The application of geological advanced prediction in tunnel construction

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Abstract: This article studied the theoretical composition of tunnel geological prediction (TGP), put forth the concepts of broad-sense TGP, narrow-sense TGP and comprehensive TGP and established a technical solution of broad-sense TGP on this basis, including three steps: macroscopic prediction of unfavorable geologies in the tunnel area, prediction of unfavorable geological bodies in the tunnel (i.e.: narrow-sense TGP) and alarm on approaching of geological hazards in the tunnel. The article also researched the methods and technical means of short-term geological prediction and long-term geological prediction of narrow-sense TGP and proposed a fault parameter prediction method, a surface geological body projection prediction method and a precursor prediction method of unfavorable geological bodies in the tunnel. In addition, the article also introduced the concept of alarm on approaching of geological hazards in tunnel construction and established a method for alarm on approaching of geological hazards in the tunnel. In the end, the article concluded that the implementation of comprehensive prediction is the most effective means to achieve expected prediction effect and increase prediction accuracy.

1 Introduction

The 21st century is a century of exploitation of underground space as a resource, also a century of Western Development of China. China is a mountainous country. Two thirds of its national territorial area is mountains and plateaus. The large-scale development of railway and highway transport projects, hydropower projects, South-to-North Water Diversion Project, mine projects and military and protective projects all involves construction of enormous mountain tunnels, long tunnels in particular. We can see this century will witness great progress in Chinese tunnel construction.

Tunnels usually refer to the engineering works used as underground passages. By characteristics of wall rock, tunnels are classified into two categories in general. One category is rock tunnels, built in rock strata. As rock tunnels are mostly built in mountains, they are also called mountain tunnels; the other category is soft soil tunnels, built in soil strata or quasi-soil strata. As soft soil tunnels are often built under water or urban overpasses, they are also called underwater tunnels or urban road tunnels. Due to the complexity and variability of geological conditions in the longitudinal direction, railway and highway tunnels bear the characteristics of both rock tunnels and soft soil tunnels. As tunnels are also located in underground rock masses with complex hydrogeology and engineering geology, the precondition for safe and high-quality tunnel construction without future troubles is to get to know and foresee surrounding hydrogeological and engineering geological conditions. Following enormous construction of mountain tunnels, geological work of tunnel construction as a necessary step of tunnel construction certainly will be widely popularized.

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Geological work of tunnel construction is conducted after design submission, in tunnel construction stage and throughout construction process.

With regard to geological work of tunnel construction, in foreign countries, general work has been done universally and academic research also has reached a certain depth, but all-round and systematic geological work of construction and academic research is yet to be done. In China, general work is conducted only in a minority of tunnels and basically is still in a starting stage, and academic research is seldom reported and not deep. In order to avoid the blindness of tunnel excavation and construction, we must do well in geological work of tunnel construction.

Tunnel geological prediction (TGP) is a key link of geological work of tunnel construction. Its importance goes without saying. Following the increase of quantity and the enlargement of scale of tunnels to be built, how to implement TGP with "high quality and high accuracy" becomes an urgent and important issue. A major measure for fast construction is elimination of geological hazards in construction. The most effective means to eliminate geological hazards in construction is to do well in TGP [2].

2 Concept and Technical Solution of TGP

TGP includes broad-sense TGP and narrow-sense TGP.

Broad-sense TGP is a generic term of prediction of geological hazards inside and outside the tunnel during tunnel construction, and consists of three parts of content or three steps: macroscopic prediction of unfavorable geologies in the tunnel area, prediction of unfavorable geological bodies in the tunnel (i.e.: narrow-sense TGP) and alarm on approaching of geological hazards in the tunnel.

Macroscopic prediction of unfavorable geologies in the tunnel area is a precondition and basis of prediction of geological hazards during tunnel construction, and the first step. From macroscopic prediction of unfavorable geologies of a tunnel on the basis of analyzing geological condition in the tunnel area, we may know the type, scale and possible location and direction of unfavorable geologies that might be encountered during tunnel construction, and may also know the possibility that these unfavorable geologies induce geological hazards during construction, the type and intensity of the geological hazards and their impact on tunnel construction. Therefore, only under the guidance of the principle of macroscopic prediction of unfavorable geologies of the tunnel, can we more accurately and more effectively predict unfavorable geological bodies in the tunnel and geological hazards during construction. The former is the work basis of the latter two.

The basis of macroscopic prediction of unfavorable geologies in the tunnel area is analysis of geological conditions of the tunnel. This is because most of the unfavorable geological bodies of a tunnel constitute a part of stratum, geological structure or karstic geological body in the tunnel area. For example, cores of folds, fault fracture zones, steeply inclined rock strata and interlayer sliding faults are parts of a geological structure; karst caves, underground rivers and karst silt zones are parts of a karst geological body. Whether they will meet with the tunnel not is closely related to the erosion basis to the tunnel area; high pressure high concentration gassy seams, old coal kilns and goafs are parts of a coal seam stratum.

Precondition of analysis of geological conditions of a tunnel: on the basis of the tunnel design specification and design drawings submitted by a design institute, the geological technicians for tunnel construction conduct in-depth and detailed surface geological review or survey on the strata (coal seam strata in particular), geological structure, karst and hydrologic regime of the tunnel area again. As the accuracy required in the design stage is limited, the tunnel design specification and design drawings submitted by the design institute only roughly describe major unfavorable geologies and construction-related geological hazards of the tunnel. As far as the analysis of geological conditions of the tunnel and the analysis of geological conditions of the tunnel needed by macroscopic prediction are concerned, the submitted data is far from enough in research depth, and also has a gap in accuracy.

3 Prediction of Unfavorable Geological Bodies in the Tunnel

Prediction of unfavorable geological bodies in the tunnel (narrow-sense TGP, "TGP in the tunnel" for

short, the same below) is the second step of broad-sense TGP.

At present, enormous work has been done on TGP in the tunnel in construction practice at home and abroad, but scientific research is still in a state of "piling" of scattered and sporadic raw data or results. It not only does not ascend to a certain height of theoretic research but also lacks in-depth and systematic research findings.

3.1 Long-Term TGP

A rock strength reduction zone is shown in Fig. 1. Practice has proved that in every fault influenced zone, there is a change zone of physical and mechanical properties of rocks, which faces the direction of the fault and shows reduction of rock strength. From the perspective of geomechanics, the mechanical mechanism for existence of this change zone is as follows: in the process of generation of the fault, the instant violent displacement of the rocks on the two walls inevitably generates a local stress field in the walls. The strong internal stress not only may form folds, joints (minor faults) and other macroscopic structures inside the fault influenced zone but also will form numerous microscopic structures in a certain width of rock mass near the fault, particularly a large number of microscopic fissures. The latter is the fundamental reason for strength reduction of the rocks in a certain range on the two sides of the fault.

Rock strength reduction zone consists of a gradual reduction zone and a dramatic reduction zone.

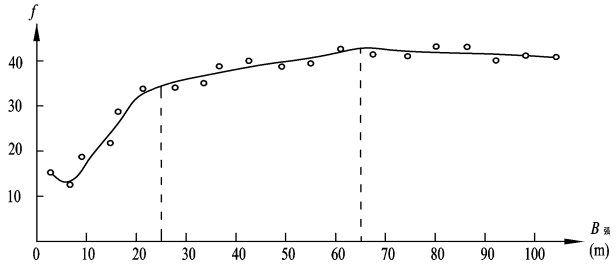


Fig. 1 Two inflection points of the rock strength reduction zone

The dramatic reduction zone of rock strength is almost in the range of the fault fracture zone and is meaningless to both long-term and short-term TGP.

According to the rough distribution characteristics of discrete points, the type of a functional equation of an approximation curve that can represent scatter distribution law is preliminarily determined. Data fitting method is used to repeatedly compare the preliminarily determined curve equation with other types of curve equations to get an optimal curve equation.

The least square method is used to determine the coefficients and constants of the optimal curve equation.

Expression of the functional equation:

$$f(x) = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$$

At point x_i, the difference between function value and measured value y_i is:

$$r_i = f(x_i) - y_i$$

where, r_i-residual.

Residual sum of squares at every measuring point:

$$s = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} \left[f(x_i) - y_i \right]^2$$

Residual sum of squares should be reduced to minimum. If s is regarded as a function of polynomial constant coefficient, then according to the principle of function value in mathematical analysis, in order to minimize s, the following condition must be met:

$$\frac{\partial s}{\partial a_i} = 0(i = 1,2,3,\ldots n)$$

$$\text{i.e.: } \frac{\partial\left\{\sum_{i=1}^{n}\left[f(x_i)-y_i\right]^2\right\}}{\partial a_i} = 0$$

From the above expression, the following system of linear equations may be obtained:

$$\begin{bmatrix} S_0 & S_1 & S_2 & \ldots & S_n \\ S_1 & S_2 & S_3 & \ldots & S_{n+1} \\ S_2 & S_3 & S_4 & \ldots & S_{n+2} \\ M & M & M & \ldots & M \\ S_n & S_{n+1} & S_{n+2} & \ldots & S_{2n} \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ M \\ a_n \end{bmatrix} = \begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ M \\ T_n \end{bmatrix}$$

where, $S_k = \sum_{i=1}^{n} x_i^k (k = 1,2,3,\ldots,2n+1).$

$$T_k = \sum_{i=1}^{n} y_i x_i^k$$

a_0、a_1、a_2、$a_3 \ldots a_n$ obtained from the above expression are constant coefficients of the optimal curve equation.

A lot of practice proves that when stratigraphic separation N is ≤5m, the scatters in the scatter diagram are roughly in linear distribution, the optimal curve is a straight line and the optimal functional equation is a linear equation in one unknown.

If the optimal curve equation is a linear equation in one unknown, then the general expression will be $y = a_0 + a_1 x$, $\frac{\partial S}{\partial a_i} = 0$, get

$$\begin{bmatrix} S_0 & S_1 \\ S_1 & S_2 \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \begin{bmatrix} T_0 \\ T_1 \end{bmatrix}, \text{ i.e.: } \begin{cases} S_0 a_0 + S_1 a_1 = T_0 \\ S_1 a_0 + S_2 a_1 = T_1 \end{cases},$$

so

$$\begin{cases} a_0 = \dfrac{S_2 T_0 - S_1 T_1}{S_2 S_0 - S_1^2} \\ a_1 = \dfrac{S_1 T_0 - S_0 T_1}{S_1^2 - S_0 S_2} \end{cases}$$

where, $S_0 = \sum_{i=1}^{n} x_i^0 = n$; $S_1 = \sum_{i=1}^{n} x_i^1$; $S_2 = \sum_{i=1}^{n} x_i^{\,2}$; $T_0 = \sum_{i=1}^{n} y_i x_i^{\,0}$; $T_1 = \sum_{i=1}^{n} y_i x_i^1$.

In order to combine with TGP, the expression of linear equation is rewritten into $B = a_1 N + a_0$, then

$$\begin{cases} a_0 = \dfrac{\sum_{i=1}^{n} B_i \times \sum_{i=1}^{n} N_i^2 - \sum_{i=1}^{n} N_i B_i \times \sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} N_i^2 \times n - \left(\sum_{i=1}^{n} N_i \right)^2} \\ a_1 = \dfrac{\sum_{i=1}^{n} N_i B_i \times n - \sum_{i=1}^{n} B_i \times \sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} N_i^2 \times n - \left(\sum_{i=1}^{n} N_i \right)^2} \end{cases}$$

The above formula is applied in the practice of engineering prediction. Its accuracy may meet the requirements of engineering construction.

3.2 Short-Term TGP

At present, only one detection means is adopted in most cases at home and abroad, such as: geological radar, infrared [14] and sound wave detector. In China, a face compiling record method and advance drilling are also used for short-term TGP. This article established a method for prediction of unfavorable geological bodies in the tunnel and studied the face compiling record method in depth. Similarly, in prediction practice, two or more than two methods and means are comprehensively used to achieve the purpose of verifying each other, making the best of the both worlds and improving prediction effect. Particularly, during short-term prediction applying geological radar and other geophysical prospecting means, it is more suitable to combine them with at least another short-term geological analysis method because the result of geophysical prospecting often has multiple solutions and limitation, and only the combination of multiple means can turn multiple solutions of the result of geophysical prospecting into a single solution.

Short-term TGP is prediction conducted on the basis of long-term TGP, so the main task of short-term TGP is to more accurately predict the following information in a range of 15~20m, maximum 30m in advance of face: possible rock stratum, nature of adjoining unfavorable geological bodies, possible nature of underground water bodies, extension of unfavorable geological bodies at or near face towards the front of face, and grade of wall rock. Different prediction methods and technical means may result in different prediction distance, accuracy and effect. If at least two of the abovementioned methods and technical means are adopted to implement comprehensive short-term TGP, the general technical indexes that should be achieved include:

Prediction of distance: It may reach 20m in advance of face; prediction of the nature of fault fracture zone and most unfavorable geological bodies: Full accuracy may be achieved; prediction of the positions of unfavorable geological bodies: The accuracy may exceed 95%; prediction of the scale of unfavorable geological bodies: The accuracy may exceed 90%; it may predict both the existence of water enriched zones and the nature of underground water bodies; both the relative quality and accurate grade of wall rock.

Short-term TGP focuses on the sections with complex geological conditions during tunnel excavation and advancement on the basis of long-term TGP.

Basic principle:

In most cases, the position, sequence, thickness, lithology and stratal combination of surface rock strata correspond to the position, sequence, thickness, lithology and stratal combination of the rock strata in the tunnel. By applying this principle, we may compare the position, sequence, thickness, lithology and stratal combination of surface rock strata obtained from surface geological review and survey with the rock strata at and near the face. When it is confirmed that the rock strata exposed at and near tunnel face are identical to the characteristics of a rock stratum on ground surface, we may deduce the position, thickness, lithology and strata combination of the rock stratum that will appear in a certain range in advance of face as well as its position in the tunnel, as shown in Fig. 2.

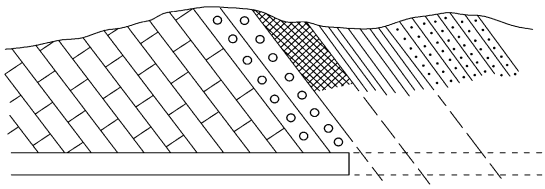


Fig. 2 Short-term prediction of rock strata in the tunnel

4 Alarm on approaching of Geological Hazards in the Tunnel

The technology for alarm on approaching of geological hazards in the tunnel, i.e.: the technology for monitoring and judgment on approaching geological hazards in the tunnel, is a core task of broad-sense TGP, also its third step. It is to judge whether geological hazards will occur in front of the working face during tunnel advancing when the unfavorable geological bodies stated in short/long-term TGP are drawing near, and to make further confirmation when the unfavorable geological bodies are drawing near so as to work out a construction improvement plan and reinforcement measures in time, and avoid occurrence of geological hazards. Therefore, we may say all other geological work of tunnel construction, such as: macroscopic prediction of unfavorable geologies in the tunnel area, long-term and short-term TGP, and wall rock stability evaluation, serves alarm on approaching of geological hazards in the tunnel and centers on it in the final analysis. It assumes a very important position in geological work of tunnel construction. Alarm on approaching of geological hazards in the tunnel is based on long-term and short-term TGP, mainly by method of monitoring and judging approaching unfavorable geological bodies.

5 Conclusion

TGP includes broad-sense TGP and narrow-sense TGP. Broad-sense TGP is a generic term of prediction of geological hazards inside and outside the tunnel during tunnel construction; narrow-sense TGP is geological prediction of unfavorable geological bodies inside the tunnel during tunnel construction.

The combination of long-term and short-term TGP and alarm on approaching of geological hazards during construction is called comprehensive TGP. A lot of construction practice proves that only combining geological methods with physical methods, inside the tunnel with outside the tunnel, and long-term prediction with near-term prediction and implementing comprehensive prediction can achieve the purpose of verifying each other, making the best of the both worlds and improving prediction effect.

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