Study on Fast Test and Calculation Method of Integrity Coefficient of Surrounding Rock During Tunnel Construction

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Abstract. In this paper, the need of obtaining the rock integrity index in the rapid classification of surrounding rock during the tunnel construction is briefly described. The conventional rock integrity index is introduced and the rapidity of its test acquisition is analyzed. Based on the design of quick test arrangement for rock integrity coefficient, a method of data acquisition and preprocessing for field test of wave velocity of rock block (body) in face is proposed. For the first time, two calculation models of rock block wave velocity and rock mass wave velocity are put forward, one is the calculation model of asymptote method, the other is the calculation model of trend line method. The principle, calculation process, reliability and adaptability of the two calculation models are analyzed and compared. Finally, the trend line method is proposed as the integrated solution of rock block and rock mass wave velocity. Thus, the rapid acquisition of rock integrity coefficient is realized, which lays the key technical foundation for the rapid classification of surrounding rock and the research and development of equipment system during the tunnel construction period, and finally provides the basis and guidance for the dynamic design and construction of tunnel engineering.

1. Introduction

The main tunnel constructed using the new Austrian tunneling method (NATM) should be provided with initial support in time after excavation, so as to protect the surrounding rock to the maximum extent, which requires that the surrounding rock level of the tunnel face can be determined quickly and accurately after excavation [1].

Tunnel engineering is high-risk concealed engineering. The preliminary investigation is the surrounding rock classification provided by the tunnel engineering design, which is the pre-classification of the surrounding rock, and needs to be constantly revised in the construction process. There are many qualitative factors in the conventional surrounding rock classification method, and it is difficult to test and analyze the quantitative indexes. At present, the classification of surrounding rock in the construction period is mainly determined by subjective judgment and artificial observation on the site of the tunnel, which is lack of objectivity and scientificity. Therefore, there are many collapse accidents caused by the failure of surrounding rock classification, resulting in a lot of loss of life and property, and the situation of resource waste caused by excessive support strength is countless. Generally speaking, there is a lack of fast and reliable method for surrounding rock classification during tunnel construction. Therefore, it is an urgent problem to study the rapid determination method of surrounding rock level and the software and hardware system in tunnel construction [2-3].
Index of Rock Mass Integrality (IRMI) is one of the two basic indexes of surrounding rock classification. The rapidity and reliability of tunnel face rock mass integrity coefficient test during tunnel construction directly affect and restrict the rapidity and reliability of surrounding rock classification. Therefore, the research on the rapidity test and calculation method of IRMI is conducive to the research and development of related supporting instruments for the rapid determination of the surrounding rock level during the tunnel construction period, and ultimately can provide basis and guidance for the dynamic design and construction of the tunnel engineering [4].

2. Selection of IRMI

2.1 IRMI

The integrity of rock mass mainly refers to the cutting degree of rock mass by structural plane, the size of unit rock block, and the combination state between blocks. Therefore, the integrity of the rock mass is related to the geometric characteristics of the structural plane and the properties of the structural plane, i.e. it’s determined by the density, group number, occurrence and extension length of the structural plane, tensile cracking, roughness, undulation, filling conditions, filling properties, etc. There are many indexes that can be used to represent the integrity degree of rock mass. The most commonly used indexes at home and abroad are the integrity coefficient of rock mass Kv, the volume joint number of rock mass Jv, the rock quality designation RQD, the average joint spacing Dp, etc., followed by the number of fractures contained in the 1.0m long core section, the block size designation BSD, the dynamic and static elastic modulus ratio of rock mass to rock block, etc. These indexes reflect the integrity degree of rock mass from different emphasis planes and different degrees. Based on the main classification methods at home and abroad, most of the above indexes, Kv, Jv and RQD can reflect the integrity of rock mass more comprehensively [5-6].

The integrity coefficient of rock mass Kv can also be called fracture coefficient of rock mass. Its value is determined by the square of the ratio of the acoustic P-wave velocity of the same rock mass to the P-wave velocity of the rock block. Jv is an index to evaluate the joint degree of rock mass and to express the block degree of unit rock block. It refers to the number of joints in the unit volume (m$^3$) of rock mass. The rock quality designation RQD requires that the rock core acquisition rate of rock core length over 10cm drilled by small caliber diamond bit and double-layer rock core tube shall be used.

2.2 Analysis and Selection of Rapidity Test IRMI

Through the comparative analysis of the factors, test principle, test instrument, test method and test rapidity of Kv, Jv and RQD, it can be seen that the factors considered in the integrity coefficient Kv is the most sufficient. If the test layout design and test method can be innovated to achieve quick acquisition, it is the best choice (Table 1).

| Index name | Factors considered | Testing principle | Testing instrument & test method | Possibility of quick test |
|------------|--------------------|-------------------|----------------------------------|---------------------------|
| Kv         | Rock structure and composition, development degree, property, filling, water. | $K_v = (V_{pr}/V_{pm})^2$ | Sonic, need to drill. | The traditional method can’t realize the fast test in the tunnel. |
| Jv         | Combined cutting action of structural plane. | $J_v = n_1/L_1 + n_2/L_2 + \ldots + n_n/L_n$ | Ruler, simple to calculate, but requires 3D outcrop. | Almost no 3D outcrop and easy to be covered. |
| RQD        | Combined cutting action of structural plane. | RQD = (cumulative length of core above 10cm / drilling length) $\times$ 100%. | Ruler, simple to calculate, but it needs drilling and coring, the result is greatly affected by drilling tools. | High cost and time consuming, seriously affecting the construction. |

$V_{pr}$—P-wave velocity of rock(m/s); $V_{pm}$—P-wave velocity of rock mass (m/s); $n_1, n_2, \ldots, n_n$—Total number of joints in each group on the survey line; $L_1, L_2, \ldots, L_n$—Length of line perpendicular to each joint direction (Generally equal to or equal to 5m)
3. Layout Design of Quick Test for the Integrity Coefficient of Rock Mass KV

3.1 Optimal ranging of trigger and receiver
According to my previous research [7], when using the acoustic wave propagation method to test the wave velocity of rock mass, when the integrity of rock mass is "complete", the space between the matching conservative structural planes is more than 1.5m. Therefore, when selecting the number and distance of trigger point and receiver point, the principle of meeting the longest distance measurement greater than 1.5m is adopted.

3.2 Layout of Testing Area in "∴" Configuration
According to the excavation method of the tunnel face, the tunnel face is divided into 1-3 survey areas, and the "∴" configuration survey area is arranged best, which is divided into three survey areas, i.e. lower left, upper middle and lower right, because it can best represent the whole tunnel face. In the layout of the "∴" configuration measuring area, the series measuring line of the tunnel face transducer is in the form of "three-phase socket" on the plane (tunnel face) (Figure 1), which is actually in "L" configuration in the space. The so-called "L" configuration refers to that each measuring area contains one trigger point layout line and one receiving transducer in series. The two lines are in a vertical state, approximately "L". One side of the "L" is the receiving transducer in series and the other is the transmitting transducer.

Fig. 1 Layout of test transducer on the tunnel face

6 receiving transducers are arranged at equal intervals of 25cm on each receiving transducer line. 4-8 trigger points are arranged at 10-30cm intervals on the layout line of each trigger point. Each test point is triggered by 6 receiving transducers at the same time, i.e. 6 acoustic pairs are generated. When there are 6 trigger points, 36 acoustic pairs can be generated, thus forming a CT tomographic effect that can represent a test area. The closer the distance between adjacent trigger points or adjacent receiver points, the finer the tomographic effect and the higher the resolution [8].

3.3 System Design of Six Point Series Fixed Receiver Transducer
When selecting the hole-outside trigger and hole-inside receiver mode, 6 transducers are fixed in series with ABS tube to form a series fixed receiving transducer system, which can realize the quick test of one trigger and six receivers. The 6 transducers location are relatively fixed, distributed at 25cm equal spacing, in the shape of rods, and are mainly used for the test mode of hole-inside receiver.
In view of the above layout requirements of receiving transducer, we specially designed and manufactured a six point series fixed receiving transducer rod system (Figure 2). Each rod is connected with two ABS tubes by thread, and 6 transducers are implanted into ABS tubes by grafting. When not in use, it can be disassembled into two sections for packing and storage.

![Fig.2 Structure graphing of receiving transducer link system](image)

4. Field Test and Pretreatment of Rock Block (Mass) Wave Velocity

4.1 Test Process Design
The data collection process of the overall test is as follows: basic observation of the tunnel face - selection of test layout method - fixed point marking of the tunnel face - wave velocity test - qualitative evaluation input of correction index - data processing and conclusion evaluation - output of the result report.

4.2 Test Process
After the identification record of the test point and debugging instrument, the data collection can be carried out. Take the "three-phase socket" type line layout method in "\(\ldots\)" configuration test area as an example: Firstly, insert six point series fixed receiving transducer rod into the blast-hole of test area 1; Secondly, take the blast-hole orifice as the starting point, trigger one by one at four to six different distance trigger points from near to far, so that 24 to 36 wave curves can be obtained in test area 1; With this kind of extrapolation, 24 to 36 wave curves can be obtained in test area 2 and test area 3, that is, 72~108 wave curves are obtained in the whole tunnel face. The on-site original data is preliminarily sorted out to meet the requirements of computer input and processing methods. It mainly includes the basic steps of disintegration, editing, extraction and true amplitude recovery.

4.3 Waveform Analysis and Eigenvalue Extraction
(1) Spectrum analysis
It is necessary to distinguish the difference of frequency characteristics between the effective signal and the interference signal, so as to suppress the interference and highlight the effective signal with a suitable frequency filter [9-10].

If the seismic trace is \( f(t) \) and frequency spectrum is \( F(\omega) \), then

\[
F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt
\]

Its amplitude spectrum is:

\[
|F(\omega)| = \sqrt{[\text{Re}F(\omega)]^2 + [\text{Im}F(\omega)]^2}
\]

Phase spectrum is:

\[
\phi(\omega) = \tan^{-1} \frac{\text{Im}F(\omega)}{\text{Re}F(\omega)}
\]

Frequency division filtering can be used:
\[
F'(\omega) = F(\omega) \cdot H(\omega)
\]

\(H(\omega)\) is a band-pass filter in the formula. Then does the inverse Fourier transform to get:
By examining a series of $f'(t)$, we can find out the frequency band range of shallow, medium and deep effective signals and interference signals.

(2) Correlation analysis
The function of correlation analysis can be used to analyze the similarity degree between channels, calculate the static correction time shift, and perform seismic wavelet extraction and correlation filtering [11].

(3) Eigenvalue extraction
After simple processing, the effective signal is clearer. Next, for the processing of each waveform, only three links are needed: the initial (time) value $T_0$ extraction, the termination (time) value $T_i$ extraction, the trigger and the receiver distance confirmation, and the corresponding rock mass wave velocity value of the line can be calculated as

$$\vartheta_{pr} = (T_i - T_0) / L_i$$

5. Analysis and Processing Method of Wave Velocity Data of Rock Block and Rock Mass

5.1 Solution Principle and Process of Asymptote Method
(1) Solution principle of asymptote method
Among the many waveforms obtained by wave velocity test, the length of test line (point distance between trigger and receiver) is widely and regularly distributed in the range of 20-240cm, which has significant statistical significance. The shorter the test line is, the fewer the structural planes it crosses, the closer the wave velocity value obtained is to the rock block wave velocity; the longer the test line is, the more structural planes it crosses, the closer the wave velocity value obtained is to the rock mass wave velocity of the whole test area. Based on a certain scale of test data, with the longitudinal wave velocity of $\vartheta_p$ (m/s) as the ordinate and the test line distance of $d_i$ (m) as the abscissa, the test distance~wave velocity curve can be drawn. The upper asymptote of the curve represents the rock block wave velocity $\vartheta_{pm}$, and the lower asymptote represents the rock mass wave velocity $\vartheta_{pr}$ (Fig. 3).

(2) Determination of representative value of P-wave velocity of rock block and rock mass in a single survey area
Taking a single test area as the basic analysis unit, the test distance~wave velocity curve in the test area is drawn, and the upper asymptote of the curve is the representative value of rock block wave velocity $\vartheta_{pm}$, and the lower asymptote is the representative value of rock mass wave velocity $\vartheta_{pr}$.

(3) Method description
Based on the principle of asymptote, the wave velocity of rock block in each test area is larger, and the wave velocity of rock mass is smaller. If the integrity coefficient is calculated according to the test area, the integrity coefficient calculated is smaller, that is, it is more safe and conservative. In order to reduce or avoid the influence of this kind of error, when determining the wave velocity of rock block and rock mass in the tunnel face, we prefer to use the each average value of the test area which conforms to the deviation limit. When the deviation exceeds the limit, the maximum value of rock block wave velocity and the minimum value of rock mass wave velocity are removed, so as to reduce the conservative transition of integrity coefficient calculation caused by the asymptote method.

5.2 Solution Principle and Process of Trend Line Method
(1) Solution principle of trend line method
In the same way as the asymptote method, the first step is to draw test distance–wave velocity curve. A large number of experiments and fitting analysis show that the correlation coefficient of linear function regression analysis is very ideal, generally can reach $R^2 > 0.95$. After the regression analysis model $\vartheta_p = k_1 \cdot d + k_2$ is obtained through analysis, the upper range eigenvalue $d_m$ is substituted into the calculation and results in $\vartheta_p = \vartheta_{po}$, and the lower range eigenvalue $d_r$ is substituted into the calculation and results in $\vartheta_p = \vartheta_{pr}$ (Figure 4). (According to the author's previous research results, the upper limit eigenvalue $d_m$ is 2.4m, and the lower limit eigenvalue $d_r$ is 0.1m.)

(2) Determination of representative value of P-wave velocity of rock block and rock mass in a single survey area

Taking a single test area as the basic analysis unit, draw the test distance–wave velocity curve in the test area and carry out regression analysis, determine the regression model of ideal correlation coefficient ($R^2 > 0.95$), substitute the upper range eigenvalue $d = d_m = 2.4m$ into the regression model calculation and results in $\vartheta_p = \vartheta_{po}$, and substitute the lower range eigenvalue $d = d_r = 0.1m$ into the calculation and results in $\vartheta_p = \vartheta_{pr}$.

5.3 Determination of Representative Value of P-wave Velocity of Rock Block and Rock Mass in the Whole Tunnel Face

Taking the whole tunnel face as the research object, the maximum, minimum, average and deviation of wave velocity of rock blocks in n test areas are calculated. If the deviation is less than 30% of the average value, the average value is the representative value of the longitudinal wave velocity of the tunnel face rock block; If the deviation is greater than 30% of the average value, check and analyze the original data and calculation process, if the data and calculation are correct, remove the maximum value, and take the average value of the wave velocity of the other n-1 test areas as the representative value of the longitudinal wave velocity of the tunnel face rock block.

In the same way, the representative value of P-wave velocity of the tunnel face rock mass can be obtained.

5.4 Determination of Rock Mass Integrity Coefficient

It can be seen from the above section that the methods that can be used to determine the wave velocity of rock block and rock mass are asymptote method and trend line method. In theory, the asymptote method is based on the "limit" principle. The wave velocity of the rock block obtained is larger and the wave velocity of the rock mass is smaller, so the integrity coefficient calculated is relatively small. The trend line method defines the upper and lower limits of the independent variables, that is, the
relative asymptote method reduces the gap between the rock block wave velocity and the rock mass wave velocity, and the calculated integrity coefficient is larger than the former. The asymptote method has a high requirement for the number of test samples and the statistical regularity of the data, especially for the measured curve with obvious convergence. However, in the process of the actual test in the field, it is inevitable that the sample data in some test areas may be limited by the field conditions (such as the test area at vault) or the curve does not have convergence, so the trend line method can overcome such problems.

In conclusion, the trend line method is actually an empirical revision of the asymptote method, which is more in line with the practice of using single hole method or cross hole method to test the wave velocity and calculate the integrity coefficient in the conventional survey and design stage. Therefore, when calculating the integrity coefficient of rock mass, the trend line method with ideal correlation is recommended to calculate the longitudinal wave velocity of rock block and rock mass.

After determining the P-wave velocity of rock block and rock mass in the whole tunnel face according to the above trend line method, the rock mass integrity coefficient can be calculated directly according to the following formula:

$$K_V = \left( \frac{\varphi_{pr}}{\varphi_{pr}} \right)^2$$

### 6. Conclusion

1. Compared with the indexes of volume joint number of rock mass \( J_V \), rock quality designation RQD and average joint spacing \( d_v \), the factor of rock mass integrity coefficient \( K_V \) is the most fully considered and the most reliable index of rock integrity.

2. The "V" configuration test area can represent the whole tunnel face, and the three-dimensional "L" configuration test line can form a good tomographic effect, which together constitute the best test layout. This test method of rock integrity coefficient can achieve the purpose of rapidity test under the premise of global control of the whole tunnel face and different occurrence structural planes.

3. Based on the asymptote method, the wave velocity value of rock block in each test area is larger, and the wave velocity value of rock mass is smaller, that is, the integrity coefficient of rock mass calculated is smaller, that is, it is more safe and conservative.

4. The trend line method is an empirical revision of the asymptote method, which is technically equivalent to the mature single hole method (or cross hole method) wave velocity test. The integrity coefficient obtained is accurate and reliable, which can lay a key technical foundation for the rapid classification of surrounding rock and the research and development of equipment system during the tunnel construction period.

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