Research Journal of Applied Sciences, Engineering and Technology 7(11): 2185-2192, 2014
DOI:10.19026/rjaset.7.515
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 20, 2012 Accepted: April 02, 2013 Published: March 20, 2014

Research Article

Classification of Soft-rock Tunnels and the Corresponding Large-section Construction Methods

[1]Huang Mingli, [2]Guan Yanpeng and [3]Peng Feng
[1]Department of Tunnel Engineering,
[2]Department of Underground Engineering, Beijing Jiaotong University, Beijing 10044, China
[3]Beijing China Railway Ruiwei Foundation Engineering Co., Ltd., Beijing 100055, China

Abstract: This study is concerned with the classification of soft-rock tunnels which could instruct the tunnel construction more efficiently and effectively. It is difficult for NATM which is based on the geological classification to adapt to soft-rock tunnel construction. Through comparative study of the numerical models with different surrounding rock and different cross-sectional dimensions, the deformation characteristics of the soft-rock tunnel is put forward. Soft-rock tunnel is divided into four classes: A, B_1, B_2 and C. The classification is based on the proportion of the advanced displacement in the total radial displacement and the value of tunnel face extrusion. According to the different characteristics of these four classes of soft-rock tunnel, a high-speed construction with reinforcements of the surrounding rock in front of the face is put forward. The characteristics of the four classes of soft-rock tunnels are: In the general initial support conditions, the proportion of the advanced displacement in the total radial displacement of Class-A tunnels is low, which enables them to achieve self-stabilization. The corresponding proportions of Class-B_1 and Class-B_2 tunnels are beyond the limit, which can only enable them to achieve short-term stability. The extrusion of Class-B_2 tunnel's face is larger but it does not break the limit. The extrusion of Class-C tunnels breaks the limit which cannot maintain stability if without face reinforcements.

Keywords: Classification of tunnels, large section, rock deformation, the soft-rock tunne1

INTRODUCTION

Currently, the design and construction methods of underground projects are divided into two categories: the experience methods and the theory methods. The experience method researchers have proposed a classification system based on geological classification, which can help engineers design the tunnel primary support and lining structure.

RMR system by Bieniawski (1984) and Q system by Barton *et al*. (1974) are the most famous systems among the geological classification systems. Each of them is a kind of geo-mechanical classification based on a series of rock mechanics parameters and geological structure parameters. They can bring forward the support measures and the forms of the cross-sections according to the rock types. In theory, one can select appropriate forms of tunnel sections to ensure the long-term stability of the tunnels by the parameters of the rock samples and the direct measurement results in the tunnels.

But it is difficult to apply these methods to soft-rock, flysch and muddy soil, because they do not take full account of the impact on the deformation characteristics of the tunnels from the initial state of stress, the physical dimension of the tunnel excavation and the new building system, which makes the design and construction methods based on these objective inadequacies imperfect and lack applicability. Therefore, the geological classification method can be used as a supplementary tool for tunnel design and construction, but completely relying on it for the design of the tunnel construction is unscientific and makes it difficult to determine a reasonable construction method, especially in soft rock tunnels.

The New Austrian Tunneling Method (NATM) which is commonly used in tunnel construction in China was put forward by Pacher and Rabcewicz and Olser (1984) from 1957 to 1965. It is a kind of design and construction method based on the surrounding rock classification system and tunnel observing. It determines the amount of the sections and forms of tunnel sections of the partial excavation method according to the class of the surrounding rock. This method cannot achieve reliable time and cost estimates because this tunnel design and construction method cannot provide details of the initial construction design and the parameters are mainly qualitative, which present a lot of subjectivity in the practical application. Partial excavation method can solve the unclarity of the

Corresponding Author: Guan Yanpeng, Department of Underground Engineering, Beijing Jiaotong University, Beijing 10044, China

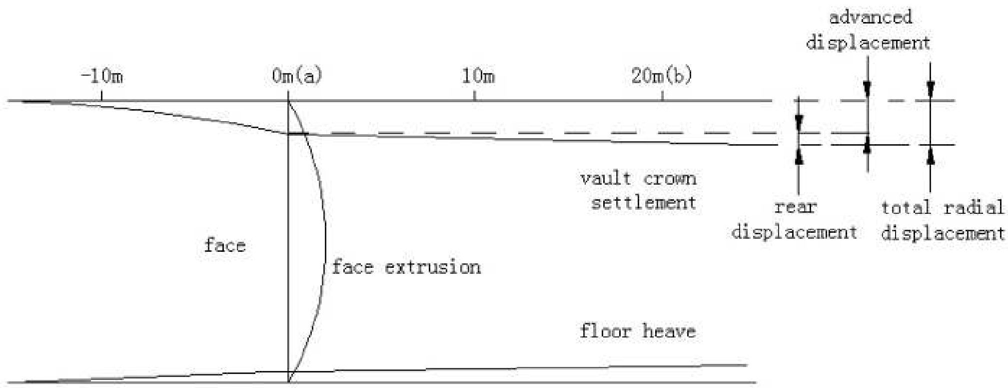

Fig. 1: The deformation of the tunnel

design parameters of NATM to some extent, but there are also other problems like a host of wasted works, low safety factors, large tunnel deformations, slow construction progresses and high costs in it.

At present, there are numerous researches on soft rock tunnel design and construction problems. for example, the stud y on construction characteristic and dynamic behavior of soft rock tunnel by Yan *et al*. (2006), the study of reasonable support scheme for soft rock tunnel in high gestures zone by Tian *et al*. (2011), the analysis of failure properties and formatting mechanism of soft rock tunnel by Wang *et al*. (2012). However, there are less researches on the systematic classification of soft rock tunnel and the pointed construction methods in accordance with their classes in the systemic classification of soft rock tunnel. It is still difficult to find an advanced, effective and universal design and construction method in soft rock tunnel projects. The Italian Lunardi (2011) put forward the NITM which emphasizes the classification of the tunnel by the stability of the face, but it lacks specific operational methods of classification. In order to solve the above-mentioned problems of tunnel design and construction, this study will research on an operational method of soft rock tunnel classification and put forward a high-speed construction method with large section excavation in accordance with the responding class of the tunnel classification mentioned above, which could provide reference to the design and construction of other soft rock tunnel projects.

DEFORMATION CHARACTERISTICS OF THE SURROUNDING ROCK IN SOFT-ROCK TUNNEL

As shown in Fig. 1, the deformations of the tunnel in construction can be divided roughly into 3 kinds of displacements: the advanced displacement, the face extrusion and the rear displacement. Three kinds of deformations occur at the same time and the main purpose of the support is to suppress the development of these deformations. Along the tunnel longitudinal direction, the vault crown settlement at 0 m can be understood as the maximum of the advanced displacement. Even in soft rock tunnel with large section, surrounding rock deformation at 20 m behind the tunnel face basically has converged, so the radial displacement value here can be regard as the total radial displacement, which is stated clearly by Guan and Zhao (2011).

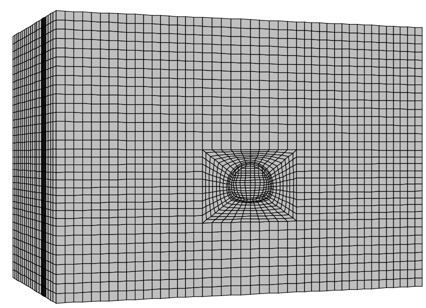

Fig. 2: Three-dimensional numerical model

The study will take the typical sections of the high-speed railway tunnels in China for example to discuss the changing characteristics of the advanced displacement, the face extrusion and the rear displacement. The tunnel models are established to calculate the tunnel deformations at the depth of 50 m with Class-IV, Class-V and Class-VI surrounding rock respectively. The scope of the model is: 80 m along the tunnel axis direction, 4 times the tunnel span in both sides of the tunnel, twice the tunnel span in the lower part of the model. The displacement boundary conditions are taken as boundary conditions and each displacement of the outer surfaces is constrained in the normal direction. As shown in Fig. 2, the models are meshed into 43600 units and 47708 nodes.

The study is a kind of three-dimensional elastic-plastic analysis. The surrounding rock is calculated as Mohr-Coulomb model while the primary and secondary linings are calculated as elastic model. The work of steel arch structure is applied by improving the parameters of the shotcrete. The parameters of different

Table 1: Physico-mechanical parameters of rock and support

Material type	Elasticity modulus/GPa	Poisson ratio	Unit weight/KN/m^3	Cohesion/KPa	Friction angle/°
Class-IV rock	1.00	0.35	22	220	27
Class-V rock	0.71	0.37	19	80	22
Class-VI rock	0.52	0.40	16	30	19
Primary lining	24.00	0.20	25		
Secondary lining	32.50	0.20	25		

Table 2: Result of the tunnel deformation

Class of surrounding rock	Cross-sectional area (m^2)	Vault settlement in the longitudinal direction (taking the distance from the face of the tunnel as standard) (mm)				a/b (%)	Face maximal extrusion (mm)
		-10 m	0 m (a)	10 m	20 m (b)		
IV	80	0.45	0.72	8.77	9.08	28.3	8.32
IV	120	1.08	1.81	15.01	15.52	34.3	14.54
IV	170	3.74	5.35	25.13	27.34	42.6	34.73
V	80	2.53	3.83	23.22	23.54	40.7	22.53
V	120	4.35	8.32	28.74	29.34	53.5	38.98
V	170	8.20	18.79	44.83	45.63	64.4	70.34
VI	80	6.84	17.34	52.25	52.74	50.4	43.98
VI	120	11.43	28.57	58.76	59.86	69.3	72.62
VI	170	Misconvergence	Misconvergence	Misconvergence	Misconvergence	-	Misconvergence

kinds of surrounding rocks and supports are obtained by consulting Highway Tunnel Specification synthetically and all the specific parameters are shown in Table 1.

According to the standards proposed by Tunnelling Association of Japanese and the practical experience of the tunnel construction in China, the tunnels with the cross-section area larger than or equal to 100 m^2 could be regarded as large section tunnels and the tunnels with the cross-section area larger than or equal to 140 m^2 could be regarded as super-large section tunnels. Therefore, the study selects the tunnels with the cross-section area of 80, 120 and 170 m^2 as the representative of middle section tunnels, large section tunnels and super-large section tunnels respectively to analyze the deformation characteristics of the soft rock tunnels. The tunnel cross-section forms are the same as the cross-section of standard railway in China. With the combination between the Class-IV, Class-V, Class-VI surrounding rocks and the three tunnel cross-sections, 9 numerical models could be obtained and the calculation results of the vault settlements and face maximal extrusions of the 9 models are shown in Table 2.

The following viewpoints can be concluded from the results of the above calculations:

- The proportion of advanced displacement in total radial displacement is large in soft rock tunnels (under general surrounding rock conditions, the advanced displacement value accounting for 20 to 30% of total radial displacement), with the decrease of the surrounding rock quality and the increase of the cross-sectional area, the advanced displacement rises increasingly steeply and the proportion of advanced displacement in total radial displacement also becomes larger.
  Typically, under general rock conditions, the advanced displacement does not need control. But if the surrounding rock is Soft and weak, the advanced displacement will increase steeply. For example, it can occupy more than 30% of the total radial displacement, even up to 50%, which will cause face collapses and large deformations of the surrounding rock if without control.
- The face extrusions of Soft rock tunnels are large generally. In most of the models the extrusions have reached cm level. The controlling value of tunnel face extrusion is 7 cm in Japanese experiences. That is to say, the tunnel face will collapse easily if the extrusion is beyond 7 cm. Consulting Japan's experience in controlling value, the tunnels with the extrusion beyond controlling value (e.g., class-V surrounding rock tunnels with large section, VI class surrounding rock tunnels with large or super-large section of the previous models) should be controlled on extrusion besides the advanced displacement controlling method.

THE METHOD OF THE SOFT ROCK TUNNEL CLASSIFICATION

The deformation of the soft rock tunnel has two significant characteristics. One is that the proportion of advanced displacement in total radial displacement is large. The other is that the face extrusion is large. Soft rock tunnels could be classified According to these two characteristics and the classifying indicators are the proportion of advanced displacement in total radial displacement and the face extrusion, respectively.

First, tunnels with the low proportion of advanced displacement in total radial displacement and small extrusion could be classified as Class-A, which could maintain the tunnel stability with only general initial supports.

Then, tunnels with the proportion of advanced displacement in total radial displacement beyond the

Table 3: The classification index of soft-rock tunnels

	The proportion of advanced displacement	Face extrusion
Class-A tunnels	Not beyond the limit	-
Class-B_1 tunnels	Beyond the limit	Small and not beyond the limit
Class-B_2 tunnels	Beyond the limit	Large but not beyond the limit
Class-C tunnels	-	Beyond the limit

Table 4: The classification of soft-rock tunnel

	Tunnels with a middle section	Tunnels with a large section	Tunnels with a super-large section
Class-IV rock	A	B_1	B_2
Class-V rock	B_1	B_2	C
Class-VI rock	B_2	C	C

limit (e.g., over 30%) and extrusion not beyond the limit could be classified as Class-B which could only maintain the tunnel stability in a short period with general initial supports.

Class-B tunnels are universal in soft-rock tunnel projects, so they can be divided into Class-B_1 and Class-B_2 tunnels in accordance with the tunnel face extrusion. The extrusion of Class-B_1 tunnels is small and do not need the reinforcement of the face while the extrusion of Class-B_2 tunnels is larger but not beyond the controlling value. Class-B_2 tunnels could also be excavated without reinforcement of the face while they can maintain stability better and be excavated in large section at a high speed if the face is reinforced.

Finally, since the advanced displacement universally occupies a high proportion in total radial displacement among tunnel projects with the extrusion beyond the controlling value, tunnels with the extrusion beyond the controlling value could be classified uniformly as Class-C tunnels which could not maintain the tunnel stability without the reinforcement of the face. The deformation characteristics of all the classes of tunnels are shown in Table 3.

With the combination of the classification method and the calculation results of the nine models mentioned in the previous section, the nine types of models can be roughly classified. This study takes 30% as the controlling value of the proportion of the advanced displacement in the total radial displacement and 7cm as the controlling value of the face extrusion. The classification result is shown in Table 4 and it is to be noted that this is a qualitative classification without considering particular conditions (e.g., the tectonic stress, groundwater or unsymmetrical loading conditions). Tunnel conditions differ from one another, so the tunnels should be analyzed on a case-by-case basis.

By years of tunnel constructions, engineers have summed up that: soft rock tunnels are made up of Class-V, Class-VI surrounding rock tunnels and Class IV surrounding rock tunnels with a large section or a super-large section which is stated clearly by Guan and Zhao (2011). Compared with Table 4, it could be found that the classification results in Table 4 match the tunnel construction experience in China.

THE CORRESPONDING LARGE SECTION EXCAVATION METHODS OF PARTICULAR CLASSES OF SOFT ROCK TUNNEL

In the long-term soft-rock tunnel construction processes, different types of partial excavation methods have been summed up in China. There are many partial excavation forms while the basic principle of them is common. As shown in Fig. 3, the partial excavation methods always turn big section into small ones which could be excavated one by one, but there are numerous problems in them like a vast of wasted works, low safety factors, large tunnel deformations, slow construction progresses and high costs, which are mentioned above.

It is difficult to control the deformation by turning big section into small ones under soft rock tunnel section conditions, for the reason that the partial excavation methods can only control the rear displacement effectively. Soft rock tunnel construction has two features: a large deformation of surrounding rock and a slow construction speed. It is hard for the partial excavation to control the deformation, which makes the construction speed even lower.

However, with the core principle of "controlling the deformation of the rock ahead of the tunnel face", the deformations of the tunnels can be controlled effectively through the reinforcements of the rock ahead of the face. Once the tunnel deformations are controlled, the large section excavation and the high-speed construction could be applied instead of partial excavation methods and the realization of the high speed construction will reduce the time of un-stability, which enables the support to be applied before when the deformations have totally developed.

In summary, with the core principle "controlling the deformation of the rock ahead of the tunnel faces", the large section excavation and the high-speed construction are applicable theoretically. There have been successful precedents in foreign countries and domestic tunnels such as Liuyang River Tunnel and Taoshuping Tunnel applied this principle and achieved expected effects. This study will research on construction methods of each class of tunnel according to the characteristics of each class mentioned above.

Class-C tunnels: Class-C tunnels are under the worst construction conditions in all tunnels and the faces of them are not stable. The stability of Class-C tunnels should be improved to the stability of Class-B_2 namely the short-term stabilization with the face reinforcement. Then they can be excavated with bench cut method or

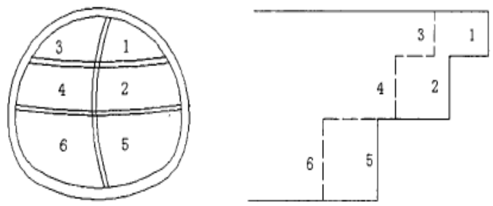

Fig. 3: Partial excavation method

even full section method at a high speed, which could not only improve the efficiency but also reduce the wasted works.

The bench cut method: The following support measures could be taken in Class-C tunnels to achieve bench cut method:

- In terms of controlling the advanced displacement, since the range of influence of the advanced displacement is large along the longitudinal direction, the long advanced supports (e.g., long pipes, pipe roofs, horizontal rotary jet grouting piles) are needed to reinforce the vault roof and two flanks of the tunnels and a certain length of lap should be also retained.
- In terms of controlling the face extrusion, the long advanced supports (e.g., working face anchor, horizontal rotary jet grouting piles) are needed to reinforce the face. the length of tunnel face reinforcement is preferably more than twice the tunnel span and a certain length of lap is also important.
- In terms of controlling the rear displacement, changing the performance of the support structure materials may achieve better effects and it is advisable not to improve the thickness of the shotcrete or reduce the spacing between the steel arches, for the reason that these methods add the weight and cost time which are adverse to the stability of the face.

Taoshuping Tunnel, for example, is a double-line railway tunnel, with the cross-section area of 140 m^2. It is designed by Class VI surrounding rock, which can be classified as a kind of Class-C tunnel by the classification method mentioned above. According to the studies by Peng *et al*. (2012), the parameters of the advanced support in Taoshuping Tunnel which are shown in Fig. 4 are:

- Horizontal rotary jet grouting piles with the diameter of 800 mm and the length of 18 m in the vault roof and two flanks.
- Horizontal rotary jet grouting piles with the diameter of 800 mm and the length of 18 m ahead of the face, which are decorated with the spacing of 1.5 m.
- Locking rotary jet grouting piles with the diameter of 600 mm, the length of 9 m and the spacing of 1 m, which are driven at the angle of 35~45°.

With the reinforcements mentioned above, Taoshuping Tunnel has achieved bench cut method and the construction speed has reached 25 m/month, which is 3 times the speed of the partial excavation method.

The full section excavation method: Class-C tunnel can achieve full section excavation by the reinforcement of the face. But this method is rare among domestic projects. Taoshuping Tunnel, for example, presents such following difficulties in full section excavation:

- The length of Taoshuping Tunnel with Class VI is only 600 m.
- An imported large mechanical equipment is needed if choosing full section excavation.

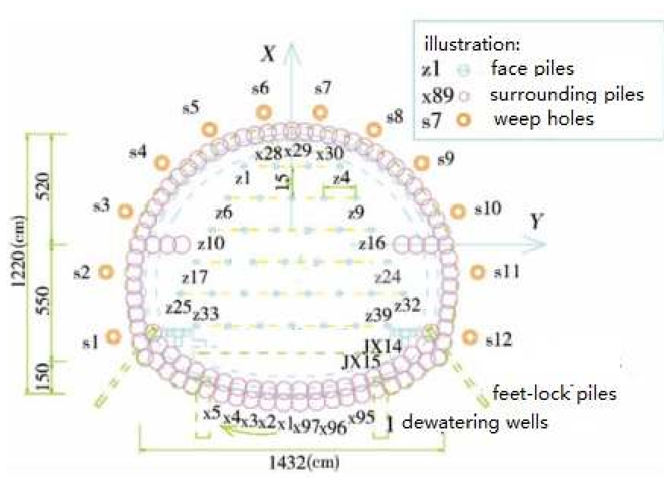

Fig. 4: The cross section of taoshuping tunnel with advanced reinforcement support

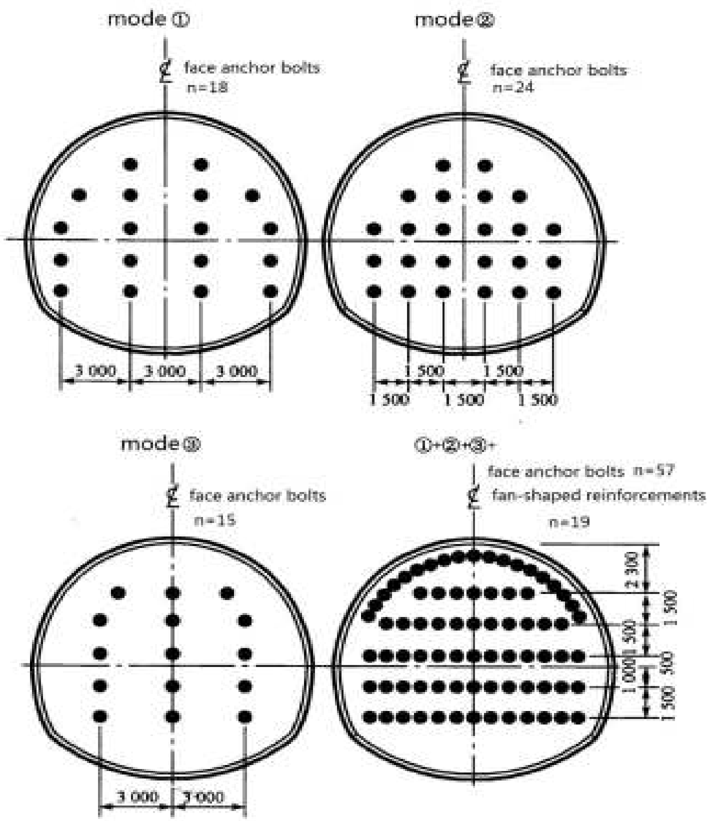

Fig. 5: The reinforcing long bolt method in iiyama tunnel

- There are 240~270 horizontal rotary jets grouting piles in the design of full section excavation method while the responding number in bench cut method is only 110 to 140.

However, it does not mean that the full section excavation cannot be applied in Class-C tunnels and this is mainly because: the long Class-C tunnels exist objectively. With the development of technology, machinery costs fall gradually while the quality of the machinery products increases gently, which makes the cost and time decline continuously. With the development of technology and the economy in the world, full section excavation method in Class-C will be applicable in the future.

Class-B_2 tunnels: The construction conditions of Class-B_2 tunnels are better than these of Class-C tunnels and the "three-stage seven-step excavation method" is widely used in Class-B_2 Tunnel while it has many weaknesses like more construction procedures, the lack of the space of every stage, inferior deformation controls and long unstable time. The stability of Class-B_2 tunnels should be improved to the stability of Class-B_1 with the face reinforcement. Then they can be excavated with "super-short step based construction method" or full section method at a high speed.

Class-B_2 tunnels could be reinforced consulting the Class-C tunnels while the length and density of the reinforcements could be reduced to some extent. It is also advisable to develop the reinforcing effects by changing the performance of the support structure materials.

Japanese Iiyama Tunnel, for example, is a tunnel with a section area of about 80 m^2 in which there are mudstones, sandstones and volcanic tuffs. The surrounding rocks have a feature of extrusion and its strength-stress ratio is blow 1.

Seeing that the section area in Iiyama Tunnel is only 80 m^2, it can be classified as a kind of Class-B_2 Tunnel. The Specific construction parameters of Iiyama Tunnel are shown in Fig. 5 and 6. It takes the close of inverted arch in early time and long face anchors as the main reinforcements, through which the full section excavation has been applied successfully. The excavation method is machinery excavation with Roadheaders with single arm, which makes the full section excavation possible.

Class-B_1 tunnel: Among soft rock tunnels, construction conditions of Class-B_1 tunnel is the best, bench cut method is applied widely in such class of

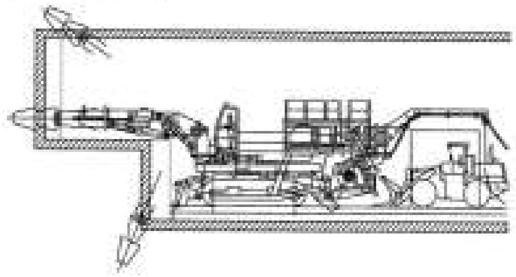

Fig. 6: The construction of road header with single arm in iiyama tunnel

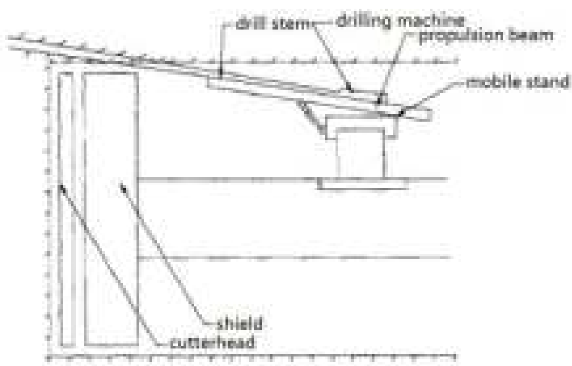

Fig. 7: Drilling machines in TBM

tunnel. The extrusion of Class-B_1 is small so it could achieve full section excavation with merely the reinforcement of the vault roof. For instance, when crossing the fracture zone with soft rock in middle section tunnels, TBM with drilling machines or roof-bolters may be a good choice.

For example, a TBM with the model number of WITRHTB88E and the diameter of 8.8 m was applied in the construction of Xian-Taikang Qinling railway Tunnel where the tunnel with Class-VI surrounding rocks was 502 m in length and the tunnel with Class-V was 1364 m in length. The section area of this railway tunnel is small therefore the tunnel with Class-VI and Class-V can be classified as Class-B_1 tunnel.

The Specific construction parameters of Qinling Tunnel are shown in Fig. 7. In order to cross the fracture zone smoothly, TBM of Qinling Tunnel has taken drilling machines and roof-bolters as the supplementary tools. Drilling machines could drill holes outside to explore the rock and reinforce the rock by grouting and roof-bolters could drive the anchors into the front upper place of the face. The holes drilled by the drilling machines are 3 m in depth, 38 mm in diameter.

CONCLUSION

- The two deformation characteristics of soft rock tunnels are: The proportion of the advanced displacement in the total radial displacement is high and the face extrusion is large.
- According to the deformation characteristics of the soft rock tunnels, soft rock tunnels can be divided into Class-A tunnels, Class-B_1 tunnels, Class-B_2 tunnels and Class-C tunnels. The classification indicators are the proportion of the advanced displacement in the total radial displacement and the face extrusion.
- The characteristics of the four classes of tunnels are: In general primary support conditions, the proportions of the advanced displacement in the total radial displacement of Class-A tunnels are low, which enables them to achieve self-stabilization. The proportions of the advanced displacement in the total radial displacement of Class-B_1, B_2 are beyond the limit, which could only enable them to achieve short-term stabilization. The face extrusions of Class-B_2 tunnels are larger but not beyond the limit while the extrusions of Class-C tunnels are beyond the limit, which cannot maintain stability without face reinforcements.
- Different reinforcements could be taken to achieve large section excavation with a high speed according to the different classes of the tunnels. Through the reinforcements of the face, Class-C could achieve the excavation with bench cut method and Class-B_2 could achieve the excavation with "super-short step based construction method" or full section method. Class-B_1 could achieve full section excavation only by the reinforcement of the vault roofs.
- The soft-rock tunnel classification method proposed in this study is a kind of rough classification based on the deformation characteristics of soft-rock tunnels. This classification should be applied according to the specific conditions of the tunnels. It is still need discussion whether the tunnels under the tectonic stress, groundwater or unsymmetrical loading conditions suit the classification.

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