Study on the evaluation of adaptability of shield machine type selection in coastal complex stratum

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Abstract: The design and manufacture of the traditional shield machine not only does not strictly consider the various influencing factors of the shield tunneling but also directly selects the existing shield machine or carries on the adaptive transformation to the existing shield machine. According to the characteristics of shield tunneling construction, to solve the problem of blind selection of shield machines in the coastal complex stratum. First of all, an evaluation index system of shield type selection and adaptability considering the design parameters, hydrogeological conditions, and surrounding tunnel environments was established. After that, the fuzzy analytical hierarchy process (Fuzzy-AHP) is adopted to calculate the weight of different indices. However, it is difficult to pass the consistency test when calculating the weight of the analytical hierarchy process (AHP). An improved genetic algorithm (IGA) is introduced to make up for the weight calculation of AHP. Finally, based on summarizing various theories and experiences, the membership functions of each evaluation index are constructed according to the fuzzy theory, and the adaptive fuzzy comprehensive evaluation model of the selected type of the shield machine in the coastal complex stratum is proposed. A case study on shield machine selection of shield-driven tunnel works of the Xiamen Metro Line 4 Pengcuo North Station- Caicuo Station in China is introduced to illustrate the application of the proposed model. Moreover, the results provide a reliable basis for the selection and adaptability evaluation of shield machines in coastal complex formations.

Keywords: shield machine, type selection, adaptability, AHP, IGA, evaluation method

1. Introduction

As an essential shield tunnel method of an urban subway in coastal complex stratum, shield machine and stratum adaptability are fatal in coastal subway engineering. The adaptability of the shield machine to the stratum has become a prominent feature, which determines the success of the shield tunnel. Edalat et al (2010) used a multi-standard analysis method to study shield machine type
selection of line 2 of Tabriz urban subway. Cordes et al (2014) classified the tunnel from west to east, which provides a basis for the section of shield tunnel in Baltimore. Rengshausen et al (2014) discussed the advantages and disadvantages of earth pressure balance and slurry balance shield machines in the Thames River tunnel and evaluated these risks. Hyun et al. (2015) adopted fault-tree analysis (FTA) and analytic hierarchy process (AHP) applicable to risk analysis of shield TBM tunnels. These methods provide practical suggestions for shield machine type selection, but they lack objective evaluation criteria and are easily affected by subjective factors. Therefore, it is urgent to establish an evaluation model that can comprehensively evaluate the shield machine type selection in coastal complex stratum.

Based on the previous qualitative analysis of adaptability for shield machine type selection, this paper proposes the evaluation system of shield machine type selection in coastal complex stratum considering the influencing factors of adaptability. According to an improved genetic algorithm (IGA) and analytic hierarchy process (AHP), the weight of the evaluation index of shield selection is obtained, and the membership function of each evaluation index is determined. Moreover, a fuzzy comprehensive evaluation model is established to make a quantitative evaluation for the adaptability of shield machine type selection in coastal complex stratum.

2. Evaluation method of adaptability of shield machine type selection

2.1 Comprehensive adaptability of shield machine type selection

In order to reasonably evaluate the adaptability of shield machine type selection in different geological shield zones, the concept of comprehensive adaptability \( \overline{D} \) could be defined by Equation (1).

\[
\overline{D} = \frac{1}{L} \sum_{i=1}^{a} D_i L_i
\]  

(1)

where \( L \) is the total length of the shield zone, \( L_i \) is the \( i \)th length of the shield zone, and \( D_i \) is the adaptability of \( L_i \).

Based on the investigation of multiple shield tunnels in coastal complex formations, the adaptability evaluation of shield machine type selection can be classified into five grades (Table 1). Herein, we defined an evaluation set \( V = \{v_1, v_2, v_3, v_4, v_5\} \).

| Grade | Rating scale | Adaptablety | Evaluable conditions |
|-------|--------------|-------------|----------------------|
| \( v_1 \) | I \( [0.9,1] \) | Complete adaptation |
| \( v_2 \) | II \( [0.8,0.9] \) | Severely adapted |
| \( v_3 \) | II \( [0.7,0.8] \) | Moderately adapted |
| \( v_4 \) | III \( [0.6,0.7] \) | Slightly adapted |
| \( v_5 \) | IV \( [0.4,0.6] \) | Weakly adapted |
| \( v_5 \) | V \( [0,0.4] \) | Inadaptation |

2.2 Evaluation system of adaptability of shield machine type selection

Based on the basis and principles of shield machine type selection, this paper analyzes various risk
sources that shield tunneling difficulties. The critical factors of shield machine type selection mainly include the following three aspects: (1) shield tunneling parameters; (2) hydrogeological conditions; (3) environmental conditions.

As we all know, SPB and EPB have the same equipment composition except for the different working principles of maintaining the tunnel face stability. Hence, the evaluation system of adaptability of shield machine type selection is established, as shown in Figure 1.

![Figure 1: The evaluation system of adaptability.](image)

3. Calculating the weight using the AHP-IGA

3.1 IGA-AHP

A GA is one of the evolutionary algorithms inspired by Darwin's theory of biological evolution. Standard genetic algorithm (SAG) achieves an approximate optimal solution of the objective function through a series of genetic operations, so genetic operations are the basis of the optimal global ability of SAG; however, SAG has the disadvantage of poor robustness and local convergence. In this article, an improved genetic algorithm (IGA) can improve the deficiencies of SGA. Ultimately, the global optimal ability and robustness of the algorithm can be enhanced. 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: To solve the problem that the high-quality individuals have weak selection ability in the later stage of the algorithm. The function of fitness is expressed by the reciprocal for the objective function; the fitness value of each individual in \(P(t)\) is calculated.

Step 3: based on improved selection operation, the fitness ranking of individuals is divided into elite populations and other populations requiring a genetic operation.
Step 4: based on improved crossover operation, an adaptive two-point crossover operator with crossover probability related to individual fitness is adopted.

Step 5: based on improved mutation operation, an adaptive random crossover operator is adopted, related to the probability of mutation and individual fitness.

Step 6: the elite population and the newly generated population are mixed to select individuals within the top 5000 ranked fitness values.

Step 7: through many trials, check whether the termination condition is satisfied. It is found that the algorithm convergence 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.

Usually, the judgment matrix is obtained by using an expert scoring method based on AHP, but experts have a different understanding of the objectives, resulting in multiple influencing factors. In this case, although the consistency test of the judgment matrix satisfies the conditions, the consistency of the judgment matrix above 5 (including 5) is poor. The eigenvector method is often used to calculate the weights of the higher-order judgment matrix, however, if the judgment matrix has been determined, then the weight (w) and consistency test index (CR) have been determined, so the calculated weight is inaccurate. Furthermore, we can find a formula (Equation (2) and (3)) (Saaty, 1977) relating the consistency test and the weight, where \( x_i \) is an element of the set of evaluation factors. Then, the minimum value of Equation (3) is taken as the objective function to calculate the optimal weight for IGA. This method of calculating weights using Equation (4) and (5) is called AHP-IGA.

\[
\lambda_{max} = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_{ij}w_j}{w_i}, i, j = 1, 2, 3, \ldots, n
\]  
(2)

\[
CI = \frac{1}{n(n-1)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left[ \frac{(a_{ij}x_j - x_i)^2}{a_{ij}x_j} \right], i = 1, 2, 3, \ldots, n
\]  
(3)

\[
\min f = \frac{1}{n(n-1)} \sum_{i=1}^{n} \sum_{j=1}^{n} \left[ \frac{(a_{ij}x_j - x_i)^2}{a_{ij}x_j} \right], i = 1, 2, 3, \ldots, n
\]  
(4)

\[
\begin{align*}
0 < x_i < 1, i = 1, 2, 3 \ldots, n \\
\sum_{i=1}^{n} x_i = 1 \\
\frac{1}{9} \leq \frac{x_i}{x_j} \leq 9, i, j = 1, 2, 3 \ldots, n
\end{align*}
\]  
(5)

3.2 The weight of evaluation index

The weight reflects the importance of each index to different evaluable objectives in the evaluation process, and the method used to calculate the weight has a direct influence on the result of this evaluation. According to Equation (4) and (5), the collected expert scores of the criterion level are integrated into a single judgment matrix \( D \). Similarly, the judgment matrix of hydrogeological
condition \( P_2 \) is obtained using Figure 1 as shown in Equation (6).

\[
D = \begin{pmatrix}
1 & 0.35 & 3 \\
2.86 & 1 & 4.25 \\
0.33 & 0.24 & 1 \\
\end{pmatrix}
\quad P_2 = \begin{pmatrix}
1 & 0.47 & 0.35 \\
2.14 & 1 & 0.68 \\
2.82 & 1.46 & 1 \\
\end{pmatrix}
\]

(6)

Based on IGA-AHP, the consistency index of judgment matrix \( D \) is \( CI = 0.0283 \), and the consistency ratio is \( CR = 0.049 < 0.1 \). The judgment matrix of criterion level \( D \) of the evaluation system satisfies the requirements of the consistency test. Therefore, the normalized weight set \( w = \{0.263, 0.626, 0.111\} \) corresponding to the evaluation index set \( D = \{P_1, P_2, P_3\} \) of the criterion level, and the ranking of weights of evaluation indexes can be obtained: hydrogeological condition \( (P_2) \rangle \) shield tunneling parameters \( (P_1) \rangle \) environmental conditions \( (P_3) \). At the same time, the consistency index of judgment matrix \( P_2 \) is \( CI = 0.0006 \), and the consistency ratio is \( CR = 0.001 < 0.1 \). So, the judgment matrix of criterion level \( P_2 \) of the evaluation system also satisfies the requirements of the consistency test. To sum up, the consistency index \( CR \) and the global ranking weight of evaluation indices are shown in Table 2.

| The evaluation indices | Shield tunneling parameters \( (P_1) \) | Hydrogeological condition \( (P_2) \) | Environmental conditions \( (P_3) \) | The weight of index level \( U \) to target level \( D^a \) |
|------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| \( u_{11} \)           | 0.263                                | 0.626                                | 0.111                                | 0.263                                |
| \( u_{21} \)           | 1                                    | 0                                    | 0                                    | 0.103                                |
| \( u_{22} \)           | 0                                    | 0.164                                | 0                                    | 0.214                                |
| \( u_{23} \)           | 0                                    | 0.342                                | 0                                    | 0.308                                |
| \( u_{31} \)           | 0                                    | 0                                    | 1                                    | 0.111                                |

\(^a\) Note: \( CR = 0.049 < 0.1 \), satisfied the requirements of consistency.

Table 2 illustrated that the consistency ratio of the global ranking of the evaluation indices satisfied the consistency test, and the weight ranking of the evaluation indices includes: pressure of groundwater \( (u_{23}) \rangle \) diameter of shield tunnel \( (u_{11}) \rangle \) permeability of soils \( (u_{22}) \rangle \) the settlement \( (u_{31}) \rangle \) grain composition of soils \( (u_{21}) \).

### 3.3 Membership function of evaluation indices

Based on the evaluation system of adaptability of shield machine type selection, the membership functions of slurry pressure balance shield (SPB) and earth pressure balance shield (EPB) were established. Based on the investigation of multiple shield tunnels (Code for the design of metro lines in China; Shanghai and Xiamen Metro) and related literature on shield tunneling (Shi et al., 2011; Zhao et al., 2018; Zhang et al., 2018), these interval points can be easily implemented by grading evaluation indices (Table 3).

| The evaluation index | Membership functions of SPB | Membership functions of EPB |
|----------------------|-----------------------------|-----------------------------|
|                      |                             |                             |

5
### Fuzzy comprehensive evaluation model

The fuzzy theory is 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 \( O = \{ O_1, O_2, \cdots, O_n \} \) is \( U = \{ x_1, x_2, \cdots, x_m \} \). Furthermore, Equation (7) (Zadeh, 1978) demonstrated the fuzzy comprehensive evaluation model.

\[
B = A \cdot R = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix} \times \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = \begin{bmatrix} D_1 & D_2 & \cdots & D_n \end{bmatrix}
\]

\( B \) is the set of comprehensive evaluation values of the target set \( O \); \( D_i \) is the adaptability of the
evaluation target $O$; $A$ is the global ranking weight set of the evaluation index set $U$; $R$ is the membership matrix of the evaluation index $U$ to the target set $O$.

Based on the fuzzy comprehensive evaluation model, the evaluation system of adaptability of shield machine type selection is proposed, and IGA is introduced to solve the global ranking of evaluation indices under the minimum consistency index. Finally, combined with the evaluation system of adaptability and each evaluation index's weight and membership function into the model, the relevant parameters are obtained, as shown in Table 4.

**Table 4.** Fuzzy comprehensive evaluation model of adaptability of shield machine type selection

| The target level | The criterion level | Local weights | The index level | Local weights | Global weights | Membership functions |
|------------------|---------------------|---------------|----------------|---------------|----------------|---------------------|
| Shield tunneling | 0.263               | $u_{i1}$      | 1              | 0.263         | $f_{i1}$       |
| parameters      |                     |               |                |               |                |
| Adaptability    | Hydrogeological     | 0.626         | $u_{i21}$      | 0.342         | 0.214          | $f_{i21}$           |
| $D^a$            | condition           |               |                |               |                |
| Environmental   | 0.111               | $u_{i31}$      | 1              | 0.111         | $f_{i31}$       |
| conditions      |                     |               |                |               |                |

$a$ Note: $D$ is the sum of the global ranking weight of all the evaluation indexes in the index layer and their corresponding membership functions.

**4. Case study**

The underground traffic project of Xiamen Metro Line 4 Pengcuo North Station to Caicuo Station is located north of Xiangan District, Xiamen City, China. The subway is built from west to east along Xiangan West Road (under Xiangan West Road, and elsewhere beneath farmland or wasteland). The soil cover thickness of the shield tunnel is 10 to 21.4 m.

In this paper, the right branch of the shield zone is selected to evaluate the adaptability of shield machine type selection. Firstly, the evaluation index of adaptability is selected. According to the principle of shield zone segmentation, the right branch of the Peng - Cai shield zone is divided into six sections for adaptability evaluation. Secondly, the value of the evaluation index of the right branch of the Peng - Cai shield zone is submitted with the corresponding membership function, and the membership matrix ($R_{EPB}$, $R_{SPB}$) and corresponding weight matrix $A$ of two shields types are proposed, respectively. The adaptability $D_i$ and comprehensive adaptability $\tilde{D}$ of the $i$th segment of different shield types are calculated, as shown in Table 5.

**Table 5.** The adaptability of EPB the right branch of Peng - Cai shield zone

| Segment | Length/m | $D_i$ (EPB) | $D_i$ (SPB) | $\tilde{D}$ (EPB) | $\tilde{D}$ (SPB) |
|---------|----------|-------------|-------------|-------------------|-------------------|
| L1      | 150      | 0.98        | 0.37        |                   |                   |
| L2      | 840      | 0.87        | 0.39        | 0.86              | 0.39              |
| L3      | 615      | 0.84        | 0.39        |                   |                   |
| L4      | 150      | 0.78        | 0.39        |                   |                   |
As can be seen from Table 5, the comprehensive adaptability of EPB in Peng-Cai shield zone is 0.86, and the evaluation result is severely adapted; The comprehensive adaptability of the SPB is 0.39, and the evaluation result is inadaptation. Based on the comprehensive adaptability evaluation results of shield machine type selection, the EPB should be selected in the Peng-Cai shield zone, consistent with the EPB in practice.

5. Conclusion
This study proposed a fuzzy theory to determine the membership functions and establish a consistent judgment matrix in the IGA-AHP. The proposed model was successfully employed to assess the adaptability in Xiamen Metro Line 4 Pengcuo North Station-Caicuo Station. The significant findings are summarized as follows:

1) The calculation method and classification standard of the comprehensive adaptability of shield machine type selection are determined. According to the domestic and overseas experience, the evaluation system of shield machine type selection is established from the following aspects of shield tunneling parameter, hydrogeological conditions, and environmental conditions.

2) The local ranking weight and global ranking weight of the evaluation index are determined by IGA-AHP, which satisfied the consistency test. The fuzzy theory is introduced to create the membership function of each evaluation index, and the membership matrix of shield machine type selection is obtained.

3) Through the practical field dates in the Peng-Cai shield zone, the effectiveness of the evaluation model was verified. Finally, the EPB is selected, which is consistent with the selection of the actual engineering.

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