Study on stability and supporting measures of surrounding rock during Breakthrough in Deep Highway Tunnel

Xiaoming Sun\textsuperscript{1}, Bo Zhang\textsuperscript{1,2}, Yong Zhang\textsuperscript{1,2}, Xiaobing Qiao\textsuperscript{3}, Zhijiao Wang\textsuperscript{4} and Zhigang Tao\textsuperscript{1,2}

\textsuperscript{1} State Key Laboratory for Geomechanics & Deep Underground Engineering, Beijing 100083, China
\textsuperscript{2} School of Mechanics and Civil Engineering, China University of Mining & Technology, Beijing 100083, China
\textsuperscript{3} Gansu Provincial Highway Aviation Tourism Investment Group Co., Ltd, Gansu 730000, China
\textsuperscript{4} Gansu Changda Highway Co., Ltd, Gansu 730030, China

*Corresponding author’s e-mail: Bo zhang (zhangbo1363331@163.com)

Abstract: During the construction of the Muzhailing tunnel, the maximum deformation of the surrounding rock was more than 2500 mm. When the tunnel is in the breakthrough stage, more attention should be paid to the danger of large deformation in order to ensure the safety of construction. This paper comparatively analyzed the deformation characteristics and stress distribution of the Muzhailing tunnel surrounding rock under the bolt support and the prestressed anchor cable support by numerical simulation. Then through theoretical analysis, a new method of tunnel support using high prestressed constant resistance and large deformation anchor cable is proposed. The field test results showed that the combination support form of long and short anchor cables with constant resistance and large deformation can improve the stability of the stop working face, and the rock pillar between the working faces, and reduce the influence of excavation disturbance on the surrounding rock of the stop working side. When the tunnel breakthrough construction was completed, the displacement difference of surrounding rock on both sides of the breakthrough position was controlled within 100 mm, and the maximum displacement of surrounding rock was 223 mm. The support method can well control the large deformation of the surrounding rock and improve the stability of the surrounding rock.

1. Introduction

For soft rock tunnels, due to the weak self-stability of the surrounding rock and difficult construction, tunnels with long distances have to be constructed in two directions. When the tunnel is approaching the breakthrough stage, the surrounding rock at the shut-down place is prone to large deformation during the construction of the tunnel on the other side. Therefore, controlling the possible large deformation of the tunnel becomes the guarantee of tunnel breakthrough.

Researchers have done a lot of research on tunnel surrounding rock deformation and support methods. The deformation and failure of tunnel surrounding rock are mainly divided into complete shear failure, bending failure, and shear sliding failure (Aydan et al., 1993). Moreover, rock mass strength and ground stress are the key factors affecting the stability of the tunnel surrounding rock (Hoek et al., 2005). In the high geostress environment, the surrounding rock of tunnel shows the
The characteristics of soft rock, and it is easy to produce large deformation. Different rock structures will make the surrounding rock deform unevenly, which will destroy the supporting structure (Tao et al., 2018; He, 2011). Through the numerical simulation method to analyze the deformation and mechanical characteristics of surrounding rock, the tunnel support measures can be more reasonable (Kang et al. 2014; Meguid et al., 2006). The reinforcement measures of the tunnel surrounding rock are anchor bolt support, which can increase the overall strength of tunnel shallow surrounding rock, thus limiting the large deformation of the tunnel (Brox et al., 1999; Huaning et al., 2018; Meng Q et al., 2018; Zhang et al., 2018). In recent years, many researchers have proposed many new support methods for large deformation of surrounding rock, such as pouring foam concrete between the primary lining and the secondary lining to limit the development of plastic zone (Wu et al., 2018), using a new type supporting system of grid steel frame-core tube to control the large deformation of the surrounding rock (Xu et al., 2017). These methods have played a positive role in tunnel engineering.

The anchor bolt support method based on NATM is widely used in tunnels, but the application of prestressed anchor cable support in tunnels is less. Prestressed anchor cable support belongs to active support, which is widely used in the coal mine roadway (Kang 2014). This support method can not only strengthen the shallow surrounding rock (Goel et al., 2007; Karanam et al., 2005), but also can mobilize the deep surrounding rock and the shallow surrounding rock to jointly improve the bearing capacity of the surrounding rock, so as to control the large deformation of the tunnel (Zhang et al., 2016, Peng 1998). Therefore, the prestressed anchor cable support method can be introduced into tunnel engineering.

This paper introduces a new support method for the soft rock tunnel with high geostress. In this method, a constant resistance device is added to the anchor cable, which can provide constant resistance when the surrounding rock deforms, keep the integrity of the surrounding rock and prevent the breakage of the anchor cable (He et al., 2014). Through the Flac3D numerical simulation method, the deformation and stress characteristics of the surrounding rock were compared and analyzed under the original bolt support and prestressed anchor cable support respectively during the tunnel breakthrough. Based on the theoretical analysis and numerical analysis, a high prestressed constant resistance anchor cable support strategy was proposed. Then the long and short constant resistance anchor cable combination support method was used to strengthen the surrounding rock of the Muzhailing tunnel in the field. Through the field application and monitoring test, the results show that the method can effectively control the large deformation of surrounding rock and ensure the tunnel breakthrough.

2. Project overview
Muzhailing tunnel is located in Lanzhou, Gansu Province, China (Fig. 1). According to the geological survey, the surrounding rock of the tunnel is composed of thin-layer moderately weathered carbonaceous slate, the strength of rock mass is about 30MPa, and the dip angle of the rock mass is between 0 ° and 30 °. This small amount of sandstone, shale, and quartz are distributed in the rock stratum. The rock fissures are rich in water, and the rock mass is easy to swell and soften in contact with water. The surrounding rock exposure is shown in Fig. 2.
Figure 1. The location of Muzhailing tunnel

Figure 2. The exposure of surrounding rock

The total length of the tunnel is 15.226 km and the maximum buried depth is 629.1 m. There are three inclined shafts in the tunnel, which are excavated by three benches with multiple tunnel faces. When the two tunnel faces meet for about 20 m, the single tunnel face excavation starts and the other side will be shut down. The original tunnel support mainly adopts bolt support and steel arch support, as shown in Fig. 3. During the construction of the tunnel, large deformation has occurred, and the maximum deformation was more than 2m, as shown in Fig. 4. Therefore, there are risks in the construction of the tunnel.

(a) The Cross Section of the Tunnel
4

(b) The longitudinal section of the tunnel

Figure 3. Construction technology of three benches excavation

(a) Large deformation  (b) Bending of steel arch

(c) Tunnel surface collapse  (d) Concrete cracking

Figure 4. Photos of large deformation and failure

3. Numerical analysis

3.1 Model and parameters

Through the field investigation, the original bolt support cannot well control the stability of the tunnel surrounding rock. To solve the large deformation of the surrounding rock, the numerical simulation method was used to analyze the stability of the surrounding rock under the original support and prestressed anchor cable support respectively.

Based on the Mohr-Coulomb failure criterion, the ubiquitous joint model was established in the Flac3D, so that the deformation and failure characteristics of the surrounding rock with the dip angle can be analyzed. The dip angle of the rock layer is set to 30°, and the tunnel in the model passes through the rock layer (Fig. 5). The monitoring section of the numerical model is shown in Fig. 6. According to the geological survey data, the horizontal stress is set at 12 MPa in the x-axis direction, 21 MPa in the y-axis direction, while the vertical stress is set to be 12 MPa. The process of tunnel excavation is full section excavation by steps. When the tunnel faces meet for 20 m, excavation continued on one side and stopped on the other side. The inverted arch uses elastic solid modeling to
simulate concrete, and shell elements to simulate lining. Anchor cable support uses two lengths of 5m and 10m. The prestress is set to 350 kN. The numerical model is shown in Fig. 7. The main parameter values are shown in Tables 1 and 2.

Figure 5. Relationship between tunnel and rock layer

Figure 6. Location of slice plane

Figure 7. The numerical model

| Parameter      | Density  $(\text{Kg/m}^3)$ | Bulk modulus $(\text{GPa})$ | Shear modulus $(\text{GPa})$ | Cohesion $(\text{MPa})$ | Frictional angle $(^\circ)$ | Tensile strength $(\text{MPa})$ |
|----------------|-----------------------------|-----------------------------|----------------------------|-------------------------|-----------------------------|------------------------------|
| Rock           | 2500                        | 0.44                        | 0.25                       | 1.7                     | 22                          | 0.6                          |
| Rock joint     | /                           | 2                           | 1                          | 0.1                     | 25                          | 0.05                         |
| Concrete       | /                           | 16.9                        | 11.6                       | /                       | /                           | /                            |
| Primary branch | /                           | 3.15                        | 1.2                        | /                       | /                           | /                            |

Table 2. Computation parameters of cable

| Parameters | Elastic modulus $(\text{GPa})$ | Cross-sectional area $(\text{m}^2)$ | Cohesive $(\text{kN/m})$ | Tensile strength $(\text{kN})$ |
|------------|-------------------------------|-------------------------------------|--------------------------|-------------------------------|
| Cable      | 0.2                           | 373                                 | 5000                     | 600                           |
| Bolt       | 20                            | 491                                 | 1000                     | 420                           |
3.2 Stability analysis of tunnel face and rock pillar

As shown in Fig. 8, under the two supporting schemes of the surrounding rock, the plastic zone of the middle rock pillar is connected when the distance between the two tunnel faces is 10m, which is not conducive to the stability of the surrounding rock. However, under the support of prestressed anchor cable, the development range of plastic zone of surrounding rock is reduced, and the stress of rock column at stop working side is smaller than that under original anchor bolt support (Fig. 9a). During the tunnel excavation process, when the distance between the two tunnel faces is 2m, the tunnel face displacement under the prestressed anchor cable support is about 90mm smaller than that under the original anchor bolt support (Fig. 9b). At the same time, the stress on both sides of the top of the upper bench rock pillar is relieved (Fig. 10). Therefore, prestressed anchor cable support can improve the stability of tunnel face and rock pillar.

![Figure 8](image1.png)

(a) Bolt support  
(b) Prestressed anchor cable support

**Figure 8.** Distribution characteristics of plastic zone before breakthrough (slice plane 1)

![Figure 9](image2.png)

(a) Bolt support  
(b) Prestressed anchor cable support

**Figure 9.** Stress of rock column between faces and displacement of stop working face (slice plane 2)
3.3 Analysis of surrounding rock displacement and stress

As shown in Fig. 11, after the breakthrough of tunnel is completed, the displacement of surrounding rock at the breakthrough position under the support of anchor bolt has obvious difference, and the height difference on both sides is about 260mm. However, under the support of prestressed anchor cable, the displacement difference of surrounding rock on both sides of the breakthrough position is not obvious. The maximum displacement of surrounding rock under bolt support is 720mm, while that under prestressed anchor cable support is 280mm (Fig. 12). Under the influence of the dip angle of rock stratum, the stress distribution of surrounding rock is not uniform in the longitudinal direction of tunnel. However, under the support of prestressed anchor cables, the uneven stress is relieved and the stress of surrounding rock is increased (Fig. 13). In the process of excavation, the surrounding rock stress after support will be affected by excavation disturbance. As shown in Fig. 14a, for the surrounding rock 5m away from the stop working face, during the breakthrough excavation, the surrounding rock stress supported by prestressed anchor cable is less disturbed than that supported by anchor bolt. For the surrounding rock 1m away from the stop working face, although the surrounding rock stress under the two kinds of supports are affected by the breakthrough excavation, the surrounding rock stress under the anchor cable support keeps a high level, which can better maintain the stability of the surrounding rock (Fig. 14b).
4. Tunnel support measure

4.1 Support mechanism

The prestressed anchor cable can quickly improve the bearing capacity of the surrounding rock, and form a coordinated bearing community between the support and the surrounding rock. As shown in
Fig. 15, the prestressed anchor cable can quickly improve the bearing capacity of the surrounding rock, and form a coordinated bearing community between the support and the surrounding rock. The supporting form of long and short anchor cables can simultaneously reinforce the surrounding rock in the shallow part and the surrounding rock in the deep part to form a double-layer composite arch structure (Xu et al., 1999; Gong et al., 2002; Xu et al., 2010).

In order to establish the relationship between rock mass parameters and support parameters, and fully consider the degree of rock fragmentation, the rock mass after support can be used as the elastic-plastic medium, and the rock mass after failure follows the Hawk-Brown criterion.

\[
\sigma_1 = \sigma_3 + \sigma_c (m_b \frac{\sigma_3}{\sigma_c} + s)^\alpha \tag{1}
\]

\[
m_b = \exp \left( \frac{GSI-100}{28} \right) m_l \tag{2}
\]

\[
s = 0 \tag{3}
\]

\[
a = 0.65 - \frac{GSI}{200} \tag{4}
\]

When the surrounding rock is relatively broken, the strength index $GSI < 25$. $\sigma_1, \sigma_3$ are the maximum and minimum principal stress (MPa) in the rock mass, $\sigma_c$ represents the uniaxial compressive strength (MPa) of the complete rock, $m_b$, $s$ and $a$ are the empirical parameters that reflect the characteristics of the rock mass. The surrounding rock will be deformed after excavation, and the formula (1) will be satisfied when the surrounding rock is damaged. If the binding force of anchor cable is $P$, the stress on the free faces of surrounding rock is generally $P$, then $\sigma_3 = P$. The relationship between $P$ and the pull-out force of anchor cable is as follows:

\[
P = \frac{Q}{D_aD_b} \tag{5}
\]

$Q$ is the pull-out force (kN) of the anchor cable (kN), $D_a$ and $D_b$ are the spacing and row spacing (m) of the anchor cable respectively.

According to the formula derived in the literature (Xu et al., 2010), we can get the bearing force $N$ of the composite arch on the axial unit length of tunnel as follows:

\[
N = \sigma_1 b + 1/2mb^2 = \sigma_1 (L - D_b) + 1/2m(L - D_b)^2 \tag{6}
\]

$m$ is the increasing slope of radial stress, $m = 0$ in the anchoring of unstable broken rock mass; $b$ is the thickness of composite arch (m), $L$ is the length of anchor cable, $D_b$ is the row spacing of anchor cables.

Under the effect of supporting force, the circumferential axial force generated by the composite arch formed by the surrounding rock is:

\[
N_0 = (R + L - D_b)q \tag{7}
\]
$q$ is the external load. When $N = N_D$, the combined arch is in the limit equilibrium state. When $N > N_D$, the combined arch formed by the anchor cable can be stable and reliable.

When the long and short anchor cables work together, we can get the bearing capacity formula of double-layer composite arch according to the above formula:

$$q_o = \frac{q_L - D_a}{R + L - D_a} \left[ \frac{Q_s}{D_aD_b} + \sigma_c \left( \frac{m_0Q_s}{\sigma_cD_aD_b} \right)^a \right] + \frac{L_s - D_a}{R + L_s - D_a} \left[ \frac{Q_s}{D_aD_b} + \sigma_c \left( \frac{m_0Q_s}{\sigma_cD_aD_b} \right)^a \right]$$

(8)

$Q_s$, $Q_L$ is the pull-out force (KN) of long anchor cable and short anchor cable respectively, $D_a$, $D_b$ is the spacing and row spacing of the long anchor cable(m) respectively. $D_a$, $D_b$ is the spacing and row spacing of the short anchor cable(m) respectively. $L_s$, $L_a$ is the length of long cable and short cable respectively (m), $R$ is the radius of tunnel arch (m).

We estimate the value of the external load $q$ based on the “Specifications for Design of Highway Tunnels JTG 3370.1-2018,” and considering the influence of the grade and span of the surrounding rock. We regard the rock mass covered by the anchor cable as the reinforcement structure of the tunnel, and take it into the tunnel span, thus obtaining the formula:

$$q = 0.45 \times 2^{s-1} \times \gamma [1 + 0.1 \times (B - 5)]$$

(9)

$s$ is the grade of the surrounding rock, $\gamma$ is the weight of the surrounding rock, and $B$ is the span of tunnel. By comparing the values of $q$ and $q_o$, when $q_o \geq q$, the anchor cable support can maintain the stability of the surrounding rock.

### 4.2 A New kind of prestressed anchor cable

The new support scheme uses a constant resistance large deformation anchor cable (Fig. 16), which is a negative Poisson’s ratio anchor cable (NPR anchor cable). Due to the existence of the constant resistance device, the cone unit of the anchor cable can be slipped in the casing pipe, so that the outer diameter of the casing pipe is expanded, thereby realizing the negative Poisson’s ratio effect. When the device is in operation, the large friction will be generated between the cone unit and the casing pipe, so as to realize the large deformation resistance while allowing the deformation of the surrounding rock. According to the constitutive relation of constant resistance and large deformation anchor cable (He et al., 2014), constant resistance anchor cable support uses its constant resistance force, so the support force of anchor cable can be regarded as constant force:

$$Q_0 = 2\pi I_s f I_c$$

(10)

$I_c$ is the geometric parameter, $I_s$ is the elastic parameter of the sleeve, and $f$ is the static friction coefficient.

Let the constant resistance force $Q_0 = Q_L = Q_s$ in formula (10), and bring it into formula (8) to get:

$$q_o = \left[ \frac{2\pi I_s f I_c}{D_aD_b} + \sigma_c \left( \frac{2\pi I_s f m_b}{\sigma_cD_aD_b} \right)^a \right] \left( \frac{L_s - D_a}{R + L_s - D_a} + \frac{L_s - D_a}{R + L_s - D_a} \right)$$

(11)

$\mu$ is the correction coefficient.

In this way, we get the relationship between the parameters of the constant resistance anchor cable and the bearing capacity of the surrounding rock, which provides a quantitative basis for the constant resistance anchor cable support measures of the tunnel.
Based on the above numerical analysis and theoretical analysis, the combined support method of long and short constant resistance anchor cable is proposed. The excavation scheme is in accordance with the original design. Under the condition that the original technology remains unchanged, the original bolt support system is canceled and the double-layer steel arch frame is replaced by a single layer. We adopt the support form of “NPR anchor cable + W-shaped steel belt + steel mesh”, and the anchor cable pretension is 350kN, as shown in Fig. 17.

(a) Cross section of the tunnel supported by the NPR anchor cable.
5. Analysis of monitoring results

5.1 Field test project
The stability of surrounding rock near the stop working face of the tunnel under the support of constant resistance anchor cable is tested by monitoring the axial force of anchor cable, surrounding rock deformation, and steel arch stress. The location of the monitoring section is shown in Fig. 18.

5.2 Force analysis of anchor cable
The test results of the anchor cable axial force are shown in Fig. 19. The prestress applied by the anchor cable was 350 kN, and the prestress loss was about 50 kN. The axial force of the anchor cable gradually increased with time, but the axial force of all anchor cables maintained about 350 kN after a period of support. The relatively high axial force of anchor cable at arch crown indicates that the deformation of surrounding rock is large, but it is always in good working condition.
5.3 Analysis of Surrounding Rock Surface Displacement and Steel Arch Stress

As shown in Fig. 20, the stress of the steel arch and the deformation of the surrounding rock have a synchronous trend. The stress of the steel arch of the vault and the deformation of surrounding rock are slightly larger than that of the two arch shoulders. After the upper bench was penetrated, the stress of the steel arch and the deformation of the surrounding rock were in a rapid growth stage (0-8d). The stress of the steel arch vault exceeded its ultimate strength, which will cause the deformation of the primary support. But after the invert excavation and the steel arch closed, the stress of the steel arch gradually decreases below its ultimate strength with the stability of the surrounding rock deformation. After the completion of the invert construction, the increasing trend of surrounding rock displacement and steel frame stress gradually slowed down, and finally tended to be stable. After the tunnel is connected (Fig. 21), the displacement difference between the two working faces was about 51mm, which meets the construction requirements.

Figure 19. Monitoring of Anchor Cable axial force

Figure 20. Relationship between arch stress and surrounding rock displacement
6. Conclusion
This paper introduces the application of high prestressed constant resistance and large deformation anchor cable in tunnel. Through numerical simulation, theoretical analysis, and field test, the following conclusions are drawn:

(1) Numerical simulation results show that the displacement of the tunnel face and the unsymmetrical stress of the rock column can be reduced under the support of the prestressed anchor cable, and the deformation of the surrounding rock can be greatly reduced. After the tunnel is connected, the surrounding rock height difference between the two working faces is not obvious. At the same time, the influence of excavation disturbance on the surrounding rock near the stop working side is reduced, and the surrounding rock keeps a high-stress level, which ensures the stability of the surrounding rock.

(2) Based on the Hawk-Brown criterion and theoretical analysis, the relationship among the constant resistance anchor cable support parameters, rock mass parameters, and surrounding rock bearing capacity is obtained. The active support measures of long and short prestressed constant resistance anchor cable can make the surrounding rock form a double-layer composite arch structure and improve the bearing capacity of surrounding rock.

(3) The field monitoring results showed that the constant resistance anchor cables maintained a high pre-stress state and worked well. The displacement of surrounding rock keeps synchronous with the stress change of steel arch. In the rapid growth stage of surrounding rock deformation, the stress of steel arch was large. After the tunnel was connected, the surrounding rock displacement difference between the two working faces was controlled within 100 mm. Finally, the maximum displacement of surrounding rock was 223 mm, and the stress of steel arch tended to be stable gradually.

Acknowledgments
This work was supported by the National Key Research and Development Plan of China (Grant No. 2016YFC0600901), the National Natural Science Foundation of China (Grant No. 51904306; 51874311; 41941018), and State key Laboratory for Underground Engineering of Deep Geotechnical Mechanics (Beijing) Open-ended Fund Project (Grant No. SKLGDUKEK1826), This work was also supported by Gansu Provincial Science and Technology Program (Grant No.19ZD2GA005).
References

[1] Brox, D., & Hagedorn, H. 1999. Extreme Deformation and Damage during the Construction of Large Tunnels. Tunnelling and Underground Space Technology, 14(1), 23-28.

[2] Dong, F. T., Song, H. W., Guo, Z. H., 1994. Roadway support theory based on broken rock zone,” Journal of China Coal Society. 19(1), 21-32.

[3] Goel, R. K., Swarup, A., & Sheorey, P. R. 2007. Bolt length requirement in underground openings. International Journal of Rock Mechanics and Mining Sciences, 44(5), 802-811.

[4] Gong, H. F., Zhang, W. J., Li, X. Q., 2002. Discussion about rational parameters of supporing with combined arch. Coal Mining Technology, vol. 01, pp. 42-44+62, 2002.

[5] He, M., 2011. Physical modeling of an underground roadway excavation in geologically 45° inclined rock using infrared thermography. Engineering Geology. 121(3), 165-176.

[6] He, M., Gong, W., Wang, J., Qi, P., Tao, Z., Du, S., & Peng, Y. 2014. Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance. International Journal of Rock Mechanics and Mining Sciences. 67, 29-42.

[7] Hoek, E., Marinos, P. G., Marinos, V. P., 2005. Characterisation and engineering properties of tectonically undisturbed but lithologically varied sedimentary rock masses. International Journal of Rock Mechanics and Mining Sciences. 42(2), 277-285.

[8] Kang, H. 2014. Support technologies for deep and complex roadways in underground coal mines: a review. International Journal of Coal Science & Technology, 1(3), 261-277.

[9] Kang, Y., Liu, Q., Gong, G., & Wang, H., 2014. Application of a combined support system to the weak floor reinforcement in deep underground coal mine. International Journal of Rock Mechanics and Mining Sciences. 71, 143-150.

[10] Karanam, U. M., & Dasyapu, S. K. 2005. Experimental and numerical investigations of stresses in a fully grouted rock bolts. Geotechnical and Geological Engineering, 23(3), 297-308.

[11] Meguid, M. A., & Rowe, R. K. 2006. Stability of D-shaped tunnels in a Mohr-Coulomb material under anisotropic stress conditions. Canadian Geotechnical Journal, 43(3), 273-281.

[12] Meng, Q., Zhao, H., Zhu, C., & Ru, Z. 2018. Analytical and Reliability Study of the Tunnel with Rockbolts in Rock Masses. Periodica Polytechnica-civil Engineering. 62(3), 783-791.

[13] Ö. Aydan, Akagi, T., Kawamoto, T., 1996. The squeezing potential of rock around tunnels: theory and prediction with examples taken from japan. Rock Mechanics & Rock Engineering. 29(3), 125-143.

[14] Peng, S., 1998. Roof bolting adds stability to weak strata. Coal Age Mag. 11, 32-38.

[15] Tao, Z., Zhu, C., Zheng, X., Wang, D., Liu, Y., He, M., & Wang, Y., 2018. Failure mechanisms of soft rock roadways in steeply inclined layered rock formations. Geomatics,Natural Hazards and Risk. 9(1), 1186-1206.

[16] Wang, H., Xiao, G., Jiang, M., & Crosta, G. 2018. Investigation of rock bolting for deeply buried tunnels via a new efficient hybrid DEM-Analytical model. Tunnelling and Underground Space Technology. 82, 366-379.

[17] Wu, G., Chen, W., Tian, H. F., Jia, S., Yang, J., & Tan, X. 2018. Numerical evaluation of a yielding tunnel lining support system used in limiting large deformation in squeezing rock. Environmental Earth Sciences, 77(12), 439.

[18] Xu, F., Li, S., Zhang, Q., Li, L., Shi, S., & Zhang, Q. 2017. A new type support structure introduction and its contrast study with traditional support structure used in tunnel construction. Tunnelling and Underground Space Technology. 63, 171-182.

[19] Xu, J. H., Shi, B. H., Wang, Y. H., 1999. Research on strength of reinforced unit and bearing capability of broken rock arch and its application. Journal of China University of Mining and Technology. 28(5), 481-483.

[20] Xu, W. J., Gao, Q., Zhu, C. Q., 2010. Study of strength theory and application of overlap arch bearing body for deep soft surrounding rock. Chinese Journal of Rock Mechanics and Engineering. 10, 195-203.

[21] Zhang, J., Xu, W. J., Du, S. H. 2016. Optimization design of long and short anchor support for
extremely fractured stoping roadway. Mining Research & Development. 36(8), 56-60.

[22] Zhang, Z., Shi, X., Wang, B., & Li, H. 2017. Stability of NATM tunnel faces in soft surrounding rocks. Computers and Geotechnics. 96, 90-102.