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A two-step interval risk assessment method for water inrush during seaside tunnel excavation

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Abstract. Water inrush may occur during seaside urban tunnel excavation. Various factors affect the water inrush, and the water inrush mechanism is complex. In this study, nine evaluation indices having potential effects on water inrush were analysed. Specifically, the geographic and geomorphic conditions, unfavourable geology, distance from the tunnel to sea, strength of the surrounding rock, groundwater level, tidal action, cyclical footage, grouting pressure, and grouting reinforced region were analysed. Furthermore, a two-step interval risk assessment method for water inrush management during seaside urban tunnel excavation was developed by a multi-index system and interval risk assessment comprised of an interval analytic hierarchy process, fuzzy comprehensive evaluation, and relative superiority analysis. The novel assessment method was applied to the Haicang Tunnel successfully. A preliminary interval risk assessment method for water inrush was performed based on engineering geological conditions. As a result, the risk level fell into a risk level IV, which represents a section with high risk. Subsequently, a secondary interval risk assessment method was performed based on engineering geological conditions and construction conditions. The risk level of water inrush is reduced to a risk level II. The results agreed with the current tunnel situation, which verified the reliability of this approach.

Keywords: construction management; seaside urban tunnel; two-step interval assessment; water inrush

1. Introduction

The continental coastline of China is almost 18,000 kilometres long, with various projects built close to the coast. Seaside urban tunnels became significant demand which is developed with its axis parallel or perpendicular to the coastline. It can improve the transportation conditions of bays and expand the development space of cities (Kang *et al*. 2016, Xue *et al*. 2020). However, a series of geological hazards led us to address the construction of the seaside urban tunnel. For instance, subsea tunnels excavation make unfavourable geology form conduits which causes the tunnel prone to water inrush (Dammyr *et al*. 2017, Lee and Nam 2004, Nilsen 2014, Xue *et al*. 2021a).

Numerous theoretical, experimental, and numerical analyses have studied the tunnel water inrush mechanism. In particular, previous studies have well analysed the characteristics of the tunnel displacement field, stress field, seepage field, and potential conditions of water inrush. These studies showed that geographic and geomorphic conditions, unfavourable geology, groundwater level, the strength of the surrounding rock, the excavation and supporting could influence the tunnel water inrush (Aalianvari 2017, Fahimifar and Zareifard 2014, Hong *et al.* 2010, Lee *et al*. 2016, Ma *et al*. 2017, Mazek 2014, Quevedo and Bernaud, 2018, Shin *et al.* 2011, Xue *et al*. 2021b, Zhang *et al*. 2020). The above factors can be summarized as engineering geological and construction conditions. Though the results have laid a solid theoretical foundation for evaluating tunnel water inrush, the effect of these factors on water inrush is difficult to quantify.

Several methods have been used for assessing the construction risk combined with the influencing factors of water inrush. Different factors have diverse effects on water inrush. The relative importance of these factors was obtained using the weight analysis method (Cardenas 2014, Mohammadi and Azad 2021, Xue *et al.* 2019). A fuzzy comprehensive method and unascertained measure theory were developed to assess the risk of water inrush, which considered the synthetic weight of influencing factors (Wu *et al*. 2017). Moreover, a framework for evaluating the probability of occurring a water inrush accident was presented using the scenario analysis methodology combined with Bayesian networks (Wu *et al*. 2016). The evaluation indices are mainly unique values from the above results, which cannot completely reflect the actual situation in the research area. The values considered as intervals is a more reasonable assumption because of the geotechnical complexity and uncertainty (Li *et al*. 2016). Based on the fuzzy comprehensive evaluation, an interval risk assessment method of water inrush was established (Wang *et al*. 2019). The results applied successfully to practical engineering and provided a reference for the risk assessment of water inrush.

Currently, the interval risk assessment has been mainly

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focused on mountain tunnels. Water inrush in seaside urban tunnels is greatly affected by the sea. Therefore, the risk must be dynamically adjusted along with the sea conditions; however, similar risk assessment methods have not yet been proposed. In this paper, an effective and practical method named a two-step interval risk assessment method for water inrush management during seaside urban tunnel excavation was developed using interval analytic hierarchy process, fuzzy comprehensive evaluation, and relative superiority analysis. The term "two-step" means that the second step of modelling is carried out based on the first step of modelling. This method makes the selected indicators more rigorous and better for use in tunnels construction management. First, a preliminary interval risk assessment method for water inrush was performed based on engineering geological conditions. If the results is dangerous, then a secondary interval risk assessment method is performed based on engineering geological conditions and construction conditions. The results provide a reference and a guide for future research on water inrush assessment of seaside urban tunnel.

2. Interval risk assessment method

The water inrush process in seaside urban tunnel is extremely complex, and it is the result of various factors included engineering geological conditions and construction conditions. The relationship among different factors presents multi-dimensional nonlinear characteristics. Furthermore, it is difficult for a definite value reflecting the uncertainty of the factors affecting water inrush. Thus, the index value, evaluating these factors, is generally obtained as an interval number. Therefore, the interval risk assessment method is established by the analytic hierarchy process and fuzzy comprehensive evaluation.

2.1 Interval analytic hierarchy process

The analytic hierarchy process is a multi-objective decision analysis method that can quantify the significance of each factor in a complex system and assign weights to the factors (Mathew *et al.* 2020). Wu *et al.* (1995) combined the interval number and analytic hierarchy process to develop an interval analytic hierarchy process that can solve uncertainty and fuzziness problems under incomplete information. In this method, an interval number expresses the unit element of a comparison matrix.

In this paper, the interval analytic hierarchy process is developed to solve the above-stated problem. First, the hierarchical structure model is established based on the interrelation among factors. Afterwards, according to the multi-layer analysis of the structure model, the interval number matrix of the system is constructed by using the 1-9 scale method. Finally, the weight vector of the number comparison matrix is calculated.

The interval number matrix can be expressed as Eq. (1).

$$\tilde{X}=\begin{bmatrix} [1,1] & [x_{12}^-,x_{12}^+] & \cdots & [x_{1m}^-,x_{1m}^+] \\ [\frac{1}{x_{12}^+},\frac{1}{x_{12}^-}] & [1,1] & \cdots & [x_{2m}^-,x_{2m}^+] \\ \vdots & \vdots & \ddots & \vdots \\ [\frac{1}{x_{1m}^+},\frac{1}{x_{1m}^-}] & [\frac{1}{x_{2m}^+},\frac{1}{x_{2m}^-}] & \cdots & [1,1] \end{bmatrix} \tag{1}$$

$P=\left(p_{ij}\right)_{m\times m}$, the consistency of the number comparison matrix, can be calculated using Eq. (2).

$$p_{ij}=\sqrt[2m]{\prod_{k=1}^{m}\frac{x_{ik}^-x_{ik}^+}{x_{jk}^-x_{jk}^+}} \tag{2}$$

Where $x_{ji}=\frac{1}{x_{ij}}$, the weight vector of $P=\left(p_{ij}\right)_{m\times m}$ is $w=\left(w_1,w_2,\cdots,w_{m-1},w_m\right)$, and w_j can be calculated using Eq. (3).

$$w_j=\frac{1}{\sum_{i=1}^{m}p_{ij}}=\frac{\sqrt[2m]{\prod_{k=1}^{m}x_{jk}^-x_{jk}^+}}{\sum_{i=1}^{m}\sqrt[2m]{\prod_{k=1}^{m}x_{ik}^-x_{ik}^+}} \tag{3}$$

The range matrix, $\Delta_1 P$ and $\Delta_2 P$, can be calculated using Eqs. (4) and (5).

$$\Delta_2 p_{ij}=x_{ij}^+-p_{ij} \tag{4}$$

$$\Delta_1 p_{ij}=p_{ij}-x_{ij}^- \tag{5}$$

According to the random error transfer, $\Delta_1 w_j$ and $\Delta_2 w_j$ can be calculated using Eq. (6).

$$\left(\Delta_k w_j\right)^2=\frac{\left(\sum_{i=1}^{m}\Delta_k p_{ij}\right)^2}{\left(\sum_{i=1}^{m}p_{ij}\right)^4} \tag{6}$$

Subsequently, the weight interval of an indicator *j*, $\left(w_j^{(L)},w_j^{(R)}\right)$, can be obtained using Eqs. (7) and (8).

$$w_j^{(L)}=w_j-\Delta_1 w_j \tag{7}$$

$$w_j^{(R)}=w_j+\Delta_2 w_j \tag{8}$$

Finally, the indicator weights, $w=\left[\left(w_1^{(L)},w_1^{(R)}\right),\left(w_2^{(L)},w_2^{(R)}\right),\cdots,\left(w_m^{(L)},w_m^{(R)}\right)\right]$, can be determined.

2.2 Fuzzy comprehensive evaluation

Fuzzy mathematics is a tool to describe and solve uncertainty problems with a stable mathematical basis (Gao *et al.* 2020, Huang, *et al.* 2020, Chen *et al.* 2015, Feng and Xu 1999). It can model the uncertainty in tunnel water inrush and provide an intuitive approach for describing the relationship among various risk factors. In this study, a fuzzy comprehensive evaluation model is established by a multi-index assessment system and fuzzy set theory. The result vectors can be expressed as interval numbers. Moreover, the fuzzy evaluation function is calculated using Eqs. (9) to (11).

$$A=W\cdot B_i \tag{9}$$

$$B_i=W_i\cdot C_i \tag{10}$$

$$C_i = \left[c_{ijk}\right] = \begin{bmatrix} c_{i1\mathrm{I}} & c_{i1\mathrm{II}} & \cdots & c_{i1k} \\ c_{i2\mathrm{I}} & c_{i2\mathrm{II}} & \cdots & c_{i2k} \\ \vdots & \vdots & \vdots & \vdots \\ c_{ij\mathrm{I}} & c_{ij\mathrm{II}} & \cdots & c_{ijk} \end{bmatrix} \quad (11)$$

where A is the vector of the destination layer; W is the weight vectors of the influence factor layer; B_i is the vector of the influence factor layer; W_i is the weight vectors of the indicator layer; C_i is the evaluation layer; c_{ijk} is the membership degree for the evaluation index c_{ij} belonging to risk grade k. The interval analytic hierarchy process can establish the weight vectors.

The membership function is a quantitative description concerning the fuzzy concept. Determining membership functions, correctly, is the basis of solving practical problems using the fuzzy set theory. Various forms of membership functions exist. The most conventional forms of membership function include normal type, triangular fuzzy numbers, and parabola membership function. The form of various membership functions is different; however, the final analysis concluding results are consistent (Wang *et al.* 2012). In this study, the triangular fuzzy number membership function is selected.

When the index value belongs to the minimum or maximum level, the membership function can be adopted as Eq. (12).

$$f\left(x;a,b,c\right) = \begin{Bmatrix} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ \dfrac{c-x}{c-b} & b \le x \le c \\ 0 & c \le x \end{Bmatrix} \quad (12)$$

In the membership curve, the domain is defined by the vector x, and the curve shape is determined by a, b, and c. In the equation, a corresponds to the left vertex at the lower part of the triangle, c corresponds to the right vertex at the low part of the triangle, and b corresponds to the vertex at the top of the triangle. Here, $a \leqslant b \leqslant c$, the generated membership function always has a uniform height.

2.3 Relative superiority analysis

In the multi-attribute decision, the comparison of the scheme is due to the ordering problem of the interval fuzzy number when the interval fuzzy number represents the comprehensive attribute value of the scheme (Chen et al., 2014; Wang and Wan, 2020). Assuming the interval number, a_1= [a_1^-, a_1^+] and a_2= [a_2^-, a_2^+], the relative dominance is denoted in Eq. (13).

$$q\left(a_1 > a_2\right) = \begin{cases} \dfrac{1}{l\left(a_1\right)}\ln\left(\dfrac{1+e^{a_1^+}}{1+e^{a_1^-}}\right) - \dfrac{1}{l\left(a_2\right)}\ln\left(\dfrac{1+e^{a_2^+}}{1+e^{a_2^-}}\right) & l\left(a_1\right)\ne 0, l\left(a_2\right)\ne 0 \\ \dfrac{e^{a_1^-}}{e^{a_1^-}+1} - \dfrac{1}{l\left(a_2\right)}\ln\left(\dfrac{1+e^{a_2^+}}{1+e^{a_2^-}}\right) & l\left(a_1\right)= 0, l\left(a_2\right)\ne 0 \\ \dfrac{1}{l\left(a_1\right)}\ln\left(\dfrac{1+e^{a_1^+}}{1+e^{a_1^-}}\right) - \dfrac{e^{a_2^-}}{e^{a_2^-}+1} & l\left(a_1\right)\ne 0, l\left(a_2\right)= 0 \\ \dfrac{e^{a_1^-}}{e^{a_1^-}+1} - \dfrac{e^{a_2^-}}{e^{a_2^-}+1} & l\left(a_2\right)= 0, l\left(a_2\right)= 0 \end{cases} \quad (13)$$

where $l(a_1) = a_1^+ - a_1^-$, $l(a_2) = a_2^+ - a_2^-$.

The relative dominance matrix $Q = \left(q_{ij}\right)_{n\times n}$ can be obtained, which is the fuzzy complementary matrix, $q_{ij} = q\left(a_i > a_j\right), q_{ij} + q_{ji} = 0, i, j = 1, 2, \ldots, n$.

Furthermore, $Q^{'} = \left(q_{ij}^{'}\right)_{n\times n}$, where $q_{ij}^{'} = \left(q_{ij}+1\right)/2, q_{ij}^{'} + q_{ji}^{'} = 0, i, j = 1, 2, \ldots, n$ and $Q^{'}$ is the relative dominance judgment matrix for Q. Finally, the ranking index value of the interval number is calculated using Eq. (14).

$$r_i = \frac{\sum_{j=1}^{n} q_{ij}^{'} + \dfrac{n}{2} - 1}{n\left(n-1\right)} \quad (14)$$

2.4 Two-step interval risk assessment method

A two-step interval risk assessment method for water inrush management during seaside urban tunnel excavation was developed using the interval analytic hierarchy process, fuzzy comprehensive evaluation, and relative superiority analysis. A preliminary interval risk assessment method for water inrush was performed based on engineering geological conditions. If the results is dangerous, then a secondary interval risk assessment method is performed based on engineering geological conditions and construction conditions. Fig. 1 shows the flow chart of the two-step interval risk assessment method.

3. Engineering application

3.1 Geological background

Haicang Tunnel comprises a left tunnel, right tunnel and service tunnel. The service tunnel is previously constructed as a geological guide tunnel. From the west to east, the service site area of the tunnel is a denudation monadnock zone of the Haicang Bank in the sea area-denudation monadnock of Xiamen Island. The quaternary strata in the tunnel site area are mainly intrusive residual soil, with a small quantity of artificial fill soil, alluvion, clayey soil, and sludge. The underlying bedrock is mainly composed of granite in late Yanshanian epoch with locally dynamic metamorphic rocks, with granite interspersed with diabase in the tunnel site area (Fig. 2).

3.2 Multi evaluation indices of water inrush in seaside urban tunnel

The water inrush process in seaside urban tunnel is extremely complex, and it is the result of various factors. Once tunnel excavation creates unfavourable geology form of water inrush conduits, the seawater becomes the source of water inrush, which is prone to water inrush hazards. As shown in Fig. 3, the influencing factors of water inrush in seaside urban tunnel can be divided into engineering geological conditions and construction conditions.

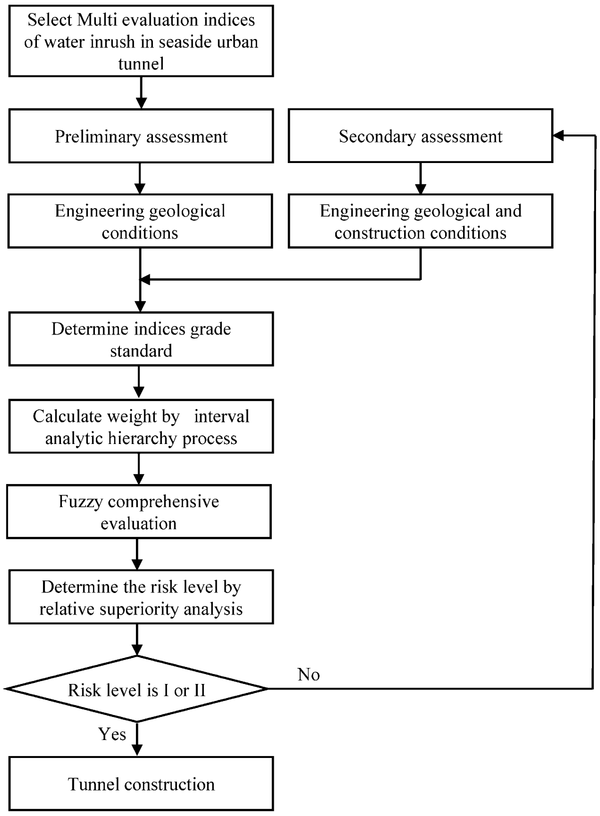


Fig. 1 The flow chart of two-step interval risk assessment method

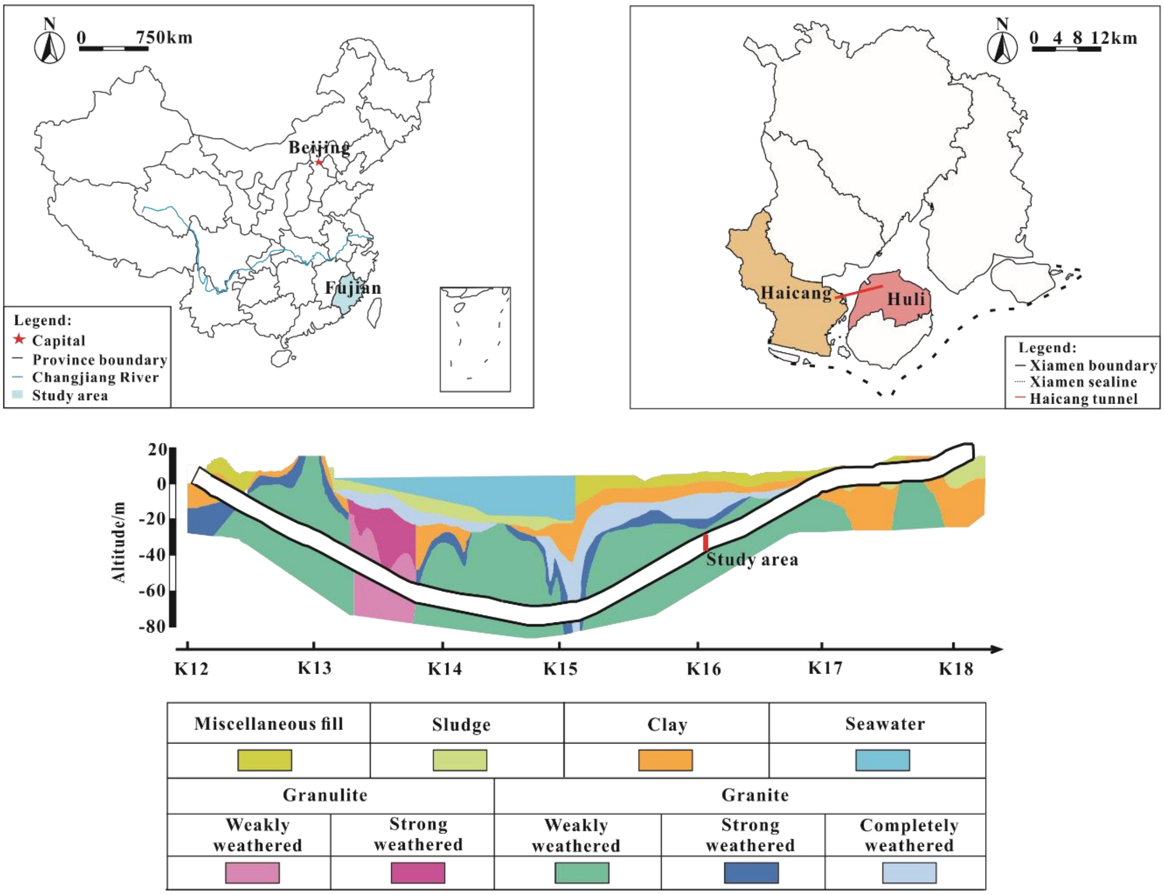


Fig. 2 Geographic sketch maps of Haicang Tunnel (Li *et al*. 2021)

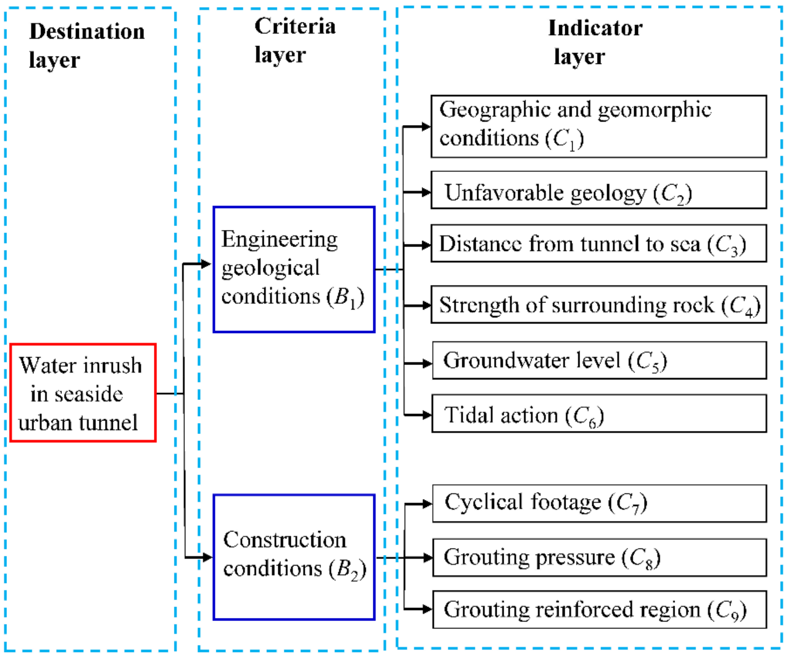


Fig. 3 Evaluation indicators system of water inrush

(1) Engineering geological conditions (B_1)

Geographic and geomorphic conditions (C_1)

Geographic and geomorphic conditions play an essential role in the supply, runoff, and drainage of groundwater, which is a crucial factor affecting the groundwater circulation. Different geographic and geomorphic conditions, such as surface slope, drainage distribution, and river trend, reflect the distribution of groundwater discharge datum locally and regionally and control the overall trend of groundwater development. The velocity of the surface runoff is fast in a steep terrain, and steep terrains have a large water-collecting amount that is more favourable to the development of groundwater. However, the velocity of the surface runoff is slow in gentle terrain, and gentle terrains have a little water-collecting amount that is an inconvenience for the development of groundwater.

Unfavourable geology (C_2)

The unfavourable geologic structures, such as faults, and fissures, are usually a potential water inrush conduits or water inrush source near the tunnel. The water yield, hydraulic conductivity, and spatial position relation of unfavourable geologic structure mainly determine the water inrush risk. Furthermore, the amount of inrush is determined by the degree of water abundance and the recharge conditions of the aquifer. The greater the supply area of groundwater, and the greater the threat of an inrush.

The distance from the tunnel to sea (C_3)

The faults, cracks, and other geological structure may be connected with seawater. Subsea tunnels excavation make unfavourable geology form conduits which causes the tunnel prone to water inrush. The further the tunnel is horizontal from seawater, the less the tunnel is affected by seawater.

The strength of the surrounding rock (C_4)

The rock strength is related to the integrity, groundwater, and structural surface of the surrounding rock. The basic quality of the surrounding rock (BQ), quality index of engineering rock mass in Chinese, is selected as the index for the surrounding rock strength. BQ affects the stability of the surrounding rock. The lower the BQ, the lower the resistance to deformation, and the poorer the selfstabilization ability.

Groundwater level (C_5)

The groundwater plays the dual role of being material carrier and source power in the process of water inrush. The groundwater contains three forms including pore water, fissure water and karst water, which has a strong hazard-causing capacity. The vertical dynamic zoning of the groundwater at different elevations is diverse. The altitude difference between the underground water level and the tunnel floor can represent the level of danger of water inrush largely.

Tidal action (C_6)

Tide is a natural phenomenon in coastal areas, which refers to the periodic movement of seawater under the tidal-generating force of celestial bodies (Kasper *et al.* 2008). During the tidal change, the stress of the surrounding rock decreases when the low tide rises to high tide. At this point, the surrounding rock stress exerts a certain pressure effect relative to the low tide. However, the stress of the surrounding rock increases when the high tide descent to low tide. At this point, the surrounding rock stress exerts a certain tensile force effect relative to the high tide. This cyclic load is extremely unfavourable to the stability of the surrounding rock because it can activate the potential water inrush conduits or water inrush source near the tunnel, causing water inrush disaster in the tunnel.

(2) Construction conditions (B2)

Cyclical footage (C_7)

The process of transfer and balance repeatedly in the tunnel excavation produces stress and deformation of the surrounding rock. Therefore, the longer the length of the

Table 1 Evaluation indices and grading standards of water inrush

Evaluation indices	Grading standards	Grade division			
		I	II	III	IV
Geographic and geomorphic conditions (C_1)	Qualitative description	The terrain is gentler and the velocity of the surface runoff is slower.	The terrain is gentle and the velocity of the surface runoff is slow.	The terrain is steep and the velocity of the surface runoff is fast.	The terrain is steeper and the velocity of the surface runoff is faster.
Unfavorable geology (C_2)	Supply area of groundwater (km^2)	(0, 5]	(5, 7.5]	(7.5, 10]	(10, +∞)
Distance from tunnel to sea (C_3)	Distance (m)	(1500, +∞)	(1000, 1500]	(500, 1000]	(0, 500]
Strength of surrounding rock (C_4)	Basic quality of surrounding rock	(450, +∞)	(350, 450]	(250, 350]	(0, 250]
Groundwater level (C_5)	Altitude difference between underground water level and tunnel floor (m)	(-∞, 0]	(0, 30]	(30, 60]	(60, +∞)
Tidal action (C_6)	Tidal range (m)	(0, 1.5]	(1.5, 3]	(3, 4.5]	(4.5, +∞)
Cyclical footage (C_7)	Excavation length (m)	(0, 1]	(1, 2]	(2,3]	(3, +∞)
Grouting pressure (C_8)	Grouting pressure (MPa)	(3, +∞)	(2,3]	(1, 2]	(0, 1]
Grouting reinforced region (C_9)	Grouting reinforced area (Represented by tunnel diameter D)	(1.2D, 3D]	(0.5D, 1.2D]	(0.2D, 0.5D]	(0, 0.2D]

Table 2 Comparison matrix among C_1–C_6

Evaluation indices	C_1	C_2	C_3	C_4	C_5	C_6
C_1	[1,1]	[1/4, 1/2]	[1/2, 2]	[3, 5]	[1/3, 1/2]	[1/5, 1/3]
C_2	[2, 4]	[1,1]	[2, 3]	[2, 4]	[1/2, 2]	[1/2, 2]
C_3	[1/2, 2]	[1/3, 1/2]	[1,1]	[2, 5]	[1/4, 1/2]	[1/4, 1/2]
C_4	[1/5, 1/3]	[1/4, 1/2]	[1/5, 1/2]	[1, 1]	[1/3, 1/2]	[1/3, 1/2]
C_5	[2, 3]	[1/2, 2]	[2, 4]	[2, 3]	[1, 1]	[1/2, 2]
C_6	[3,5]	[1/2, 2]	[2, 4]	[2, 3]	[1/2, 2]	[1,1]

excavation footage, the higher the unloading pressure will be, thereby affecting the stability of the excavation face. It will worsen the formation of the tunnel surrounding rock water conduits, causing water inrush hazard.

Grouting pressure (C_8)

Grouting pressure is a crucial grouting parameter in grouting construction that directly affects the diffusion range of grout in the complete grouting process and the final grouting reinforcement quality. With the increase of grouting pressure within an specific grouting range, the energy driving the grout diffusion increases. It is enough to separate the injected medium, to realize the smooth expansion of grouting path and completely diffuse the grouting.

Grouting reinforced region (C_9)

Grouting reinforcement consists of injecting grout into the surrounding rock through drilling. By the grouting pressure, the grout diffuses to the cracks of the surrounding rock, forming a reinforcement zone. The surrounding rock has a strong bearing capacity and high stability with increasing the grout reinforcement region. It will decrease pore water pressure of lining and water inflow.

As shown in Table 1, these evaluation indices are classified quantitatively as four grades.

Table 3 Comparison matrix among C_7–C_9

Evaluation indices	C_7	C_8	C_9
C_7	[1,1]	[3, 5]	[1/6, 1/2]
C_8	[1/5, 1/3]	[1,1]	[1/2, 2]
C_9	[2, 6]	[1/2, 2]	[1,1]

Table 4 Comparison matrix between B_1 and B_2

Evaluation indices	B_1	B_2
B_1	[1,1]	[1/4, 2]
B_2	[1/2, 4]	[1,1]

3.3 Weight determination analysis

Different factors have contrasting effects on the water inrush of the seaside urban tunnel. The relative importance of each factor was obtained using the principle of comparison between each indicator. The weight of water inrush for multiple evaluation indices was calculated through the analytic hierarchy process theory. Based on the site engineering conditions, the comparison matrix for the criteria layer (B) and the indicator layer (C) was developed

Table 5 The weight vector of comparison matrix

Evaluation indices	The weight vector
W_A	[0.303, 0.502], [0.428, 0.709]
W_{B1}	[0.097, 0.120], [0.181, 0.284], [0.086, 0.125], [0.057, 0.067], [0.181, 0.278], [0.204, 0.302]
W_{B2}	[0.263, 0.314], [0.131, 0.242], [0.345, 0.509]

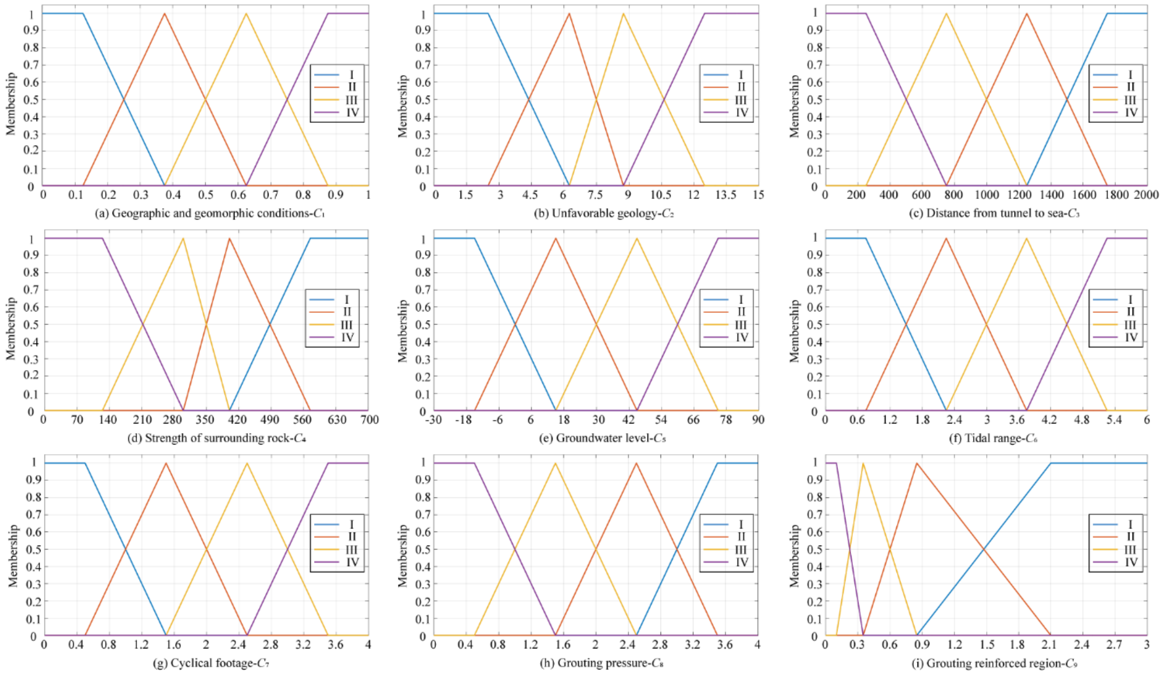


Fig. 4 Membership degree curves of evaluation indices C_1–C_9

by the 1-9 scale method seen in Tables 2-4. The weight vector W of the judgment matrix was calculated using Eqs. (1)-(8), shown in Table 5.

3.4 Water inrush risk assessment

The qualitative index, geographic and geomorphic conditions, should be quantified for calculation convenience. We assumed that the qualitative index for the risk grade is [0, 1], and the width of each range is 0.25. Based on the engineering geological conditions (B_1) and construction conditions (B_2), the membership functions of the evaluation index (C_1–C_9), corresponding to every grade in evaluation risk of water inrush, are obtained using Eq. (12), as shown in Table 6 and Fig. 4.

A preliminary interval risk assessment method for water inrush was performed. From FWK16+210 to FWK16+060 in Haicang Tunnel, the service tunnel undergoes the Chang'an section covered with miscellaneous fill, clay, and completely weathered granite. The tunnel surrounding rock is delimited by seawater, and its self-stabilizing ability is poor. The tunnel is located below the normal water level; thus, it is greatly affected by tidal action. Table 7 lists the values of the interval fuzzy comprehensive evaluation indices that are obtained combining engineering geological conditions. Table 8 shows the results of the interval membership degree. By combining the evaluation indices for engineering geological conditions; that is, C_1-C_6, and the weight vectors W_i, the final interval number result vector can be determined as follows: A_1=[[0, 0.056], [0.188, 0.378], [0.047, 0.623], [0.161, 0.731]]. Subsequently, the relative dominance judgment matrix, Q_1', was calculated using Eq. (13) following the relative superiority analysis method, the results are shown in Eq. (15). Finally, the evaluation grade of the water inrush, r_1, was determined by Eq. (14), with the results shown in Eq. (16). Thus, the final risk level of FWK16+210 to FWK16+060 section is IV, which represents a high-risk section. Therefore, a contingency plan for water inrush should be implemented before construction.

$$Q_1' = \begin{bmatrix} 0.5 & 0.4684 & 0.4623 & 0.4490 \\ 0.5316 & 0.5 & 0.4939 & 0.4806 \\ 0.5377 & 0.5061 & 0.5 & 0.4867 \\ 0.5510 & 0.5194 & 0.5133 & 0.5 \end{bmatrix} \tag{15}$$

$$r_1 = \begin{bmatrix} 0.240, & 0.250, & 0.253 & 0.257 \end{bmatrix} \tag{16}$$

The advance grouting method and controlled excavation footage were adopted to reduce the risk of water inrush in seaside urban tunnel. When excavated to FWK16+195, the

Table 6 Membership functions of evaluation indices C_1–C_9

Indices	Grade division I	II	III	IV
C_1	$C_{1\mathrm{I}}=\begin{cases}1 & x\le 0.125\\ \frac{0.375-x}{0.25} & 0.125<x<0.375\\ 0 & x\ge 0.375\end{cases}$	$C_{1\mathrm{II}}=\begin{cases}0 & x\le 0.125\\ \frac{x-0.125}{0.25} & 0.125<x\le 0.375\\ \frac{0.625-x}{0.25} & 0.375<x<0.625\\ 0 & x\ge 0.625\end{cases}$	$C_{1\mathrm{III}}=\begin{cases}0 & x\le 0.375\\ \frac{x-0.375}{0.25} & 0.375<x\le 0.625\\ \frac{0.875-x}{0.25} & 0.625<x<0.875\\ 0 & x\ge 0.875\end{cases}$	$C_{1\mathrm{IV}}=\begin{cases}0 & x\le 0.625\\ \frac{x-0.625}{0.25} & 0.625<x<0.875\\ 1 & x\ge 0.875\end{cases}$
C_2	$C_{2\mathrm{I}}=\begin{cases}1 & x\le 2.5\\ \frac{6.25-x}{3.75} & 2.5<x<6.25\\ 0 & x\ge 6.25\end{cases}$	$C_{2\mathrm{II}}=\begin{cases}0 & x\le 2.5\\ \frac{x-2.5}{3.75} & 2.5<x\le 6.25\\ \frac{8.75-x}{2.5} & 6.25<x<8.75\\ 0 & x\ge 8.75\end{cases}$	$C_{2\mathrm{III}}=\begin{cases}0 & x\le 6.25\\ \frac{x-6.25}{2.5} & 6.25<x\le 8.75\\ \frac{12.5-x}{3.75} & 8.75<x<12.5\\ 0 & x\ge 12.5\end{cases}$	$C_{2\mathrm{IV}}=\begin{cases}0 & x\le 8.75\\ \frac{x-8.75}{3.75} & 8.75<x<12.5\\ 1 & x\ge 12.5\end{cases}$
C_3	$C_{3\mathrm{I}}=\begin{cases}1 & x\ge 1750\\ \frac{x-1250}{500} & 1250<x<1750\\ 0 & x\le 1250\end{cases}$	$C_{3\mathrm{II}}=\begin{cases}0 & x\ge 1750\\ \frac{1750-x}{500} & 1250<x<1750\\ \frac{x-750}{500} & 750<x\le 1250\\ 0 & x\le 750\end{cases}$	$C_{3\mathrm{III}}=\begin{cases}0 & x\ge 1250\\ \frac{1250-x}{500} & 750<x<1250\\ \frac{x-250}{500} & 250<x\le 750\\ 0 & x\le 250\end{cases}$	$C_{3\mathrm{IV}}=\begin{cases}0 & x\ge 750\\ \frac{750-x}{500} & 250<x<750\\ 1 & x\le 250\end{cases}$
C_4	$C_{4\mathrm{I}}=\begin{cases}1 & x\ge 575\\ \frac{x-400}{175} & 400<x<575\\ 0 & x\le 400\end{cases}$	$C_{4\mathrm{II}}=\begin{cases}0 & x\ge 575\\ \frac{575-x}{175} & 400<x<575\\ \frac{x-300}{100} & 300<x\le 400\\ 0 & x\le 300\end{cases}$	$C_{4\mathrm{III}}=\begin{cases}0 & x\ge 400\\ \frac{400-x}{100} & 300<x<400\\ \frac{x-125}{175} & 125<x\le 300\\ 0 & x\le 125\end{cases}$	$C_{4\mathrm{IV}}=\begin{cases}0 & x\ge 300\\ \frac{300-x}{175} & 125<x<300\\ 1 & x\le 125\end{cases}$
C_5	$C_{5\mathrm{I}}=\begin{cases}1 & x\le -15\\ \frac{15-x}{30} & -15<x<15\\ 0 & x\ge 15\end{cases}$	$C_{5\mathrm{II}}=\begin{cases}0 & x\le -15\\ \frac{x+15}{30} & -15<x\le 15\\ \frac{45-x}{30} & 15<x<45\\ 0 & x\ge 45\end{cases}$	$C_{5\mathrm{III}}=\begin{cases}0 & x\le 15\\ \frac{x-15}{30} & 15<x\le 45\\ \frac{75-x}{30} & 45<x<75\\ 0 & x\ge 75\end{cases}$	$C_{5\mathrm{IV}}=\begin{cases}0 & x\le 45\\ \frac{x-45}{30} & 45<x<75\\ 1 & x\ge 75\end{cases}$
C_6	$C_{6\mathrm{I}}=\begin{cases}1 & x\le 0.75\\ \frac{2.25-x}{1.5} & 0.75<x<2.25\\ 0 & x\ge 2.25\end{cases}$	$C_{6\mathrm{II}}=\begin{cases}0 & x\le 0.75\\ \frac{x-0.75}{1.5} & 0.75<x\le 2.25\\ \frac{3.75-x}{1.5} & 2.25<x<3.75\\ 0 & x\ge 3.75\end{cases}$	$C_{6\mathrm{III}}=\begin{cases}0 & x\le 2.25\\ \frac{x-2.25}{1.5} & 2.25<x\le 3.75\\ \frac{5.25-x}{1.5} & 3.75<x<5.25\\ 0 & x\ge 5.25\end{cases}$	$C_{6\mathrm{IV}}=\begin{cases}0 & x\le 3.75\\ \frac{x-3.75}{1.5} & 3.75<x<5.25\\ 1 & x\ge 5.25\end{cases}$
C_7	$C_{7\mathrm{I}}=\begin{cases}1 & x\le 0.5\\ 1.5-x & 0.5<x<1.5\\ 0 & x\ge 1.5\end{cases}$	$C_{7\mathrm{II}}=\begin{cases}0 & x\le 0.5\\ x-0.5 & 0.5<x\le 1.5\\ 2.5-x & 1.5<x<2.5\\ 0 & x\ge 2.5\end{cases}$	$C_{7\mathrm{III}}=\begin{cases}0 & x\le 1.5\\ x-1.5 & 1.5<x\le 2.5\\ 3.5-x & 2.5<x<3.5\\ 0 & x\ge 3.5\end{cases}$	$C_{7\mathrm{IV}}=\begin{cases}0 & x\le 2.5\\ x-2.5 & 2.5<x<3.5\\ 1 & x\ge 3.5\end{cases}$
C_8	$C_{8\mathrm{I}}=\begin{cases}1 & x\ge 3.5\\ x-2.5 & 2.5<x<3.5\\ 0 & x\le 2.5\end{cases}$	$C_{8\mathrm{II}}=\begin{cases}0 & x\ge 3.5\\ 3.5-x & 2.5<x<3.5\\ x-1.5 & 1.5<x\le 2.5\\ 0 & x\le 1.5\end{cases}$	$C_{8\mathrm{III}}=\begin{cases}0 & x\ge 2.5\\ 2.5-x & 1.5<x<2.5\\ x-0.5 & 0.5<x\le 1.5\\ 0 & x\le 0.5\end{cases}$	$C_{8\mathrm{IV}}=\begin{cases}0 & x\ge 1.5\\ 1.5-x & 0.5<x<1.5\\ 1 & x\le 0.5\end{cases}$
C_9	$C_{9\mathrm{I}}=\begin{cases}1 & x\ge 2.1D\\ \frac{x-0.85D}{1.25D} & 0.85D<x<2.1D\\ 0 & x\le 0.85D\end{cases}$	$C_{9\mathrm{II}}=\begin{cases}0 & x\ge 2.1D\\ \frac{2.1D-x}{1.25D} & 0.85D<x<2.1D\\ \frac{x-0.35D}{0.5D} & 0.35D<x\le 0.85D\\ 0 & x\le 0.35D\end{cases}$	$C_{9\mathrm{III}}=\begin{cases}0 & x\ge 0.85D\\ \frac{0.85D-x}{0.5D} & 0.35D<x<0.85D\\ \frac{x-0.1D}{0.25D} & 0.1D<x\le 0.35D\\ 0 & x\le 0.1D\end{cases}$	$C_{9\mathrm{IV}}=\begin{cases}0 & x\ge 0.35D\\ \frac{0.35D-x}{0.25D} & 0.1D<x<0.35D\\ 1 & x\le 0.1D\end{cases}$

cumulative footage of daily excavation becomes 0.6~1.2 m. During advance grouting, the grouting pressure was 1.2~2.5 MPa. After grouting, the drilling samples method is used to test the grouting effect, and the results show that the range of grouting reinforced region is D~2D. Subsequently, a secondary interval risk assessment method for water inrush was performed based on engineering geological conditions and construction conditions. Table 9 lists the values of interval fuzzy comprehensive evaluation indices that are obtained combining the construction conditions. The interval membership degree was determined, and the results can be seen in Table 10. By combining evaluation indices

Table 7 Values of evaluation indices C_1-C_6

Indices	C_1	C_2	C_3	C_4	C_5	C_6
Value	[0.8, 0.9]	[9, 12]	[990, 1140]	[160, 200]	[8, 15]	[4, 6]

Table 8 Membership degree of evaluation indices C_1-C_6

Indices	Grade division			
	I	II	III	IV
C_1	0	0	[0, 0.3]	[0.7, 1]
C_2	0	0	[0.1, 0.9]	[0.1, 0.9]
C_3	0	[0.5, 0.8]	[0.2, 0.5]	0
C_4	0	0	[0.2, 0.4]	[0.6, 0.8]
C_5	[0, 0.2]	[0.8, 1]	0	0
C_6	0	0	[0, 0.8]	[0.2, 1]

Table 9 Values of evaluation indices C_7-C_9

Indices	C_7	C_8	C_9
Value	[0.6, 1.2]	[1.2, 2.5]	[1, 2]

Table 10 Membership degree of evaluation indices C_7-C_9

Indices	Grade division			
	I	II	III	IV
C_7	[0.7, 1]	[0, 0.3]	0	0
C_8	0	[0, 1]	[0, 0.7]	[0, 0.3]
C_9	[0.12, 0.92]	[0.08, 0.88]	0	0

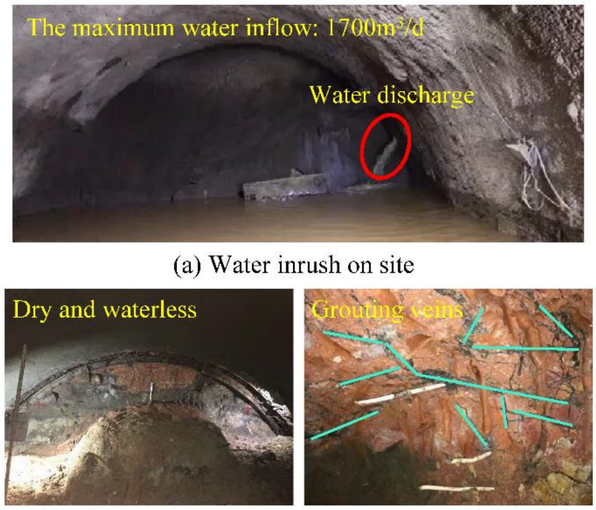
for construction conditions, C_1-C_9, and the weight vectors W_i, the final interval number result vector can be determined as follows: A_2=[[0.097, 0.583], [0.069, 0.746], [0.014, 0.433], [0.049, 0.419]]. Afterwards, the relative dominance judgment matrix, Q_2', was calculated using Eq. (13) following the relative superiority analysis method, the results are shown in Eq. (17). Finally, the evaluation grade of water inrush, r_2, was determined using Eq. (14), the results are shown in Eq. (18). Therefore, the final risk level of this section is II. The water inrush risk reduces, and the seaside urban tunnel construction is safe.

$$Q_2' = \begin{bmatrix} 0.5 & 0.4921 & 0.5142 & 0.5129 \\ 0.5079 & 0.5 & 0.5221 & 0.5208 \\ 0.4858 & 0.4779 & 0.5 & 0.4987 \\ 0.4871 & 0.4792 & 0.5013 & 0.5 \end{bmatrix} \tag{17}$$

$$r_2 = [0.252, \ 0.254, \ 0.247 \ \ 0.247] \tag{18}$$

3.5 Tunnel excavation verification

From FWK16+210 to FWK16+195, the seaside urban tunnel was excavated for 15 m. The bearing capacity of surrounding rock is poor, and it is connected to the sea. As shown in Fig. 5(a), the excavation revealed a water discharge at the right side of the wall. The maximum water inflow was 1700 m^3/d. The overall subsidence of the excavated section reached 78 mm, and the maximum cumulative settlement of the temporary invert closure section was 52 mm. After implementing the advanced grouting scheme, the tunnel surface was dry and waterless, and the surrounding rock was compact and firm, the grouting veins are well distributed (Fig. 5(b)). Moreover, the deformation of the surrounding rock is controlled effectively, and the maximum settlement value was 11 mm.



(a) Water inrush on site

(b) Advanced grouting effect

Fig. 5 Site conditions of tunnel excavation

4. Discussions

Relative superiority analysis was used to determine the risk level of water inrush in seaside urban tunnel. The traditional relative superiority analysis consists of sorting the probability of the interval number endpoint and the part information of the interval number. Under the circumstances, some important information may be missed, such that the sorting method based on the probability of interval number will fail. In this study, the endpoint information and the difference information of the internal correspondence point for the interval number were considered. This study also developed a novel sorting method of relative superiority analysis for the interval number based on the properties of *Sigmoid* function. As shown in Table 11, the improved relative superiority analysis method in this paper has good applicability.

Various factors affect the water inrush in seaside urban tunnel, and the water inrush mechanism is complex. In this study, combined with the seaside urban tunnel characteristics and construction conditions, the distance from the tunnel to the sea, tidal action, grouting pressure, and grouting reinforced region were considered for the first

Table 11 Result comparison of the improved relative superiority analysis method

Interval number	Sorting result	Notes
A=[[2, 4], [1, 5], [0, 6]]	R=[0.333, 0.333, 0.333]	Wan and Dong (2014)
	R=[0.333, 0.333, 0.333]	Garg and Kumar (2020)
	R=[0.340, 0.347, 0.325]	In this study

time to study water inrush. Currently, no uniform standard is available to classify the values of the evaluation indices. It is necessary to perform a deeper study on the relevant influencing factors by following a theoretical analysis and numerical simulation. Simultaneously, the grading standards should be more reasonable to improve the recognition accuracy of each influence factor. The classification standard of this study provided proper calculation results in practical applications; thus, providing an effective reference for future research.

After a preliminary interval risk assessment, a contingency plan for water inrush was performed from FWK16+210 to FWK16+195. Advanced grouting was adopted. First, the temporary invert and the sidewall are used for vertical grouting. Subsequently, the curtain grouting was performed on the tunnel surface. The grouting started at the bottom and arch foot, then at the middle and upper part. The number of grouting holes was 100, totalling about 2149 m. The grouting slurry consisted of 75% of ordinary double-liquid slurry and 25% ultra-fine cement slurry. Moreover, an appropriate amount of disodium hydrogen phosphate was added as a retarder to control the initial setting time of the double-liquid slurry effectively and ensure the uniform diffusion of the slurry. During the advance grouting, special grouting pipe for the entire hole grouting at one time was adopted, one hole and one injection, and the grouting pressure was 1.2~2.5 MPa. When grouting, the construction should be symmetrical, first the outer ring, following the inner ring, first the down and then the up part. Through this technology, the grouting time of each cycle curtain is reduced from several months to fifteen days, which greatly improves the construction efficiency and reduces the construction cost. After grouting, the reserved core soil step method with temporary invert was used for excavation, where cumulative footage of daily excavation becomes 0.6~1.2 m, which can control the deformation and reduce the water inrush risk effectively. The contingency plan presented a good control effect on this section and could provide insights for similar engineering constructions.

5. Conclusions

In this study, a novel method for predicting water inrush risk in seaside urban tunnels based on a multi-index system and interval risk assessment was established. Nine evaluation indices that can potentially affect water inrush, geographic and geomorphic conditions, unfavourable geology, the distance from the tunnel to sea, the strength of the surrounding rock, groundwater level, tidal action, cyclical footage, grouting pressure, and grouting reinforced region, were analysed. This multi-index system, reflected the information of water inrush mechanism, represented a good generalization of the influence factors, which were generally classified into engineering geological conditions and construction conditions, and the quantitative standards of the assessment indices were proposed.

A two-step interval risk assessment method for water inrush management during seaside urban tunnel excavation was developed using the interval analytic hierarchy process, fuzzy comprehensive evaluation, and relative superiority analysis. The novel assessment method was applied to the Haicang Tunnel from FWK16+210 to FWK16+060 successfully. A preliminary interval risk assessment method for water inrush was performed relying on engineering geological conditions, and the risk level fell into IV, which represents a high-risk section. After implementing a contingency plan, a secondary interval risk assessment method was performed based on engineering geological conditions and construction conditions. The risk level of water inrush reduced to II. The results were in good agreement with the current situation, which verified the reliability of the proposed approach.

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