A Novel Evaluation Model of Grouting Effect in Weak and Water-Rich Stratum

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Abstract. The development of underground engineering promotes the development of grouting technology, but due to its particularity, the research of grouting theory lags behind the application requirements of actual engineering, and the evaluation of grouting effect is a weak link in grouting theory. Grouting effect is influenced by many factors with uncertainty and nonlinear characteristics. Four factors, anti-inference method of slurry filling rate, displacement monitoring method, exposure observation method, core method in access hole, were proposed, and the corresponding quantitative indexes were determined. In this study, a novel evaluation model was developed using analytic hierarchy process and ideal point method to study grouting effect in weak and water-rich stratum. The results show that this method is feasible. With its strong operability, the proposed method provides a new means to evaluate grouting effect.

1. Introduction
During underground engineering construction, there are more and more difficult construction problems, such as crossing weak and water-rich strata [1, 2]. Grouting, an effective auxiliary method to solve the construction problems of underground engineering, is to inject slurry into the loose soil layer or the crack of water-bearing rock by means of compression [3, 4]. After the slurry solidifies, the particles of the soil fill the crack of rock can improve the performance of rock. To some extent, the success of grouting reflects the technical level of underground engineering construction.

In recent years, a series of engineering accidents have occurred in the construction process of underground engineering, such as collapse and water gushing, many of which are related to grouting [5, 6]. Nikakhtar et al. [7] investigated the influence of the grout material hardening process using Flac3D software. Liu et al. [8] determined the relationships between the grouting pressure, the diffusion radius, and the initial fracture pressure using theoretical analysis and numerical calculations. The relationship between the surface settlement and the theoretical grouting volume was derived based on the inhomogeneous distribution mode for loose ground by Lin [9]. Cheng et al. [10] shown how the water inflow decreases as the hydraulic conductivity of the grouting circle diminishes and the thickness of the grouting circle increases. Gong et al. [11] developed a multiple times grouting method, and the mechanical deformation behavior of surrounding rock is analyzed. Shi et al. [12] have evaluated the effects of the various curtain grouting parameters using simulate the construction of the curtain grouting section.
The development of underground engineering promotes the development of grouting technology, but due to its particularity, the research of grouting theory lags behind the application requirements of actual engineering, and the evaluation of grouting effect is a weak link in grouting theory. Many projects often do not carry out effect detection after grouting, or there is no scientific and effective method and index system for effect detection. With the rapid development of nonlinear method, more and more cases of tunnel engineering evaluation are applied [13, 14]. Through the research on the comprehensive evaluation technology of grouting effect, the evaluation work can be made scientific and quick, and the grouting effect can be judged quickly and effectively. In this study, a novel evaluation model was developed using analytic hierarchy process and ideal point method to study grouting effect in weak and water-rich stratum.

2. Methodology

2.1. Analytic hierarchy process theory

Analytic hierarchy process is a multi-objective decision analysis method which combines qualitative and quantitative analysis methods. The main idea of this theory is to decompose complex problems into several levels and several factors. By calculating the maximum eigenvalues and corresponding eigenvectors of the comparison matrix, the weight of the importance degree of different schemes can be obtained to provide the basis for the selection of the best scheme [15, 16].

Analysis of evaluation factors weights, a hierarchical structure model is built at first, then construct the comparison matrix \( P = (a_{ij})_{n \times n} \) of each level by using 1~9 scale method proposed by professor Saaty. Eqs (4) to (7) are used to calculate the factor weight vector \( \omega \), the maximum eigenvalue \( \lambda_{\text{max}} \), the random consistency ratio \( CR \). When \( CR < 0.1 \), it is considered that the consistency of the comparison matrix is acceptable, and if it is not satisfied, the comparison matrix \( P = (a_{ij})_{n \times n} \) must be modified again. When \( n \) is from 3 to 10, the value of the average random consistency ratio \( RI \) are listed in Table 1.

Substation to analyze the sampling value anomaly of the relay protection device, the synchronization anomaly between multiple MUs and the SV data anomaly of the merging unit, and gives a description of the evaluation method.

| No. | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI  | 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|

\[
W_i = \left( \prod_{j=1}^{n} a_{ij} \right)^{\frac{1}{n}} \sum_{j=1}^{n} \left( \prod_{i=1}^{n} a_{ij} \right)^{\frac{1}{n}} (1)
\]

\[
\lambda_{\text{max}} = \left( \sum_{i=1}^{n} \left( P \omega \right)_i / \alpha_i \right) / n (2)
\]

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} (3)
\]

\[
CR = \frac{CI}{RI} (4)
\]
2.2. Ideal point method

The Ideal point method is an evaluation function method for solving multi-objective programming problems, which makes each objective value approach its ideal value as much as possible. This method has been widely used in engineering evaluation [17].

(1) Positive ideal point and anti-ideal point

The assessment indicators can be divided into two categories: positive indicators and negative indicators.

The larger the positive indicator value, or the smaller the negative indicator value, the higher the level. Assuming assessment indicators show a monotonically changing trend, we can determine the positive ideal point and anti-ideal point.

When the assessment indicator is positive, the ideal point and the anti-ideal point are shown in Eq.(5).

\[
\begin{align*}
    f_i^*(+) &= \max f_i(x), i = 1, 2, \cdots, n \\
    f_i^*(-) &= \min f_i(x), i = 1, 2, \cdots, n
\end{align*}
\]

When the assessment indicator is negative, the ideal point and the anti-ideal point are shown in Eq.(6).

\[
\begin{align*}
    f_i^*(+) &= \min f_i(x), i = 1, 2, \cdots, n \\
    f_i^*(-) &= \max f_i(x), i = 1, 2, \cdots, n
\end{align*}
\]

Where \( f_i^*(+) \) and \( f_i^*(-) \) are the positive ideal point and negative ideal point respectively of the \( i \)th assessment index, and \( f_i(x) \) is the assessment index value.

(2) The ideal point evaluation function

The ideal point evaluation function determines the distance from the evaluation index to the ideal point and the anti-ideal point. The Euclidean distance is used to define this relative distance.

The distance between the indicator value and the positive ideal point can be expressed as Eq.(7).

\[
D_1 = \left( \sum_{i=1}^{n} W_i \left( \frac{f_i(x) - f_i^*(+)}{L_i} \right)^2 \right)^{1/2}
\]

The distance between the indicator value and the negative ideal point can be expressed as Eq.(8).

\[
D_2 = \left( \sum_{i=1}^{n} W_i \left( \frac{f_i(x) - f_i^*(-)}{L_i} \right)^2 \right)^{1/2}
\]

Where \( L_i = |f_i(x)_{\text{max}} - f_i(x)_{\text{min}}| \).

(3) Calculating the proximity degree of ideal point

The ideal point proximity \( T \) is the final parameter directly used to calculate risk level, which is calculated as Eq.(9).

\[
T = \frac{D_1}{D_1 + D_2}
\]
The value of $T$ is from 0 to 1. The larger the value of $T$, the closer the tunnel segment is to the corresponding risk level. The final assessment result takes the risk level corresponding to the maximum closeness.

3. Overview of engineering project
The A2 section of Xiamen Second West Passage (Haicang Subsea Tunnel) has a total length of 2190 m, and is mainly composed of a main line section of 1890 m, a double-arch section of 160 m, and 140 m deep excavation. The 160 m deep excavation section of Xinghu Road is an ultra-shallow buried, variable cross-section, asymmetric ultra-large span double-arch tunnel. The tunnel adopts the three-layer lining type of double primary support, single two lining. The initial support is composed of advanced support, steel frame, reinforced mesh, and shotcrete. The overburden is miscellaneous filling soil and residual soil, the structure is uneven and uneven, the lower part is residual silty clay, weakly weathered rock is not developed, it is a block stone masonry structure, the rock body is complete, and the rock is hard [18]. The groundwater in the site is mainly stagnant water, there is no unified free water surface, the water volume is limited, and the buried depth is about 3.1 m. The tunnel body and the top layer of the tunnel are mainly overburden and fully-strongly weathered rock, and locally are slightly weathered rock and miscellaneous fill. The excavation method adopts the double-wall guide pit method for partial excavation, and the step method is the main method for each step.

![Geological map of tunnel.](image)

4. Evaluation index of grouting effect
Reasonable evaluation of grouting effect is the key to ensure safe construction and grouting quality. The usual methods are anti-inference method of slurry filling rate, displacement monitoring method, exposure observation method, and core method in access hole.

(1) Anti-inference method of slurry filling rate
The slurry filling rate can reflect the grouting effect. The higher the slurry filling rate, the better the grouting effect. Through the statistics of the total grouting amount, the Eq.(10) can be used to calculate the slurry filling rate, according to the slurry filling rate to evaluate the grouting effect. The slurry filling rate is divided into four grades as shown in Table 2.

$$\sum Q = Vn\alpha (1 - \beta)$$ (10)

Where $\sum Q$ is total grouting quantity, $V$ is solid volume, $n$ is formation porosity, $\alpha$ is slurry filling rate, $\beta$ is slurry loss rate.

| Classification | Description                      | Value        |
|----------------|----------------------------------|--------------|
| I              | The slurry filling is very intact.| (0.75, 1)    |
| II             | The slurry filling is intact.     | (0.5, 0.75)  |
| III            | The slurry filling is incomplete.| (0.25, 0.5)  |
| IV             | The slurry filling is very incomplete.| (0, 0.25) |
(2) Displacement monitoring method
Field monitoring can understand the change of surrounding rock deformation after grouting, which is helpful to grasp the displacement characteristics. The displacement variation can reflect the grouting effect to some extent. In this study, the displacement is divided into four grades as shown in Table 3.

| Classification | Description                  | Value    |
|----------------|------------------------------|----------|
| I              | The displacement is very small. | (0, 20]  |
| II             | The displacement is small.    | (20, 40] |
| III            | The displacement is large.    | (40, 60] |
| IV             | The displacement is very large. | (60, 100] |

(3) Exposure observation method
The cracks in the surrounding rock of the region have slurry diffusion, which indicates that the slurry has filled the cracks adequately under the premise of full grouting. Tunnel wall is relatively dry, the position such as arch, arch shoulder by grouting dripping water into wet or dry, before the tunnel whole does not appear large deformation of surrounding rock after excavation, this shows that the radial grouting in the lining of the external form of the whole section is relatively stable grouting circle, take some of the external load to improve the strength of surrounding rock, at the same time reduces the permeability coefficient of surrounding rock, has played a very good waterproof and water plugging effect. In this paper, the tunnel palm condition is divided into four grades as shown in Table 4.

| Classification | Description                  | Value   |
|----------------|------------------------------|---------|
| I              | The tunnel palm is very dry.  | (0, 0.25] |
| II             | The tunnel palm is dry.      | (0.25, 0.5] |
| III            | The tunnel palm is moist.    | (0.5, 0.75] |
| IV             | The tunnel palm is very moist.| (0.75, 1] |

(4) Core method in access hole
The core method in access hole is based on the distribution characteristics of grouting quantity after grouting and the characteristics of engineering geology and hydrogeology revealed in the grouting process. The method taking rate, shown in Eq.(11), is to take cores from the injected strata after grouting, and to evaluate the grouting effect by calculating the proportion of the complete core in all cores. In this paper, the coring rate is divided into four grades as shown in Table 5.

$$q = \frac{L_w}{L_z} \times 100\%$$

Where $L_w$ is length of complete core, $L_z$ is total length of coring hole.

| Classification | Description                  | Value     |
|----------------|------------------------------|-----------|
| I              | The core is very intact.     | (0.8, 1]  |
| II             | The core is intact.          | (0.6, 0.8] |
| III            | The core is broken.          | (0.4, 0.6] |
| IV             | The core is very broken.     | (0, 0.4]  |
5. Evaluation model of grouting effect
The construction method of seaside tunnel with rich water and weak surrounding rock is to plug the water and reinforce the stratum with curtain grouting.

5.1. Standard for grouting effect
Based on experience and previous study results, Standard for grouting effect is divided into four levels, and the grading standard is shown in Table 6.

|                        | I   | II  | III | IV  |
|------------------------|-----|-----|-----|-----|
| Anti-inference method of slurry filling rate | (0.75, 1] | (0.5, 0.75] | (0.25, 0.5] | (0, 0.25] |
| Displacement monitoring method | (0, 20] | (20, 40] | (40, 60] | (60, 100] |
| Exposure observation method | (0, 0.25] | (0.25, 0.5] | (0.5, 0.75] | (0.75, 1] |
| Core method in access hole | (0.8, 1] | (0.6, 0.8] | (0.4, 0.6] | (0, 0.4] |

5.2. Ideal point and negative ideal point
Among the evaluation indicators of grouting effect, exposure observation method and displacement monitoring method are categorized as income indicators. That is, if the value is large, the evaluation grade is high. Meanwhile, core method in access hole and anti-inference method of slurry filling rate are categorized as loss indicators. That is, if the value is large, the evaluation grade is low. Based on Eqs.(5) and (6), the positive ideal point matrix \( F(p) \) and the negative ideal point matrix \( F(n) \) can be obtained as follows:

\[
F(p) = \begin{bmatrix}
1 & 0 & 0 & 1 \\
0.75 & 20 & 0.25 & 0.8 \\
0.5 & 40 & 0.5 & 0.6 \\
0.25 & 60 & 0.75 & 0.4 \\
0.75 & 20 & 0.25 & 0.8 \\
0.5 & 40 & 0.5 & 0.6 \\
0.25 & 60 & 0.75 & 0.4 \\
0 & 100 & 1 & 0
\end{bmatrix}
\]

\[
F(n) = \begin{bmatrix}
0.75 & 20 & 0.25 & 0.8 \\
0.5 & 40 & 0.5 & 0.6 \\
0.25 & 60 & 0.75 & 0.4 \\
0 & 100 & 1 & 0
\end{bmatrix}
\]

5.3. Evaluation factor weights
The weight of grouting effect for different influencing factors was calculated using the analytic hierarchy process theory. The judgment matrix was constructed using 1-9 scale method as proposed by Professor Saaty.

\[
P = \begin{bmatrix}
1 & 2 & 3 & 1 \\
1/2 & 1 & 2 & 1/2 \\
1/3 & 1/2 & 1 & 1/2 \\
1 & 2 & 2 & 1
\end{bmatrix}
\]

Eqs.(1)-(4) were used to determine the weight of each evaluation index. The results are shown in Fig.2. The maximum eigenvalue \( \lambda_{\text{max}} = 4.04 \), \( CI = 0.0153 \), randomconsistency ratio \( CR = 0.017<1 \), satisfying the consistency condition.
5.4. Evaluation of grouting effect

The evaluation section information of anti-inference method of slurry filling rate, displacement monitoring method, exposure observation method, and core method in access hole is shown in Table 7. Based on the maximum criteria of ideal point closeness, the evaluation level of each section can be confirmed.

Table 7. The information of evaluation.

| No. | Anti-inference method of slurry filling rate | Displacement monitoring method | Exposure observation method | Core method in access hole |
|-----|------------------------------------------|--------------------------------|----------------------------|---------------------------|
| 1   | 0.82                                     | 15                             | 0.3                        | 0.75                      |
| 2   | 0.71                                     | 10                             | 0.2                        | 0.7                       |
| 3   | 0.56                                     | 24                             | 0.25                       | 0.65                      |

The closeness between tunnel section 1 and Level I risk source is calculated as follows. The six risk factors of cave-ins in tunnel section 1 are $f_i(1) = \{0.82, 15, 0.3, 0.75\}$. The positive ideal point of Level I risk source can be obtained from $F^*(p)$ as follows: $f_i^*(+) = \{1, 0, 0, 1\}$, weight $W = \{0.36, 0.12, 0.2, 0.32\}$. The distance of the positive ideal point can be obtained using Eq.(7), namely, $D_1 = 0.228832$. The positive ideal point of Level I risk source can be obtained from $F^*(n)$ as follows: $f_i^*(-) = \{0.75, 0.5, 0.25, 0\}$. The distance of the negative ideal point can be obtained using Eq.(8), namely, $D_2 = 0.058$. The closeness between tunnel section 1 and Level I risk source can be obtained using Eq.(9), namely, $T = 0.798$.

The other evaluation results of each section are presented in Table 8.

Table 8. The evaluation results of grouting effect.

| NO. | Closeness of the ideal point | Evaluation level | Actual level |
|-----|-----------------------------|------------------|--------------|
|     | $T_I$, $T_{II}$, $T_{III}$, $T_{IV}$ |                  |              |
| 1   | 0.798, 0.192, 0.342, 0.376 | I                | I            |
| 2   | 0.779, 0.253, 0.331, 0.371 | I                | I            |
| 3   | 0.715, 0.518, 0.277, 0.346 | I                | I            |

6. Conclusion

Grouting effect is influenced by many factors with uncertainty and nonlinear characteristics. Four factors, anti-inference method of slurry filling rate, displacement monitoring method, exposure observation method, core method in access hole, were proposed, and the corresponding quantitative indexes were determined. Each factors have different effects. The weight of anti-inference method of
slurry filling rate is 0.36. The weight of displacement monitoring method is 0.12. The weight of exposure observation method is 0.2. The weight of core method in access hole is 0.32.

A novel evaluation model was proposed based on analytic hierarchy process theory and Ideal point method. Project applications show that this method is feasible. With its strong operability, the proposed method provides a new means to evaluate grouting effect.

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