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Adaptability of earth pressure balance shield tunneling in coastal complex formations: a new evaluation method

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Abstract. It is difficult to tunnel in the coastal region of complex formations due to the lack of research into the adaptability of shield tunneling. A new method based on the fuzzy comprehensive evaluation model and analytic hierarchy process (AHP) approach was proposed to evaluate the adaptability of shield tunneling. Furthermore, an improved genetic algorithm (IGA) was introduced to calculate the weight of the index, which overcomes the defect of the AHP in terms of consistency testing. The evaluation model of adaptability was established based on the comprehensive analysis of the factors influencing adaptability in coastal complex formations. A case study on the adaptability evaluation of the Peng-Cai shield zone of Xiamen Metro was introduced to verify the application of the proposed method. The results indicated that the evaluation result accords with engineering practice and the proposed method can be used to evaluate the adaptability of shield tunneling.

Keywords: adaptability evaluation, AHP; evaluation method; IGA; shield tunneling

1. Introduction

With the process of urbanization, shield tunneling has become the preferred method of urban underground traffic construction on account of its characteristic safety and efficiency. Earth pressure balance (EPB) shield machines are widely applied in the construction of metro tunnels in granular soils, such as sand, gravel, and cobble (Guglielmetti *et al.* 2008). Moreover, the excellent adaptability of shield tunneling is vital to the success of shield tunneling operations. In India, on the Dul Hasti engineering project, the shield machine was stuck for eight months when it traversed a fault fracture zone, and the machine was destroyed (Vibter *et al.* 2005). In the Guangfo Metro shield tunnel, the cutterhead generated excessive torque, leading to auto-rotation of the shield machine (Wang 2019). The main reason for these construction accidents is the lack of ability to evaluate shield tunneling operations, justifying the present work.

The performance of the shield machine is the result of interaction between the machine and strata, which also reflects adaptability between machine and strata (Ramoni and Anagnostou 2006). If the adaptability of shield tunneling and formation is mismatched, such as when a shield machine based on EPB bores through uneven, composite, and boulder-bearing formations in coastal areas, the following events become more likely: i) blockage of the soil chamber by large boulders; ii) mud caking on the bulkhead; iii) excessive requirements for thrust force and cutterhead torque; iv) severe abrasion of the shield machine; v) frequent jamming of the screw conveyor (Giampiero *et al.* 2006). China is a vast country and prevailing geological conditions are complicated. Any new subway shield tunnel will inevitably pass through a variety of different special formations, and there has been extensive research regarding the adaptability of shield tunneling. For example, Song *et al*. (2019) evaluated the adaptability of the EPB shield machine in a clay stratum based on Xuzhou Metro Line 1 and proposed the appropriate excavation parameters. Wan *et al*. (2020) assessed the performance of three types of EPBs in water-rich sandy and cobble stratum through a case associated with Chengdu Metro Line 6, and they summarized that the maximum opening size and opening position are the most critical factors influencing the strata-adaptability of the cutterhead. Luo *et al*. (2020) modified the adaptability of the shield machine, and they applied the modified shield machine to one section of the tunnel (Binhai New Town-Lianhua) on Metro Line 6 in Fuzhou City; however, most of the past studies concentrate on parameter optimization during shield tunneling, and little attention has been paid to the evaluation of the adaptability of shield tunneling in the design phase.

In practice, when a single shield machine operates in geologically different strata, the adaptability between the shield machine and the strata is roughly matched. Even if their adaptability does not match, the existing shield machine can be directly put into constructing the next shield zone after technical modification. At present, adaptability evaluation of shield tunneling relies on an empirical and qualitative approach (Sapigni *et al.* 2002, Rostami 2016), which has low reliability and is subject to significant human bias. These methods can only be analyzed in a single soil

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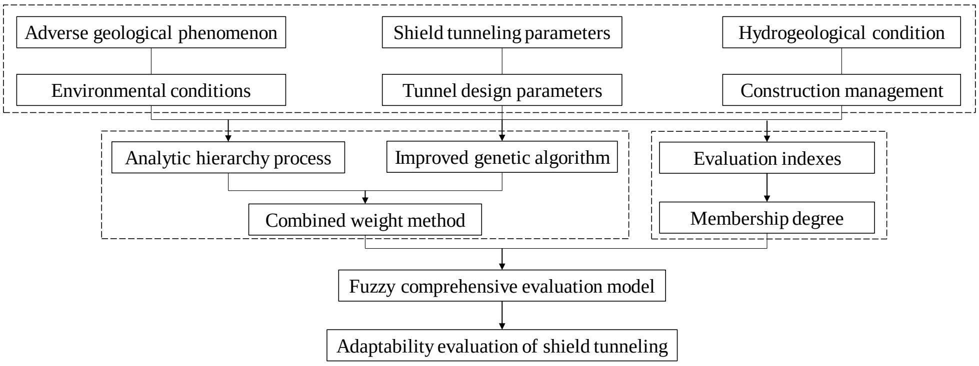


Fig. 1 Flowchart of the adaptability evaluation of shield tunneling study

layer and set of operating conditions, and there are significant limitations associated. Moreover, it is difficult to quantitatively evaluate the adaptability of shield tunneling through coastal complex formations. Thus, the present study of an adaptability evaluation model of shield tunneling in coastal complex formations has certain theoretical value and practical significance.

As is known, the interaction between shield machine and surrounding stratum shows non-linear, time-dependent, stochastic properties (Meschke 2018). Hence, it is difficult to provide an analytical investigation of their adaptability. For the adaptability evaluation of shield tunneling, many researchers have used model tests and numerical simulations. As for model tests, only one structure and one set of operating parameters of shield tunneling can be simulated at one time. Numerous tests are essential to draw valuable conclusions, albeit at high cost. Although numerical simulations are easier to achieve ideal results, they are idealistic not realistic in engineering practice during shield tunneling, so the adaptability of shield tunneling is difficult to be assessed by numerical simulations.

In fact, many uncertainties remain in shield tunneling construction stemming from a lack of specific information, data scarcity, misleading or conflicting information due to the complex nature of geo materials, and even the ambiguity in the concept of secure shield tunnel. In this context, fuzzy set theory could be applied to represent these uncertain characteristics more realistically, a series of fuzzy methods were employed to evaluate the adaptability of shield tunneling in previous research (Grima *et al.* 2000, Acaroglu *et al.* 2008, Barpi and Peila 2012). Moreover, the analytic hierarchy process (AHP) approach was integrated into fuzzy models owing to its ability to handle multi-criteria and simultaneous evaluation issues (Buckley 1985), and this method has been successfully utilized in the evaluation of shield tunneling and established a series of evaluation model (Hamidi *et al.* 2010, Yazdani-Chamzini and Yakhchali 2012, Xue *et al.* 2019). However, there is a gap between theory and practice due to insufficient evaluation indices of those existing theoretical models. Most evaluation index selections are based on a single stratum or specific engineering projects, and there is no evaluation system for the adaptability of shield tunneling in complex formations, hence why the indices are insufficient. Simultaneously, with the increasing gap between environmental and geological conditions in different projects, their indices are not universally applicable and cannot effectively solve the problem of selection of the evaluation index for new shield tunnels. The project delay and resource waste caused by inadequate adaptability analysis of shield tunneling have severely restricted the application of shield tunneling in complex coastal formations. Therefore, a new model for evaluating the adaptability of shield tunneling is needed.

In this work, a fuzzy comprehensive evaluation model of adaptability of shield tunneling in coastal complex formations was constructed firstly (Fig. 1). The weight of the evaluation index of adaptability was determined based on the IGA and AHP, and the membership function of each evaluation index was established. The adaptability of shield tunneling in coastal formations was quantitatively evaluated with the engineering case study of Xiamen Metro Line 4 Pengcuo North Station - Caicuo Station in China.

2. Analytic hierarchy process improved genetic algorithm (AHP-IGA)

2.1 Limitation of traditional AHP and GA

AHP was originally proposed by Saaty (1980). The AHP is a multi-criterion and multi-objective decision-making method that combines qualitative and quantitative analyses and is especially applicable to problems that are difficult to quantify fully. Firstly, the AHP method is used to decompose a problem into an ordered hierarchical structure model. Secondly, experts evaluate pairwise comparisons on the importance of these factors according to Saaty's nine-point scale to form judgment matrix $\boldsymbol{A} = (a_{ij})_{n\times n}$ (Saaty 1977). Finally, if judgment matrix $\boldsymbol{A}$ satisfies the consistency judgment condition (Eq. (1)), we can calculate the weight values $\boldsymbol{w} = \{w_1, w_2, \cdots, w_m\}$, using $\boldsymbol{Aw} = \lambda\boldsymbol{w}$, where λ is an eigenvalue of judgment matrix $\boldsymbol{A}$.

$$CR = \frac{\frac{\lambda_{\max} - n}{n-1}}{RI} < 0.1 \tag{1}$$

where, λ_{max} is the maximum eigenvalue of judgment matrix $\boldsymbol{A}$. RI is the average random consistency indicator;

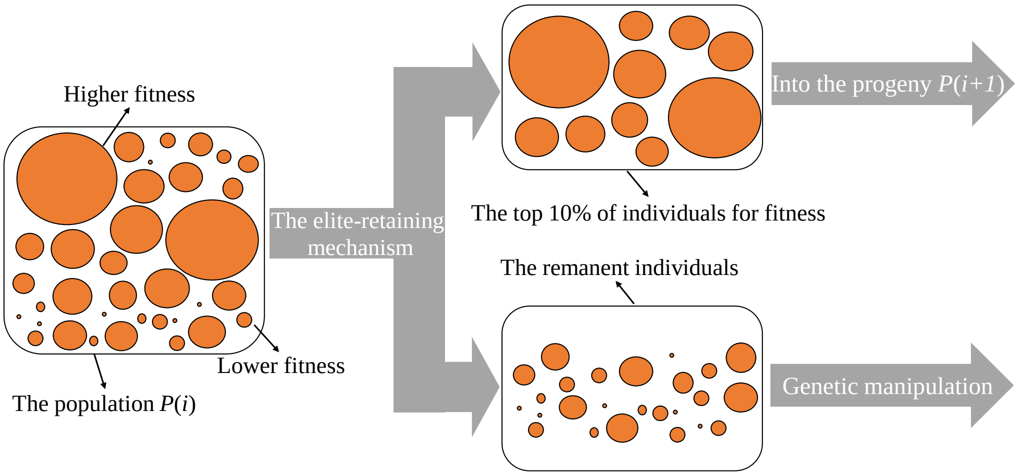


Fig. 2 The implementation of the mechanism with the improved selection operation

certain *RI* values are determined as described by Saaty (1980). When $CR < 0.1$, the consistency of the matrix is acceptable; otherwise, it must be modified by reconstructing the judgment matrix.

As mentioned above, the judgment matrix of AHP is the key to the algorithm. Generally, the expert grading method was used to obtain the judgment matrix for the target problem. Considering the different working experiences and background knowledge of experts, the influence of individual expert on the overall decision-making results is different (Wei *et al.* 2020); the evaluation indices also influence each other. In this case, although the consistency test of the judgment matrix returning a score of below 5 satisfies the conditions, the consistency of the judgment matrix greater than, or equal to, 5 is poor.

The eigenvector method was often used to calculate the weights of higher order judgment matrix. However, if the judgment matrix has been determined, then the weight ($\boldsymbol{w}$) and consistency test index (*CR*) are determined, the calculated weight is inaccurate. If the consistency test of the judgment matrix is not satisfied, and the judgment matrix can be modified in general, but the correction of the higher-order judgment matrix (order ≥ 5) is too difficult. Consequently, we propose an IGA and use this improved algorithm to find the weight while ensuring the optimal consistency of the judgment matrix.

The genetic algorithm (GA) is one of the evolutionary algorithms inspired by Darwin's theory of biological evolution (Elbaz *et al.* 2021). A GA has been applied for optimizing the parameters of the control system that are difficult to solve by traditional optimization techniques (Jalalkamali *et al.* 2015). For instance, Shen *et al.* (2021) constructed a framework to incorporate Bi-LSTM and data sequencing to predict diameter of jet-grouted columns in soft soil in real time. Elbaz *et al.* (2021) proposed a new model to estimate the disc cutter life by integrating a group method for use with a data-handling (GMDH)-type neural network (NN) with a GA. Gao *et al.* (2020) developed a predictive model by integrating a new cost function (relative mean square error) with a gated recurrent unit (GRU). The standard genetic algorithm (SGA) achieves an approximate optimal solution of the objective function through a series of genetic operations, so the weight of the high-order judgment matrix can be calculated by the AHP-SGA. However, to improve the performance and efficiency of the algorithm, we improved three operators involved in SGA operation in the present work. Moreover, the processes used in this IGA will be further introduced.

2.2 Improved selection operator

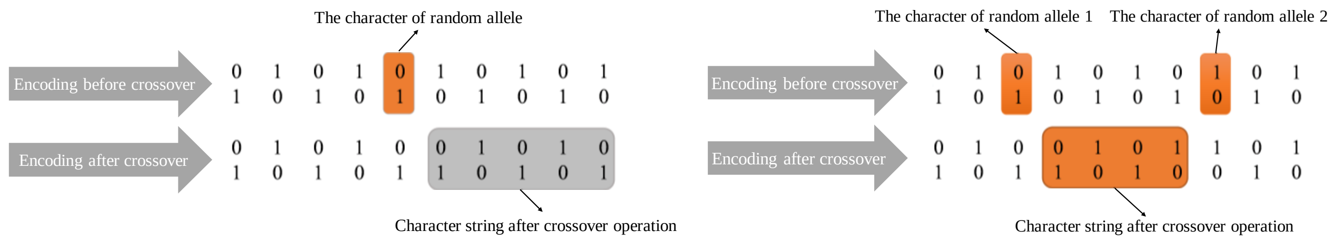
SGA uses the proportional selection method as its selection operator. First, assuming that there are n individuals in the parental population, and $f(i)$ denotes the fitness of individual i. Then, the single probability and cumulative probability of selecting the parental individuals to produce progeny are $p(i)$ and $q(i)$ (Eqs. (2)-(3)), respectively. At last, the generated random number r is compared with $q(i)$, if $q(i\text{-}1) < r < q(i)$, and the ith individual in the parental population is selected for crossover operation. The method means that the probability of individuals being selected in the population is proportional to their fitness, that is, individuals with high fitness are more likely to be selected than those with low fitness.

$$p(i) = \frac{f(i)}{\sum_{i=1}^{n} f(i)}, i = 1, 2, 3, \cdots, n \tag{2}$$

$$q(i) = \sum_{j=1}^{i} p(j), j = 1, 2, 3, \cdots, i \tag{3}$$

To sum up, this method can ensure that the fitness of individuals in the population is improved from generation to generation, and the solution of the objective function gradually approximates the optimal solution. However, it only implies that individuals with high fitness are more likely to be selected into the next generation than individuals with low fitness. It is not guaranteed that individuals with the highest fitness in the population will enter the next generation, and it is more likely that the individuals will be lost.

The fitness of individuals in the population is ranked by selection, and the top 10% of the individuals are directly



(a) single-point (b) two-point

Fig. 3 Schematic diagram of crossover operation

brought into the progeny without genetic operation, and then the rest of individuals in the population are genetically manipulated; this approach is the elite-retaining mechanism. Fig. 2 displays the improvements to the selection operation when using the elite-retaining mechanism.

As a result, based on the above defects, we adopt the elite-retaining mechanism combined with the proportion selection method as an improved selection operator. Individuals are divided into the population of elite and those requiring genetic operation according to the fitness ranking of individuals. Furthermore, the improved selection operator not only ensures that the optimal solution of the parental population directly enters the progeny population, but also accelerates the speed of algorithmic global convergence.

2.3 Improved crossover operator

An allelic character in the genetic code of an individual in a population is randomly selected and the sequences of characters following the allelic character are crossed. This approach is the single-point crossover operation. Hence, SGA typically performs the single-point crossover operation on individuals in a population with a fixed probability P_c. In the initial stage of algorithm, the greater probability was used to enlarge the space for determining the optimal solution. In the later stage of the algorithm, there are more high-quality individuals in the population, and it uses a smaller probability to ensure the stability of the population. In this way, the algorithm can gradually converge to the optimal solution. However, SGA adopts a constant large probability, which will destroy high-quality individuals in the later stage of the algorithm. Based on defects of crossover operator with SGA, the two-point crossover operator was used in this work. The two-point crossover operation indicates that the probability P_c changes with the change of population fitness and two-point crossover is better than single-point crossover in protecting individuals with high fitness in the population and enhancing the global convergence ability. The value of crossover probability P_c and fitness of individual f can be expressed as Eq. (4).

$$P_c = P_{c\max} - k_1 \frac{f - f_{\min}}{f_{\max} - f_{\min}} \tag{4}$$

Where $P_{\max}$ is the maximum crossover probability, and its value is 0.9; $f_{\min}$ and $f_{\max}$ are the minimum and maximum fitness of the contemporary population, respectively. k_1 denotes the crossover probability adjustment coefficient, and its value is 0.5.

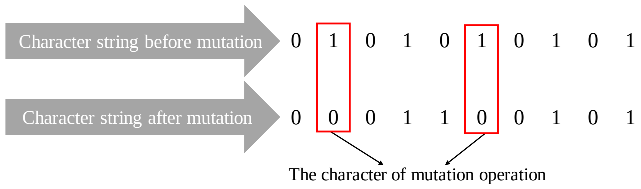


Fig. 4 Schematic diagram of improved mutation operation

The single-point and two-point crossover operation processes are shown in Fig. 3. Two allelic characters in the genetic code of an individual in a population are randomly selected and a series of characters between the two allelic characters are crossed. This improved crossover operator is the two-point crossover operation.

2.4 Improved mutation operator

By mutation, it is conceivable to adjust the diversity of the population and improve the search capacity to avoid convergence of the algorithm to local optima (Khalid Elbaz *et al.* 2019). In SGA, a fixed mutation probability P_m was generally used to mutate individuals in the population. In the later stage of SGA, there are many high-quality individuals. If the probability P_m is large, then it will destroy high-quality individuals leading to algorithmic non-convergence. However, in the early stage of SGA, the greater probability is easier to avoid local convergence of the algorithm and obtain the global optimal solution of the objective function.

In view of the defective nature of the SGA mutation operator, an improved mutation operator based on individual fitness was adopted. In other words, the mutation probability of an individual is related to its own fitness. The improved mutation operator P_m can be determined by Eq. (5).

$$P_m = P_{m\max} - k_2 \left(\frac{f - f_{\min}}{f_{\max} - f_{\min}} \right) \tag{5}$$

Herein $P_{m\max}$ is the maximum mutation probability, and its value is 0.9. k_2 represents the crossover probability adjustment coefficient, and its value is 0.1.

Here, the improved mutation operation is the mutation of basic position. Two gene characters in the genetic code of individuals ($r < P_m$) are randomly selected, and then the binary complement is taken. The operation of improved mutation is illustrated in Fig. 4.

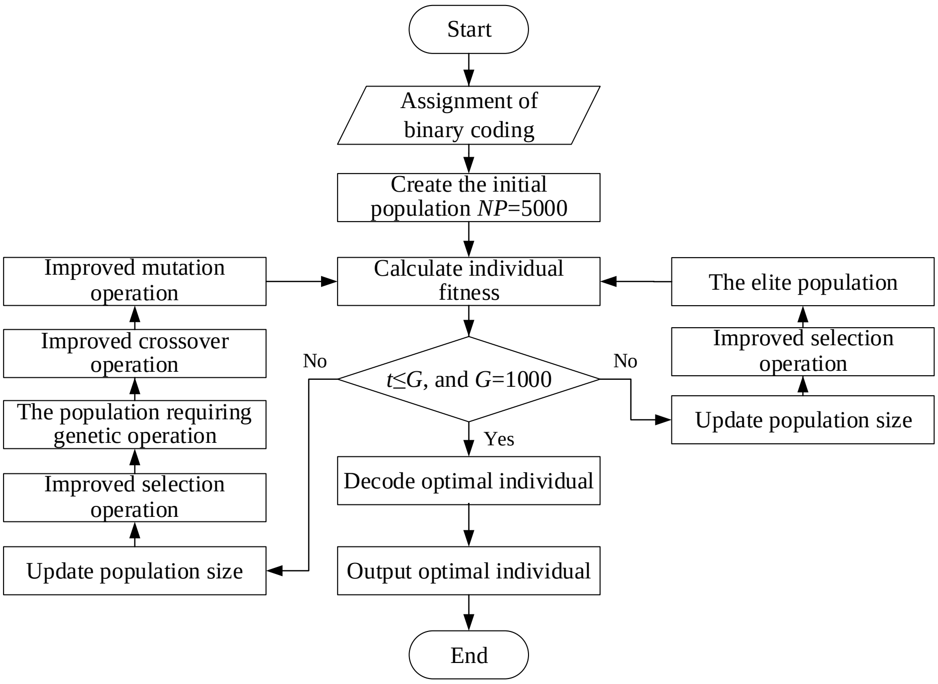


Fig. 5 The IGA procedure

2.5 AHP-IGA

In conclusion, IGA essentially improves the selection, crossover, and mutation operation of SGA. Fig. 5 demonstrates the procedure of IGA. The implementation of IGA is presented thus:

Step 1: the current number of evolutionary iterations is 0, and the maximum number of evolutionary iteration (G) is 1000, and 5000 randomly generated individuals constitute the initial population $P(0)$.

Step 2: the purpose of this work is to obtain the minimum value of the objective function, and the fitness of high-quality individuals in the later stage of the algorithm is little different. Therefore, the selection of high-quality individuals declines. In addition, high-quality individuals have weak ability of selection in the later stage of the algorithm. The function of fitness is expressed by the reciprocal of the objective function, and the fitness value of each individual in $P(t)$ is calculated. The fitness function $f(i)'$ can be deduced by Eq. (6).

$$f(i)' = \frac{1}{f(i)+1}, i = 1, 2, 3, \cdots, n \tag{6}$$

Where $f(i)'$ is the fitness of the ith individual, $f(i)$ denotes the value of objective function for the ith individual. Since the minimum value of objective function f(i) may be equal to 0, [f(i)+1] can guarantee the mathematical correctness of the function.

Step 3: based on improved selection operation, the fitness ranking of individuals is divided into elite populations and other populations requiring genetic operation. Then, improved crossover operation and mutation operation are used to genetically operate on other populations.

Step 4: the elite population (improved selection operation) and the newly generated population (after improved selection, crossover, and mutation operations) are mixed to select individuals within the top 5000 ranked fitness values.

Step 5: through many trials to check whether the termination condition is satisfied, it is found that the algorithm converges when the number of iterations reaches 300 generations. Therefore, the number of iterations is set to 1000; if the number of iterations exceeds 1000, the algorithm is terminated.

$$CR = \frac{1}{RI \cdot n(n-1)} \sum_{i=1}^{n} \sum_{j=i+1}^{n} \left[\frac{\left(a_{ij}x_j - x_i\right)^2}{a_{ij}x_i x_j} \right], i = 1, 2, 3, \cdots, n \tag{7}$$

$$\begin{cases} \min f = \dfrac{1}{RI \cdot n(n-1)} \displaystyle\sum_{i=1}^{n} \sum_{j=i+1}^{n} \left[\frac{\left(a_{ij}x_j - x_i\right)^2}{a_{ij}x_i x_j} \right], i = 1, 2, 3, \cdots, n \\ s.t. \begin{cases} \displaystyle\sum_{i=1}^{n} x_i = 1 \\ 0 < x_i < 1, i = 1, 2, 3 \cdots, n \\ 1/9 \le x_i / x_j \le 9, i, j = 1, 2, 3, \cdots, n \end{cases} \end{cases} \tag{8}$$

Defects of AHP when calculating weights mean that an objective function was established by combining calculating weights with a consistency test; it is inefficient to calculate the weight using an AHP-SGA, so the objective function value is calculated by IGA, and the weight of the judgment matrix was obtained when the consistency test is optimal. Thus, the weight obtained by this method is relatively accurate. Furthermore, based on the equation $\boldsymbol{Aw} = \lambda \boldsymbol{w}$, we can find a formula (Eq. (7)) relating the consistency test and the weight, where x_i is an element of the set of evaluation

Table 1 Parametric analysis of evaluation indices of adaptability

The criterion level (Evaluation factors)	The index level (Evaluation indices)	*AVG*	*SD*	*DC*
Adverse geological phenomenon	Residual soils	1.28	0.37	0.29
	Muddy soils	3.0	0.71	0.24
	Rich water sands	6.42	0.98	0.15
	Hard rocks	6.60	1.47	0.22
	Fault fracture zone	4.83	2.19	0.45
	Lightly weathered rocks bulge	6.75	2.12	0.31
	Karst topography	8.17	0.90	0.11
	Uneven soft and hard sections	6.75	0.99	0.15
	Boulders	6.5	1.61	0.25
Tunnel design parameters	Depth of shield tunnel	3.25	1.07	0.33
	Length of shield tunnel	7.55	0.82	0.11
	Radius of horizontal curve of shield tunnel	8.83	0.47	0.05
	Slope of shield tunnel	9.17	0.47	0.05
	Size section of shield tunnel	3.5	1.29	0.37
Hydrogeology condition	Uniaxial compressive strength of rocks	6.08	0.34	0.06
	Grain composition of soils	7.67	0.99	0.13
	Flow plasticity of soils	7.42	1.17	0.16
	Permeability of soils	6.17	0.90	0.15
	Pressure of groundwater	7	0.58	0.08
Shield tunneling parameters	Total thrust of the shield machine	6.25	0.48	0.08
	Rated torque of the cutterhead	7.58	0.93	0.12
	Maximum torque of the cutterhead	5.58	0.93	0.17
	Rotary velocity of the cutterhead	6.5	0.65	0.10
	Opening rate of the cutterhead	7.67	0.90	0.12
	Configuration of cutters	4.17	1.07	0.26
	Spacing of cutters	6.25	0.56	0.09
	Altitude difference of combined cutters	6.75	0.69	0.10
	Support structure of the cutterhead	3.42	0.45	0.13
	The amount of excavation by screw conveyor	3.17	0.69	0.22
	Correlative auxiliary system	4.42	0.93	0.21
Environmental conditions	Shield tunnel underneath piled foundation	6.17	0.62	0.10
	Shield tunnel underneath existing tunnels	6.92	0.61	0.09
	Shield tunnel underneath existing lines	7.92	0.61	0.08
	Shield tunnel underneath existing pipelines	5.17	0.69	0.13
Construction management	Technical level of construction	7.25	0.69	0.09
	Level of construction management	6.08	1.02	0.17
	Maintenance and service	2.92	0.73	0.25
	Crane lifting operations	1.92	0.73	0.38

factors. Then, the minimum value of the Eq. (7) is taken as the objective function to calculate the optimal weight for IGA. This method of calculating weights using Eq. (8) is called AHP-IGA.

3. Evaluation model of adaptability of shield tunneling

3.1 Evaluation system

The adaptability of shield tunneling in coastal complex formations is affected by various quantitative and qualitative factors, such as adverse geological phenomena, shield tunneling parameters, hydrogeological conditions, environmental conditions, tunnel design parameters, and construction management. For successful shield tunneling, we define the degree of influence of the above factors on shield tunneling as adaptability, due to the different attributes of these influence factors, they are not commensurable and rarely compare. In addition, it is challenging to select the critical factors from numerous influence factors and describe them through a series of measurable indices. A proposed model is established based on the fuzzy comprehensive evaluation method, in which

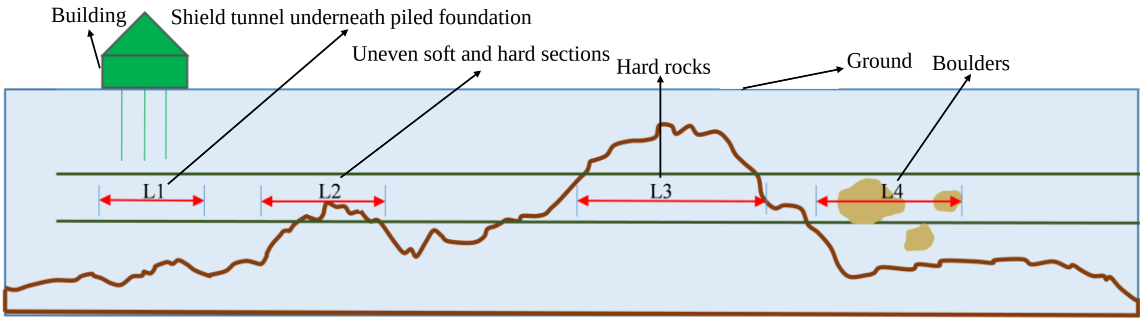


Fig. 7 Schematic diagram of segmented evaluation of shield zone

the quantitative results of adaptability evaluation were obtained.

In practical construction projects, many factors affect the adaptability evaluation of shield tunneling. The evaluation system of adaptability of shield tunneling is supposed to include all the influencing factors; this makes the evaluation system both tedious and inefficient, but some qualitative factors can barely be quantified, and the final evaluation is seldom convincing. To establish a rational evaluation system, we must further filter these factors. The adaptability of shield tunneling not only needs to consider the design and construction, but also the environmental impact. Six evaluation factors for adaptability of shield tunneling are proposed, including adverse geological phenomena, shield tunneling parameters, hydrogeological conditions, environmental conditions, tunnel design parameters, and construction management. Here, the expert brainstorming method was used to improve the evaluation index of the adaptability of shield tunneling. The evaluation indices are then scored by using the expert grading method. Based on the index score, the average value (*AVG*), standard deviation (*SD*), and discrete coefficient (*DC*) are analyzed using SPSS software to determine the ultimate evaluation indices.

Typically, the evaluation indices $AVG > 6$ and $DC < 0.25$ in Table 1are selected to construct the evaluation system of adaptability of shield tunneling. A bottom-up approach is employed for the development of evaluation system. That is, through expert brainstorming and grading methods, the evaluation indices related to the adaptability of shield tunneling were selected. Then, the evaluation indices that may affect from the adaptability are categorized on a layer-by-layer basis until the top layer of the evaluation indices framework is received. Typically, the evaluation index framework of adaptability of shield tunneling breaks down into three layers: the target level, the criterion level, and the index level (Fig. 6).

As shown in Fig. 6, the ultimate objective of first layer identified is the adaptability of shield tunneling which can be divided into six evaluation factors, including: adverse geological phenomena, shield tunneling parameters, hydrogeological conditions, environmental conditions, tunnel design parameters, and construction management. These six evaluation factors constitute the second layer, and the criterion level factor should be denoted as P_i. At the same time, twenty-four evaluation indices in the third layer can be obtained by decomposition of these six evaluation factors, among which the index level factor is expressed as U_i.

Table 2 Adaptability grades of shield tunneling and rating scale

Grade	Rating scale	Adaptability	Evaluable conditions
v_1	I	[0.8,1]	Severely adapted
v_2	II	[0.6,0.8]	Moderately adapted
v_3	III	[0.4,0.6]	Slightly adapted
v_4	IV	(0,0.4]	Inadaptation

3.2 Comprehensive adaptability of shield tunneling

Given the complex geological conditions in coastal formations, shield tunneling has a different adaptability under different geological conditions: however, a shield tunnel consists of varying lengths of shield zones, and the adaptability of each shield zones exhibits diversity in complex formations. To evaluate the adaptability of shield tunneling of whole shield tunnel under different geological conditions, the comprehensive adaptability $\overline{D}$ is defined by Eq. (9).

$$\overline{D} = \frac{1}{L}\sum_{i=1}^{n} D_i L_i \tag{9}$$

where L is a total length of shield zone, L_i is the i^{th} length of the shield zone and D_i denotes the adaptability of the zone with length L_i.

On the one hand, because the shield tunnel is longer, not all shield zones are inferior in terms of adaptability in complex coastal formations. Fig. 7 shows an evaluative diagram of shield zones. On the other hand, if the most shield zones are of superior adaptability, Eq. (9) will not only reduce the evaluative efficiency, but also render the evaluation is more optimistic. To improve efficiency and reduce workload, the adaptability of shield tunneling in different shield zones is evaluated based on the following criteria.

(1) Shield zones with favorable geological conditions or low construction risks may not be evaluated.

(2) If the evaluation results are acceptable in shield zones with adverse geology or high construction risks, and the result of adaptability evaluation can also be abandoned.

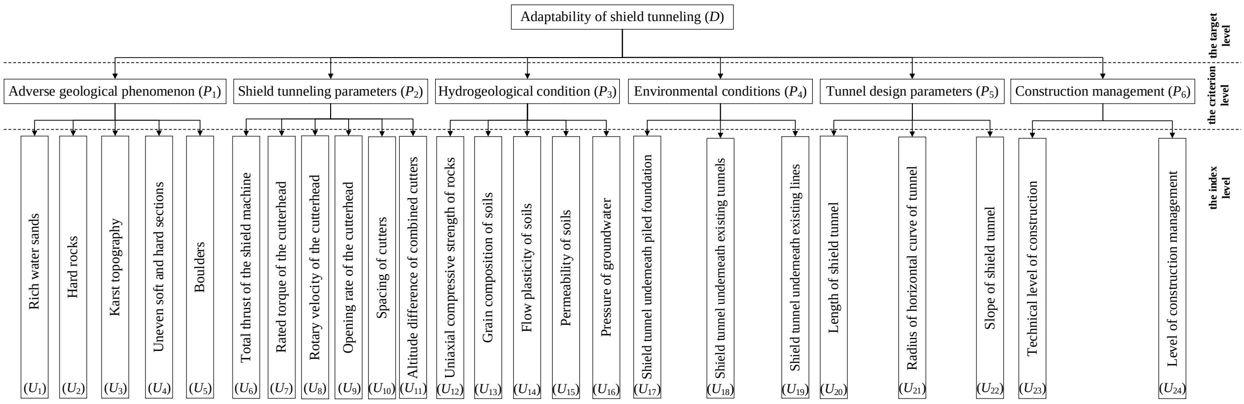


Fig. 6 Evaluation system of the adaptability developed during shield tunneling

Table 3 Weights of evaluation indices of adaptability

The criterion level (local weights)	The index level (local weights)	Global weights
Adverse geological phenomenon (0.313)	Rich water sands (0.194)	0.061
	Hard rocks (0.115)	0.036
	Karst topography (0.367)	0.115
	Uneven soft and hard sections (0.142)	0.044
	Boulders (0.182)	0.057
Shield tunnelling parameters (0.225)	Total thrust of the shield machine (0.186)	0.042
	Rated torque of the cutterhead (0.269)	0.061
	Rotary velocity of the cutterhead (0.088)	0.020
	Opening rate of the cutterhead (0.172)	0.039
	Spacing of cutters (0.167)	0.038
	Altitude difference of combined cutters (0.118)	0.027
Hydrogeological condition (0.152)	Uniaxial compressive strength of rocks (0.323)	0.049
	Grain composition of soils (0.148)	0.022
	Flow plasticity of soils (0.191)	0.029
	Permeability of soils (0.171)	0.026
	Pressure of groundwater (0.167)	0.025
Environmental conditions (0.116)	Shield tunnel underneath piled foundation (0.119)	0.014
	Shield tunnel underneath existing tunnels (0.558)	0.065
	Shield tunnel underneath existing lines (0.323)	0.037
Tunnel design parameters (0.136)	Length of shield tunnel (0.201)	0.027
	Radius of horizontal curve of shield tunnel (0.421)	0.057
	Slope of shield tunnel (0.378)	0.051
Construction management (0.058)	Technical level of construction (0.6)	0.035
	Level of construction management (0.4)	0.023

(3) If all the above conditions are not satisfied, the results of adaptability evaluation can be retained.

Based on the investigation of multiple shield tunnel in coastal complex formations, the evaluation of the adaptability of shield tunneling can be classified into four grades (Table 2). Herein, we use four evaluable grades, which also represent all the elements in an evaluation set, with evaluation set $\boldsymbol{V}=\{v_1, v_2, v_3, v_4\}$.

3.3 Calculating the weight using the AHP-IGA

The weight reflects the importance of each index to different evaluable objectives in the process of evaluation, and the method used to calculate the weight has a direct

Table 4 Consistency test of evaluation factors

The criteria level	*RI*	*CR*
Adverse geological phenomenon	1.12	0.089732
Shield tunneling parameters	1.24	0.020081
Hydrogeological condition	0.58	0.001379
Environmental conditions	1.12	0.008304
Tunnel design parameters	0.58	0.077586
Construction management	0	Fully consistent

Note: When the order of judgment matrix is 1 or 2, $RI = 0$, and the matrix is fully consistent.

influence on the result of this evaluation. Although we used a traditional questionnaire, we surveyed a large amount of data and adopted an IGA-AHP to ascertain the consistency of the judgment matrix. Partial judgment matrices are presented in Appendix I. According to the evaluation system of adaptability of shield tunneling (Fig. 8), Eq. (8) is employed to calculate the weighting factors as shown in Table 3. Moreover, the consistency ratio $CR < 0.1$ (Table 4) satisfies the requirements of consistency testing. Ultimately, weight-ranking of the total level on the evaluation system of adaptability of shield tunneling is obtained.

3.4 Membership function of evaluation indices

The membership function was used to describe the degree of membership of the evaluation indices, which is key to fuzzy comprehensive evaluation and affects the accuracy of the evaluation results. In this article, the trapezoidal fuzzy number (Zadeh 1965, Wei *et al.* 2020) was employed as the piece-wise fuzzy distributions for the membership function. Trapezoidal distribution can be divided into three genres: large-scale $F_1(x)$; medium-scale $F_2(x)$; and small-scale $F_3(x)$, and the membership function can be written as follows:

$$F_1(x) = \begin{cases} 1 & x < a \\ \dfrac{b-x}{b-a} & a \le x \le b \\ 0 & x > b \end{cases}$$

$$F_2(x) = \begin{cases} \dfrac{(x-a)}{b-a} & a < x < b \\ 1 & b \le x \le c \\ \dfrac{d-x}{d-c} & c < x < d \\ 0 & otherwise \end{cases} \tag{10}$$

$$F_3(x) = \begin{cases} 0 & x < a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1 & x > b \end{cases}$$

The membership function is a method of quantitative description of fuzzy concepts, and it is also the key of fuzzy comprehensive evaluation; due to the different properties of indices in the evaluation model, it is necessary to quantify both qualitative and quantitative indices. As can be seen, the evaluation index has its corresponding evaluation criterion. The distribution of these membership functions can be easily implemented as illustrated in Table 5.

According to the formulae (Eq. (10)), it is necessary to obtain the interval points between the evaluation grades of all such evaluation indices. Notably, the above formulae are only applicable to the membership degree of continuous factors. Based on the investigation of multiple shield tunnels (Code for design of metro lines in China; Shanghai and Xiamen Metro) and related literature on shield tunneling (Ma *et al.* 2014, Martinelli *et al.* 2015, Zhang *et al.* 2016), these interval points can be easily implemented by grading evaluation indices (Table 6). Eventually, the membership function of each index in the evaluation system can be determined by integrating the data in Tables 5-6. Representative membership functions are listed in Appendix II.

Table 5 Evaluable criteria of evaluation indices

Evaluation indices	Evaluable criteria	Distributional genres
Rich water sands	Slump value	Medium-scale
Hard rocks	Uniaxial compressive strength	Small-scale
Karst topography	l/d	Large-scale
Uneven soft and hard sections	S'/S	Medium-scale
Boulders	Boulder diameter	Small-scale
Total thrust of the shield machine	$0.25\pi D^2 P_j$	Large-scale
Rated torque of the cutterhead	$D^3 K_\alpha$	Large-scale
Rotary velocity of the cutterhead	$n = v_r/\pi D$	Medium-scale
Opening rate of the cutterhead	Optimum opening rate	Medium-scale
Spacing of cutters	The shortest distance	Medium-scale
Altitude difference of combined cutters	Height difference	Medium-scale
Uniaxial compressive strength of rocks	Uniaxial compressive strength	Medium-scale
Grain composition of soils	Grain composition	Large-scale
Flow plasticity of soils	I_L	Medium-scale
Permeability of soils	κ	Small-scale
Pressure of groundwater	Pressure of water	Small-scale
Shield tunnel underneath piled foundation	B_1	Large-scale
Shield tunnel underneath existing tunnels	B_2	Large-scale
Shield tunnel underneath existing lines	B_3/D	Large-scale
Length of shield tunnel	L	Medium-scale
Radius of horizontal curve of tunnel	Planar radius	Large-scale
Slope of shield tunnel	i	Small-scale
Construction management	A score of 10	Large-scale

3.5 Fuzzy comprehensive evaluation model

The fuzzy comprehensive evaluation method is a quantitative evaluation method proposed by Zadeh (1978). The method makes a general evaluation of processes or objects subject to a variety of factors (Cheng and Tao 2010). Fuzzy theory was applied to the adaptability evaluation, and the fuzziness is transformed into definiteness by membership degree. It is assumed that the evaluation index of evaluation target set $\boldsymbol{O} = \{O_1, O_2, \cdots, O_n\}$ is $\boldsymbol{U} = \{u_1, u_2, \cdots, u_m\}$. The adaptability set $\boldsymbol{D}$ is the comprehensive evaluation set of $\boldsymbol{O}$; the element D_i ($0 \le D_i \le 1$) is the adaptability of O_i in the evaluation objective set. Meanwhile, "$D_i = 0$" means absolutely not adapted, or "$D_i =$

Table 6 Gradation of evaluation indices

Evaluation indices	I	II	III	IV
Rich water sands	195-205	180-195, 205-210	160-180, 210-220	<160, >220
Hard rocks	≤ 80	80-120	120-200	≥ 200
Karst topography	≥ 3/2	9/10-3/2	0-9/10	0
Uneven soft and hard sections	< 10, > 90	20-40, 60-80	10-20, 80-90	40-60
Boulders	0-0.25	0.25-2	2-D	> D
Total thrust of the shield machine	≥ 550	330-550	262.5-330	≤ 262.5
Rated torque of the cutterhead	≥ $K_{\alpha max}D^3$	(0.8-1)$K_{\alpha max}D^3$	($K_{\alpha min}$-0.8$K_{\alpha max}$)D^3	< $K_{\alpha min}D^3$
Rotary velocity of the cutterhead	(15-20)η	(9-15)η, (20-26)η	(0-9)η, (26-30)η	≥ 30η, 0
Opening rate of the cutterhead	30-40	15-30, 40-50	10-15, 50-60	≤ 10, ≥ 60
Spacing of cutters	100-130	90-100, 130-148	60-90,148-160	< 60, > 160
Altitude difference of combined cutters	35-45	30-35,45-50	25-30, 50-55	≤ 25, ≥ 55
Uniaxial compressive strength of rocks	≤ 80	80-120	120-200	≥ 200
Grain composition of soils	> 50%	40%-50%	30%-40%	< 30%
Flow plasticity of soils	0.4-0.6	0.4-0.6, 0.6-0.8	0-0.4, 0.8-1.0	< 0, > 1.0
Permeability of soils	< 10^{-7}	10^{-7}-10^{-6}	10^{-6}-10^{-5}	> 10^{-5}
Pressure of groundwater	< 0.3	0.3-0.4	0.4-0.6	> 0.6
Shield tunnel underneath piled foundation	≥ 3D	(2-3)D	(0.25-2)D	≤ 0.25D
Shield tunnel underneath existing tunnels	≥ 3D	(2-3)D	(0.8-2)D	< 0.8D
Shield tunnel underneath existing lines	≥ 4	3-4	2-3	< 2
Length of shield tunnel	2-3	1.3-2, 3-4.2	0.3-1.3, 4.2-6	< 0.3, > 6
Radius of horizontal curve of tunnel	> 300	250-300	150-200	< 150
Slope of shield tunnel	≤ 30	30-35	35-40	≥ 40
Construction management	8-10	6-8	4-6	0-4

Note: D, tunnel diameter; K_{α}, torque coefficient; $\eta = 1/\pi D$.

1" means absolutely adapted. $\boldsymbol{R}$ is the membership matrix of $\boldsymbol{U}$ to $\boldsymbol{O}$. The final membership matrix $\boldsymbol{D}$ is synthesized by combining the weight $\boldsymbol{w}$ with the fuzzy matrix $\boldsymbol{R}$, which can be expressed as shown in Eq. (11). In addition, the evaluation result is determined according to the principle of maximum membership degree.

$$\boldsymbol{D} = \boldsymbol{w} \cdot \boldsymbol{R} = \{w_1, w_2, \mathrm{L}, w_m\} \times \begin{bmatrix} r_{11} & r_{12} & \mathrm{L} & r_{1n} \\ r_{21} & r_{22} & \mathrm{L} & r_{2n} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ r_{m1} & r_{m2} & \mathrm{L} & r_{mn} \end{bmatrix} = \{D_1, D_2, \mathrm{L}\ D_n\} \quad (11)$$

Where r_{ij} is the fuzzy connection of u_i to v_j, which can be calculated from Eq. (10); m is the number of evaluation indices (herein, equal to 24); and n represents the number of evaluation ratings domains (herein, equal to 4).

4. Case study

4.1 Project overview

The underground traffic project of Xiamen Metro Line 4 Pengcuo North Station to Caicuo Station is located in the north of Xiangan District, Xiamen City, China (Fig. 7). The subway was built from west to east along Xiangan West Road (under Xiangan West Road, and elsewhere beneath farmland or wasteland) (Fig. 7(b)). The chainage of right branch of the shield tunnel is DK57+011.156-DK59+197.857, and the total length of the right branch is 2186.701 m. The chainage of left branch of the shield tunnel is DK57+011.156-DK59+199.422, and the total length of the left branch 2188.266 m. The soil cover thickness of shield tunnel is 10 to 21.4 m. Since the subway system consists of the left and right branches in the shield tunnel, the left and right branches were evaluated according to the different formations and their surrounding environments. Expressways and water-related planning zones mainly cover the surface in this section, and this tunnel section essentially passes through strata with weathered granites (slightly or strongly or full weathered granite), soft soils (silt or mucky soil), and sandy clay (Fig. 7(c)).

4.2 Evaluation of the adaptability of shield tunneling: results

From the above, according to the Eq. (11), a fuzzy comprehensive evaluation matrix $\boldsymbol{D}$ can be obtained when global weight matrix $\boldsymbol{w}$ (Table 3) and fuzzy matrix $\boldsymbol{R}$ (Tables 5-6) are known. At this moment, the evaluation grade corresponding to the largest element in matrix $\boldsymbol{D}$ was selected as the result of evaluation, that is, an adaptability evaluation model of shield tunneling in coastal complex formations was developed.

First, the shield zone to be evaluated was divided into several different sections according to the factors

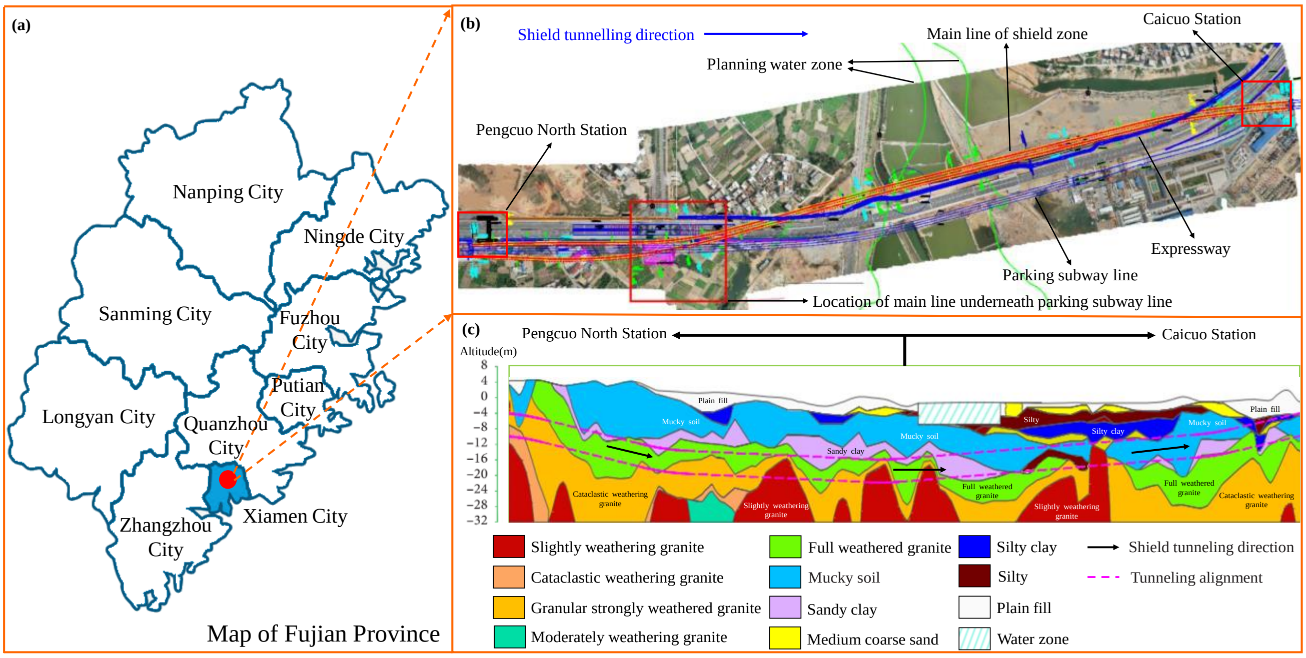


Fig. 7 Location of Peng-Cai shield zone: (a) administrative region of Fujian; (b) plan view of the works; (c) longitudinal geological profile

Table 7 Values of evaluation indices of shield tunneling parameters in shield zone

Evaluation indices	Values	Membership degrees
Total thrust of the shield machine	49,588 kN	1
Rated torque of the cutterhead	7778 kN m	1
Rotary velocity of the cutterhead	3.6 rpm	1
Opening rate of the cutterhead	33%	1
Spacing of cutters	80 mm	0.5
Altitude difference of combined cutters	30 mm	0.5

Table 8 Adaptability of shield tunneling on the right branch of the shield zone

Section	Length/ m	D	$\overline{D}$	
L1	150	0.95		
L2	202.5	0.96		
L3	397.5	0.94		
L4	240	0.96		
L5	60	0.87		
L6	82.5	0.90		
L7	64.5	0.91		
L8	183	0.94	$\overline{D}=\frac{1}{L}\sum_{i=1}^{n}D_iL_i$	0.92
L9	97.5	0.86		
L10	127.5	0.90		
L11	120	0.87		
L12	37.5	0.89		
L13	315	0.94		
L14	22.5	0.85		
L15	97	0.87		

influencing adaptability. Then, according to Eq. (10), the evaluation results of each section are converted into the result of comprehensive adaptability $\overline{D}$ evaluation of the whole shield zone.

Since there are so many adaptability evaluation indices of shield tunneling, it is impossible to cover all evaluation indices in the whole shield zone. The membership degree of the evaluation index that does not exist in the evaluation section of shield tunneling is set to one, which indicates that the adaptability of the evaluation index is strong.

China Railway 11th Bureau Group Fourth Engineering Corporation has contracted to build Xiamen Metro Pengcuo North Station-Caicuo Station. This company has abundant construction experience and strong managerial ability. Therefore, in adaptability evaluation, two evaluation indices of construction management factors are scored 8, and the membership degree is 1.

The left and right branches of the shield tunnel were excavated with the same type of EPB shield machine, so the evaluation indices of shield tunneling parameters in the criteria level of the evaluation system are identical, and their values are listed in Table 7.

According to geological data pertaining to the Peng-Cai shield zone, the whole right branch of the shield zone is divided into 15 sections for adaptability evaluation. There are two categories of section with different geological conditions, one is that there is no adverse geology or adjacent construction area in the shield zone; the other is that there is adverse geology or adjacent construction within the shield zone. Accordingly, membership matrices are constructed and multiplied with global weight matrices of evaluation index values to determine the adaptability of

Table 9 Adaptability of shield tunneling on the left branch of the shield zone

Section	Length/m	D	$\overline{D}$
L1	120	0.92	
L2	165	0.93	
L3	247.5	0.96	
L4	52.5	0.81	
L5	420	0.93	
L6	45	0.86	
L7	78	0.94	$\overline{D}=\frac{1}{L}\sum_{i=1}^{n}D_iL_i$ 0.91
L8	75	0.87	
L9	184.5	0.91	
L10	91.5	0.83	
L11	238.5	0.88	
L12	337.5	0.94	
L13	127.5	0.87	

each section on the right and left branches. Finally, the overall adaptability of the right and left branches of Peng-Cai shield zone is calculated using Eq. (10), and the results are shown in Tables 8-9.

The comprehensive adaptability $\overline{D}$ of shield tunneling on left and right branches of the Peng-Cai shield zone is 0.91 and 0.92 respectively. According to Table 2, the evaluation results suggest severe adaptation. During shield tunneling, there is no great risk to construction posed by geological or other reasons. It can be considered that the evaluation results are consistent with those practical results on the shield tunneling site. Hence, the evaluation model of adaptability of shield tunneling has certain accuracy and reasonableness.

5. Discussions

5.1 Verification

To verify the effect of calculating weights through the proposed method (AHP-IGA), the judgment matrices P and Q are selected to calculate their weights and ratio of consistency. Based on different methods, the weights and ratio of consistency calculated by using the judgment matrices P and Q (Eq. (11)) are summarized in Table 10.

$$P=\begin{pmatrix} 1 & 2 & 4 & 0.5 & 0.666 \\ 0.5 & 1 & 3 & 0.333 & 0.444 \\ 0.25 & 0.333 & 1 & 0.222 & 0.111 \\ 2 & 3 & 4.5 & 1 & 0.5 \\ 1.5 & 2.25 & 9 & 2 & 1 \end{pmatrix}$$
$$Q=\begin{pmatrix} 1 & 1/7 & 1/2 & 1/8 & 2 \\ 7 & 1 & 3 & 1 & 8 \\ 2 & 1/3 & 1 & 1/5 & 5 \\ 8 & 1 & 4 & 1 & 5 \\ 1/2 & 1/8 & 1/5 & 1/5 & 1 \end{pmatrix} \quad (11)$$

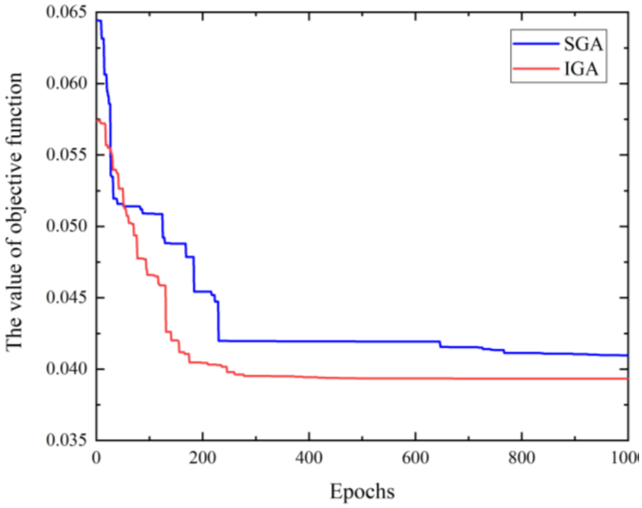


Fig. 8 The convergence curves of two algorithms

By comparison, the results of IGA-AHP presented here are smaller than those of traditional calculation, such as group eigenvalue, and pattern recognition methods: the consistency ratio of AHP-IGA is then also smaller than that of AHP-SGA and AHP-AGA. However, the consistency ratio is inversely proportional to the accuracy of the weights. Therefore, it can be considered that the weights of evaluation index calculated based on AHP-IGA in this paper are more consistent with reality than that of traditional AHP.

To choose the judgment matrix of criterion levels in the evaluation system, we find the solution through SGA and IGA. The parameters are set as follows: NP = 5000; G = 1000; P_c = 0.8; P_m = 0.2, and the calculated results are illustrated in Fig. 8. The results suggest that IGA converges faster than SGA, and the optimal solution thus obtained is more accurate, yet the local convergence of the SGA is subject to a certain instability. Eventually, the population diversity and global search ability of the algorithm are improved, and it can be considered that the algorithm of IGA offers excellent performance.

5.2 Limitation

In the previous work, a traditional questionnaire (Saaty 1977) was adopted to collect the data forming the basis for the judgment matrix. There are two shortcomings in this questionnaire method: i) the consistency of the judgment matrix is poor, and ii) collecting expert judgments is onerous. Although some scholars have improved the method, inconsistency of the judgment matrix has been lessened to a certain extent. For instance, Li *et al.* (2013) developed an improved AHP method by designing a new questionnaire and a convenient method for improving the consistency of the judgment matrix by involving a sorting and ranking method; however, uses of this improved AHP method encounter difficulties in establishing consistent matrices when the total number of assessment factors exceeds five. In this respect, the present work entails use of an AHP-IGA to find the weights when ensuring the optimal consistency of the judgment matrix, which can better overcome the issue of inconsistency of the judgment matrix

Table 10 Results of weights and ratio of consistency for different methods

Matrix	Weights and ratio of consistency	w_1	w_2	w_3	w_4	w_5	CR
P	Group eigenvalue method	0.196	0.119	0.047	0.271	0.366	0.0334
	Patter recognition method	0.192	0.107	0.047	0.275	0.377	0.0364
	AHP-SGA	0.194	0.117	0.047	0.281	0.361	0.0339
	AHP-AGA	0.218	0.110	0.046	0.227	0.397	0.0478
	AHP-IGA	0.203	0.111	0.048	0.281	0.357	0.0320
Q	Group eigenvalue method	0.0612	0.3743	0.1342	0.3869	0.0434	0.0453
	The minimum bias procedure	0.0522	0.3957	0.1402	0.3581	0.0530	0.0687
	Generalized least square method	0.0664	0.3925	0.1364	0.3618	0.0421	0.0465
	AHP-SGA	0.0625	0.3829	0.1250	0.3867	0.0430	0.0545
	AHP-AGA	0.0606	0.3771	0.1320	0.3953	0.3953	0.0487
	AHP-IGA	0.0679	0.3772	0.1428	0.3691	0.0430	0.0425

Note: AHP-AGA indicates the AHP accelerated GA. By comparison, the results of IGA-AHP presented here are smaller than those of traditional calculation, such as group eigenvalue, and pattern recognition methods: the consistency ratio of AHP-IGA is then also smaller than that of AHP-SGA and AHP-AGA. However, the consistency ratio is inversely proportional to the accuracy of the weights. Therefore, it can be considered that the weights of evaluation index calculated based on AHP-IGA in this paper are more consistent with reality than that of traditional AHP.

when using data from a traditional questionnaire. Therefore, a major reason as to why the present work is somewhat limited is that the data collection is onerous. However, given that the main objective of this research is to evaluate the adaptability of shield tunneling in complex coastal formations, this limitation will not affect the ultimate evaluation. Consequently, the study has practical engineering significance.

Despite the efficiency of the AHP-IGA method, it still has some uncertainties. The method proposed in this article obtains results based primarily on limited data and expert judgment with high subjectivity. Although trapezoidal fuzzy numbers are used to eliminate the uncertainty in the evaluation process, the results are still subjective and inevitably uncertain (Zheng *et al.* 2021). Some scholars developed that a series of methods to overcome these limitations. For instance, Lin *et al*. (2020, 2021) improved an ideal solution (TOPSIS) method to perform comprehensive environmental impact evaluation. Lin *et al.* (2021) presented the applications of fuzzy set theory and machine learning methods in risk assessment during excavation.

It is, however, undeniable that a good questionnaire method will greatly improve the efficiency of the proposed evaluation method. For example, Lyu *et al*. (2020) proposed a new questionnaire, which can get not only the appropriate experts' reply but also can determine the fuzzy number based thereon. We believe that the questionnaire can boost efficiency and weaken the subjectivity of experts' replies. In future, better questionnaire-based methods can be used in the evaluation system proposed in this article, hence, the exploration of basic data-collection methods warrants further investigation.

6. Conclusions

In this paper, the authors selected adverse geological phenomenon, shield tunneling parameters, hydrogeological conditions, environmental conditions, tunnel design parameters, and construction management as evaluation factors for adaptability of shield tunneling according to the background of complex coastal formations. The evaluation standards of corresponding grades were established and the quantitative evaluation system of adaptability of shield tunneling was proposed. The main conclusions of this study are outlined as follows:

- The improved genetic algorithm (IGA) method was developed to overcome the limitations of the standard genetic algorithm (SGA). The genetic operation of selection, crossover, and mutation was improved by using an elite-retaining mechanism, two-point crossover, and basic position mutation. By introducing IGA and improved genetic operation, the proposed method AHP-IGA for calculating the optimal weight was established. Moreover, the global weight of each evaluation index in an adaptability evaluation system of shield tunneling was calculated by AHP-IGA, and the convergence of this method is proved.
- Based on the expert advice and related literature on evaluation adaptability of shield tunneling, 24 relatively important evaluation indices were selected from six evaluation factors, adverse geological phenomenon, shield tunneling parameters, hydrogeological condition, environmental conditions, tunnel design parameters, and construction management: the evaluation system of adaptability of shield tunneling is established by means of statistical analysis.

- Based on fuzzy set theory, the membership function of evaluation indices of adaptability of shield tunneling was constructed, which solved a difficult problem whereby different evaluation indices cannot be directly compared. An adaptability evaluation model of shield tunneling in coastal complex formations was constructed by way of a fuzzy matrix and global weight matrix. This model was then used to evaluate the left and right branches of Xiamen Metro Line 4 Pengcuo North Station to Caicuo Station. It showed that the evaluation results were in accordance with the actual reality facing the construction team, which adequately verified the accuracy of the adaptability evaluation model of shield tunneling in coastal complex formations.

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Appendix I: Judgment matrices

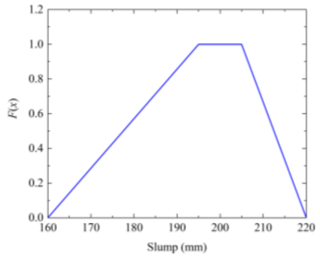
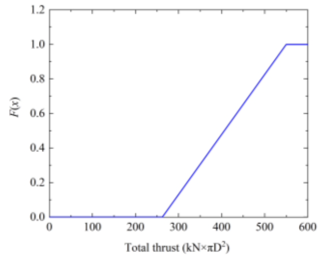
Eq. (12) demonstrates two representative judgment matrices at the criterion level and the index level of shield tunneling parameters.

$$D=\begin{pmatrix} 1 & 2.13 & 4.04 & 1.80 & 1.93 & 5.22\\ 0.47 & 1 & 1.50 & 1.65 & 2.27 & 3.07\\ 0.25 & 0.67 & 1 & 0.65 & 1.93 & 2.25\\ 0.56 & 0.61 & 1.54 & 1 & 0.97 & 2.90\\ 0.52 & 0.44 & 0.52 & 1.03 & 1 & 2.52\\ 0.19 & 0.33 & 0.44 & 0.34 & 0.40 & 1 \end{pmatrix}$$
$$P_2=\begin{pmatrix} 1 & 0.70 & 3.25 & 1.56 & 0.82 & 1.18\\ 1.43 & 1 & 3.15 & 2.07 & 1.75 & 2.00\\ 0.31 & 0.32 & 1 & 0.44 & 0.57 & 0.90\\ 0.64 & 0.48 & 2.26 & 1 & 1.05 & 1.85\\ 1.22 & 0.57 & 1.76 & 0.95 & 1 & 1.25\\ 0.85 & 0.50 & 1.11 & 0.54 & 0.80 & 1 \end{pmatrix} \quad (12)$$

Appendix II: Membership function of evaluation indices

Table 11 lists three representative membership functions of evaluation indices, such as water-rich sands, total thrust delivered by the shield machine, and the slope of the shield tunnel.

Table 11 Membership function of evaluation indices

Evaluation indices	Membership function	Graph of membership function
Water-rich sands (Slump/ mm)	$F(x)=\begin{cases} 0, & x<160, x>220\\ \frac{x-160}{35}, & 160<x<195\\ 1, & 195\le x\le 205\\ \frac{220-x}{15}, & 205<x<220 \end{cases}$	
Total thrust of the shield machine ($F\pi D^2$ (kN))	$F(x)=\begin{cases} 0, & x<262.5\\ \frac{x-262.5}{550-262.5}, & 262.5\le x\le 550\\ 1, & x>550 \end{cases}$	
Slope of shield tunnel (*i*/ ‰)	$F(x)=\begin{cases} 0, & x>10^{-5}\\ \frac{10^{-5}-x}{10^{-5}-10^{-7}}, & 10^{-7}\le x\le 10^{-5}\\ 1, & x<10^{-7} \end{cases}$