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The Informational Dynamic Design and Construction Technology Application in the Soft Rock Tunnel

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Abstract: Informational dynamic design and construction technology are emerging new technologies at home and abroad. There are many applications in deep foundation pit stability, side slope stability, tunnel engineering and bridge engineering. This paper takes the West Qinling soft rock tunnel as an example to discuss engineering pre-design, construction and information collection, and pre-design modifying. Finally, this paper lists some problems in the construction of the soft rock tunnel project.

1. INTRODUCTION

The New Austrian Tunneling Method (NATM) was proposed by the Austrian Professor L.V. Rabcewicz in 1948. The theory holds that the surrounding rock has a certain bearing capacity, and in the process of the construction, the surrounding rock should be protected to the maximum degree, and the self-supporting ability of the surrounding rock should be fully utilized[1-5]. The method considers the surrounding rock mass and various supporting structures as a integrated system, and then guides the design and construction of tunnel support[4-7].

In combination with the practice and the need of the engineering, this paper proposes information dynamic design and construction technology based on the New Austrian Tunneling Method. The main contents of this paper include three aspects: engineering pre-design(before the construction), information collection(during the construction), and the design revision(according to the state of surrounding rock). Based on the dynamic evolution of surrounding rock, the sub-technology are assembled into a total technology according to the principle of simple operation and easy construction. Finally, the rationality and feasibility of the technology are verified by engineering practices, so as to provide reference for the same or similar soft rock engineering.

2. PROJECT OVERVIEW

The West Qinling Tunnel is located in Wudu District, Weinan City, Gansu Province. It is 8.72 kilometers long and 250 meters deep. The tunnel is built in the middle and low mountains of the ridges covered by thick layers of erosion and deposition loess, and the surface trenches are severely cut. The results of geological survey indicate that the surrounding rock of this tunnel is mainly Quaternary sandstone, and the axis of the tunnel mainly passes through the soft rock and extremely soft rock of lacustrine deposit. The lithology is sandstone, pebbly sandstone and sandy mudstone with poor diagenesis and cementation, which are discontinuously distributed in shallow and medium-thick layers.

The in-situ test of the mechanical properties of the surrounding rock was carried out by the bearing plate method. The mechanical parameters of the surrounding rock are shown in Table 1.

2.1 Rock Mass Mechanical Parameters and Surrounding Rock Classification

According to the surrounding rock classification[2] in the "Railway Tunnels Design Code" (TB10003-2005), the ground formation is a Class V surrounding rock according to Table 1.

Table 1 Rock physical mechanical parameters

Name	deformation modulus *E*/MPa	Adhesion *C*/MPa	internal friction angle *φ*/°	uniaxial compressive strength R_c/MPa
Value	1031	0.151	35	0.57
Name	Passion ratio μ	unit weight γ/kg/m^3	porosity	
Value	0.30	2152	26%～30%	

2.2 Surrounding rock pressure of the tunnel

(1) Determine the surrounding rock pressure according to the specifications

The Railway Tunnels Design Code (TB10003-2005) recommends calculating the surrounding rock pressure according to the following empirical formula (1.1):

$$p_0=\gamma b$$
$$b = 0.45 \times 2^{S-1}\omega \qquad (1.1):$$

p_0——surrounding rock pressure, kN / m^2;

γ——bulk density of rock mass, kN/m^3;

b——calculation height of surrounding rock pressure, m;

S——the surrounding rock level;

ω—the tunnel width influence coefficient , $\omega = 1 + i(W-5)$, m；

W——the tunnel span, m;

i——increase/decrease rate of surrounding rock pressure per W 1m increase/decrease, when W <5, i=0.2; when W>5, i=0.1.

(2) Calculating the surrounding rock pressure according to the Platts theory

Platts theory is suitable for calculating the surrounding rock pressure of deep tunnels in loose formations. According to Platts theory, the surrounding rock pressure can be calculated according to formula (1.2):

$$p_0=\gamma b$$
$$b = \frac{a_1}{f} = \frac{a + H \times \tan(45° - \frac{\phi}{2})}{f} \qquad (1.2)$$

p_0 - surrounding rock pressure, kN / m^2;

γ—— bulk density of rock mass, kN/m^3;

b——pressure arch height, m;

H——the height of the tunnel, m;

$a1$——pressure arch half span, m;

a——tunnel half span, m;

f —— Rock solidity coefficient. For loose rock mass, soil and sandy soil, $f \approx \tan\varphi$ [7];

φ——internal friction angle, degree.

(3) Confirm the surrounding rock pressure by experience

Terzagh gives a load height empirical algorithm. As for a fully fractured surrounding rock , the load height is 1.10 × (W + H) (W - tunnel span, m; H - tunnel height, m). Bill Bowman gives the empirical value of the top formation pressure. As for gravel and particularly broken rock formations, the top formation pressure takes 0.20-0.25 MPa.

According to the surrounding rock pressure calculation method listed above, the surrounding rock pressure of tunnels with different sections is calculated (Table 2).

Table 2 Calculation Results of Tunnel Surrounding Rock Pressure(MPa)

Methods	Tunnel Section Size $W \times H$ 6.0 m× 7.0 m
Platts Theory	0.21
Specification	0.17 (Only related to tunnel span W, regardless of height H)
Terzagh	0.15
Bill Bowman	Excavation (0.20～0.25)MPa，Aftermath 0.35 MPa，Strong pressure, need strong support with small spacing
Value of This Project	0.18

3. THE APPLICATION OF NATM

This mountain tunnel project adopts the NATM. According to the flow of the information dynamic design and construction technology (Fig.1), the information dynamic design and construction technology are divided into three parts in practice：engineering pre-design, construction and dynamic information collection, and the reversion of the design. The initial excavation is guided by the pre-design. With the advancement of the tunnel face, the information is collected in time to analyze whether the surrounding rock is safe and stable, so the pre-design can be revised accordingly. Execute the loop until all the projects are completed.

On the basis of engineering pre-design, various dynamic information about the stability of the surrounding rock and the working state of the supporting system are obtained through on-site observation and measurement. Then the necessary mechanical calculations and theoretical analysis are carried out to evaluate the surrounding rock and supporting system's safety and economical efficiency according to some criteria, in order to modify the supporting system's design parameters, support timing and construction countermeasures. If the geological conditions change, the surround rock level of tunnel face should be redetermined according to the new geological descriptions, and then adjust the support system, construction method and construction organization accordingly. The analysis results of the dynamic measurement information should be promptly fed back to the engineering design and construction, so the engineering pre-design parameters will be further revised and improved, and the project construction will achieve the expected goal of safe, efficient and economical.

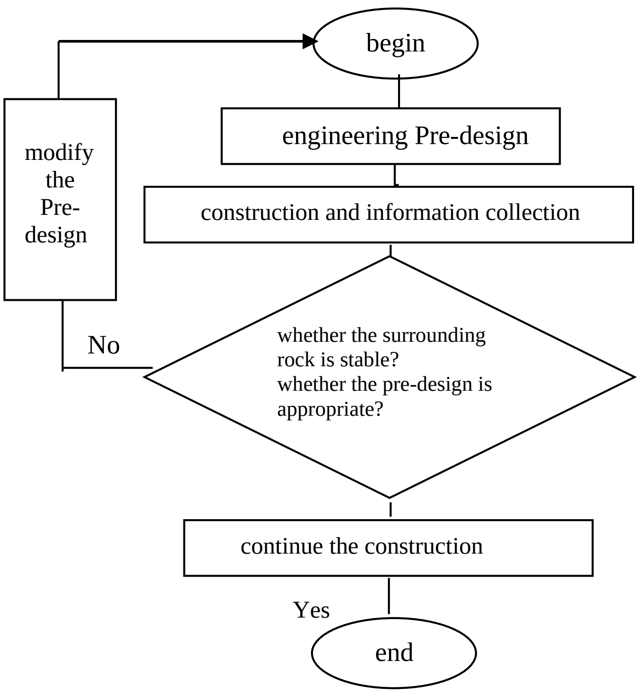


Fig. 1 Process of informational dynamic Design and Construction Technology

3.1 Engineering Pre-design Before Construction

Engineering pre-design is the technical basis and foundation of construction, information collection and design reversion. Based on the relevant requirements, engineering geological conditions, rock mechanics parameters, surrounding rock classification, tunnel's surrounding rock pressure and other related materials, the pre-design embarks the works on the tunnel section size, supporting structure form, preliminary parameters, construction technology, etc. Finally, the engineering construction drawings will be formed. Here the author will focus on the supporting structure form and the construction technology.

3.1.1 The form of supporting structure

Considering the engineering geological characteristics, use characteristics, and the requirement for convenience and economical, supporting structure form of this project is determined as steel frame-mesh reinforcement shotcrete support. The most important feature of steel frame (or steel grating) support is that it can be immediately loaded after erection,so it is suitable for soft broken or terrene surrounding rock support. Under the same model or member section conditions, with the reduction of steel frame spacing the carrying capacity will be greatly improved, so the form has a strong adaptability to the earth pressure. In order to improve the integrity of the support system, steel frame support is used in combination with shotcrete and steel mesh. Because of the pipe sticking and hole collapse when drilling in the gravel layer , the anchor support is not selected.

The advanced support learns from the concrete arch shell construction method, and the steel frame and the steel mesh are inserted into the arch groove instead of backfilling the concrete or mortar. After the gallery is excavated, the steel frame is used as a part of the supporting structure. This advanced support method fully utilizes the advantages of. the steel frame, and the process is relatively simple.

3.1.2 Construction Technology

The West Qinling Tunnel is constructed by the NATM. The construction method of "short-scale footage, weak blasting, strong support and diligent measurement" is adopted for the full-section cycle operation. Tunnel excavation works close with initial anchor, spray, net and steel arch support. The project combines the drilling and blasting method with mechanical excavation(RD-80 excavator). The RD-80 excavator relies on the rotary drilling cutting into the surrounding rock, so the disturbance to the surrounding rock is small, and the tunnel is formed according to the tunneling section, and the strength of the weak surrounding rock is maintained and fully exerted.

3.2 Dynamic information collection and results

Information collection is the technical link in the entire informational dynamic design and construction technology. It is the basis for judging the surrounding rock and the engineering pre-design, as well as the basis for revising the pre-design. The dynamic information collection is achieved by on-site measurement, and the measurement results are analyzed and the design is corrected based on the measurement reference value and the development of the safety management mechanism.

The principles for choosing the measurement project are as follows: simple process, reliable results, low cost, easy to implement, analyze and feedback. In order to correctly reflect the dynamics of surrounding rock and support structure, these on-site measurement projects are arranged: the observation of the cave inside, the monitoring of the surrounding rock surface, the monitoring of the internal displacement of the surrounding rock, geological advance forecast.

3.2.1 Cave Inside Observation

The cave inside observation is essentially an "experience analogy". The observations include the observations of the tunnel face and the constructed section. The observation survey of the constructed section should be recorded according to the actual conditions, and each cycle operation should be observed once to facilitate the analysis of the anomaly and the prediction of the development trend. During the construction period, the following main phenomena were observed in the cave:

(1) The cavern is completely located in the gravel layer, and the stability of surrounding rock is relatively good. Excavating is difficult. After blasting, there is a block of rock mass, and the tunnel face is stable without falling block. The surrounding rock has a long period of self-stabilization.

(2) The supporting structure has no deformation abnormality. The shotcrete has no cracking, and the steel bracket has no deformation abnormality.

3.2.2 Convergence Measurement of Surrounding Rock Surface in the Cave

The most obvious manifestation of the deformation of surrounding rock caused by underground excavation is the shrinkage of the clearance in the cave. The change of clearance in the cave refers to the relative displacement value of the two relatively fixed points on the perimeter of the tunnel. It is the most intuitive and important information for judging the surrounding rock dynamics, and it is also the main content of the on-site monitoring and measurement.

The initial reading of the first measurement is the key data. According to the specifications, the measuring point is set within 1 meter from the tunnel face, and the workers take the initial reading within 12 hours after excavation(before next excavation) of the tunnel face. The initial readings should be read repeatedly. When the error of 3 consecutive measurements is less than 0.18mm, the drilling can continue. The arrangement of measuring points is shown in Figure 2. The monitoring results of the convergence of the surrounding rock surface are shown in Table 3.

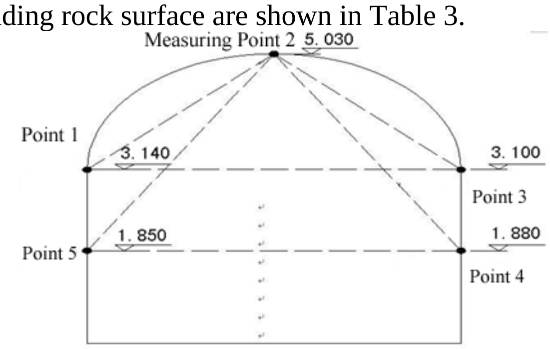


Fig. 2 Arrangement plan for measuring points

Table 3 Statistical data of rock surface convergence monitoring

Monitoring Number	Monitoring days (*d*)	Maximum Convergence Value(*mm*)	Maximum Convergence Rate ($mm \cdot d^{-1}$)	Average Convergence Rate ($mm \cdot d^{-1}$)
1—2	17	1.83	0.85	0.26
1—3	17	1.33	1.08	0.43
3—2	17	0.99	0.94	0.48
4—2	13	0.78	0.78	0.26
4—5	13	0.74	0.71	0.28
5—2	13	0.79	0.66	0.31

3.2.3 Internal Displacement Measurement of Surrounding Rock

By drilling holes in the surrounding rock around the tunnel and embedding displacement gauges at different depths in the hole, the relative displacement value between the measuring points on the surrounding rock surface and the measuring points inside the surrounding rock is measured (principles and results are shown in Figure 3 and 4). According to the relationship between the displacement of the surrounding rock and the depth, the extent of the loose zone and the elastic zone of the surrounding rock after excavation could be concluded

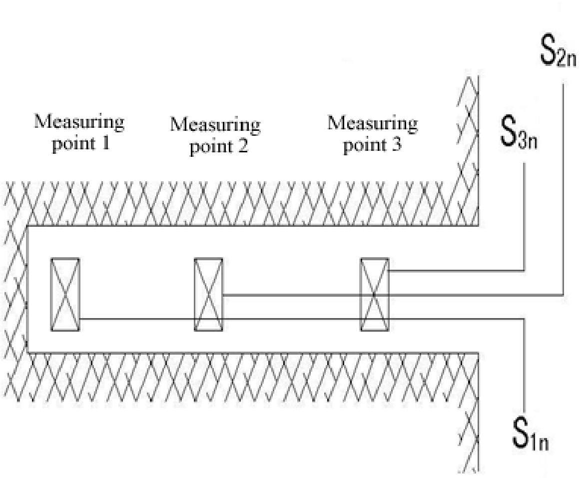


Fig.3 Interior of wall rock displacement measurement principle

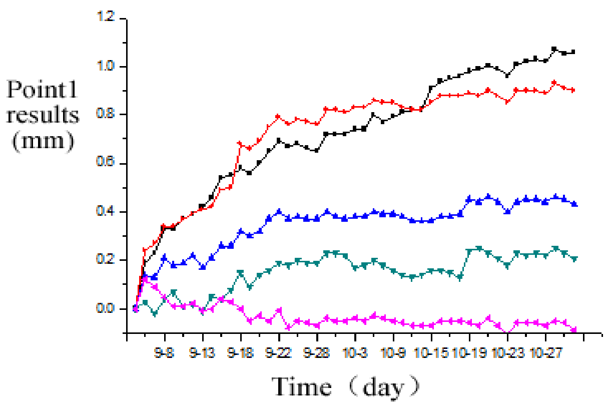


Fig.4 Displacement measurement result of surrounding rock interior

3.2.4 Geological Advance Prediction

After comparative analysis of the geological survey method, drilling method and geophysical prospection, this project chooses the drilling method to carry out geological advance prediction. The specific method is, with the advancement of the tunnel face, to drill a 6m deep hole at the top of the cave and the center of the tunnel face every 10m, in order to find out whether the geological conditions around the hole are changing.

3.3 Design Revision

The design reversion is based on the pre-design and information collection. The fundamental purpose is to build a tunnel that is both safe and economical. In order to overcome the limitations and shortcomings of engineering pre-design, it is necessary to master the measurement reference value and continuely compare it with the on-site measurement dynamic data, so as to make partial corrections or fundamental modifications to the pre-design in time to ensure safety.

3.3.1 Measurement benchmark value determination and measurement result comparison

The setting of the measurement reference value is a key issue in the information dynamic design and construction technology, and it determines whether to modify the design.

3.3.1.1 Observation Value in the Hole

For the observation items in the cave, it is necessary to pay attention to the various deformation anomalies listed in Table 4 in time, and corrective measures must be taken after such deformation abnormalities occur.

Table 4 Several serious deformation abnormality

Abnormal Deformation Parts	Abnormal Deformation Situation
Tunnel face and its around	Sand interlayer, sand layer or quicksand layer
	Instablized
	Falling block increase
	Lack of support strength, subsidence increased
Shotcrete layer	Stripping or abscission
	Stress increase,causing cracks or shear failure
Steel support	Stress increase, causing yield deformation

Considering the surrounding rock of the tunnel has good stability and a long self-stabilization time, and the supporting structure has no deformation abnormality, besides the shotcrete has no cracking, and the steel bracket has no deformation abnormality, so the weakening support correction could be exerted.

3.3.1.2 The reference value of the surface convergence measurement of the surrounding rock in the *cave*

Refer to "Technical Specifications for Anchor Concrete Support" GB50086-2001, the allowerd relative displacement values of the tunnel surrounding are shown in Table 5.

Table 5 The relative value of tunnel around allowable displacement（％）

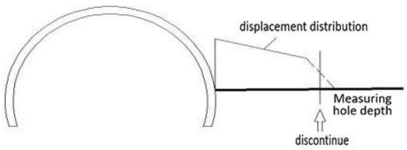
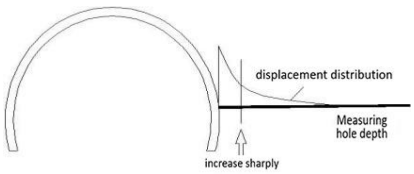
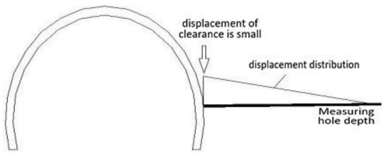
Level of surrounding rock	Buried Depth(m)		
	＜50	50～300	＞300
III	0.10～0.30	0.20～0.50	0.40～1.20
IV	0.15～0.50	0.40～1.20	0.80～2.00
V	0.20～0.80	0.60～1.60	1.00～3.00

For a tunnel with a depth of 50 to 300 m and a surrounding rock class of Class V, the relative displacement of the surrounding displacement is 0.60 to 1.6%. From the safest point of view, take 0.6%. Taking the maximum convergence amount in Table 3, the results are all less than 0.6%, indicating that the deformation of the surrounding rock has not reached the ultimate deformation value, and the tunnel is in a stable state.

3.3.1.3 Reference value of internal displacement measurement of surrounding rock

The internal displacement measurement reference value is the same as the relative clearance measurement reference value. It is also necessary to judge the range of the surrounding rock loose zone according to the internal displacement mode in Table 6.

Table 6 A model and judgement of displacement inside the surrounding rock

Models of displacement inside the surrounding rock	Results
	There is a discontinuous surface inside the surrounding rock, which is the maximum position of the loose area.
	A loose zone is created near the wall of the tunnel, which has the risk to generate anaphase loads.
	The hole (displacement meter) is insufficiently deep and the end point is in the loose zone and cannot be regarded as a fixed point

It can be seen from Fig. 4 that the thickness of the surrounding rock loose circle at the wall waist is about 5 m, and the thickness of the vault loose ring is 3 to 4 m. If the thickness of the vault loose ring takes 4 m, the vertical surrounding rock pressure is about 0.09 MPa. The pre-designed support resistance is approximately 0.3 MPa.

3.3.2 Correcting pre-designed conditions

During the construction process, the observation and record of the surrounding rock condition should be carried out immediately after the tunnel excavation, and the engineering geological characteristics should be described. After the completion of the support, the surface of the sprayed layer should be observed and recorded; The predetermined analysis and prediction methods should offer the change law and the predicted final value according to pre-determined methods. Judging from the above analysis, if it is considered that the relevant support and construction parameters meet the expected requirements of the pre-design, the construction will continue according to the pre-design parameters. If the expected requirements are not met, the pre-design parameters should be corrected.

The main contents of the amendment method are to strengthen the support, change the construction method and weaken the support. The specific measures for the three cases are shown in Table 7.

Table 7 The contents of modified design methods

	Strengthen the support	Change construction methods (reinforcement)	Weaken the support
Contents	·adding more steel frames ·increasing the thickness of the shotcrete layer ·adding the horizontal support to the steel-arch arch bridge ·advanced support for archway method ·adding the horizontal beam to form the closed supporting ring ·changing the shape of section （straight wall to curved wall ）	·shortening the cyclical footage and controlling the degree of surrounding rock disturbance ·division excavation, retaining core soil during excavation ·reducing the time between excavation and support ·spraying concrete early and spraying concrete on the tunnel face ·thickening the concrete at	·increasing the spacing of the steel frame ·reducing the thickness of the spray layer ·full-section excavation, increasing the cyclical footage

		the foot of the supporting structure to increase the bearing area	

3.4 Revise the Design

According to observation and measurement results, engineering experience, surrounding rock conditions and construction methods, considering the shotcrete has no cracking and deformation anomaly, the measured values of the internal and surface displacement of the surrounding rock are slow, and the accumulated value is small, and the thickness of the rock loose zone is only 3~5m. It can be seen that the pre-design is safe and reliable, and the distance between the steel frames can be appropriately increased to speed up the construction progress.

4. Problems in applications of NATM

4.1 On-site monitoring

Problems are as follow: lack of effective on-site measurement methods and technical means in the construction, lack of accurate drilling and blast design and support construction basis, construction waste and safety hazards.

4.1.1 Prospects Based on the NATM

Due to the complexity of rock mass formation and geological processes, the complexity of construction conditions, and the precise requirements of the NATM for design parameters, many measurement are needed to monitor surrounding rock and supporting structure during the construction. The results are used to analyze parameters and modify the design in time, so as to take timely measures to improve the safety of the construction. If the drilling and blasting scheme is formulated according to the measurement results, the smooth blasting effect and safety factor will be improved. The initial support timing is determined by the monitoring of the surrounding rock deformation and the appropriate support means are adopted accordingly to make the rock mass reach its initial yield strength without deformation, so as to prevent the loss of surrounding rock strength and achieve the purpose of fully exerting the surrounding rock bearing capacity.

4.1.2 Construction Status and Problems

(1) Drilling and blasting design is based on experience and lacks accurate on-site measurement value.

At present, the tunnel construction method adopted by the project is the drilling and blasting. The whole process of drilling and blasting can be summarized as: drilling and blasting, shipping out of the raft, spray anchor support, and other support meausres such as ventilation, drainage, power supply,etc. According to the engineering geological conditions and section size, the whole-section excavation is adopted, and the drilling and blasting design of the differential smooth blasting technology is adopted to improve the excavation. However, the ideal effect of the differential smooth blasting is based on the accurate judgment and understanding of the excavation section's surrounding rock lithology. Due to the sharp change of lithological in the site and the poor working environment after the explosion, rapid measurement is difficult to implement.

(2)Due to the large lithological changes, the deformation of the surrounding rock is fast after the explosion. It is difficult to determine the optimal support time of the surrounding rock according to the deformation rate of the surrounding rock.

After excavation of the tunnel, the section of the surrounding rock will definitely undergo deformation-flexion deformation, and the surrounding rock stress will be redistributed to form a new stress balance point, so the surrounding rock gradually reaches a temporary self-stability state. It is difficult to achieve the purpose of tunnel stability(and the optimal use of the surrounding rock's bearing capacity to jointly support the load) according to the monitoring value of deformation,

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especially founding the optimal support time and adopting thin-walled flexible supporting structure closed to surrounding rock to form a rock-support system.

4.2 Support technology

The operation of shotcrete support has obvious problems as follow: untimely construction, thin and uneven coverage, high rebound rate and waste of materials. It can not exert the ideal sealing and cohesive effect,so the support effect is greatly undermined.

4.2.1 Prospects Based on the NATM

The NATM advocates the maximum use of the bearing capacity of the surrounding rock itself. The surrounding rock is allowed to be deformed in a certain degree, but the deformation of the surrounding rock must be controlled within a certain range, so as to fully exert the inherent strength of the surrounding rock to alleviate the huge pressure from the tunnel and reduce the supporting load. The initial support of the surrounding rock is supported by anchor bolts and shotcrete, so that the spray layer and the surrounding rock could be closely combined to form a rock-support system, which could reduce the disturbance to the surrounding rock caused by blasting, and maximally utilize the bearing capacity of the surrounding rock itself.

4.2.2 Construction Status and Problems

(1) There is a problem that the spray anchor support is not in time, which brings certain hidden dangers to the quality and safety of support construction [5].

In the case of better surrounding rock conditions, bolting and shotcrete are used for initial support, but the initial support is not timely sometimes due to factors such as construction delayed or theory lags behind. If the support is not in time, the surrounding rock is likely to be disturbed by the late blasting, resulting in slumping and instability. For the broken surrounding rock with poor self-stability of IV~V, the difficulty lies in the support timing choosing. If support begins until the rock is loose, surrounding rock will lose the opportunity to use its own carrying capacity, besiede it also increases the safety risk of the construction.

(2) There is a problem of uneven thickness of shotcrete, which tends to cause stress concentration and the damage of surrounding rock.

During the construction, the thickness of the shotcrete of the initial support can meet the initial support requirements, but the thickness of the cover is uneven due to factors such as over-under excavation, etc. So that the stress is not distributed evenly in the flexible covered outer arch formed on the surface layer of the surrounding rock. In the case of the situation, cracks appear in the coating layer, and the effect of the shotcrete coating is greatly reduced. At the same time, the deformation of the surrounding rock in the stress concentration portion is intensified and the local gravel is slipped.

(3) The dry shotcrete sneeze coating method has lower utilization rate of shot material and large material waste.

Due to uneveness of the injection angle and the injection surface, the utilization rate of the injection material is low, the construction efficiency is not high, the material waste is large, and the working environment of the dry spray construction site is poor.

4.3 Excavation technology

The application of smooth blasting technology is still immature, resulting in large over-under excavation and large disturbance of surrounding rock.

4.3.1 Prospects Based on the NATM

The New Austrian Method regards the surrounding rock as part of the tunnel bearing system. Therefore, excavation of whole-section tunelling should be adopted as far as possible during construction to reduce the disturbance of the surrounding rock stress around the tunnel. Besides, the smooth blasting and pre-splitting measures should be adopted to reduce the vibration of the surrounding rock to preserve its integrity.

4.3.2 Construction status and problems

In this project, the research of the smooth blasting is not enough, and the light blasting effect is not ideal. Thses problems have appeared in practical application: the research on the lithology of surrounding rock is not enough,the layout of the borehole cannot be accurately adjusted according to the lithological change, the over-under excavation of the tunnel is large, which has a large disturbance to the surrounding rock.

5. Conclusion

Tunnel engineering is a system engineering which has dissipative structure and self-organizing functions. It is often affected by many factors. Some small changes can cause sudden changes of systematic level[8]. Therefore, informational construction is particularly important in tunnel construction. Through the above research, the following ideas could be recognized:

(1) As for tunnel construction, it is necessary to focus on monitoring and measurement work. The settlement, convergence and internal displacement law of surrounding rock should be grasped accurately in order adjust the parameters timely. It also helps to determine the time of secondary lining.

(2) The key to the tunnel construction in the weak stratum is the appropriate selection of excavation and support methods. The disturbance to the surrounding rock must be minimized. The construction organization must be tight and compact, and the cave wall must be closed immediately after excavation. Once the initial support is completed, the secondary lining must be followed to limit excessive deformation.

(3) Informational construction is reliable and indispensable in the construction of tunnels. The tunnel engineering informational construction method has such following characteristics: continuous, design integrated, construction-control, monitoring and feedback. It properly incorporates revisions into the construction and after-construction to achieve safe, economical and efficient targets.

(4) The NATM is concluded from practice, and it has been continuously enriched and developed in the practice. It is undeniable that there are still some problems and limitations in the NATM, however, with the continuous practice, the NATM will be surely improved and plays a more important role in the construction of underground works.

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