Research Progress on Safety Control of Surrounding Rock-Support System in Deep Buried Soft Rock Tunnels

Jianhe Li1,2*, Wanmin You1, Song Wu1, Jian Li3 and Jian Han1
1 Changjiang Institute of Survey, Planning, Design and Research, Wuhan, Hubei 430010, China
2 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Wuhan, Hubei 430010, China
3 Central Yunnan Water Diversion Project Co., Ltd., Kunming, Yunnan 650224, China
Email: jianhe_001@126.com

Abstract. The deep-buried soft rock tunnel has large deformation degree and long duration, which makes the surrounding rock-support very difficult. How to formulate effective design countermeasures to control soft rock deformation is one of the important technical problems in the design and construction of deep-buried soft rock tunnels. There are three critical problems in the research of soft rock deformation control, i.e. the bearing mechanism of the surrounding rock-supporting system of the soft rock tunnel, the safety control indexes and control standards of the surrounding rock-supporting system, and the reasonable support timing and support rigidity. Remarkable achievements have been made in the deformation control of deep-buried soft rock tunnel by theoretical analysis, field tests and numerical simulation over the past decades. By summarizing the research progress related to these three critical problems, the form of surrounding rock pressure is discussed, and the safety control indexes and standards for surrounding rock-supporting system are established. It is believed that based on the load-bearing law of the surrounding rock-support system and its safety control standards, an in-depth study of the reasonable support timing and reasonable support rigidity of the surrounding rock under different geological conditions is the critical and difficult problem for the safety control of deep-buried soft rock tunnels.

1. Introduction
The deep and long tunnel occupies an important position in China’s infrastructure projects. Among the major projects currently under construction, the tunnel length of the Central Yunnan Water Diversion Project is 611.31 kilometers, with a maximum burial depth of 1450 m. The tunnel length of the Hanjiang to Weihe River Diversion Project is 98.26 kilometers, with a maximum burial depth of 2012 meters. The Gaoligongshan Railway Tunnel has a total length of 34.5 kilometers and a maximum buried depth of 1155 meters. For long tunnels, it is inevitable to pass through complex and bad geological sections. When a long tunnel passes through a section of deeply buried weak surrounding rock, large deformation geological disaster often occurs. The large deformation of soft rock is another difficulty besides rock burst encountered during the construction of deep-buried underground projects. The deep-buried soft rock tunnel has large deformation degree and long duration, which makes the surrounding rock support very difficult. It poses a great threat to the construction and operation of underground projects and is one of the “bottleneck” problems that could not be avoided by the construction of long tunnels [1-4].
The large deformation problem of soft rock is very prominent in all kinds of tunnel projects under construction and planning in China. How to control the large deformation of deep-buried soft rock tunnel is a major technical challenge in the field of underground engineering. In the Central Yunnan Water Diversion Project, which is under construction, the cumulative length of the tunnel passed soft rock section is as high as 208.3 km, accounting for 34% of the total length of the tunnel. According to the preliminary analysis and prediction, the cumulative length of the tunnel with large deformation of soft rock is about 88.85 km. The problem of large deformation in deep-buried soft rocks tunnels is very serious, especially in the Xianglushan tunnel of Dali I section. In addition, the Qinling tunnel of Hanjiang to Weihe River Diversion Project and the Gaoligongshan Railway Tunnel, which are under construction, are faced with severely large deformation geological disaster. This has posed extremely challenging technical problems for the construction and operation safety of the deep-buried long tunnel project. How to determine the reasonable supporting design scheme of the deep-buried soft rock tunnel and realize the long-term safety control of the surrounding rock-supporting system is urgently needed to make breakthroughs in related basic theories and technical methods.

2. Bearing Mechanism of Surrounding Rock-Supporting System of the Deep-Buried Soft Rock Tunnel

In the study of tunnel surrounding rock-supporting bearing mechanism, it has at least experienced the stage of classical pressure theory, the stage of collapse arch theory and the stage of elastoplastic theory. The load calculation methods that commonly used in current engineering practice are usually the deepening of the above theoretical research and the development of engineering application. The collapse arch theory is based on a rigid-plastic model, which can give the amount of loose surrounding rock pressure that carried by the lining. It is a commonly used calculation method in current engineering specifications, such as “Code for Design of Hydraulic Tunnels” (SL279-2016) [5], “Code for Design of Railway Tunnels” (TB 10003-2016) [6], etc. However, it does not consider the load separation of surrounding rock self-support and initial support, so the deformation of surrounding rock cannot be answered. In addition, the calculation formula of surrounding rock pressure has nothing to do with the depth of the tunnel, which is inconsistent with the actual situation.

Based on the combined action principle of the elastoplastic mechanics method, it is more reasonable in concept and theory that the surrounding rock pressure is regarded as the deformation pressure, which fully considers the surrounding rock self-supporting and surrounding rock-supporting interaction. On this basis, domestic scholars have put forward some theories such as “surrounding rock loose zone”, “primary and secondary bearing zone”, and “key bearing zone”, and so on. In engineering practice, such support and pressure relief concepts as reserved deformation, first yielding and then resistance is often adopted. However, the co-action principle is restricted by the calculation model and parameters, so it is difficult to simulate the actual situation accurately and effectively. In addition, the co-action principle generally only reflects the deformation pressure. With the development of plastic zone and the plastic displacement, plastic zone of surrounding rock will collapse and fail. And then, the loose pressure will be produced. How to determine the minimum support pressure, there is still no better way.

The structure mainly bears deformation pressure under the condition of timely support and adequate support strength in deep-buried soft rock tunnels. When the support is not timely and the surrounding rock has the tendency of looseness and collapse, the structure mainly bears the looseness pressure. In order to ensure the safety and rationality of the design, a practical tunnel structure calculation model should be adopted according to the specific conditions. At present, some domestic relevant tunnel (channel) specifications only adopt the load-structure method according to the loose pressure. Others use the formation - structure method according to the deformation pressure. The calculation model and method are often divorced from the actual stress, which reduces the reliability of the design and results that the design of tunnel structure is mainly based on engineering experience. In addition, different design departments adopt different design methods, and there are also great
differences in the form of primary support and lining thickness, which reflects the inconsistencies of the tunneling design ideas in China.

For the deep-buried soft rock tunnels, there are some disagreements in the determination of surrounding rock pressure. For example, the form of surrounding rock pressure is deformation pressure or loose pressure. Dong Fangting [7] believed that the crushing dilation deformation force during the development of the surrounding rock loose zone was the main support load. According to the stability of surrounding rock, Zhang Dingli [8] divided the surrounding rock of deep-buried soft rock tunnel into two regions: the deep surrounding rock and the shallow surrounding rock. They also believed that the supporting load includes the deformation pressure of deep surrounding rock and the loose pressure of shallow surrounding rock. Zhu Hehua [9] studied the whole process of gradual failure of surrounding rock after excavation of soft tunnel through model test and believed that the damaged area of surrounding rock was the source of the loose load of tunnel. However, in practical engineering, designers often want to know when to calculate according to the loose pressure, when to consider the deformation pressure, or how to incorporate the loose pressure into the common action principle. Currently, there is no good solution.

Combining the modified Fenner formula (deformation pressure) and Carco formula (loosening pressure), the author puts forward a discriminant method for reference. According to the co-action principle of surrounding rock-supporting system, the bearing capacity of surrounding rock increases with the expansion of plastic zone (or the development of plastic deformation), while the surrounding rock pressure acting on the support structure decreases. If the plastic zone (or plastic displacement) is allowed to develop, the plastic zone will collapse and break away from the original rock. At the same time, loosening pressure will generate. At this time, there is a critical state. That is, when the plastic zone develops to \( R'_p \) (or the cave wall displacement develops to \( u'_p \)), the plastic ring and the original rock have a tendency to break away. And the deformation pressure (based on the modified Fenner solution) and the loose pressure (based on the Caco solution) are in Equivalent in this critical state, namely,

\[
(p_0 + c \cot \varphi)(1 - \sin \varphi)\left(\frac{r_0}{R'_p}\right)^{2 \sin \varphi / (3 \sin \varphi - 1)} - c \cot \varphi - c \cot \varphi \left(\frac{r_0}{R'_p}\right)^{2 \sin \varphi / (3 \sin \varphi - 1)}
= \gamma r_0 (1 - \sin \varphi) (1 - \left(\frac{r_0}{R'_p}\right)^{3 / (3 \sin \varphi - 1)}) / (3 \sin \varphi - 1) - c \cot \varphi
\]

(1)

Namely

\[
\left(\frac{r_0}{R'_p}\right)^N + A \left(\frac{r_0}{R'_p}\right)^{N-1} - A = 0
\]

(2)

where \( p_0 \) is the initial stress of the tunnel, \( c \) is the cohesive force of surrounding rocks, \( \varphi \) is the internal friction, \( r_0 \) is the radius of the tunnel, \( R'_p \) is the radius of the plastic zone, \( \gamma \) is the weight of rock mass, \( N = 2 \sin \varphi / (1 - \sin \varphi) \).

\[
A = \gamma r_0 / ((N - 1)(p_0 (1 - \sin \varphi) - c \cos \varphi))
\]

Equation (2) is a nonlinear equation, and the dichotomy method can be used to solve \( R'_p \). At the same time, the critical displacement \( u'_p \) can be obtained by substituting \( R'_p \) into the Fenner formula, namely,

\[
u'_p = \sin \varphi (p_0 + c \cot \varphi) R'_p^2 / (2G r_0)
\]

(3)

According to the above answer, when \( u > u'_p \) (or \( R_p > R'_p \)), the rigid plastic medium model is followed, and only the loose pressure is considered. When \( u < u'_p \) (or \( R_p < R'_p \)), the deformation pressure must be considered.
The siltstone surrounding rock of Xianglushan Tunnel is taken as an example. The relevant calculation parameters are, $\gamma = 20\text{kN/m}^3$, $H=400\text{ m}$, $R=5\text{ m}$, $c=0.7\text{ MPa}$, $\tan \varphi = 0.8$, deformation modulus is $E=0.25\text{ Gpa}$, Poisson's ratio is $\nu = 0.3$, and $G = E/2(1+\nu) = 37.04\text{ MPa}$. By substituting them into (2-2) and (2-3), the solution is obtained by MATLAB tool to write the dichotomy calculation program, which is $u_p' = 0.16m$. That is, at $u_p' > 0.16m$, the surrounding rock pressure follows the rigid plastic model and it is calculated according to the loosening pressure. When $u_p' \leq 0.16m$, surrounding rock pressure follows the elastic-plastic model and it is calculated according to the deformation pressure.

Another key problem, which is related to the bearing capacity of surrounding rock-supporting system, is the sharing proportion of surrounding rock load. Due to the high degree of deformation of the deep-buried soft rock tunnel and the high pressure of the surrounding rock, the stress of the surrounding rock and secondary lining is usually considered. However, there are many disputes about how much load should be shared by the surrounding rock, primary support and secondary lining. “Highway Tunnel Design Rules” puts forward the bearing ratio of surrounding rock, initial support and secondary lining. For IV, V class surrounding rock, the secondary lining bearing ratio is relatively high (V class surrounding rock, lining bearing ratio is 60% ~ 85%). But its suitable for deep soft rock tunnel is up for debate. The high bearing ratio of the second lining will inevitably increase the thickness of the lining and the amount of reinforcement, which will greatly increase the engineering cost. Therefore, the distribution characteristics and evolution law of surrounding rock pressure under different occurrence conditions should be studied in combination with in-situ monitoring of deep-buried soft rock tunnel and numerical simulation of multiple working conditions. And then, the load sharing ratio of surrounding rock, primary branch and secondary lining should be proposed.

3. Safety Control of Surrounding Rock-Supporting System of Deep-Buried Soft Rock Tunnel

Because of the complexity and variability of surrounding rock conditions, the dynamic characteristics of load effects and the uncertainty of support structure performance, the safety control of surrounding rock-supporting system of deep-buried soft rock tunnel has been a hot and difficult issue for scholars at home and abroad. Firstly, to achieve safety control of surrounding rock-supporting system of deep-buried soft rock tunnel, it is necessary to establish the reasonable control index and control standards. Secondly, on the premise of meeting safety control standards, studying and determining reasonable support time and support strength is very important to achieve the balance between reasonable release of ground stress and effective constraints.

3.1. Safety Control Indexes and Control Standards of Surrounding Rock-Supporting System

For the safety control of surrounding rock-supporting system, scholars at home and abroad have conducted extensive studies on the identification of tunnel surrounding rock stability. For example, Zhang Dingli [8] conducted statistical analysis on a large number of mountain tunnel surrounding rock deformation monitoring results and pointed out the method for determining the instability mode, mechanism and range of tunnel surrounding rock instability. Wan Zhijun [10] successfully predicted the range of a roadway failure circle through the elastoplastic viscous element combination model. Xie Jun [11] discussed the problem of determining the early warning value during the operation period of Longtoushan Tunnel in Guangzhou. Shen Caihua [12] proposed a method for judging the safety of bolting and shotcrete support of steel arch on the basis of the monitoring and measurement data of the steel arch. In terms of design and construction, there is no uniform technical standard for the safety controlling of deep soft rock tunnels. For example, the measures specified in the “Code for Design of Railway Tunnels” [13] are: reinforced strata, sprayed layers of longitudinal joints, net sprayed or sprayed steel fiber reinforced concrete, long bolts, steel or shrinkable frame restraints, reinforcement or closure, The large-scale deformation of class III can be supported by two or more times.

How to evaluate the safety status of surrounding rock-supporting system? For the safety control index of surrounding rock-supporting system, two schemes are proposed. Firstly, the total displacement of surrounding rock-supporting system is controlled,
sup lim \( K \) \( U \) \( \text{rock port} \)

\[ K_{\text{rock-soprt}} = \frac{U_{\text{limit}}}{U} \quad (4) \]

where \( U_{\text{limit}} \) is the ultimate displacement of the surrounding rock-supporting system, which is numerically equal to the reserved deformation of surrounding rock. And, \( U \) is the monitored value or calculated value of the stage displacement. Secondly, according to the bearing state of the support system, the first failure of a certain support structure is regarded as the failure of the whole initial support system.

\[ K_{\text{sup-port}} = \min \left( \frac{P_{\text{limit}}}{P} \right) \quad (5) \]

where \( P_{\text{limit}} \) is the bearing limit of various support structures, \( P \) is the load borne by the support structure, which can be obtained by stress monitoring or numerical calculation of the support structure. As a reasonable design requirement, \( P_{\text{limit}} \) should not be too much less than \( P \), meanwhile maintaining a certain safety margin.

In the specific implementation, the control standard values can be established based on the different distance from the palm face and safety control index of surrounding rock-supporting system, which is process control. And it can meet the overall safety control requirements of the surrounding rock-support system.

Taking the displacement control index as an example, in order to avoid the deformation of surrounding rock exceeding the limit, the total displacement value after the initial support shall not exceed the reserved deformation value. According to the Technical Guide for Railway Tunnel Engineering Construction [13], the control standards for the displacement stage of the surrounding rock-supporting system is established as table 1.

| Category         | From the working face 1D | From the working face 2D | Far from the working face |
|------------------|--------------------------|--------------------------|---------------------------|
| Allowable convergence rate | 65%                      | 90%                      | 100%                      |
| Krock-supported | 1.5                      | 1.1                      | 1.0                       |

\[ ^a \] Notes, \( D \) is the diameter of the tunnel excavation.

3.2. Reasonable Supporting Time and Supporting Strength of Deep-Buried Soft Rock Tunnels

The essence of the support timing and support strength of the tunnel is the balance between the reasonable release of in-situ stress and the effective restraint, which is one of the hotspots in tunnel construction mechanics. Scholars at home and abroad have conducted extensive research on the reasonable timing of tunnel support. For example, Farias et al. [14] used three-dimensional numerical simulation to study the displacement control of NATM tunnel excavation. Su Kai [15] et al. analyzed and calculated the surrounding rock stability of underground cavern with different support opportunities. Wang Zhongwen et al. [16] considered the creep characteristics of the surrounding rock in the tunnel. He also gave the reasonable supporting opportunity of the secondary lining combined with the field measurement. However, there is a lack of quantitative research on the reasonable support strength which is required for effective control of soft rock deformation at home and abroad. This makes the support design mostly rely on experience, or the numerical simulation carried out for a specific project, resulting in lacking of reliable theory as a guide.

According to the safety control standard of surrounding rock-supporting system, how to determine the reasonable supporting time and support strength for surrounding rock? An effective method is to determine the support resistance required in each excavation stage according to the stage control standards mentioned above and determine the specific support type and support timing in combination with the load sharing ratio of the support structure. As the bearing ratio of bolt, shotcrete, steel arch and other initial support structures depend on their structural stiffness and bearing strength limit, the
initial support measures are more economical and reasonable when the difference between their stiffness ratio and bearing strength limit ratio is not large. Otherwise, when a support structure quickly reaches its strength limit and fails, most of the load will be transferred to other support structures, which is unfavorable to the overall bearing capacity of the structure. Therefore, when determining the specific type and strength of support, comprehensive considerations should be taken. This part of the work is currently under way and will be described in follow-up studies.

4. Conclusion
(1) The key to solve the bearing mechanism of the surrounding rock-supporting system is to define the action type of the surrounding rock load and the load sharing proportion of the surrounding rock-supporting system. For deep-buried soft rock tunnel, the support structure mainly bears deformation pressure under the condition of timely support and adequate support strength. When the support is not timely and the surrounding rock has the tendency of looseness and collapse, the structure mainly bears the looseness pressure. In order to ensure the safety and reality of the design, a practical tunnel support structure calculation model should be adopted according to the specific conditions.

(2) Effective safety control indexes and standards are the basis of safety control of surrounding rock-supporting system. The failure modes and causes, whether it is surrounding rock or support structure, should be considered comprehensively when safety control index is established. The control standard can be established according to the different distance from the working face, and the process control can meet the overall safety control requirements of the surrounding rock-supporting system.

(3) Based on the bearing law of surrounding rock-supporting system and its safety control indexes and standards, it is the key and difficult problem to study and determine the reasonable support timing and support strength for the safety control of the surrounding rock-supporting system in deep-buried soft rock tunnel. And it is also the main technical bottleneck that the tunnel spans from the empirical design to quantitative design.

Acknowledgments
This research was supported by the Open Research Fund of State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences (Grant No. Z018016), Independent scientific research project of Changjiang Institute of Survey, Planning, Design and Research Co., Ltd. (Grant No. CX2018Z08) and the China Postdoctoral Science Foundation (Grant No. 2019M652603). In addition, the authors are also grateful to the reviewers and editors for their valuable comments and suggestions.

References
[1] Chen W Z, Xiao Z L and Tian H M, et al. 2015 Research on squeezing large displacement and its disposing method of weak rock tunnel under high in-situ stress Chinese Journal of Rock Mechanics and Engineering 11 2215-2226.
[2] Barla G 1995 Squeezing rocks in tunnels ISRM News Journal 3 44-49.
[3] Wang C H, Sha P and Hu Y F, et al. 2011 Study of squeezing deformation problems during tunneling Rock and Soil Mechanics Supp.2 143–147.
[4] Zhao Y 2012 Study on Deformation Mechanism and Control Technology of Weak Rock Surrounding Tunnel Beijing Jiaotong University.
[5] Ministry of Water Resources of the People's Republic of China 2016 SL279-2016 Specification for Design of Hydraulic Tunnel Beijing: China Water Resources and Hydropower Press.
[6] China National Railway Administration 2004 TB10003—2004 code for design of railway tunnel Beijing: China Railway Press.
[7] Dong F T, Song H W and Guo Z H, et al. 1994 Roadway support theory based on broken rock zone Journal of China Coal Society 1 21-32.
[8] Zhang D L, Chen F B and Fang Q 2014 Study on mechanical characteristics and applicability of primary lining used in tunnel Engineering Mechanics 7 78-84.
[9] Zhu H H, Huang F and Xu Q W 2010 Model test and numerical simulation for progressive failure of weak and fractured tunnel surrounding rock under different overburden depths Chinese Journal of Rock Mechanics and Engineering 6 1113–1122.

[10] Wan Z J, Zhou C L and Ma W D, et al. 2005 Nonlinear rheological mathematical-mechanical model of surrounding rock deformation of roadways or tunnels and its preliminary application Chinese Journal of Rock Mechanics and Engineering 5 761-767.

[11] Xie J, Fang Y G and Mo H H 2009 Study of long-term warning value of super large section tunnel Chinese Journal of Underground Space and Engineering 1 39-44.

[12] Shen C W and Tong L Y 2007 Discussion on predicting the stability of flexible shotcrete and steel arch frame support for tunnels China Civil Engineering Journal 3 88–91.

[13] Ministry of Railways Economic Planning and Research Institute 2008 TZ 204-2008 Construction Technology Guide for Railway Tunnel Engineering Beijing: China Railway Press.

[14] Farias M M, Moraes A H and Assis A P 2004 Displacement control in tunnels excavated by the NATM: 3-D numerical simulations Tunneling and Underground Space Technology 3 283-293.

[15] Su K, Cui J P and Zhang Z M 2015 Method of choosing initial supporting time during tunnel excavation Journal of Central South University (Science and Technology) 8 3075-3082.

[16] Wang Z W, Fang J Q, Xia C C, et al. 2010 Determination method of supporting time for secondary lining in tunnel considering rock creep behaviors Chinese Journal of Rock Mechanics and Engineering S1 3241–3246.