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A new decision method for construction scheme of shallow buried subway station

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Abstract. With the development of the economy, people's utilization of underground space are also improved, and a large number of cities have begun to build subways to relieve traffic pressure. The choice of subway station construction method is crucial. If an inappropriate construction method is selected, it will not only waste costs but also cause excessive deformation that may also threaten construction safety. In this paper, a subway station construction scheme selects model based on the AHP-fuzzy comprehensive evaluation. The rationality of the model is verified using numerical simulation and monitoring measurement data. Firstly, considering the economy and safety, a comprehensive evaluation system is established by selecting several indicators. Then, the analytic hierarchy process is used to determine the weight of the evaluation index, and the dimensionless membership in the fuzzy comprehensive evaluation method is used to evaluate the advantages and disadvantages of the construction method. Finally, the method is applied to Liaoyang east road station of Qingdao metro Line 2, and the results are verified by numerical simulation and monitoring measurement data. The results show that the model is scientific, practical and applicable.

Keywords: analytic hierarchy process; fuzzy comprehensive evaluation; monitoring measurement; numerical simulation; selection of construction method; subway station

1. Introduction

With the rapid development of urbanization, the problems of urban traffic congestion and residents' difficulty in taking buses are becoming more and more prominent. In order to alleviate traffic congestion, more and more cities begin to build subway (Gao *et al.* 2014; Eskandari *et al.* 2018). The selection of appropriate construction method of the subway station is particularly critical. The selection of the construction method greatly influences structural form, construction stress, deformation, construction period and project cost. Once the inappropriate construction method is selected, it will cause an extremely negative impact (Fang *et al.* 2011). Therefore, scientific and reasonable comparison and selection of subway station construction schemes are significant for improving construction quality, speeding up construction progress, and saving construction cost.

In recent decades, many scholars have used numerical simulation to study the characteristics and optimization of construction methods of Underground Engineering (Chen *et al.* 2015, Ma *et al.* 2018, Wang *et al.* 2009, Xue *et al.* 2010, Zhang *et al.* 2020), which makes the construction method safer, reduces the occurrence of geological disasters in the construction process, and provide more ideas for the selection of tunnel construction methods. At the same time, (Ding *et al.* 2017, Gao and He 2017, Ieronymaki *et al.* 2018, Zhang *et al.* 2019) and others, using different methods, put forward the settlement prediction method caused by underground engineering construction, and provides the basis for predicting the displacement size that various construction methods may produce.

Based on the above research, many scholars have used numerical simulation or model test to compare and select the excavation methods of Underground Engineering (Li *et al.* 2014a, Zhang *et al.* 2013). Yuan and Zhan (2019) compared the three-step method, Center Diaphragm method and double pilot hole method by numerical simulation method. Through the comparison and analysis of various parameters, it is suggested that the double pilot tunnel method should be used to construct the large-span shallow buried tunnel in soft rocks. Sui *et al.* (2013) compared three typical engineering methods: the bench method, the centre diaphragm method and the cross diaphragm method in controlling the vault settlement of new tunnels and the deformation of existing tunnels. Finally, the simulation results are checked by comparing with measured field data and the selected results have been found to be applicable and useful practical engineering. But only limited to numerical simulation, the data lacks comprehensiveness and accuracy, limited to the control of displacement and does not considered the cost of construction.

Skibniewski and Chao (1992) proposed an analytical method to evaluate the construction technology using the analytic hierarchy process (AHP), which laid a foundation for selecting underground engineering construction methods. Based on this, Geng *et al.* (2018) applied AHP to

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select subway construction methods and achieved excellent results. However, use of the analytic hierarchy process (AHP) relies too much on expert experience. To obtain more accurate selection results, (Golestanifar *et al.* 2011, Wu *et al*. 2018a) the combination weighting methods such as entropy weight method and fuzzy set theory are used to study the selection of underground engineering construction scheme. The results show that the model established by multiple combination weighting methods is more accurate than AHP. However, it is still difficult to solve the complicated fuzzy situation due to the quantitative consideration of qualitative problems. Moreover, the above methods are not enough to verify the selection results and can not explain the advantages of the selection results.

Based on the shortcomings of the existing research, this paper establishes a selection model of the construction method of shallowly buried metro station based on AHP-fuzzy comprehensive evaluation method and verifies the rationality of the model by using numerical simulation and monitoring measurement data. Combined with the characteristics of the project, the influencing factors of subway station construction are determined and the influence index system is established. This paper uses the analytic hierarchy process to determine the weight of the evaluation index. Then, the dimensionless membership degree of fuzzy comprehensive evaluation method is used to evaluate the advantages and disadvantages of the construction method, to establish the selection model of construction method for the underground excavation subway station. Finally, the construction method selection model is applied to Liaoyang East Road Station of Qingdao Metro Line 2 and verified by numerical simulation and monitoring data. The application results show that the method is scientific and practical.

2. Materials and method

2.1 Engineering background

Qingdao Metro is an urban public transport system in Qingdao, Shandong Province, China. The study area is Liaoyang East Road Station of Qingdao Metro Line 2, as shown in Fig. 1. Liaoyang East Road station is located at the intersection of Songling road and Liaoyang East Road, along the north-south direction under Songling road. Because of the large traffic flow on Songling Road, the open-cut method can not be used. The station's main structure is 157 m long and 21.22 m wide, which is a single arch double-deck station. The overburden soil on the arch at the central mileage of the station is about 11 m. The strata from top to bottom are plain fill, silty clay, coarse sand and gravel sand containing cohesive soil, strong weathering lower subzone layer, moderately weathered granite and slightly weathered granite. The arch foot is located in a slightly weathered granite layer. Due to the discontinuous distribution of groundwater aquifers in the site area, it is impossible to form a unified runoff in the site area. Most of them are connected with bedrock fissure water and form a runoff discharge relationship. The groundwater volume is small, so it does not necessiate to consider the impact of groundwater in the construction scheme selection.

Fig. 1 Qingdao Line 2 Route Map

According to the geological data and the site exploration results, the station stratigraphic condition gradually becomes better from north to south, with a section in the north containing faulted fracture zones and no adverse geology in the south. The natural risks are mainly rainstorm, typhoon and earthquake. Since the station's construction is concealed excavation, there is very little construction exposed on the surface, so the threat of rainstorm and typhoon is relatively small.

2.2 AHP-fuzzy comprehensive evaluation method

AHP-fuzzy comprehensive evaluation method has been widely used in the field of geotechnical engineering since it was put forward and has achieved good application effect. It plays an important role in disaster prediction and method evaluation (Ding *et al.* 2019, Li *et al.* 2014b, Zhang *et al.* 2015). In the current research, the AHP-fuzzy comprehensive evaluation method is used to evaluate the subway station construction method and select the best scheme.

2.2.1 Analytic Hierarchy Process (AHP)

The weight vectors of the first and second level evaluation indexes are obtained by analytic hierarchy process, a method proposed by Satty that is suitable for processing and selecting from multiple alternatives (Satty 1980). The weight vectors of the primary and secondary evaluation indicators were obtained by hierarchical analysis, The analytic hierarchy process (AHP) subdivides problems into multiple levels in the hierarchical structure. It combines quantitative analysis with qualitative analysis for multi-objective decision-making and evaluation of complex problems (Xu *et al.* 2018).

AHP is divided into the following steps (Papathanasiou and ploskas, 2018):

(1) Build the AHP model. Use the expert survey method to determine the influencing factor indicators P_1, P_2, …, P_n.

(2) Construct a comparative judgment matrix. Many experts are asked to use the 1-9 scale to score the selection index of the construction method according to the importance index, as shown in Table 2. Establish an *n*-th order judgment matrix $B=[b_{ij}]n\times n$. Where b_{ij} represents the ratio of the influence of P_i and P_j on target *A*.

(3) Calculate the relative weight of elements according

Table 1 Nine scales and its meaning

Scaling	Meaning
1	Compared with two indicators, they have the same importance.
3	Compared with the two indicators, the former is slightly more important than the latter.
5	Compared with the two indicators, the former is significantly more critical than the latter.
7	Compared with the two indicators, the former is more important than the latter.
9	The former is more important than the latter.
2, 4, 6, 8	The above figures represent the median of the above adjacent decisions.
	The index *i* divided by index *j* equals b_{ij}, then *j* divided by *i* is equal to $1/b_{ij}$.

to a single standard and its consistency check. Calculate the sum of each column of the judgment matrix, normalize the elements of the column, add the normalized column vectors row by row to obtain the square root vector, and then normalize the square root vector to obtain the ranking weight vector *W*.

(4) Consistency check. First, calculate the maximum eigenvalue $\lambda_{\max}$ of the judgment matrix, and then perform the consistency check $CI = \frac{\lambda_{\max} - n}{n-1}$, calculate the consistency ratio *CR*, when $CR = \frac{CI}{RI} < 0.1$, it means that the consistency of the judgment matrix is acceptable.

2.2.2 Fuzzy comprehensive evaluation

To deal with the ambiguity of human thought. Zadeh (1965) first introduced the fuzzy set theory. The essence of the fuzzy comprehensive evaluation method is to determine the value of an evaluation target element through the membership matrix and the weighting factor. First of all, the fuzzy comprehensive evaluation method needs to determine the combination *U,* of influencing factors and the corresponding level combination *V*. Every single factor of the influencing factor combination *U* corresponds to the horizontal combination *V* of the corresponding single criterion fuzzy matrix *R*. Then according to the importance of each factor to its whole set, the weight matrix *A* is obtained. Finally, the fuzzy exchange from *R* to *A* is carried out to obtain the final target judgment matrix.

Determining a membership degree is the most crucial part of a fuzzy comprehensive evaluation. Because there are many qualitative indexes in this paper, we use the step-by-step estimation method to determine the membership degree. The step-by-step estimation method is also called the fuzzy set method. After the evaluation set, *V* is given, it can be estimated step by step on a given evaluation set, and the estimation is expressed by an appropriate degree of confidence. The score of confidence varies from 0 to 10. When the construction method is considered the best, the confidence of this level is the highest, which is recorded as 10 points; otherwise, if it is considered completely inappropriate, it is recorded as 0 points.

The process of fuzzy comprehensive evaluation mainly includes the following steps:

(1) Establish factor set $U=\{u_1, u_2, u_3, \ldots u_p\}$, divide factor set into several groups according to a specific attribute, that is, $U=\{U_1, U_2, U_3, \ldots U_p\}$, which needs to meet the requirements of $U = \cup U_i, U_i = \cap U_i = \phi(i \neq j)$, $I, j=1,2,\ldots,q$, called $U=\{U_1, U_2, U_3, \ldots U_q\}$ as the first level factor set.

(2) Building weight sets

Let the weight of the first-level weight set $U=\{U_1, U_2, U_3, \ldots U_q\}$ be $A=\{a_1, a_2, a_3, \ldots a_q\}$.

1) Let the weight of the second-level weight set $U_i = \{u_1^{(i)}, u_2^{(i)}, u_3^{(i)}, \ldots u_{n_i}^{(i)}\}$ be $A_i = \{a_1^{(i)}, a_2^{(i)}, a_3^{(i)}, \ldots a_{n_i}^{(i)}\}$, $i=1,2,\ldots,q$, n_i is the number of second-level index factors included in each first-level factor.

(3) First-level judgment

Set up a judgment set, $V=\{v_1, v_2, \ldots v_m\}$, first, perform a single factor judgment on the n_j factors of the second-level factor set $U_i = \{u_1^{(i)}, u_2^{(i)}, u_3^{(i)}, \ldots u_{n_i}^{(i)}\}$, and obtain the single factor judgment matrix as

$$R_i = \begin{bmatrix} r_{11}^{(i)} & r_{12}^{(i)} & \cdots & r_{1n}^{(i)} \\ r_{21}^{(i)} & r_{22}^{(i)} & \cdots & r_{2n}^{(i)} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n_i 1}^{(i)} & r_{n_i 2}^{(i)} & \cdots & r_{n_i m}^{(i)} \end{bmatrix} \tag{1}$$

Then the fuzzy comprehensive evaluation of factor *i* is $B_i = A_i \cdot R_i = \begin{bmatrix} b_{i1} & b_{i2} & \cdots & b_{im} \end{bmatrix}$.

(4) Second-level comprehensive evaluation

Then make a comprehensive evaluation of the first-level factor set, the evaluation matrix is a first-level fuzzy comprehensive evaluation matrix

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} A_1 \circ R_1 \\ A_2 \circ R_2 \\ \vdots \\ A_n \circ R_n \end{bmatrix} \tag{2}$$

Fig. 2 shows the detailes of AHP-Fuzzy comprehensive evaluation process.

3. Evaluation factors

Determining the influencing factors is the basis of establishing the construction method selection system, and the selection of the influencing factors will directly affect the final selection result of the construction method. The main influence factor is the construction index. The number of indicators should not be too many or too few, too many will increase the complexity of the system structure and blur the role of the main factors. If the number of indicators is too small, although it is easy to evaluate the specific operation process, it is difficult to objectively and comprehensively reflect the actual situation of the evaluation object. Through the research on the selection of construction methods by (Chen 2011, Ozcelik 2016, Wu *et al.* 2018) and the actual project in this study, a two-level evaluation index system is established, with five first-class indexes and ten second-class indexes. The first level is the main factor layer, including construction difficulty,

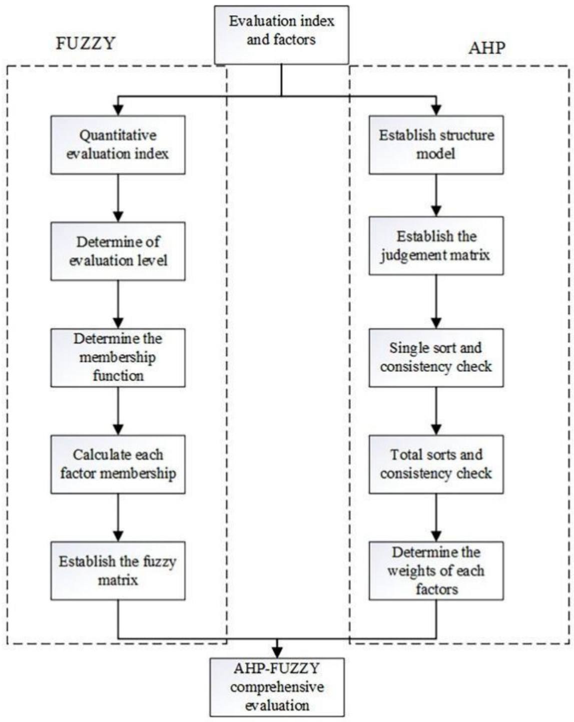

Fig. 2 AHP-Fuzzy comprehensive evaluation process

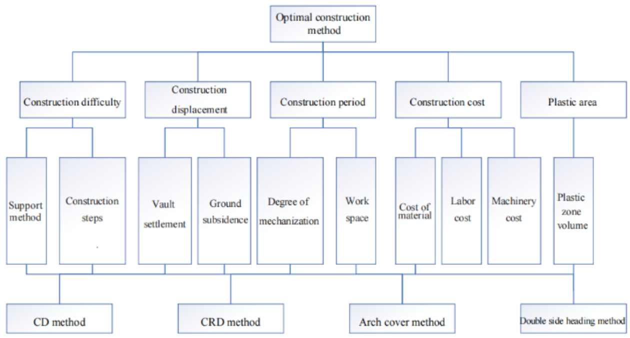

Fig. 3 Relationship between indicators at each layer

construction displacement, construction period, construction cost and plastic zone. Each factor is determined by several evaluation index factors, so that the evaluation objectives, evaluation criteria and evaluation index factors are at different levels, forming a hierarchical structure.

After determining the influencing factors, it is also necessary to determine the judgment set, the construction plan to be selected. The study area is Liaoyang East Road Station of Qingdao metro, which is close to the main road and has a heavy traffic flow. Therefore, it is not suitable to use the open cut method and the single arch and large-span station, so it is not suitable to compare with the multi heading method. Finally, four construction schemes, Center Diaphragm method, Center Cross Diaphragm method, Double side heading method and Arch cover method, are selected for comparison. The relationship of each index is shown in Fig. 3.

(1) Construction difficulty

The difficulty degree of construction is a factor that can not be ignored in the construction of the subway station. In this paper, two secondary indexes of support method and construction steps are selected to evaluate the construction difficulty.

Among them, the support method and construction steps of CD method are the most simple, because it has only the middle partition wall and no horizontal support and temporary inverted arch. During the construction, one side of the tunnel is excavated by sections, then the middle partition wall is constructed, and the other side is excavated by sections, without the complicated process.

Compared with the CD method, the arch cover method has a little more complicated support methods and construction steps. However, there is no temporary support, and the support is relatively simple. After the excavation of the upper part is completed, the secondary lining can form a closed structure, and the construction is simple.

The CRD method has middle diaphragm and diaphragm needs to be constructed as temporary invert, so the support and construction are slightly complicated. It is necessary to excavate one side of the tunnel first, using partial middle partition wall and cross partition wall. Then excavate the other side of the tunnel to complete the diaphragm construction. Then excavate the last part of the first construction site, extend the middle partition, and finally excavate the remaining part. The construction process is slightly complicated.

However, the double-side heading method is more complicated than the CRD method, and the support and construction are the most complicated among the four methods. The grades of these four methods are divided in Table 2.

(2) Construction displacement

The most important aspect of tunnel construction is to control the settlement to minimize the disturbance to nearby buildings and services (Tan and Ranjith 2003). In this paper, two parameters of vault settlement and ground subsidence are taken as the secondary indexes to evaluate the construction displacement. According to the surrounding rock conditions of the project, based on the RMR rock classification, it is grade IV to V rock and it has soft upper and lower hard stratum. According to the engineering experience (Cherlo *et al.* 2013, Sharifzadeh *et al.* 2013, Zhang *et al.* 2012), the possible displacement range of four construction methods is summarized and delimited.

(3) Construction period

The construction period affects the early operation of the metro station, so it is necessary to consider the impact of construction period. The working space, mechanization degree and construction steps are selected as sub-factors to evaluate the construction period. Combined with the actual situation of the project, the influencing factors are graded in Table 2.

(4) Construction cost

Construction cost is one of the preconditions for the selection of metro station construction methods. While meeting the construction specifications, the cost should be saved as much as possible (Petroutsatou *et al.* 2012). In this paper, material cost, labour cost and mechanical cost are selected as sub-factors, and the factors are graded according to the project's actual situation. See Table 2.

Table 2 Expert opinion questionnaire

Evaluation index		Construction method			
		CD method	CRD method	Arch cover method	Double side heading method
Construction difficulty	Support method	The simplest	Comlpex	Simple	The most complex
	Construction steps	The simplest	Complex	Simple	The most complex
Construction displacement	Vault settlement (mm)	20-40	15-30	5-15	10-20
	Ground subsidence(mm)	15-40	15-30	5-10	10-20
Construction progress	Degree of mechanization	High	Low	Highest	Lowest
	Workspace	Large	Small	Largest	Smallest
Construction cost	Material cost	Lowest	Low	High	Highest
	Labour cost	Lowest	Low	High	Highest
	Machinery cost	Low	High	Highest	Lowest
Plastic zone	Plastic zone volume (m^3)	25-50	30-45	40-60	35-50

(5) Plastic zone

When underground caverns are excavated in the rock mass, the plastic zone will inevitably appear. Like displacement, the plastic zone's scope afterstabilisation reflects the relationship between the stress state of surrounding rock and rock mass strength, a comprehensive index of in-situ stress and surrounding rock strength, and an important factor affecting tunnel construction (Behnam *et al.* 2014). The volume of plastic zone is selected as the sub-index of the plastic zone. In this paper, the scope of the construction area is defined according to the practical construction method of (Chen *et al*. 2015).

When excavating underground cavern in the rock mass, the plastic zone will inevitably appear. The range of the plastic zone after stabilization, like displacement, reflects the relationship between the stress state of surrounding rock and rock strength, is a comprehensive index of ground stress and surrounding rock strength, and is an important factor affecting tunnel construction (Behnam *et al.* 2014). The volume of plastic zone is selected as the subindex of plastic zone. Based on the research of Jiang *et al.* (2011), Pan and Chen (1990) and the general situation of actual projects, the plastic zone volume range of the four construction methods are defined as shown in Table 2.

Based on consulting literature and investigating the construction site, this paper synthesizes the opinions of relevant experts in subway construction, and sorts out the expert opinion questionnaire (see Table 2), which provides the basis for the subsequent construction of judgment matrix.

4. Calculation and selection of the final plan

Construction target, layer criteria, layer judgement matrix and check have been done. Through the questionnaire survey of experts and relevant practitioners, and comparing the score table, the relative importance of different influencing factors is compared in the following two pairs, as shown in Table 3.

The final formation of the target layer-criterion layer analysis and optimization matrix A-B is shown in Eq. (3)

Table 3 Pairwise comparison score

A	B_1	B_2	B_3	B_4	B_5
B_1	1	1/8	1/5	1/6	1/4
B_2	8	1	4	3	5
B_3	5	1/4	1	1/2	2
B_4	6	1/3	2	1	3
B_5	4	1/5	1/2	1/3	1

*Where, A indicates the best construction plan, B_1 indicates the construction difficulty, B_2 indicates the construction displacement, B_3 indicates the construction progress, B_4 indicates the construction cost, and B_5 indicates the volume of the plastic zone.

$$B=\begin{bmatrix} 1 & 1/8 & 1/5 & 1/6 & 1/4 \\ 8 & 1 & 4 & 3 & 5 \\ 5 & 1/4 & 1 & 1/2 & 2 \\ 6 & 1/3 & 2 & 1 & 3 \\ 4 & 1/5 & 1/2 & 1/3 & 1 \end{bmatrix} \tag{3}$$

The consistency test of the matrix (3) is carried out through MATLAB calculation, and the maximum eigen value of the matrix (3) is 5.1686, the ranking weight vector $W=\begin{bmatrix}0.0367 & 0.4911 & 0.1467 & 0.2307 & 0.0948\end{bmatrix}$, CI=0.0422, CR=0.0376<0.1, so the consistency meets the requirements.

The weight of the factor set of level 2 (b_i-b_{ij}) was calculated, the relevent materials of domestic and foreign subways and construction technology were accouted and questionnaire were placed to the experts and relevent tunnel construction personnels. The investigation results were summarized to determine the judgment matrix of each criterion layer-scheme layer and the final consistency test results were shown in Tables 4-8.

Finally, five judgment matrices $B_1=\begin{bmatrix}1 & 3\\ 1/3 & 1\end{bmatrix}$, $B_2=\begin{bmatrix}1 & 1/3\\ 3 & 1\end{bmatrix}$, $B_3=\begin{bmatrix}1 & 1/2\\ 2 & 1\end{bmatrix}$, $B_4=\begin{bmatrix}1 & 3 & 1/3\\ 1/3 & 1 & 1/5\\ 3 & 5 & 1\end{bmatrix}$, $B_5=\begin{bmatrix}1\end{bmatrix}$ are formed.

Table 4 Judgment of scheme layer by "Construction difficulty" Table B_1-b_{1n}

B_1	b_{11}	b_{12}
b_{11}	1	3
b_{12}	1/3	1

*Where B_1 indicates the construction difficulty, b_{11} indicates support method and b_{12} indicates construction steps.

Table 5 Judgment of scheme layer by "Construction displacement" Table B_2-b_{2n}

$B2$	$b21$	b_{22}
$b11$	1	1/3
b_{12}	3	1

*Where, B_2 indicates the construction displacement, b_{21} indicates vault settlement and b_{22} indicates ground subsidence.

Table 6 Judgment of the scheme layer in the "Construction progress" Table B_3-b_{3n}

$B3$	$b31$	b_{32}
$b31$	1	1/2
b_{32}	1/2	1

*Where $B3$ indicates the construction progress, $b31$ indicates the degree of mechanization, and b_{32} indicates the working space.

Table 7 Judgment of scheme layer by "Construction costs" Table B_4-b_{4n}

$B4$	$b41$	b_{42}	b_{43}
$b41$	1	3	1/3
b_{42}	1/3	1	1/5
b_{43}	1/3	5	1

*Where $B4$ indicates the construction costs, $b41$ indicates material cost, b_{42} indicates labour cost, and b_{43} indicates machinery cost.

Table 8 Judgment of scheme layer in "Plastic zone" Table B_5-b_{5n}

$B5$	$b51$
$b51$	1

*Where B_5 indicates the plastic region, and b_{51} indicates the volume of the plastic region.

Table 9 Consistency inspection results

	W	λ_{max}	CI	CR
B_1	$[0.7500 \quad 0.2500]$	2	0	0<1
B_2	$[0.2500 \quad 0.7500]$	2	0	0<1
B_3	$[0.3333 \quad 0.6667]$	2	0	0<1
B_4	$[0.2583 \quad 0.1047 \quad 0.6370]$	4.0674	0.0225	0.0252<1
B_5	$[1.0000]$	1	0	0<1

Carry out the consistency check, and the results of the consistency check are shown in Table 9.

It can be concluded that CR of all judgment matrices is less than 0.1, so they all meet the consistency requirements.

For the fuzzy comprehensive evaluation, the step-by-step estimation method is adopted, and the confidence score changes from 0 to 10. The membership degree of each influence index to each construction method can be obtained, and the evaluation matrix is formed, as shown in Table 10.

Table 10 Fuzzy judgment matrix

Evaluation index	Judgment matrix
Construction difficulty (B_1)	$R_1=\begin{bmatrix}0.4918 & 0.1639 & 0.2459 & 0.0984\\0.5217 & 0.1304 & 0.2609 & 0.0870\end{bmatrix}$
Construction Displacement (B_2)	$R_2=\begin{bmatrix}0.0775 & 0.1085 & 0.5426 & 0.2713\\0.0828 & 0.1448 & 0.5793 & 0.1931\end{bmatrix}$
Construction Period (B_3)	$R_3=\begin{bmatrix}0.1905 & 0.1429 & 0.5714 & 0.0952\\0.2500 & 0.1667 & 0.5000 & 0.0833\end{bmatrix}$
Construction Costs (B_4)	$R_4=\begin{bmatrix}0.5217 & 0.2609 & 0.1304 & 0.0870\\0.5793 & 0.1931 & 0.1448 & 0.0828\\0.2459 & 0.1639 & 0.0984 & 0.4918\end{bmatrix}$
Plastic Area (B_5)	$R_5=\begin{bmatrix}0.5882 & 0.1961 & 0.0980 & 0.1176\end{bmatrix}$

The first-level fuzzy comprehensive evaluation matrix is composed of a new evaluation matrix and the weight vector of the first-level factor set for fuzzy operation, and the second-level comprehensive evaluation result is obtained.

$$B = W \circ \begin{pmatrix}B_1 & B_2 & B_3 & B_4 & B_5\end{pmatrix}^T$$
$$= \begin{bmatrix}0.2291 & 0.1585 & 0.4010 & 0.2113\end{bmatrix}$$

According to the principle of maximum subordination degree, the optimal construction scheme is the arch cover method.

5. Comparison with numerical results and field actual status

5.1 Model establishment

In the actual project, due to the cross-section size, excavation size, support method, and other factors, it is impossible to adopt multiple excavation methods simultaneously. It is impossible to obtain the monitoring and measurement data of multiple methods, so it is impossible to make a completely objective judgment on the four excavation methods of the same ground condition. The numerical simulation results under the current construction state are analyzed to verify the reliability of the results.

For this work, Liaoyang East Road Station of Qingdao Metro is taken as the research object, so the excavation section size of Liaoyang East Road station is selected as the section size. Based on the relevant design data, the length of the station cross-section is 22.86 m, the total height is 17.36 m, and the thickness of the overlying soil is about 11 m. The volume size of the model to be designed is 80 m×40 m×47 m. The model is divided into four layers. The top part is miscellaneous fill, then silty clay. Due to the unique geographical conditions of Qingdao, the upper part of the tunnel is placed in the strongly weathered granitic soil layer,

Table 11 Fuzzy judgment matrix

Evaluation index	Judgment matrix
Construction difficulty(B_1)	$B_1 = w_1R_1 = [0.4993 \quad 0.1555 \quad 0.2497 \quad 0.0955]$
Construction Displacement(B_2)	$B_2 = w_2R_2 = [0.0815 \quad 0.1357 \quad 0.5701 \quad 0.2126]$
Construction Period(B_3)	$B_3 = w_3R_3 = [0.2302 \quad 0.1588 \quad 0.5238 \quad 0.0873]$
Construction Costs (B_4)	$B_4 = w_4R_4 = [0.352 \quad 0.192 \quad 0.1115 \quad 0.3444]$
Plastic Area(B_5)	$B_5 = w_5R_5 = [0.5882 \quad 0.1961 \quad 0.098 \quad 0.1176]$

Table 12 Model parameters

Model element	Model	Density /kN/m^3	Elastic Modulus/MPa	Deformation modulus/MPa	Cohesion /kPa	Friction angle/°	Tensile strength/kPa
Plain fill	Moore-Coulomb	17.5	8.5	4	10	12	0.5
Clay		18.9	25	7	30	12	2.8
Strongly weathered granite		22.5	85	50	25	45	2.3
Slightly weathered granite	Elasticity	24.5	60	30	-	-	-
Lining		25	85	60	-	-	-

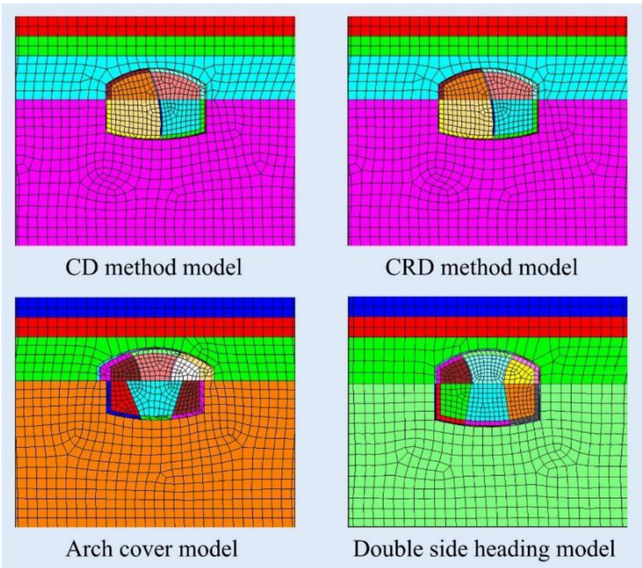

Fig. 4 Excavation model

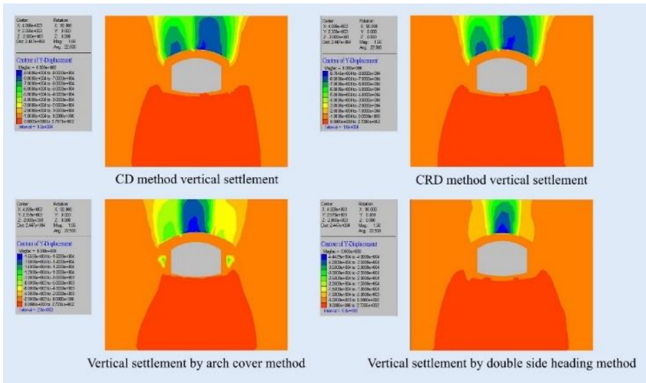

Fig. 5 Displacement contour

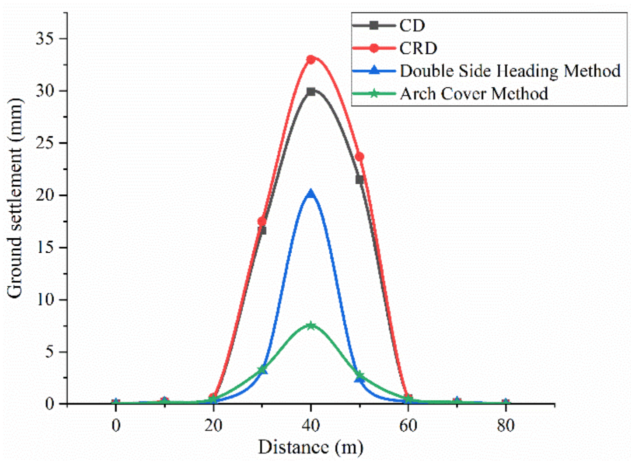

Fig. 6 Ground surface settlement

and the bottom part is designed as a slightly weathered granite layer. In the calculation, the Mohr-Coulomb model is adopted for rock and soil mass and an elastic structure is adopted for lining and slightly weathered granite. Table 12 are detailed model parameters. The support selects an entity unit for equivalent simulation, and the model is established by FLAC 3D software, as shown in Fig. 4.

5.2 Displacement analysis

Different calculations and corresponding results were employed in the analysis. Since the excavation length of the model is set to 40 m, monitoring points are arranged for the surface at 20 m excavation for calculations. One monitoring point is set every 5 m, and a total of 17 monitoring points are set. The displacement contour of each construction method are shown in Fig. 5.

According to the numerical simulation results, it can be found that the arch cover method can effectively control the development of vertical displacement when dealing with the upper soft and lower hard strata, and the maximum vertical displacement is 16.55 mm. The maximum vertical displacement of the double side heading method is 44.43 mm, but its influence on the ground settlement is minimal, almost only a single excavation distance. The CD method and CRD method using four heading excavation methods have produced sizeable eccentric stress, and the vertical

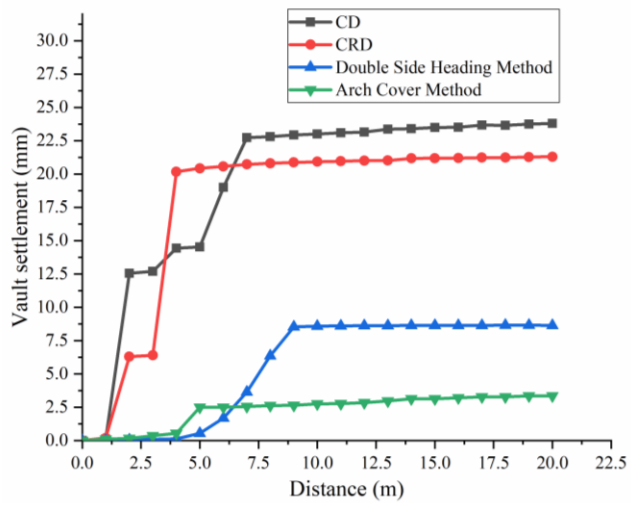

Fig. 7 Development of vault settlement at 10 m

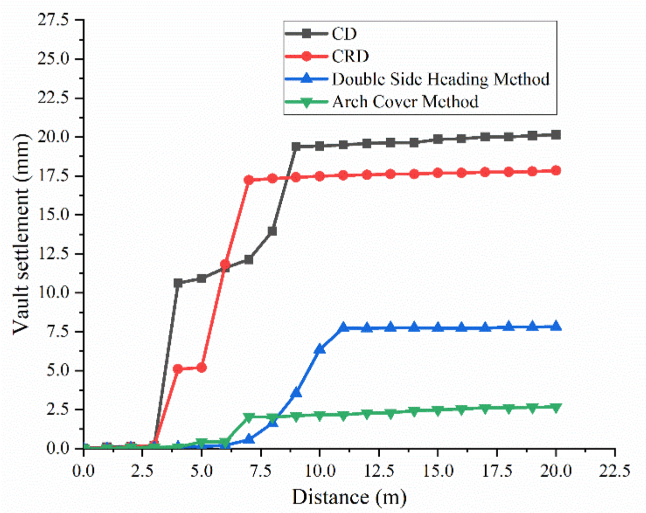

Fig. 8 Development of vault settlement at 20 m

deformation of the later excavation section is more significant than that of the first excavation section. The arch cover method is closed to form a ring, respectively, and the upper secondary lining is applied in advance, which effectively stops the deformation of surrounding rock.

It can be seen from the broken line diagram of surface settlement (Fig. 6) that the deformation of the CD method and CRD method is roughly the same as that of four heading excavation methods, and the influence range is two times of tunnel distance. The difference between the arch cover method and the double side heading method mainly focuses on controlling the displacement above the excavation section. The arch cover method can more effectively control the development of the ground settlement.

Vault settlement is the most crucial monitoring object of the underground excavation method, which is related to the stability of the underground chamber and affects the safety of the construction personnals. If there is a large deformation, it will quickly lead to the risk of rockfall or even collapse. In the construction of the urban subway, the collapse is severe, aggravating the ground deformation and

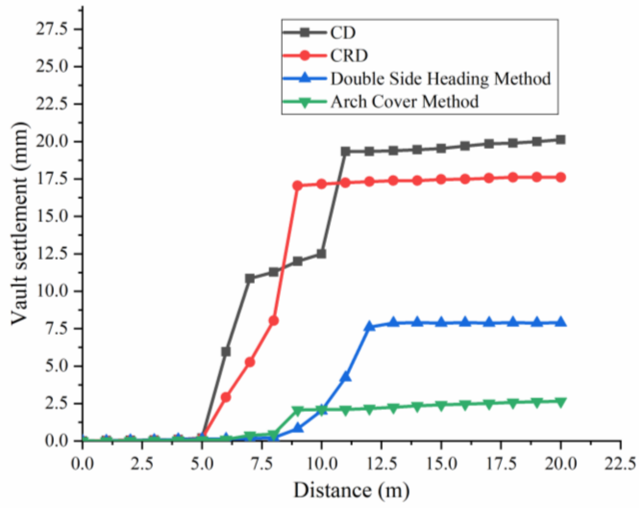

Fig. 9 Development of vault settlement at 30 m

Table 13 The volume of the plastic zone

Methods	Crushing zone volume	Plastic zone volume
CD	1.7e+10	4.2e+10
CRD	1.9e+10	4.2e+10
Arc cover method	2.1e+10	5.1e+10
Double side heading method	1.5e+10	4.5e+10

seriously threatening the safety of the surface buildings and vehicles. According to the recording command of FLAC 3D, the crown settlement development of three groups of sections 10 m, 20 m, and 30 m away from the excavation surface is recorded (Figs. 7-9).

It can be seen from the settlement development curve of the arch crown that the arch cover method plays a significant role in reducing the settlement of the arch crown, and only when the middle and upper part is excavated, the vertical displacement is visible. The CD method and CRD method disturb the arch crown when excavating in the upper left and the upper right parts, respectively. Double side heading method is to excavate the left and right sides first, with little disturbance to the vault. However, there is still apparent vertical displacement after the middle excavation, and the displacement of the arch cover method is the smallest. Hence, the arch cover method is the most effective way to control the vault settlement.

5.3 Plastic zone analysis

A plastic zone is a form of analysis provided by FLAC 3D. For the fracture zone and plastic zone identification, it is generally a single shear-n and shear-p. One is yielding, and the other is that it has yielded in the past and has now exceeded the limit to reach the re-elastic state. For the determination of the elastic stress area, there are two states: shear-*n* and shear-*p*, indicating that the cyclic material stress is elastic. The volume of plastic zone obtained by fish language in four excavation methods is shown in Table 13.

Through the volume of the plastic zone, it is found that the arch cover method is the most destructive to

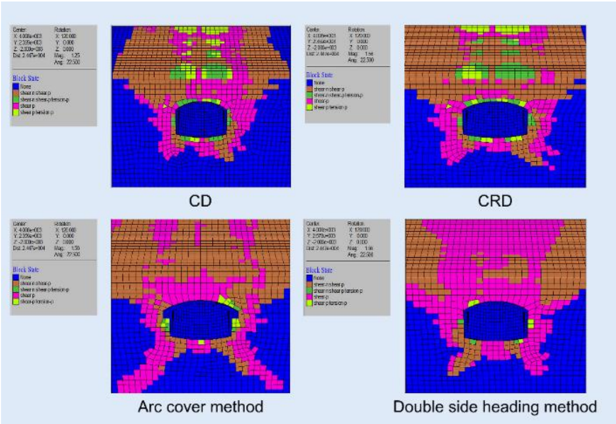

Fig. 10 Plastic zone distribution

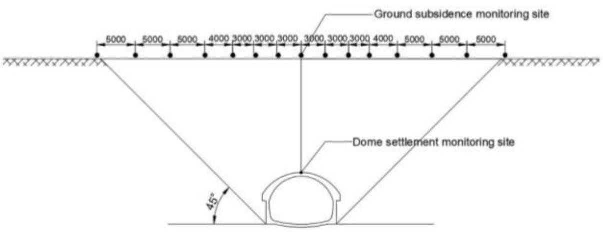

Fig. 11 Monitoring dot map

surrounding rock. Through the analysis of the distribution of the plastic zone, there is a high-pressure position under the arch foot and above the right arch shoulder. There is cross-type support under the excavation section, with an angle of 90°. It shows that after the excavation of arch cover method, due to the early construction of the upper arch cover, and then re-excavation of the lower surrounding rock, the original balance is destroyed, resulting in the stress borne by the lower surrounding rock, forming a very long surrounding rock support failure. It shows that this method is only suitable for excellent bedrock in the lower part of the surrounding rock. Otherwise, it will cause the support stress to be too large, resulting in dangerous situations. The surrounding rock and road surface of the two kinds of tunnel excavation methods have a large degree of excessive pressure, which is easy to form uneven settlement and excessive settlement. At the same time, the surrounding rock pressure is too large, which is easy to damage the lining.

5.4 Monitoring measurement

Monitoring and measurement is an indispensable part of tunnel construction, which helps to obtain the surrounding rock information in time, grasp the dynamic changes of the structure and surrounding environment, and take corresponding measures in time to improve safety. To make a lateral comparison and correction judgment with the previous numerical analysis results, two aspects of surface settlement and vault settlement are selected for analysis, and the layout of measuring points is shown in Fig. 11.

5.4.1 Surface subsidence

The top of the tunnel excavation is the crucial

Fig. 12 Field monitoring photo

monitoring area, with a measuring point spacing of 3 m and secondary monitoring points on both sides of the road. The layout width is increased to 4 m and 5 m in turn. The angle between the farthest measuring point and the arch foot is 45 °. A group of sections shall be set up along the road direction of 10 m.

The data of YSK 15+840-YSK 15+860 section is mainly analyzed. This section is the central area of the station, with good surrounding rock conditions, mainly class III surrounding rock based on the RMR rock classification, poor water yield of underground water, and slightly weathered granite as the bedrock. Fifteen measuring points of YSK 15+840 are DC 01-91 to DC 01-105 from north to south, among which point 97-101 has obvious deformation, and the deformation of other measuring points is less than 3 mm. The displacement of the central monitoring point is the largest, and the final settlement is 14 mm. Fifteen measuring points of YSK 15+850 are DC 01-106 to DC 01-120 from north to south, among which point 112-116 has obvious deformation, and the deformation of other measuring points is less than 3mm. The displacement of the central monitoring point is the largest, and the final settlement is 12 mm. Fifteen measuring points of YSK 15+860 are DC 01-121 to DC 01-135 from north to south, among which point 117-131 has obvious deformation, and the deformation of other measuring points is less than 3mm. The displacement of the central monitoring point is the largest, and the final settlement is 12 mm.

5.4.2 Vault settlement

The vault is the main stress point of the tunnel. Its importance is self-evident and directly related to the overall stability of the tunnel. Therefore, the monitoring of vault settlement is of great significance. In the actual construction process, the construction of secondary lining began shortly after the excavation of the upper part. There were many scaffolds, temporary steel supports, and the surrounding rock conditions of the project were excellent. Therefore, the site monitoring measurement only measured midpoint.

The representative construction data of YSK 15+880 and YSK 15+890 were obtained through an on-site construction team monitoring team. Through numerical analysis, it can be found that there are two large vault settlements after the excavation of the left pilot tunnel and the middle pilot tunnel. Compared with the field monitoring and measurement data, it is found that the trend is roughly the same. However, due to the relatively full support measures on-site, The changing trend is more stable than the numerical calculation. However, it can be found that there are two prominent settlements, and the final settlement is not more than 20 mm, which is within the safe and controllable range of the single-arch long-span station.

According to the actual monitoring and measurement information after construction, it can be seen that the maximum ground settlement is only 14 mm, and the maximum vault settlement is only 18 mm. Therefore, the arch cover method has achieved good results, effectively controlled the displacement and construction cost during the construction period, and ensured the construction progress.

Therefore, through comparative analysis, the arch cover method is the best for controlling surrounding rock deformation. The double-wall guide pit method has the least disturbance to the surrounding rock, but it is not as good as the arch cover method to control the settlement of the vault and the surface settlement. The CD method and the CRD method are suitable for the excavation of small-section tunnels. For large-span tunnels, neither the amount of settlement nor the disturbance of the surrounding rock can be well controlled. Given the good geological conditions of Liaoyang East Road, a comprehensive comparison of the construction period, economic benefits, and other factors, the arch cover method has better applicability than the other three methods.

6. Discussion

6.1 Comparison with other research results

Compared to the model proposed in this study with other models, Skibniewski and Chao (1992) used AHP to evaluate the construction method. However, the result of the AHP method is too subjective, and the choice of subway station construction method may be affected by many uncertain factors. The fuzzy mathematics set can describe these uncertain factors quantitatively. Through the fuzzy operation, the qualitative results can be presented quantitatively and to a certain extent, the possibility that the evaluation results are affected is avoided. Chen (2011) use AHP-TOPSIS method to compare and select the construction scheme of the metro station. Although accuracy and scientificity are improved compared with other methods, but due to the quantitative consideration of qualitative problems, it is still challenging to solve the complex fuzzy situation. Furthermore, *t* is challenging to give a quantitative description of some parts in the actual construction environment. Therefore, this paper integrates fuzzy comprehensive evaluation to make the model more feasible and better applied to engineering practice.

For the selected parameters, Wu *et al.* (2018) selected nine indexes to evaluate the tunnel construction method, including project cost, construction difficulty, safety factor, maximum ground settlement, surrounding rock plastic area. Geng *et al.* (2018) selected six indicators such as surface settlement, construction period and cost to evaluate the construction method of the metro station. Although the above studies have achieved excellent results, the indicators are still one-sided, without considering sub-indicators, and lack of project site monitoring and measurement data to verify the rationality of the selection results.

The AHP fuzzy comprehensive evaluation model proposed in this paper has clear and direct steps, can be calculated by analysis software, and programming tools can perform the matrix operation in the fuzzy comprehensive evaluation. Therefore, the AHP-fuzzy comprehensive evaluation is very feasible and can provide a scientific methodological reference for evaluating the subway station or tunnel construction methods Test, further improving the objectivity and credibility of the evaluation results.

6.2 Application of model in practical engineering

For the application of practical projects, the model proposed in this paper is to compare two construction schemes and evaluate the construction scheme by dimensionless membership degree. The larger the membership degree is, the better the construction method is. For other methods such as bench method and open-cut method, the construction method can also be evaluated by comparing the two methods. For parameters that cannot be measured on the construction site, such as displacement, if the geological conditions are similar to those in this paper, the interval defined in this paper can be used. When there are differences in geological conditions or alternatives, it can be calculated by some displacement prediction methods (Yao *et al.* 2012, Chou *et al.* 2002, Mahdevari and Torabi 2012). If the plastic zone cannot be determined, it can be replaced by other indexes such as the maximum principal stress of surrounding rock. For the construction cost, construction period and difficulty, the secondary indexes can be changed according to the actual situation of the project. After the indexes are determined, the optimal construction method can be determined by comparing the two indexes.

6.3 Limitations

Nevertheless, the method proposed in this study still has some limitations. This method relies heavily on domain experts. Although the combination of AHP and fuzzy comprehensive evaluation can reduce subjective bias and uncertainty to a certain extent, there are still some subjective biases. Future work will focus on studying other algorithms to reduce subjectivity. According to the data and reference materials collected in the literature of existing subway station construction methods, determine the factors that affect the choice of subway station construction methods. Since the engineering and geological conditions between subway station construction sites around the world vary greatly, it is necessary to further summarise more data about subway station construction projects, further discuss the choice of subway station construction methods. The results of this paper are only applicable to the subway stations with the method of excavation in the upper soft and lower hard strata. Other types of subway stations and tunnels (such as open excavation subway stations and mountain tunnels) are not applicable, so it is necessary to further such studies.

7. Conclusions

• Based on the investigation of several subway stations and the literature about the selection of construction methods, five indexes, namely, construction difficulty, construction displacement, construction period, construction cost and plastic zone, are selected as the evaluation factors for the selection of construction schemes of subway stations. At the same time, the evaluation standard of the corresponding grade is established. Thus the evaluation model of subway station construction scheme is established.
• The construction plan selection model of the subway station is established by the AHP-fuzzy comprehensive evaluation method, which is used to select the construction method of the Liaoyang East Road Station of the Qingdao Metro. The selection result indicates that the arch cover method is the best construction plan. Through numerical calculation and monitoring measurement data verification, the actual ground settlement value of the project is 14 mm, and the vault settlement value is 18 mm. This model can provide a reference for the research on the selection of related construction schemes.
• In this paper, the AHP-fuzzy comprehensive evaluation method is used to establish the subway station construction scheme selection model. AHP is used to determine the weight of evaluation indexes, and the dimensionless membership degree of fuzzy comprehensive evaluation method is used to fit the characteristics of each evaluation index, to carry out the fuzzy evaluation of the scheme. The qualitative factors affecting the selection of the construction scheme of the subway station are quantified, and the quantitative treatment of qualitative problems is realized. To make the selection of subway station construction scheme, more scientific and reasonable has certain guiding significance for the actual project. In the practical engineering application, the evaluation factors should be determined reasonably according to the engineering practice, so that the comprehensive benefit of the selected scheme is harnessed.

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CC

Notations

AHP	Analytical hierarchy process
CI	Consistency index
RI	Random consistency index
CD	Center Diaphragm
CRD	Center Cross Diaphragm