Computer assisted optimal evaluation of grouting scheme in shallow tunnel through G1 method and GRA

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Abstract. In tunnel construction, grouting technology is an extremely important reinforcement method for improving the mechanical properties and increasing the strength of surrounding rock. This paper presents an optimization evaluation method of grouting scheme for advanced reinforcement in shallow tunnel based on G1 method and grey relational analysis (GRA). In the Haicang Subsea Tunnel Project of Xiamen, the four grouting schemes were optimized and analyzed through the previous optimization evaluation method, the most suitable solution is obtained as the full-control one-time grouting solution and the result has also been verified in practice.

1. Introduction
Grouting technology is a method of injecting certain solidified grout into the cracks or pores of the rock foundation to improve its physical and mechanical properties [1]. Grouting technology was first used in actual construction in 1802 [2]. With the continuous development of transportation and construction projects worldwide, the application of grouting technology in the geotechnical field has become more and more extensive, including roadbed reinforcement [3], slope reinforcement [4], water blocking and seepage prevention [5], surrounding rock consolidation [6], etc. In China, grouting technology started late but has great potential. Many large-scale construction projects [7, 8] have great demands for grouting technology.

In the practice of grouting technology application, many scholars at home and abroad have conducted long-term theoretical and practical explorations in grouting theory, grouting schemes, grouting materials, grouting parameters, and grouting effect evaluation [9-13]. And they have achieved fruitful research results.

In order to achieve the ideal grouting effect, different grouting schemes are usually used in actual projects according to different engineering geological conditions. At present, the main grouting schemes applied to the advance reinforcement of tunnels are as follows: Forward grouting with orifice stop grouting, backward grouting with stop grouting in the hole or tube, and all-hole one-time grouting. The choice of grouting scheme depends on factors such as geological conditions, design requirements, construction methods, and construction machinery [14].
Based on the Haicang Subsea Tunnel Project in Xiamen, this paper carries out the optimization analysis of the advance grouting reinforcement scheme of the shallow-buried large-section double-arch tunnel near the sea. Combining the G1 method and GRA, the optimization evaluation model of grouting scheme is established, and the advantages and disadvantages of different grouting schemes in terms of technical conditions, stratum applicability and others are discussed. And the proposed optimization evaluation model is verified in actual construction.

2. Engineering situation
The Haicang Subsea Tunnel project is located in Xiamen, Fujian Province, China. The total length of the route is 7.1 kilometers, of which the tunnel is 6.3 kilometers long. The study area in this paper is located in the double-arch tunnel section, which is one of the key control projects with extremely difficult construction. The tunnel crosses the main road of the city, and the surrounding buildings are dense, with a minimum distance of 4.3 meters from the surrounding buildings. The excavation height of tunnel is about 14 m, and the buried depth is only about 10 m. The largest single-tunnel excavation section area is 257.2 m². The tunnel is an ultra-shallow-buried and super-large-section tunnel, and is currently the double-arch tunnel with the largest excavation section in the world [15].

The tunnel has complex geological conditions, and the top of the tunnel is filled with mixed soil, silty clay, fully weathered granite, gravel-like strongly weathered granite, and fragmented strongly weathered granite. The base rock surface of the tunnel is undulating, and the surrounding rock is grade V, as shown in the geological profile of the tunnel (Fig. 1). There is a small amount of groundwater in the stratum in this area, including perched water, pore water in unconsolidated rocks, and fissure water in bedrock. The main source of replenishment is atmospheric precipitation.

3. Evaluation of grouting scheme for tunnel advance reinforcement
3.1. Evaluation index and term weighting
From the actual engineering, five aspects were selected as the suitability evaluation indexes of tunnel advance reinforcement pre-grouting scheme, which are respectively technical conditions (I₁), stratum applicability (I₂), construction efficiency (I₃), economic cost (I₄) and social factors (I₅).

G1 method, a subjective weighting method proposed by improving AHP [16], was adopted. This method does not need to construct extremely complex matrices in the calculation process, nor does it need to carry out consistency test, which greatly reduces the amount of calculation. Due to its outstanding advantages, G1 method has been applied in many fields [17, 18].

![Geological profile of the tunnel.](image-url)
According to the principle of G1 method, nine experts were invited to sort the importance of five evaluation indicators and give the relative importance ratio between adjacent indicators in the order relation. In order to ensure the validity of the weight coefficient, the experts invited have been engaged in tunnel construction and underground engineering disaster prevention for many years and have profound understanding and rich experience. Then, according to the weight calculation formula (1)-(3) in G1 method, the weight coefficients of the evaluation indexes needed for grouting scheme selection are allocated, and the weight coefficient sequence is \[ w = \{0.205, 0.364, 0.162, 0.089, 0.125\}. \]

\[ r_k = \frac{w_k}{w_{k+1}} \quad (k = 1, 2, ..., n-1) \]  

\[ w_n = \left(1 + \sum_{k=1}^{n-1} r_k\right)^{-1} \]  

\[ w_k = r_k w_{k+1} \quad (k = n-1, n-2, ..., 1) \]

Where \( r_k \) is the relative importance between index \( x_k \) and \( x_{k+1} \); \( w_k \) is the weight coefficient of index \( k \).

3.2. Optimization analysis of grouting scheme

Grey relational analysis uses discrete data to represent the relationship between various factors in the system, which is suitable for solving the system problem of missing internal information. This theory has been applied in many research fields [19-21]. The merits and demerits of the evaluation object are evaluated through the calculation and comparison of the correlation degree. The calculation formula of correlation coefficient and weighted correlation degree is

\[ \zeta(e_i(k), f(k)) = \frac{a + \rho b}{|e_i(k) - f(k)| + \rho b} \]  

\[ \gamma(E_i, F) = \frac{1}{n} \sum_{k=1}^{n} w_k \cdot \zeta(e_i(k), f(k)) \]

Among them,

\[ a = \min_{i} \min_{k} |e_i(k) - f(k)| \]  

\[ b = \max_{i} \max_{k} |e_i(k) - f(k)| \]

Where \( \zeta(e_i(k), f(k)) \) is the correlation coefficient of the index \( k \) in the comparison sequence \( i \); \( \rho \) is the resolution coefficient, generally 0.5.

In order to represent the evaluation indexes of the suitability of the grouting scheme, five integers 1-5 were used to quantify them [22], and it was assumed that they were all effectiveness indicators. Through the application of Delphi method [23], we investigated four grouting schemes, namely, forward grouting with orifice stop grouting, backward grouting with stop grouting in the hole, backward grouting
with stop grouting in the tube, and all-hole one-time grouting respectively, and the evaluation index values for the study area were obtained (Table 1).

**Table 1.** The evaluation index value of grouting schemes.

| grouting scheme                              | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ |
|----------------------------------------------|-------|-------|-------|-------|-------|
| forward grouting with orifice stop grouting  | 4     | 2     | 4     | 4     | 3     |
| backward grouting with stop grouting in the hole | 2     | 3     | 3     | 3     | 2     |
| backward grouting with stop grouting in the tube | 2     | 4     | 2     | 2     | 2     |
| all-hole one-time grouting                   | 3     | 5     | 4     | 4     | 3     |

According to Table 1, the original matrix can be constructed. Through formulas above, the grey weighted correlation matrix $R$ of each scheme is calculated. The comparison results of the grey correlation degree of each scheme told us that the grouting scheme with the highest suitability in this study area was the all-hole one-time grouting scheme.

$$R = \begin{bmatrix} 0.5123 & 0.4395 & 0.4752 & 0.6964 \end{bmatrix}^T \tag{8}$$

In practice, engineers believed that there was underground water but not abundant in the field of double arch tunnel, so it was unnecessary to adopt the forward grouting method, while the operation efficiency of the backward grouting was low, which cannot meet the requirements of the construction period. Compared with the former two, the construction efficiency of the all-hole one-time grouting was higher and it’s drilling and injection operation was simple and convenient, so the expected grouting effect can be achieved. Therefore, the double-arch tunnel adopted the construction scheme of the all-hole one-time grouting, which a high consistency with the results had obtained in this study.

4. Conclusion

In this paper, an optimization evaluation method of grouting scheme for advance reinforcement of shallow buried tunnel was put forward. Combined with G1 method and grey relational analysis, the grouting scheme was effectively evaluated and selected. Five evaluation indexes covering all aspects of grouting technology were put forward, which are technical conditions, stratum applicability, construction efficiency, economic cost and social factors. Through the analysis of the correlation degree of the four grouting schemes, it was finally determined that the all-hole one-time grouting scheme was the scheme with the highest suitability in this study, and it has been verified in the actual construction. Therefore, it can be considered that the optimization analysis method of grouting scheme proposed in this paper has a good practical effect and a certain reference value for related research.

References

[1] Stromsvik H., Gammelsaeter B. Investigation and assessment of pre-grouted rock mass, Bulletin of Engineering Geology and the Environment, 2020, 79(5), 2543-2560.

[2] Miao Q. Q., Zhu Q. Q., Jiang S. P. Application of grouting technology in the geotechnical engineering, Applied Mechanics and Materials, 2015, 744-746(442-446).

[3] Li L., Xiang Z. C., Zou J. F., Wang F. An improved model of compaction grouting considering three-dimensional shearing failure and its engineering application, Geomechanics and Engineering, 2019, 19(3), 217-227.

[4] Ertunc A. The geological problems of the large dams constructed on the euphrates river (turkey), Engineering Geology, 1999, 51(3), 167-182.

[5] Mu W. Q., Li L. C., Liu X. G., Zhang L. Y., Zhang Z. L., Huang B., Chen Y. Diffusion-hydraulic properties of grouting geological rough fractures with power-law slurry, Geomechanics and Engineering, 2020, 21(4), 357-369.

[6] Liu Q. S., Xu X. Y., Tang X. H. A numerical study of the influence of cyclic grouting and consolidation using tough2, Bulletin of Engineering Geology and the Environment, 2021,
80(1), 145-155.

[7] Xue Y. G., Zhou B. H., Ge S. Q., Qiu D. H., Gong H. M. Optimum design calculation method for the reasonable buried depth: A case study from Hong Kong-Zhuhai-Macao immersed tunnel, Ocean Engineering, 2020, 206(9).

[8] Xue Y., Kong F., Li S., Zhang Q., Qiu D., Su M., Li Z. China starts the world's hardest "sky-high road" project: Challenges and countermeasures for Sichuan-Tibet Railway, The Innovation, 2021, 100105.

[9] Liu B., Sang H. M., Liu Q. S., Liu H., Pan Y. C., Kang Y. S. Laboratory study on diffusion and migration of grout in rock mass fracture network, International Journal of Geomechanics, 2021, 21(1), 11.

[10] Yang M. J., He Y. N., Chen M. X. System design method of grouting engineering in fractured rock mass, Leiden: A a Balkema Publishers, 2001.

[11] Zhu E. Y., Ni Y. C., Li Y. J., Zhu L. Design and experimental verification of asphalt-based material for grouting of prestressed structure, Advances in Civil Engineering, 2020(11).

[12] Cao L., Liang J. W., Jiang M. Y., Yi C., Liu S. B. Optimization of grout parameters and volume of filling grouting in karst through simulation experiment, Electronic Journal Of Geotechnical Engineering, 2019, 24(5), 1163-1176.

[13] Cai Jie. A novel evaluation model of grouting effect in weak and water-rich stratum, IOP Conference Series: Earth and Environmental Science, 2021, 632(022066-022069).

[14] Zhong Z. L., Bie C. Y., Fan Y. F., Liu X. R., Luo Y. Q., Tu Y. L. Experimental study on grouting diffusion mechanism and influencing factors of soil-rock mixture, Rock And Soil Mechanics, 2019, 40(11), 4194-4202.

[15] Xue Y. G., Gong H. M., Kong F. M., Yang W. M., Qiu D. H., Zhou B. H. Stability analysis and optimization of excavation method of double-arch tunnel with an extra-large span based on numerical investigation, Frontiers Of Structural And Civil Engineering, 2021, 15(1), 136-146.

[16] Xue Y. G., Zhou B. H., Qiu D. H., Su M. X., Qu C. Q., Zhang X. L., Li Z. Q. A prediction model for overlying rock thickness of subsea tunnel: A hybrid intelligent system, Marine Georesources & Geotechnology, 2019, 37(10), 1267-1276.

[17] Chen D., Cao Y., Xia H., Mei Y. T., Zhong Y. F. Weight fusion of dam monitoring indexes based on entropy and g1 methods, Water Resources and Power, 2012, 30(6), 92-94.

[18] Sun S. H., Huang G. Z., Jin L. Z., Li Y. G., Zhao X. Fuzzy comprehensive evaluation of emergency capability of port coal storage base with g1 method, Montreal: Mcgill Univ, 2016.

[19] Ma X. M., Xue Y. G., Bai C. H., Liu H. T., Yu Y. H. Prediction model for deformation risk grade of the soft rock tunnel based on GRA – extension, 2019 5th international conference on environmental science and material application. Bristol; IOP Publishing Ltd. 2020.

[20] Chen X. P., Pei T. T., Zhou Z. X., Teng M. J., He L., Luo M., Liu X. X. Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (pm10): A street scale investigation in Wuhan, China, Urban Forestry & Urban Greening, 2015, 14(2), 354-360.

[21] Zhao X. F., Yan L., Yang L. L., Chi F. D., Ning Y. Deformation characteristics and influential factors of a toppling rock slope based on the grey relational analysis, European Journal of Environmental and Civil Engineering, 12.

[22] Tanaka Y. An application of methods of quantification to analyze the effects of qualitative factors, 1980.

[23] Xue Y. G., Li Z. Q., Qiu D. H., Yang W. M., Zhang L. W., Tao Y. F., Zhang K. Prediction model for subway tunnel collapse risk based on delphi-ideal point method and geological forecast, Soil Mechanics and Foundation Engineering, 2019, 56(3), 191-199.