 1, & x \geq 65. \end{cases} \quad (26)$$

4.2.9. Composite Strata V_9 . This refers to the occurrence of two or more strata with significantly different strengths on the excavation surface during tunnelling. Typical examples that were encountered in the two tunnel sections under consideration included strata containing differentially weathered granite, bedrock protrusions, and so on. The average uniaxial compressive strength of the rocks was 80 MPa, although the maximum strength could reach 135 MPa. This implies substantial strength variation over the different parts of the excavation surface. The existence of hard rocks within the composite strata clearly impacted the tunnelling negatively. The strata composition ratio is defined as

$$R_c = \frac{H_h}{D_e}, \quad (27)$$

where H_h is the thickness of the hard-rock layer at the excavation surface.

TABLE 12: Case values of the shield tail void [37].

Outer diameter of shield (m)	Number of constructed tunnels		
	25 mm	30 mm	40 mm
<3	93	7	0
3–5	63	34	2
5–7	89	11	0
>7	25	25	50

Based on the observations from tunnelling through composite strata during the construction of the Shenzhen Metro, when $R_c < 15\%$, the excavation surface may be treated as a homogeneous soil layer, which does not adversely affect EPB TBM tunnelling. However, when R_c is 40%–60%, the impact on shield tunnelling is the most severe. This includes partial loading of the main bearing, increased wear and tear of the cutter bits, and difficult tunnelling and attitude control [5]. The FMF of the composite strata was determined to be as expressed by equation (28).

$$v_9(x) = \begin{cases} 1, & \\ \frac{35\% - x}{35\% - 30\%}, & x < 30\%, \\ 0, & 30\% \leq x < 35\%, \\ \frac{x - 60\%}{65\% - 60\%}, & 35\% \leq x < 60\%, \\ 1, & 60\% \leq x < 65\%, \\ & x \geq 65\%. \end{cases} \quad (28)$$

4.2.10. Spherical Weathered Boulders V_{10} . Spherical weathered boulders occur in various shapes, with their sizes ranging from tens of centimeters to several meters. Their uniaxial compressive strength is 80–200 MPa and they mostly occur in strata comprising fully and severely weathered granite. Their random spatial distributions pose severe challenges to shield tunnelling. However, construction experience has shown that boulders smaller than 0.3 m minimally impact excavation. Conversely, those larger than 2 m easily jam the cutterhead, with a supplementary measure such as manual excavation or directional blasting required to continue the tunnelling. The FMF of spherical weathered boulders is

$$v_{10}(x) = \begin{cases} 1, & x < 0.3, \\ \frac{2 - x}{2 - 0.3}, & 0.3 \leq x < 2.0, \\ 0, & x \geq 2.0. \end{cases} \quad (29)$$

4.3. Hierarchy of Evaluation Indexes. The hierarchy of the 10 evaluation indexes in Table 10 must be established before evaluating the adaptability of the EPB TBM shield tunnelling.

4.3.1. SHA. The experience gained from tunnelling through composite strata during the construction of the Shenzhen Metro was combined with existing research findings and expert opinion in assigning the judgment matrix values. This was done based on the relative importance of the evaluation indexes in the three layers. The weight of each index was then calculated before testing for consistency. The calculation results are presented in Tables 13 and 14.

4.3.2. THA. The single hierarchies of the evaluation indexes in the three layers were used to obtain the THA weights using the method in Table 2. The results are presented in Table 15.

5. Evaluation of the Composite Strata Tunnelling Adaptability of an EPB TBM

5.1. Assigning Values to the Evaluation Indexes. The values of V_1 – V_5 are given in Table 7. The values of V_6 – V_8 were obtained using the test sections of length 200 m, as presented in Table 16.

The distribution, rocks, and thicknesses of the composite strata in the two sections are given in Table 17. Because the impact of composite strata on shield tunnelling is related to the strata distribution range, the final value of V_9 should be the weighted average.

The geological exploration data indicated that spherical lightly weathered boulders occurred only in the right line of Section C-H. The sizes of the surveyed boulders range from 0.45 to 4.0 m. As mentioned previously, boulders larger than 2 m are generally removed by other methods. Thus, the value of V_{10} would be the highest value less than 2 m.

The values assigned to the evaluation indexes using the above-described process are presented in Table 18.

5.2. Adaptability Evaluation. For the evaluation target set $\mathbf{O} = \{O_1, O_2, O_3, O_4\}$, it is assumed that O_1 and O_2 represent the tunnelling adaptabilities of the EPB TBM in the left and right lines of Section C-H, respectively, and O_3 and O_4 are the corresponding values for Section N-Q.

The set of the THA weights of the evaluation indexes $\mathbf{V}$, denoted by $\bar{\mathbf{V}}$, is presented in Table 19. Substituting the values of the different evaluation indexes in Table 18 into the corresponding FMFs in Section 4.2 would give the matrix $\mathbf{R}$ of the degree of membership of $\mathbf{V}$ in $\mathbf{O}$ as follows:

TABLE 13: Weights of the evaluation indexes in the criteria layer.

D	U_1	U_2	U_3
U_1	1	3	2
U_2	1/3	1	1/2
U_3	1/2	2	1
Single-layer weight	0.5396	0.1634	0.2970
Single hierarchy	1	3	2
$\lambda_{\max} = 3.0183$, $CI = 0.0092$, $RI = 0.5149$, and $CR = 0.0179 < 0.1$			

TABLE 14: Weights of the evaluation indexes in the index layer.

U_1	V_1	V_2	V_3	V_4	V_5	
V_1	1	2	5	6	7	
V_2	1/2	1	4	5	6	
V_3	1/5	1/4	1	2	3	
V_4	1/6	1/5	1/2	1	2	$\lambda_{\max} = 5.1189$
V_5	1/7	1/6	1/3	1/2	1	$CI = 0.0297$
Single-layer weight	0.4631	0.3129	0.1087	0.0694	0.0459	$RI = 1.1185$
Single hierarchy	1	2	3	4	5	$CR = 0.0266 < 0.1$
U_2	V_6		V_7		V_8	
V_6	1		5		6	
V_7	1/5		1		2	$\lambda_{\max} = 3.0291$
V_8	1/6		1/2		1	$CI = 0.0146$
Single-layer weight	0.7258		0.1721		0.1020	$RI = 0.5149$
Single hierarchy	1		2		3	$CR = 0.0282 < 0.1$
U_3	V_9			V_{10}		
V_9	1			2		$\lambda_{\max} = 2.0$
V_{10}	1/2			1		$CI = 0$
Single-layer weight	0.6667			0.3333		$RI = 0$
Single hierarchy	1			2		$CR = 0 < 0.1$

TABLE 15: THA of the evaluation indexes.

Evaluation index	SHA			THA	
	U_1	U_2	U_3	Weight	Hierarchy
V_1	0.4631			0.250	1
V_2	0.3129			0.169	3
V_3	0.1087			0.059	6
V_4	0.0694			0.037	7
V_5	0.0459			0.025	9
V_6		0.7258		0.119	4
V_7		0.1721		0.028	8
V_8		0.1020		0.017	10
V_9			0.6667	0.198	2
V_{10}			0.3333	0.098	5
$CR = 0.056 < 0.1$					

TABLE 16: Evaluation index values obtained from the test sections.

Evaluation index	Section C-H		Section N-Q	
	Left line	Right line	Left line	Right line
V_6 (MPa)	0.137	0.149	0.189	0.168
V_7 (kPa)	242.2	269.9	221.2	141.0
V_8 (mm)	64.12	64.83	68.64	63.55

TABLE 17: Location, length, and composition ratio of the composite strata.

Tunnel section	Location	Length (m)	Rock type	Maximum thickness (m)	R_c (%)
C-H	ZCK6 + 600–ZCK6 + 700	31.6	Medium-weathered coarse-grained granite	5.8	83.1
	ZCK8 + 550–ZCK8 + 650	68.4	Medium- to microweathered coarse-grained granite	5.2	74.5
	YCK7 + 680–YCK7 + 750	52.3		4.9	70.2
N-Q	ZCK16 + 550–ZCK16 + 650	89.9		3.2	45.8
	ZCK17 + 850–ZCK17 + 900	16.6	Medium- to microweathered coarse-grained granite	4.6	65.9
	YCK15 + 550–YCK15 + 850	133.6		5.8	83.1
	YCK16 + 100–YCK16 + 250	82.3		6.2	88.8

TABLE 18: Assigned values of the evaluation indexes for assessing the tunnelling adaptability of an EPB TBM.

Evaluation index	Unit	Section C-H		Section N-Q	
		Left line	Right line	Left line	Right line
V_1	kN		49,588		
V_2	kN·m		7,806		
V_3	%		33		
V_4	m ³ /h		440		
V_5	mm		90		
V_6	MPa	0.137	0.137	0.137	0.137
V_7	kPa	242.2	269.9	221.2	141.0
V_8	mm	64.12	64.83	68.64	63.55
V_9	%	77.2	70.2	48.9	85.3
V_{10}	m	0	1.2	0	0

TABLE 19: Evaluated degrees of tunnelling adaptability of the EPB TBM.

Tunnel section	Section C-H		Section N-Q	
	Left line	Right line	Left line	Right line
Degree of adaptability D	0.9135	0.8332	0.7621	0.9556
Adaptability grade	I	II	II	I

$$R = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0.5 & 0.5 & 0.5 & 0.5 \\ 0.6024 & 0.7470 & 1 & 0.9759 \\ 0.0671 & 0.1111 & 0.0337 & 0 \\ 0.9749 & 0.9951 & 1 & 0.9586 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}.$$

The adaptability degree of $\mathbf{O}$ is obtained by substituting $\bar{V}$ and $\mathbf{R}$ into equation (9):

$$D = \bar{V} \times R = [0.9135 \ 0.8332 \ 0.7621 \ 0.9556]$$

Based on the adaptability classification in Table 3, the adaptability grades of EPB TBM tunnelling in Section C-H and Section N-Q are given in Table 19. That means this type of EPB TBM is adaptable to tunnelling through highly variable composite strata. The presence of large spherical weathered boulders along the right line of Section C-H and the left line of Section N-Q leads to a lower adaptability

grade, which was confirmed by the actual excavation. Overall, the actual excavation of two sections showed that the proposed method for evaluating tunnelling adaptability of EPB TBM is correct and reasonable.

6. Conclusions

The method for evaluating EPB TBM tunnelling adaptability to tunnel excavation is required for choosing the suitable technical parameters of the machine and to minimize the risks of tunnelling under adverse geological conditions. The evaluation is generally difficult because of the differing effects and complex relationships among the various factors involved. In the present study, a quantitative method based on AHP and fuzzy comprehensive evaluation was developed for the evaluation of EPB TBM adaptability under complex geological conditions. The rationality of the proposed method was verified by an actual tunnel construction project. The following is a summary of the proposed method and the conclusions drawn from the study:

- (1) The first step in the evaluation of EPB TBM tunnelling adaptability is the enumeration of various potential influencing factors and pairwise comparisons of their impacts. The bases of the comparison include construction experience, findings of scientific research, and expert opinion. This is used as a foundation for the application of AHP to determine the impact weights of various factors. The weights are then used to hierarchically arrange the selected evaluation indexes. An understanding of the effects of the factors would directly impact the quality of the selected evaluation indexes.
- (2) For the establishment of the EIS of the tunnelling adaptability of an EPB TBM in this study, (i) the tunnelling adaptability of the EPB TBMs applied to the composite strata encountered during the construction of the Shenzhen Metro Line 11 was used as the target layer; (ii) the EPB TBM design, tunnel construction plan, and geological conditions were used as the criteria layer; and (iii) the total thrust, cutterhead torque, cutterhead opening ratio, muck amount of the screw conveyor, cutter spacing, earth pressure in the cutterhead chamber, wall-back grouting pressure, shield tail void, composite strata, and spherical weathered boulders were used as the

index layer. The rational EIS was the foundation on which the evaluation targets were determined.

- (3) The corresponding FMFs were established based on the effects of 10 selected evaluation indexes on the tunnelling adaptability of the EPB TBMs. Each FMF prescribed the value range of the related evaluation index. Based on the proposed FMFs, the fuzzy mathematical method was used to ensure the generality of the various evaluation indexes. The validity of the FMFs was dependent on the ability to quantitatively define the effects of the influencing factors.
- (4) After the establishment of the EIS, values were assigned to different evaluation indexes using technical and geotechnical data obtained from the Shenzhen Metro Line 11 project. Fuzzy comprehensive evaluation was then used to evaluate the tunnelling adaptability of the EPB TBMs used for the tunnel excavation. The evaluation results were found to be consistent with the observations made from actual shield tunnelling.
- (5) The present study was based on the current understanding of the considered influencing factors. It should be noted that there are a few other important factors that were not taken into account owing to the difficulty of quantifying them. Further study is required to consider such factors to improve the accuracy of the proposed EPB TBM tunnelling adaptability evaluation method.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are grateful for the additional support of the China Railway Construction and Investment Group Co., Ltd. in Shenzhen. This study was supported by the National Key Basic Research Program of China (Grant no. 2014CB046906).

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