The Research on Tunnel Surrounding Rock Classification Based on Geological Radar and Probability Theory

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Abstract. In order to effectively classify the surrounding rock types of tunnels, a multi-factor tunnel surrounding rock classification method based on GPR and probability theory is proposed. Geological radar was used to identify the geology of the surrounding rock in front of the face and to evaluate the quality of the rock face. According to the previous survey data, the rock uniaxial compressive strength, integrity index, fissure and groundwater were selected for classification. The related theories combine them into a multi-factor classification method, and divide the surrounding rocks according to the great probability. Using this method to classify the surrounding rock of the Ma'anshan tunnel, the surrounding rock types obtained are basically the same as those of the actual surrounding rock, which proves that this method is a simple, efficient and practical rock classification method, which can be used for tunnel construction.

1. Introduction

Different geological conditions have some connection with the stability of surrounding rock. The different stability (fully stable, basically stable, temporarily stable, unstable, etc.) correspond to the grade of surrounding rock. There are many geological factors that affect the grading of surrounding rock, such as stratigraphic lithology, rock mass structure, structural fracture, elegance status, integrity, groundwater, etc. Not only are the factors independent of each other, but also the quality of the surrounding rock and the various factors are highly nonlinear relationship. Therefore, how to select independent factors and reasonable evaluation methods is a challenge faced by geoengineering workers. Many new methods have been introduced into the classification of surrounding rocks (Zhang Lewen, 2011; Fu Zhengfei, 2006; Wang Huafeng, 2016)

At present, the classification method of tunnel surrounding rock mainly comes from various industry norms. Generally speaking, there are single factor method and multi-factor method. The single factor method refers to the grading of the surrounding rock by means of a single comprehensive index, which is related to the development of survey technology, and its adaptability is not too high. The multi-factor method has strict requirements for the selection and combination of indexes and is relatively complicated. In traditional engineering, according to the specification, the surrounding rock mass of the tunnel is geologically graded to measure the rock mass strength $R_c$, the rock mass integrity coefficient $K_v$, the state of the structural plane and the basic mass index $BQ$ of the surrounding rock.
mass. Surrounding rock is graded through pre-survey data. In the tunnel project, the development of the fractures, faults and groundwater in the surrounding rock in front of the working face plays an important role in the stability of the surrounding rock. However, it is difficult to find and distinguish this difference in the general pre-investigation, resulting in the fact that the grade of surrounding rock determined in the survey is not completely consistent with the actual situation in construction (Qiu Daodong, 2011; Yuan Guochong, 2005; Zhang Peng, 2009; Lian Jian Fat, 2004).

According to the rock strength $R_c$ and rock mass integrity coefficient $K_v$ obtained from the previous survey data and combined with the geologic radar electromagnetic wave method used in construction, the development of the fractures, structural planes and groundwater of the surrounding rock in front of the working face is graded. And then using the theory of probability to get a new method of surrounding rock classification, and this method is applied to the Ma An Shan tunnel.

2. The Role of Geological Radar in Prediction

The advanced geological forecast of the tunnel refers to the combination of the various signals and waveform features reflected by the geophysical technology during the tunnel excavation and the disclosed geological phenomena to make the forward prediction of the surrounding rock of the working face. On the basis of previous surveys, the influence of the tunnel scale, structure type and construction method on the surrounding rock, we can further ascertain the geological conditions in a certain section ahead of the working face.

Ground penetrating radar (GPR), as a detection method of advanced geological forecasting of tunnels, has very high accuracy and can identify the basic engineering geological problems of rock and soil within a certain range around and in front of the working face, such as discontinuous interface, broken zone, caverns and filling conditions can affect the safe construction of the tunnel (Xu Jia, 2008; Pawlak Z, 2002).

In the tunneling project, the development of fractures, faults and groundwater in front of the rock face plays an important role in the stability of the surrounding rock. By analyzing the image of the geological radar, according to the structure plane, the degree of fracture development, groundwater content, we can grade the surrounding rock, grading and classification is shown in Table 1:

| classification | description | value   |
|----------------|-------------|---------|
| I              | Complete and dense rock mass without fracture fissures | 0.8-1.0 |
| II             | There are a few faults and fractures in rock mass | 0.6-0.8 |
| III            | More faults | 0.4-0.6 |
| IV             | Many faults | 0.2-0.4 |
| V              | A large number of faults | 0-0.2 |

3. Surrounding Rock Classification Based on Probability Theory

3.1. The expression of the value

According to the theory of probability theory, if event A and event B are mutually exclusive events, the probability that at least one event A and event B occur must be the sum of the two probabilities, and the probability of the two occurring separately is two separately. The product of probability, that is, (Huang Kun, 2005).

\[
P\left(A \cup B\right) = P\left(A\right) + P\left(B\right) \quad (1)\]

\[
P\left(A \cap B\right) = P\left(A\right) P\left(B\right) \quad (2)\]

Mathematical expectation is the sum of the probabilities of every possible result in the test multiplied by the result, which reflects the average value of random variables. For the possible random variables, the expression is
Further more, for such linear continuous variables that may appear, the mathematical expectation in this interval is its average value, that is,

$$E = \frac{a + b}{2}$$  \hspace{1cm} (4)

In the formula, a and b are the values of the two endpoints in a section respectively.

Assuming that any one signal value represents a random event, the classification level of the surrounding rock is used as an interval segment. To determine which interval the signal is most likely to appear in (corresponding to which level), it is necessary to calculate and compare the probability that it appears at each level. The level of maximum probability appears is the surrounding rock level at which the numerical signal is located.

$$P(x) = 1 - \left| \frac{x - E}{L} \right|$$  \hspace{1cm} (5)

Where, L is the total length of the segment, \(L = |d-a|\), E is the expected number.

3.2. Surrounding rock classification with single factor

Taking the rock uniaxial uniaxial compressive strength \(R_c\) as an example, when \(R_c\) is used as a single-factor index to classify the surrounding rock, the range of \(R_c\) is: Class I is very hard rock range (60, 120 MPa), the expected number is 90 MPa, Class II is hard rock range (30, 60) MPa, the expected number is 45 MPa, III is soft rock range (15, 30) MPa, the expected number is 22.5 MPa, IV is softer rock range (5, 15) MPa, the expected number is 10 MPa, V is very soft rock range (0, 5) MPa, the expected number is 2.5 MPa. If we measure a rock's saturated uniaxial compressive strength \(R_c\) 45 Mpa, then it belongs to the probability of each grade:

\[ P_I = 1 - \frac{45 - 90}{120} = 0.63 \]
\[ P_{II} = 1 - \frac{45 - 45}{120} = 1 \]
\[ P_{III} = 1 - \frac{45 - 22.5}{120} = 0.81 \]
\[ P_{IV} = 1 - \frac{45 - 10}{120} = 0.71 \]
\[ R_c = 1 - \frac{45 - 2.5}{120} = 0.65 \]

It shows that \(P_{II}\) is the largest probability, so the rock is a type II harder rock.

3.3. Surrounding rock classification with multiple factors

3.3.1 Selection of evaluation index. In the initial grading of engineering rock mass, rock mass grade is generally used according to the basic mass grade of rock mass determined by two indexes of rock hardness and rock integrity. When grading the engineering rock mass in detail, the scale and characteristics of the project with different types and sections should be fully considered on the basis of the grading of the basic mass of the rock mass. Based on the initial stress state, the development of groundwater, the axial orientation of the cavern, the structure Surface production and their combination of factors to determine the revised indicators (Ye Ying, 2009; Yu Zhongming, 1999). However, various norms also have different methods of grading correction (Zhang Wenxiu, 2001; Zhao Xianqiao, 2004; Xu Jia, 2009). According to the provisions of the existing codes for classification of surrounding rock, and combining the theory and research results of surrounding rock stability, three indexes of evaluating rock saturated uniaxial compressive strength, integrity index, fissure and groundwater are selected for classification (Yuan Guangxiang, 2015; Huangpi Et al., 2006).

3.3.2 Multi-factor classification of judgments. Assuming that the chosen rock saturated uniaxial compressive strength, integrity index, fissure and groundwater are classified as three random events, they are independent of each other, and the probability of occurrence is equal. According to the results of surrounding rock classification and judgment The role played by the same is true. Therefore,
according to the principle of probability theory, according to Eq. (2), the probability that the surrounding rock will obtain the final result in these three kinds of classification is the product of the probability of pre-evaluating the surrounding rock in each classification.

The upper limit of saturated uniaxial compressive strength of rock is 120 Mpa and the lower limit is 0. The upper limit of integrity index $K_v$ is 1 and the lower limit is 0. The upper limit of crack and groundwater $W$ is 1 and the lower limit is 0. According to the formula (4), respectively, the expected value of each level, see Table 4.

According to the principle of probability theory, the rock mass of each kind of tunnel under the influence of three kinds of factors, the probability calculation method belonging to a surrounding rock type is shown in Eqs. (6) ~ (10).

$$P_i = P(R_i)P(K_i)P(W) = \left(1 - \frac{R_i - 90}{120}\right)\left(1 - \frac{K_i - 0.865}{1}\right)\left(1 - \frac{W - 0.9}{1}\right)$$

$$P_{II} = P(R_i)P(K_i)P(W) = \left(1 - \frac{R_i - 45}{120}\right)\left(1 - \frac{K_i - 0.65}{1}\right)\left(1 - \frac{W - 0.7}{1}\right)$$

$$P_{III} = P(R_i)P(K_i)P(W) = \left(1 - \frac{R_i - 22.5}{120}\right)\left(1 - \frac{K_i - 0.35}{1}\right)\left(1 - \frac{W - 0.5}{1}\right)$$

$$P_{IV} = P(R_i)P(K_i)P(W) = \left(1 - \frac{R_i - 10}{120}\right)\left(1 - \frac{K_i - 0.25}{1}\right)\left(1 - \frac{W - 0.3}{1}\right)$$

$$P_V = P(R_i)P(K_i)P(W) = \left(1 - \frac{R_i - 2.5}{120}\right)\left(1 - \frac{K_i - 0.075}{1}\right)\left(1 - \frac{W - 0.1}{1}\right)$$

According to the theory of probability theory, among the many independent events, the event with the highest probability is most likely to occur. Therefore, by calculating the probability of the surrounding rock will obtain the final result in these three kinds of classification is the product of the probability of pre-evaluating the surrounding rock in each classification.

**Table 2** Classification indexes of rock mass in various standard

| num | criterion | evaluation index | classification |
|-----|-----------|------------------|----------------|
| 1   | 《Code for water resource and hydropower engineering geological investigation》 GB 50487-2008 (appendix N) | Rock strength, rock mass integrity, structural plane status, groundwater status, major structural facets | I-V (good-bad) |
| 2   | 《Code for Design of Road Tunnel》 JTJ D70-2004 (appendix A) | BQ. The basic quality indicators of surrounding rock, are determined by the degree of rock hardness and rock mass integrity. Combined with the correction of groundwater, the occurrence of structural plane and the initial stress state | I-IV (good-bad) |
| 3   | 《Code for rode engineering geological investigation》 JTG C20-2011 (appendix F) | Based on the rock hardness and rock mass integrity, and groundwater and initial stress is used to amendment. | I-IV (good-bad) |
| 4   | 《Code for design on tunnel of railway》 TB 10003-2005 (appendix A) | The basic mass index of rock mass is BQ. And groundwater, weak structural surface and initial stress is used to correction. | I-V (good-bad) |
| 5   | 《Standard for engineering classification of rock masses》 《Code for investigation of geotechnical engineering》 | | |

**Table 3** Corresponding the classification level of surrounding rocks to three factors

| Classification | Rock saturated uniaxial | Integrity | Cracks and groundwater $W$ |
|----------------|-------------------------|-----------|-----------------------------|

4
compressive strength $R_c$(MPa) & index $K_v$ & Description & Value \\
--- & --- & --- & --- \\
I & 60–120 & 0.75–1.0 & rock complete and dense, groundwater is not developed & 0.8–1.0 \\
II & 30–60 & 0.55–0.75 & there is a small amount of faults, cracks, groundwater less development & 0.6–0.8 \\
III & 15–30 & 0.35–0.55 & More faults, fractures, groundwater more developed & 0.4–0.6 \\
IV & 5–15 & 0.15–0.35 & Many faults, fractures, groundwater development & 0.2–0.4 \\
V & 0–5 & 0–0.15 & A large number of faults, cracks, voids, etc., groundwater is developed & 0–0.2 \\

**Table 4** Mathematical expectation of classification of tunnel surrounding rocks

| Classification | $R_c$(MPa) | $K_v$ | W |
|---------------|------------|-------|---|
| I             | 90         | 0.865 | 0.9 |
| II            | 45         | 0.65  | 0.7 |
| III           | 22.5       | 0.35  | 0.5 |
| IV            | 10         | 0.25  | 0.3 |
| V             | 2.5        | 0.075 | 0.1 |

4. Engineering Applications

We take 4 sections of the Ma An Shan tunnel for example. The uniaxial compressive strength $R_c$ of rock mass and the representative wave velocity of each surrounding rocks are gotten from the rock samples tested by drilling sampling. Comprehensive determination of the core to take, can get the integrity coefficient $K_v$. Based on the result of GPR, the structural surface state and groundwater condition of the surrounding rock of the target section can be gotten. Take section 1 as an example, the image of the GPR is shown in Figure 1.

![Fig.1 Geological radar image of hole 1#](image)

The results of the previous survey show that the No. 1 section is the weathered dolomitic limestone, the rock mass is relatively broken and the integrity is better. The uniaxial compressive strength $R_c$ is 27.19 and the integrity coefficient $K_v$ is 0.15. In some regions of the GPR images, the amplitudes significantly increase and vary greatly, the energy clusters are unevenly distributed, the waveforms are disorderly distributed, the events of the faults are intricate, and even the images are blurred in the deep areas. Combined with the geology of the face, the forward joints Fissures are more developed, weathered heavily, the rock is more broken, score 0.3.

The four sections of the index value of the statistics shown in Table 5.
Table 5 The sample parameters

| Num | $R_c$ | $K_v$ | $W$ |
|-----|-------|-------|-----|
| 1   | 27.19 | 0.15  | 0.3 |
| 2   | 30.22 | 0.5   | 0.3 |
| 3   | 30.22 | 0.3   | 0.2 |
| 4   | 58.32 | 0.8   | 0.5 |

The above parameters substitute into the formula (6) ~ (10), respectively, calculate the probability of the corresponding category, the results shown in Table 6 to Table 9.

The grading results are shown in Table 10. The probability of wall rock of No. 2 section in grade III is 0.636253 and the grade of grade is 0.623625, which is close to each other, indicating that the surrounding rock of this section is between the two and the actual excavation result also proves this point; the basic quality of rock mass in section 4 is better, but because of the presence of more fractures in front of the geologic radar response, the comprehensive evaluation result is level II, which is consistent with the actual results.

The evaluation results in Table 10 show that the evaluation results of the surrounding rock grade of this model are basically consistent with the actual situation. Therefore, it is feasible to apply this method to the stability evaluation of the surrounding rock of the tunnel.

Table 6 Calculation results of hole 1#

| Classification | Probability | Category |
|----------------|-------------|----------|
| I              | 0.054331    |          |
| II             | 0.255475    | $\max\{ P_I, P_{II}, P_{III}, P_{IV} \}$ |
| III            | 0.614987    | $P_{V} = 0.771075$, belongs to classification IV |
| IV             | 0.771075    |          |
| V              | 0.587745    |          |

Table 7 Calculation results of hole 2#

| Classification | Probability | Category |
|----------------|-------------|----------|
| I              | 0.127466    |          |
| II             | 0.447185    | $\max\{ P_I, P_{II}, P_{III}, P_{IV} \}$ |
| III            | 0.636253    | $P_{V} = 0.636253$, belongs to classification III |
| IV             | 0.623625    |          |
| V              | 0.35374     |          |

Table 8 Calculation results of hole 3#

| Classification | Probability | Category |
|----------------|-------------|----------|
| I              | 0.065489    |          |
| II             | 0.284971    | $\max\{ P_I, P_{II}, P_{III}, P_{IV} \}$ |
| III            | 0.622218    | $P_{V} = 0.710933$, belongs to classification IV |
| IV             | 0.710933    |          |
| V              | 0.536378    |          |

Table 9 Calculation results of hole 4#

| Classification | Probability | Category |
|----------------|-------------|----------|
| I              | 0.412896    |          |
| II             | 0.60452     | $\max\{ P_I, P_{II}, P_{III}, P_{IV} \}$ |
| III            | 0.385825    | $P_{V} = 0.60452$, belongs to classification II |
| IV             | 0.21504     |          |
| V              | 0.088248    |          |

Table 10 Comparison of evaluation results

| Num | Classification of this article | Actual level |
|-----|-------------------------------|--------------|
| 1   | V                             | IV           |
| 2   | IV                            | III ~ IV     |
| 3   | IV                            | IV           |
| 4   | I                             | II           |
5. Conclusion

(1) In the process of investigation, due to the restriction of practical conditions, the classification of surrounding rock of tunnel may not be so accurate. With the use of geological radar in the construction of the front of the working face, we can know the rock fractures and groundwater conditions, and evaluate it. This is operable.

(2) Three indexes of rock mass saturated uniaxial compressive strength, integrity coefficient and development of fissure groundwater are selected. The probabilistic method is used to evaluate the three indexes comprehensively. The evaluation results are in good agreement with the actual ones, which shows that the method is practicable and provides a new idea for the stability evaluation of the surrounding rock of the tunnel. It has played a good guiding role in the construction.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (51469007), Guizhou Science and Technology Support Project for Social development ([2015]3055), Science and technology research and development project of CSCEC(CSCEC4B-2015-KT-03). They are gratefully acknowledged.

References

[1] Construction department of the People's Republic of China. 2009. Code of Geotechnical engineering survey (GB50021-2001) [S]. Beijing: China construction industry press: 89-96 (in Chinese)

[2] Fu Zheng-fei, Zhang Shi-biao, Guo Gang, Chen Yong, Wang Yuan-han. 2006. Study on application of probability method to surrounding rock classification in Yunling tunnel[J]. Chinese Journal of Rock Mechanics and Engineering, 25(1): 3063-3068. (in Chinese with English abstract)

[3] Huang Kan, Peng Jian-guo, Ding Guo-hua, Chen shao-guang, Gong Dao-ping. 2006. application of TSP203 for geological advanced prediction in Xuefengshan Tunnel [J]. Geology and Exploration, 42(5): 103-106 (in Chinese with English abstract)

[4] Huang Kun, Chen Sen-fa, Qi Xia, Zhou Zhen-guo. 2005. A multi-source information fusion method based on rough set theory and support vector machine and its application[J].Pattern Recognition and Artificial Intelligence, 18(3): 354-358 (in Chinese with English abstract)

[5] Lian Jian-fa, Shen Nai-qi, Zhang Jie-ku. 2004. Research on surrounding rock evaluation of underground engineering based on extention method[J]. Chinese Journal of Rock Mechanics and Engineering, 23(9):1450-1453 (in Chinese with English abstract)

[6] Pawlak Z. 2002. Rough sets and intelligent data analysis[J]. Information Science, 11(147): 1–12

[7] Qiu Dao-hong, Xue Yi-Guo, Su Mao-Xing, Wang Kai, Tian Hao. 2011. Study on surrounding rock stability based on the efficacy coefficient method and rough set[J].ShandongDaxueXuebao(GongxueBan), 41(5): 92-96 (in Chinese with English abstract)

[8] The Professional Standards Compilation Group of People's Republic of China. 2004. Code for Design of Road Tunnel (JTGD70–2004)[S]. Beijing: China Communications Press (in Chinese)

[9] The second survey and design institute of the ministry of railways. 2005. Code for design on tunnel of railway(TB10003-2005) [S]. Beijing: China railway press: 36-40 (in Chinese)

[10] Water resources of the People's Republic of China. 2009. Code of Geological survey for hydropower engineering (GB5047-2008) [S]. Beijing: China planning press 52-58 (in Chinese)

[11] Wang Hua-feng, Liu Rong-quan, Zheng Qiang, Chen Ying-jun, Guo Dong, Liu Jun, Yan Jiayong. 2013. Application of comprehensive geophysical prospecting methods to goaf of metal ore mines: A case study of the Wangershan mine goaf, Jiaojia gold mine, Shandong
Province [J]. Geology and Exploration, 49(3): 0496-0504 (in Chinese with English abstract)

[12] Xu Jia, Zhang-Qin, Wu Ji-min. 2008. Application of efficacy coefficient method to determination of rock preferred structural plane [J]. Journal of Hehai University(Natural Sciences), 36(4): 538-541 (in Chinese with English abstract)

[13] Ye Ying. 2009. Tunnel synthetical parameter method geological prediction technique research [J]. Geology and Exploration, 45(4): 468-473 (in Chinese with English abstract)

[14] Yuan Guang-xiang, Li Jian-yong, Huang Zhi-quan, Wang Peng-jiao. 2015. On prediction of water inflow into tunnels during engineering surveys [J]. Geology and Exploration, 51(5): 0993-0998 (in Chinese with English abstract)

[15] Yuan Guo-hong, Chen Jian-ping, MA Lin. 2005. Application of extenics in evaluating of engineering quality of rock masses [J]. Chinese Journal of Rock Mechanics and Engineering, 24(9): 1539-1544 (in Chinese with English abstract)

[16] Yu Zhong-ming. The application of sounding radar to tunnel forecast [J]. Geology and Exploration, 35(3): 30-31 (in Chinese with English abstract)

[17] Zhang Le-wen, Qiu Dao-hong, Li Shu-cai, Zhang De-yong. 2011. Study of tunnel surrounding rock classification based on rough set and ideal point method [J]. Rock and Soil Mechanics, 32(S1): 171-175 (in Chinese with English abstract)

[18] Zhang Peng, Chen Jian-ping, QIU Dao-hong. 2009. Evaluation of tunnel surrounding rock quality with extenics based on rough set[J]. Rock and Soil Mechanics, 30(1): 246-250 (in Chinese with English abstract)

[19] Zhang Wen-xiu, Wu Wei-zhi, Liang Ji-ye. 2001. Rough sets theory and method[M]. Beijing: Science Press: 10–24 (in Chinese)

[20] Zhao Xian-qiao, Cao Xin-yu. 2004. Study of the method for determining weighting coefficient of coal ash slagging fuzzy combination forecast based on rough set theory. Journal of China Coal Society, 29(2):222—225 (in Chinese with English abstract)