Environmental Earth Sciences (2018) 77:439
https://doi.org/10.1007/s12665-018-7614-0

ORIGINAL ARTICLE

Numerical evaluation of a yielding tunnel lining support system used in limiting large deformation in squeezing rock

Guojun Wu[1] · Weizhong Chen[1,2] · Hongming Tian[1] · Shanpo Jia[3] · Jianping Yang[1] · Xianjun Tan[1]

Received: 24 January 2018 / Accepted: 16 June 2018 / Published online: 22 June 2018

Abstract
Large deformation in squeezing soft rock is a significant challenge that complicates the safety of underground construction engineering. A yielding tunnel support system allows a certain amount of over-excavation, thereby accommodating large deformation in severely squeezing rock. In this study, a special yielding support system has been developed with a type of newly developed foamed concrete material which has a cushion effect. The special yielding support uses pre-cast foamed concrete blocks which are mounted in the primary lining, and an in situ cast foamed concrete layer which is placed between the primary lining and the secondary lining. The effect of the special yielding support on squeezing rock tunnels has been validated by comparing the numerical results with those of a lining-strengthened stiff support system. The incorporation of the foamed concrete blocks can both reduce the maximum and minimum principal stress in the primary lining. Relative to the stiff support, the maximum and minimum principal stress in the primary lining are about 50 and 60% of those of the stiff support, respectively, thereby improving the stress state of the primary lining. Further, compared with that in the stiff support, the plastic zone in the secondary lining in this yielding support is significantly improved, and the deformations at the roof and the sides of the secondary lining are 40 and 46% less than that of the stiff support, respectively, resulting in a better stress state and less deformation in the secondary lining.

Keywords Support · Foamed concrete · Squeezing rock · Numerical model · Tunnel · Deformation

Introduction

Large deformation induced in rock due to tunneling is a significant challenge that complicates the safety of underground engineering. This problem has been encountered frequently, especially in squeezing soft rock tunnels, such as the Tao-En tunnel and the Al-Berg tunnel in Austria, the Jiazhuqing tunnel and the Wushaoling tunnel in China (Meng et al. 2013). With reference to the Jiazhuqing tunnel, during the initial excavation, up to 1 m deformation of the tunnel roof caved in, which resulted in a significant threat on the subsequent construction.

For deep-buried squeezing soft rock, due to its low strength and subjected to high ground stress during tunneling, there is often large deformation. When the shear stress of the soft rock gradually reaches its strength, most of surrounding rock enters the plastic state, thereby causing noticeable rock deformation encroaching into the tunnel. Hence, when facing the problem of large deformation, it is necessary to consider the factors of rock strength and creep properties (Ngoc-Anh et al. 2015; Agan 2016; Wu et al. 2017). In fact, the deformation rate of tunnel in squeezing rock largely depends on the rock mass properties, such as the in situ stress relative to rock mass strength, and geological conditions (Aydan et al. 1993; Wang et al. 2000; Scussel and Chandra 2014).

For tunnels in squeezing soft rock, the stability issue on how to support the tunnel has become one of the major concerns during tunnel excavation (Hoek 2001; Dalgic 2002; Kolymbas et al. 2006; Barla et al. 2011; Dwivedi et al. 2013, 2014). Most studies assessed the support pressure or

✉ Guojun Wu
gjwu@whrsm.ac.cn

1 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

2 Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan 250061, China

3 Research Center of Geomechanics and Geotechnical Engineering, Yangtze University, Jingzhou 434023, Hubei, China

ground-support behavior in tunnels which were excavated in squeezing ground condition, and made the decision on a suitable support system (Dwivedi et al. 2014; Vrakas and Anagnostou 2016; Mezger et al. 2017). In general, depending on the geology, ground stress, and other conditions, heavy or stiff support system and yielding support system are both effective in limiting large deformation in squeezing soft rock. Stiff supports can directly limit large deformation of tunnel (Dwivedi et al. 2013). Aksoy et al. (2012) discussed non-deformable support with certain excavation toleration. He also carried out finite elements analysis to investigate the T-13 tunnel in highly deformable rocks. The results showed that non-deformable support system can be used in highly deformable rocks without over-excavation. On the other hand, in some situations where deformations are allowable, yielding supports can be used. In combination with a certain amount of over-excavation, yielding tunnel support can accommodate deformations in squeezing and even heavily squeezing ground. Cantieni and Anagnostou (2009) used numerical analyses to investigate the interaction between the yielding supports and squeezing ground, which included the evolution of the spatial stress field around the advancing tunnel heading. Due to the stress-related failure in the rock mass in thrust zones and strike–slip faults that transected the Bolu tunnel, Dalgic (2002) discussed the feasibility of using the flexible support approaches. These approaches use a flexible support, over-excavation, longitudinal gaps in the shotcrete lining and yielding rock bolting. Barla et al. (2011) reported that to carry out excavation in severely squeezing rock conditions, a yielding support system with highly deformable concrete elements incorporated in the primary lining was implemented in the Saint Martin La Porte access adit. Mezger et al. (2018) performed a comparative analysis of radially or tangentially deformable linings and conventional rigid segmental linings and showed that deformable lining systems offer advantage for deep tunnels crossing rocks. Tian et al. (2016, 2018) focused on the interaction of shotcrete liner with rock for yielding supports and investigated the influence of the yield stress of the yielding element on the behavior of the shotcrete liner. Zeng and Xu (2013) presented a unified semi-analytical solution for elastic–plastic stress of a deep circular hydraulic tunnel with support yielding under plane strain conditions. For all yielding support systems, the idea is that the ground pressure decreases when the ground deforms at the cost of large deformation produced in the yielding supports. During construction, the yielding support system and the amount of over-excavation can be adapted to change in squeezing intensity, and make the combined efforts to ensure the stability of the openings.

Although those studies mentioned above were performed on yielding support measures or support methods, most of them are focused on the effect of the yielding elements and the feasibility of the yielding support measures. Few mentioned the systematic and direct yielding support systems. In particular, only few reported a complete yielding support system and evaluated its overall performance under the working conditions (Barla et al. 2011; Moritz 2011; Tian et al. 2016). In this study, a special yielding support system has been proposed. It uses a type of foamed concrete as a cushion material. The special yielding support makes full use of the foamed concrete to allow soft rock to deform within an acceptable range, and the performance of this support system has been compared with that of a stiff support system under the same conditions for a given amount of over-excavation.

Development of a special yielding support system

In this study, a special yielding support system has been developed. In addition to the conventional active supports, such as rock bolts and cables, it consists of several critical support components including the primary lining, foamed concrete blocks, foamed concrete layer and the secondary lining, as shown in Fig. 1.

The primary lining is mainly composed of shotcrete, steel fabrics and enclosed steel ribs. Shotcrete and steel fabrics are attached to the wall so as to prevent weathering of the surrounding rock. With the shotcrete support, the integrity of the surrounding rock is strengthened. The enclosed steel sets are the key element of the primary lining which carries the loads induced by the surrounding rock. Generally, the spacing of the steel ribs in longitudinal direction is between 50 and 80 cm.

Different from the design of conventional primary linings, the special yielding support uses a foamed concrete as a type of cushion material to resist ground pressure. First, the foamed concrete blocks are to be incorporated between shotcrete at a regular spacing. The foamed concrete blocks are precast, the role of which is to distribute large ground stresses induced by surrounding rock so as to prevent concentration of local stress on the shotcrete. The location of the foamed concrete blocks is shown in Fig. 2. Second, the foamed concrete layer is placed between the primary lining and the secondary lining, which replaces the blank of the deformation allowance of the primary lining. It acts as a cushion to absorb the loads from the primary lining. So, it is a crucial element to reduce the loads induced by the rock mass on the secondary lining. This layer is cast in situ after the installation of the primary lining.

The secondary lining is molded with reinforced concrete. Compared with the primary lining, the secondary lining is usually regarded as a strengthened support structure. The

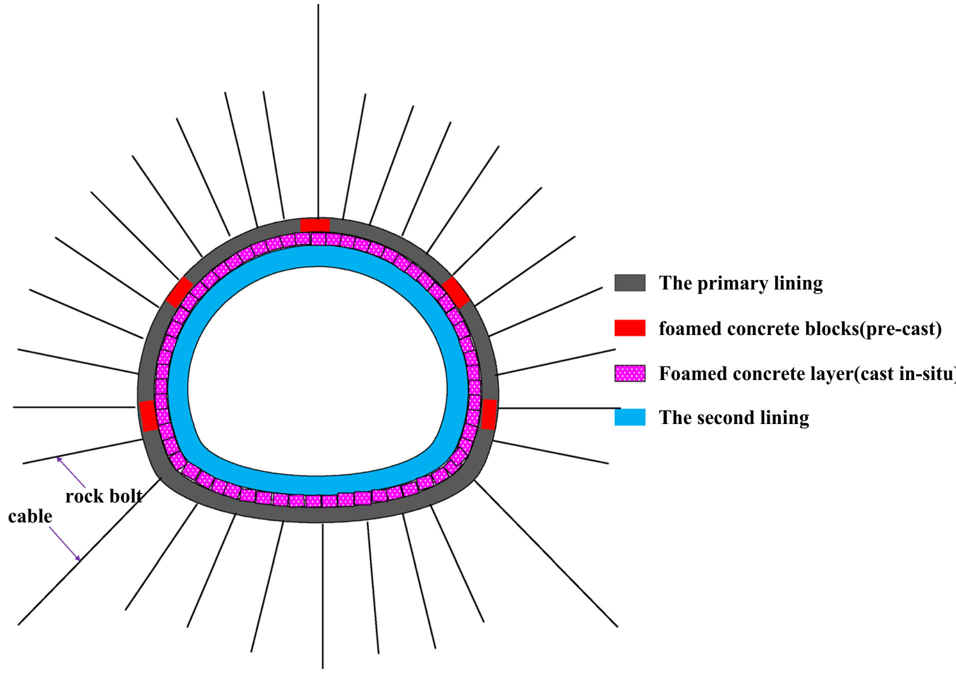


Fig. 1 Special yielding support for soft rock tunnels

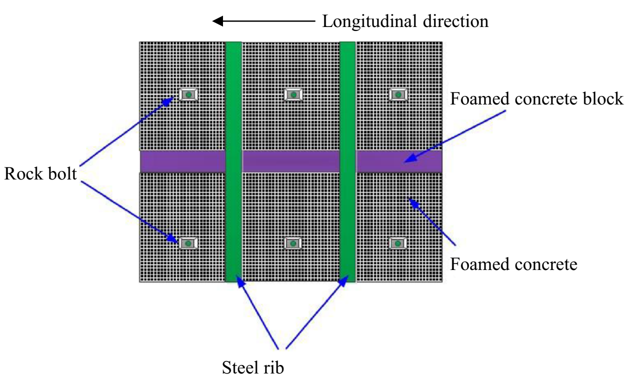


Fig. 2 Layout of the primary lining and the foamed concrete

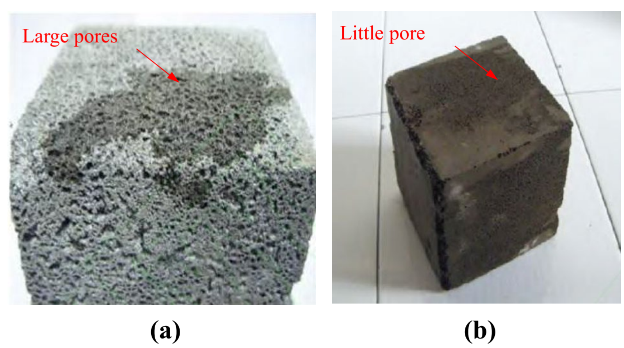


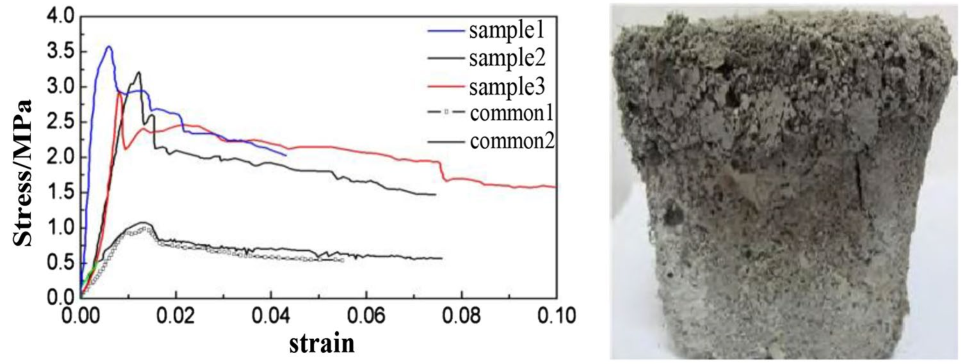
Fig. 3 Foamed concrete samples **a** common foamed concrete **b** developed foamed concrete

thickness of the secondary lining is generally between 40 and 70 cm.

Properties of the foamed concrete

Foamed concrete is widely used in house building as a type of energy-saving building material. It is a type of lightweight concrete with a large number of pores. Foamed concrete has a good capacity of deformability due to its small elasticity performance. However, there are some shortcomings, such as large shrinkage and ease of cracking for the existing pores (Fig. 3), extremely low elastic modulus and strength, especially the extremely low strength, which is not feasible to resist much more deformation toward the inside of the tunnel, thereby imposing an excess load on the lining. So these shortcomings are harmful to act as absorbing large deformation pressure of surrounding rock when tunneling.

In this study, to overcome these shortcomings, a new foamed concrete has been developed by mixing waterproof agent, fiber, and other additives together. The properties of this new foamed concrete, such as the strength, elasticity, ductility and waterproofness, are higher than those of common foamed concrete. The mechanical properties of the newly developed foamed concrete were observed through some uniaxial and triaxial compressive tests conducted by our research team (Wang et al. 2012; Zhao et al. 2013). Figure 4a shows a comparison of stress–strain curves for the samples of the new and common foamed concretes. It can be seen that the uniaxial compressive strength of the new foamed concrete (3.2 MPa on average for the three samples) is much higher than that of the common concrete



(a) (b)

Fig. 4 Uniaxial compressive test of the foamed concrete **a** stress–strain curves **b** failure of the new foamed concrete under uniaxial compression

(around 0.9 MPa). The elasticity modulus of the new foamed concrete is 0.6 GPa, while that of the common concrete is around 0.2–0.4 MPa. Figure 4b shows the axial damage after tests. Further, the triaxial compressive test has been conducted to examine the features of the foamed concrete. Figure 5a shows the stress–strain curves. It can be seen that the average peak stress of the samples reaches approximately 6.2 MPa and then almost remain at that stress level thereafter. This is an indication the behavior of the new foamed concrete is nearly elastic perfectly plastic. Figure 5b shows the shape of Sample 4 after the test. It can be seen that the integrity of the sample is well maintained. This means that the new foamed concrete has good ductility even after entering the yield stage.

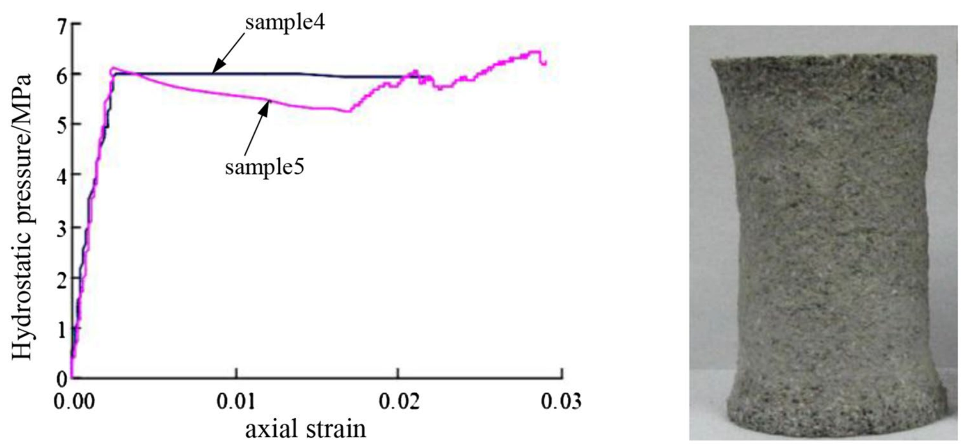
As mentioned above, due to its high compressive strength relative to common foamed concrete, it can endure much pressure; owing to its porous structures, it has better deformability than cement concrete; Most importantly, it is characterized by good ductility and is difficult to crack even in the plasticity stage. Therefore, it is introduced to be used in the special yielding support system as a cushion material.

Application of the yielding support system in a squeezing soft rock tunnel

Introduction to tunnel engineering

In this study, the Jieling tunnel in squeezing rock has been used as an example to investigate the application of the yielding support system. The Jieling tunnel is part of Yi-Ba highway in Xingshan city in Hubei province of China. It is a deep-buried tunnel with a standard two-lane highway. The tunnel is 5.0 m high and 10.25 m wide. The surrounding soft rocks are primarily mudstone and muddy fractured shale.

During the initial tunneling, due to the large ground pressures caused by the squeezing rock and insufficient support measures, there were large deformations of the tunnel lining. They include the 25 cm crown settlement and the 40 cm deformation at the sidewall and the primary lining was damaged, which resulted in the caving in of the roof and the sidewall, as shown in Fig. 6. The



(a) (b)

Fig. 5 Triaxial compressive test of the new foamed concrete **a** stress–strain curves **b** failure under triaxial compression

Fig. 6 Failure of the tunnel in squeezing rock **a** large deformation **b** damage of the primary lining

roof collapsed and the damage of the primary lining was mainly caused by the inadequacy of the original support. The damage began a few days after the installation of the primary lining. This is an indication that there was creeping of the squeezing rock, and the tunnel was subjected large ground pressure due to the creeping of the squeezing rock.

Support scheme

According to the requirements of tunnel engineering, a new support scheme needs to be installed. Since the original support is inadequate, one method to strengthen the tunnel lining, especially the secondary lining, is to install a stiff support system (Aksoy et al. 2012). After all, the secondary lining is made of reinforced concrete. So, it has a larger bearing capacity than that of the primary lining. It is also constructed after the installation of the primary lining. Another method is to install a yielding support system, which is to make use of the self-capacity of the shotcrete and surrounding rock, and utilize the cushion layer to accommodate the deformation of the primary lining and surrounding rock. Hence, there are two alternative support schemes for this tunnel, i.e., a stiff support scheme and a yielding support scheme. The following is a comparison of the two schemes.

Figure 7 shows the stiff lining support (Scheme 1). The primary lining (mainly 25-cm thick shotcrete) is used to carry the loads during tunnel excavation. After the placement of the primary lining, the deformation tolerance layer is filled by reinforced concrete which is the secondary lining. The thickness of the whole secondary lining is 65 cm, which is to strengthen the secondary lining so that it can carry the ground loads induced by the creeping of the squeezing soft rock.

Figure 8 shows the special yielding lining support (Scheme 2). The thickness of the primary lining is 25 cm

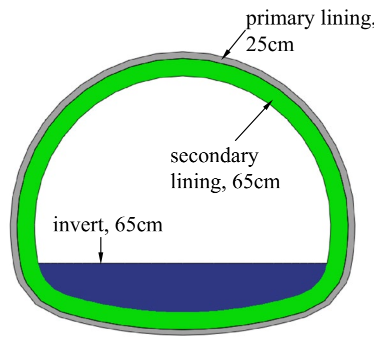


Fig. 7 The stiff lining support (Scheme 1)

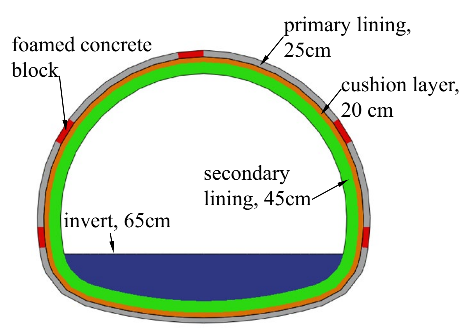


Fig. 8 The special yielding lining support (Scheme 2)

shotcrete, which is the same as that in Scheme 1. Then, along the tunnel perimeter, five pieces of foamed concrete blocks are placed at nearly equal spacing. The 50 cm long and 20 cm thick foamed concrete blocks are mounted into the primary lining. Further, the deformation tolerance layer is filled with 20 cm thick foamed concrete which is designed to act as a cushion layer. The 45 cm thick

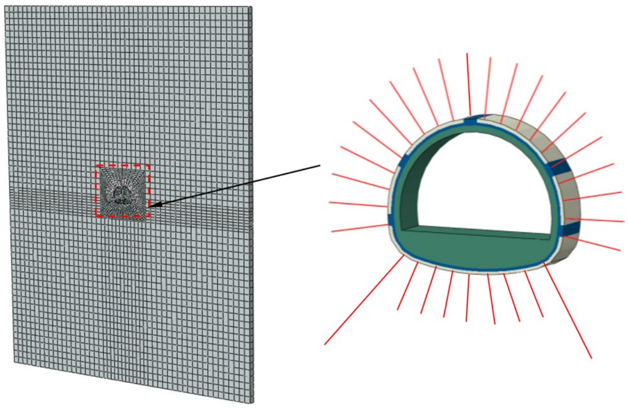


Fig. 9 Scheme 2 numerical model

secondary lining is molded to carry the ground loads induced by the creeping of the squeezing soft rock.

The same simulation procedure has been applied to the two schemes. It includes the tunnel excavation, installation of the primary lining, mold-casting of the secondary lining and creeping of the soft rock for 10 years.

Modelling analysis

Numerical model

Two numerical quasi-3D models for Schemes 1 and 2 have been developed. The geometrical sizes and boundaries of the two models are the same. The models are 100 m wide, 100 m high, and 2 m long in the longitudinal direction. In these models, vertical deformations along the base boundary and lateral deformations along the vertical boundary are not allowed. Further, an overburden of 1000 m ground stress acts on the top surface of the model. The rock mass and the supports (including the primary lining, foamed concrete blocks, cushion layer, and secondary lining) have all been simulated with solid elements, while the rock bolts have been simulated with truss elements. The Scheme 1 model has 4292 nodes and 4160 elements, whereas the Scheme 2 model has 4292 nodes and 4358 elements. Figure 9 shows the Scheme 2 numerical model.

Table 2 Creep parameters of the rock mass

A	n	m
1.4408×10^{-5}	0.383	− 0.833

Table 3 Parameters of the foamed concrete

Elastic modulus, E/Gpa	Poisson ratio, μ	Dry density, ρ_d /kg·m^{-3}	K^0	K^t	σ_c/MPa
0.60	0.41	720	0.48	0.1	3.2

Material parameters

The parameters of the rock mass and supports (Table 1) and the creep parameters of the soft rock (Table 2) are determined from laboratory tests (Chen et al. 2011). Based on the laboratory results, an empirical creep model with a power function has been developed to describe the creep strain of the squeezing rock, as follows:

$$\varepsilon_t + \varepsilon_s = A(\sigma_{eq})^n t^{m+1}, \tag{1}$$

where ε_t is the creep strain in the initial stage, ε_s is the creep strain in the stable stage, σ_{eq} is the equivalent creep stress, which is equal to $(\sigma_1 - \sigma_3)$ in the biaxial test, t is time; A, m, and n are the material creep parameters, as shown in Table 2.

According to the Chen and Zhao (Chen et al. 2011; Zhao et al. 2013), the parameters of foamed concrete are shown in Table 3. The numerical simulation can be carried out using the code ABAQUS, in which the crushable foamed material can be used to model the foamed concrete in the model.

Analyses of results

By numerical calculations, the stresses and deformations in the primary lining and the secondary lining can be determined. For Scheme 2, the calculations include the cushion layer. To evaluate the performance of the yielding support system, comparisons of the stresses and deformations in the primary and secondary linings of the two schemes have been carried out.

Due to the symmetry of the numerical models and the boundary conditions, angle ϕ is defined clockwise from the

Table 1 Parameters of the rock mass and supports

Material	Elastic modulus, E/GPa	Poisson ratio, μ	Cohesion, C/MPa	Internal friction angle, φ/°	Density, ρ/kg·m^{-3}
Soft rock	3	0.3	2.47	32	2685
Primary lining	26	0.17	3.12	41	2500
Secondary lining	30	0.17	16.99	58.7	2500
Rock bolt	210	0.2	–	–	5000

bottom to the top of the tunnel, and half of the perimeter with $\phi = 0°–90°$ has been selected for analyses, as shown in Fig. 10. As $\phi = 15°$, 49°and 90° correspond to the locations of the foamed concrete blocks in the primary lining, this means that along half of the tunnel perimeter, there are three foamed concrete blocks.

1. The primary lining

In Scheme 2, as there are some foamed concrete blocks embedded in the shotcrete linings, its stresses in the primary linings induced by tunnel excavation are different from those of Scheme 1. Figure 11 shows a comparison of the maximum principal stresses (almost in the hoop direction) in the primary linings of Schemes 1 and 2 along half of the tunnel perimeter (i.e., $\phi = 0°–90°$). It can be seen that for Scheme 1, the maximum principal stress in the primary lining is approximately 1 MPa. On the other hand, for Scheme 2, despite some vibrations in the maximum principal stress, it is still less than 1 MPa. The maximum principal stresses in these foamed concrete blocks are less than zero, meaning they are under compression state. The maximum principal stresses in the primary lining in Scheme 2 are commonly half of the those of Scheme 1. Figure 12 shows a comparison of the minimum principal stresses (almost in the radial direction) in the primary linings of Schemes 1 and 2. It can be seen that for Scheme 1, the minimum principal stress in the primary lining is 15–12 MPa for $\phi = 0°–15°$, and practically constant at 12 MPa for $\phi = 15°–90°$. On the other hand, for Scheme 2, the minimum principal stress fluctuates with peak stress at around 12 MPa, and the minimum stresses at the locations where these foamed concrete blocks were incorporated are about 0.8 MPa. The average minimum principal stress in the primary lining in Scheme 2 is about 60% of that of Scheme 1. This stress fluctuation phenomenon for the primary lining with foamed concrete blocks is found to be similar with that in literatures (Barla et al. 2011; Tian et al. 2018), where the curve of the axial thrust of the liner is fluctuant and the forces at the yielding elements are minimal. This is an indication that the installation of the foamed concrete blocks can reduce the minimum principal stress in the primary lining, particularly at the adjacent lining elements. The minus sign indicates compression in the lining. This phenomenon can be attributed to the large deformation of the foamed concrete blocks, as its elasticity modulus is largely smaller than that of shotcrete.

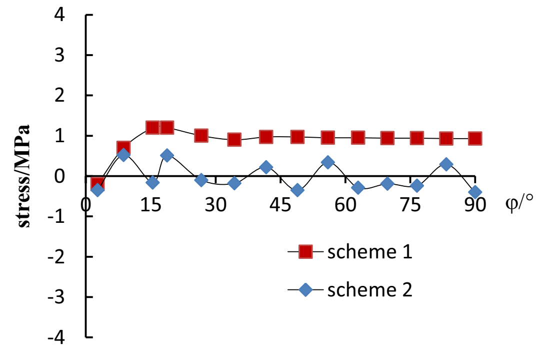


Fig. 11 Comparison of the maximum principal stress in the primary lining for two schemes

Therefore, due to the installation of the foamed concrete blocks, both the maximum and minimum principal stresses are smaller in the primary lining of Scheme 2, thereby improving the stress state of the primary lining.

2. The deformation tolerance layer

In Scheme 1, the deformation tolerance layer has been installed with strengthened concrete as a stiff support. In Scheme 2, the deformation tolerance layer has been replaced by foamed concrete as a cushion layer. For this reason, the interaction of the primary lining and the deformation layer is of great importance. Figure 13 shows the contact stresses

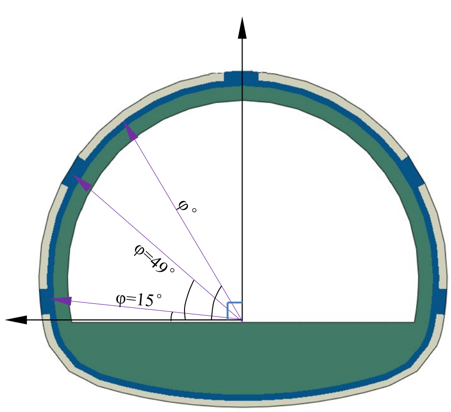


Fig. 10 ϕ increases clockwise from the bottom to the vault

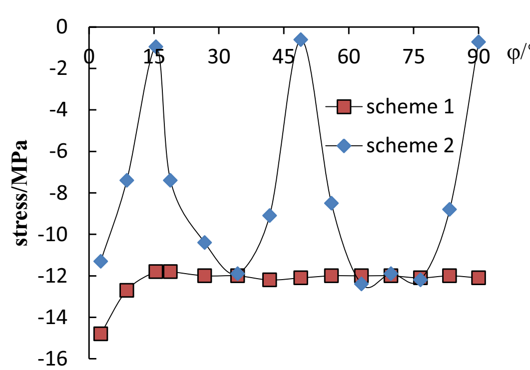


Fig. 12 Comparison of the minimum principal stress in the primary lining for two schemes

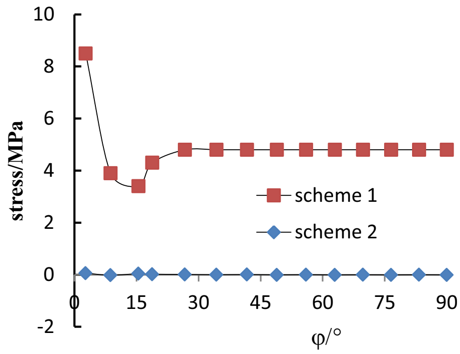


Fig. 13 Comparison of the contact stress between the primary lining and the deformation layer for two schemes

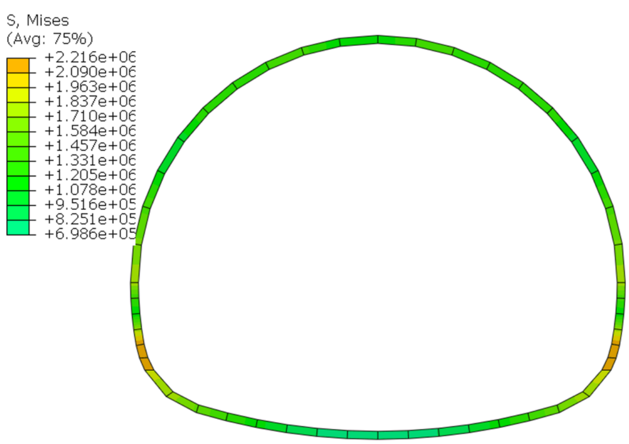


Fig. 14 Stress (Unit: Pa) distribution of foamed concrete as the deformation layer in Scheme 2

between the primary linings and the deformation layers of Schemes 1 and 2. For Scheme 1, the contact stress is large, and for $\phi = 20°–90°$, it is around 5 MPa. On the other hand, for Scheme 2, the contact stress is considerably small relative to that of Scheme 1. This is due to the foamed concrete acting as a cushion layer. Figure 14 shows the stress distribution of foamed concrete layer in Scheme 2. The stresses in this layer are small (around 1.5 MPa) and evenly distributed, except for local stress concentration at the spring sidewalls. Hence, the foamed concrete cushion layer is effective in reducing excavation loads of rock on the secondary lining. It is an important element in the yielding support system in limiting large deformation of tunnel lining in squeezing rock.

3. The secondary lining

Figure 15 shows the plastic zone distributions in the secondary linings of Schemes 1 and 2. At the arch foot of the two schemes, similar areas are deep in plastic state. For scheme 1, almost the entire secondary lining is in plastic state. On the other hand, for scheme 2, only some areas, such as the arch foot and floor, are in plastic state. Further, for Scheme 1, the maximum plastic strain is 1.09×10^{-2}, while for Scheme 2, it is 5.02×10^{-3}. Therefore, the stress state in the secondary lining of Scheme 2 is significantly better than that of Scheme 1. Similar results were reported in literatures (Wang et al. 2012, 2016; Zhao et al. 2013), where the secondary lining was largely improved in the case of adopting the reserved deformation layer. This can be attributed to the foamed concrete layer between the primary lining and the secondary lining in Scheme 2.

Similarly, for the deformation in the secondary lining, Scheme 2 also performs better than Scheme 1, especially at the roof and the lateral sides of the secondary lining, as

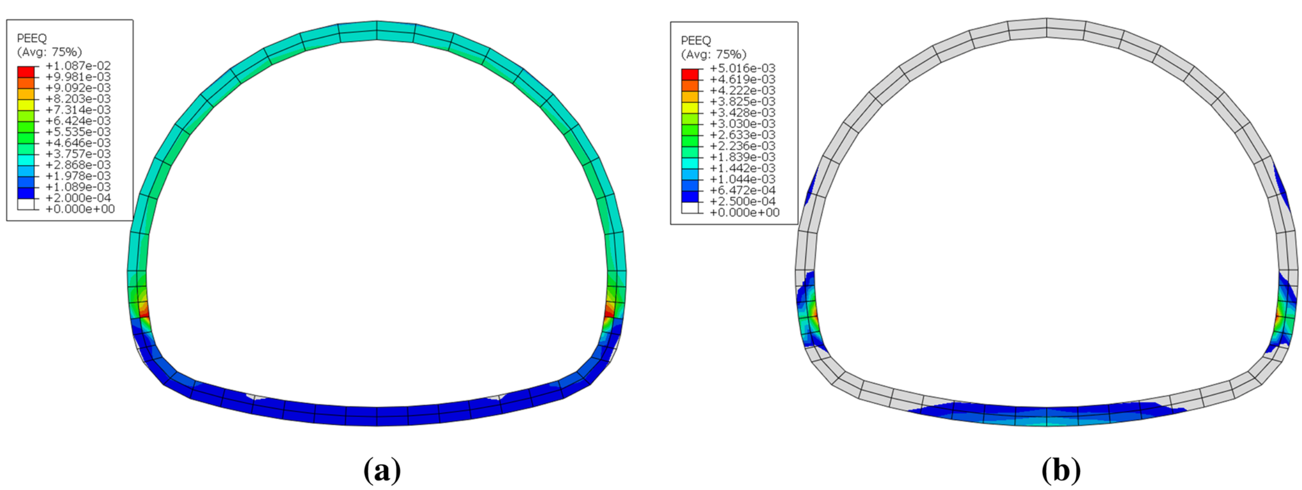


Fig. 15 Plastic zone distribution in the secondary lining of the two schemes **a** Scheme 1 **b** Scheme 2

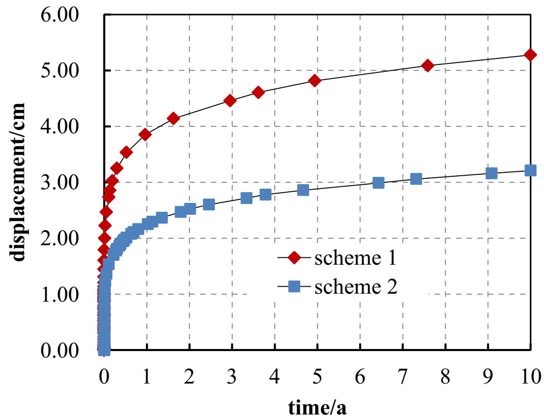


Fig. 16 Comparison of deformations at the roofs of the secondary linings for Schemes 1 and 2

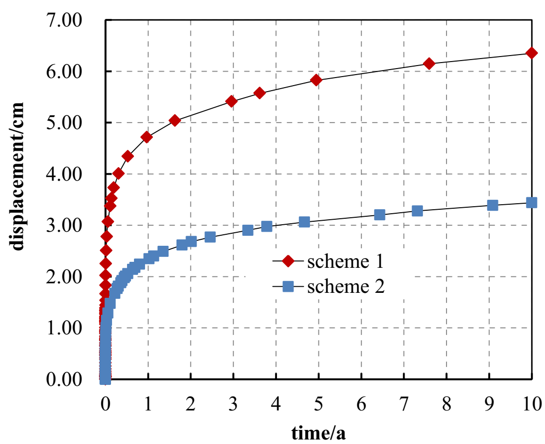


Fig. 17 Comparison of deformation at the sides of the secondary linings for Schemes 1 and 2

shown in Figs. 16 and 17. Considering the influence of creep of squeezing rock on the secondary lining for 10 years, the deformation at the roof of the secondary lining of Scheme 2 is only 3.21 cm, while for Scheme 1, it is 5.28 cm. Thus, the deformation at the roof of the secondary lining of Scheme 2 is 40% smaller as compared to that of Scheme 1. In addition, the inward deformation at the sides of the secondary lining is 3.44 cm for Scheme 2, whereas it is 6.35 cm for Scheme 1. Thus, the inward deformation at the sides of the secondary lining of Scheme 2 is 46% less than that of Scheme 1. These results show that the foamed concrete layer can effectively reduce the deformation in the secondary lining.

Conclusions

In this study, using a newly developed foamed concrete material which has the cushion effect, a special yielding support has been developed. In applying the yielding lining support to a squeezing soft rock tunnel and making a comparison with a strengthened lining stiff support, the conclusions are as follows.

The incorporation of the foamed concrete blocks can both reduce the maximum and minimum principal stress in the primary lining, especially at the adjacent lining elements. The maximum principal stresses in the primary lining in Scheme 2 (the special yielding support) are commonly half of the those of Scheme 1 (the stiff support), and the average minimum principal stress in Scheme 2 is about 60% of that of Scheme 1, thereby improving the stress state of the primary lining.

A comparison of the contact stresses at the interface between the primary lining and the deformation layer shows that Scheme 2 is much less than that of Scheme 1, due to the foamed concrete as a cushion layer. Further, the stresses in the foamed concrete layer are small (around 1.5 MPa) and evenly distributed. It is an indication that the foamed concrete layer can reduce the excavation loads of rock on the secondary lining.

The stress state in the secondary lining in Scheme 2 is significantly improved as compared with that in Scheme 1. The deformation in the secondary lining in Scheme 2 is also less than that in Scheme 1, the deformations at the roof and the sides of the secondary lining of Scheme 2 are 40 and 46% less than that of Scheme 1, respectively.

Acknowledgements The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Grant no. 51379007), the Hubei Provincial Natural Science Foundation of China (2018CFA012) and the support of the Youth Innovation Promotion Association, CAS.

Compliance with ethical standards

Conflict of interest No conflict of interest exists regarding the publication of this paper.

References

Agan C (2016) Prediction of squeezing potential of rock masses around the Suruc Water tunnel. B Eng Geol Environ 75(2):451–468

Aksoy CO, Ogul K, Topal I, Ozer SC, Ozacar V, Posluk E (2012) Numerical modeling of non-deformable support in swelling and squeezing rock. Int J Rock Mech Min 52(6):61–70

Aydan O, Akagi T, Kawamoto T (1993) The squeezing potential of rocks around tunnels—theory and prediction. Rock Mech Rock Eng 26(2):137–163

Barla G, Bonini M, Semeraro M (2011) Analysis of the behaviour of a yield-control support system in squeezing rock. Tunn Undergr Sp Tech 26(1):146–154
Cantieni L, Anagnostou G (2009) The interaction between yielding supports and squeezing ground. Tunn Undergr Sp Tech 24(3):309–322
Chen W, Tian H, Yang F, Geng Y (2011) Study of effects of foam concrete preset deformation layer on long-term stability of deep soft rock tunnel. Rock Soil Mech 32(9):2577–2583
Dalgic S (2002) Tunneling in squeezing rock, the Bolu tunnel. Anatol Motorw Turkey Eng Geol 67(1–2):73–96
Dwivedi RD, Singh M, Viladkar MN, Goel RK (2013) Prediction of tunnel deformation in squeezing grounds. Eng Geol 161(7):55–64
Dwivedi RD, Singh M, Viladkar MN, Goel RK (2014) Estimation of support pressure during tunnelling through squeezing grounds. Eng Geol 168(1):9–22
Hoek E (2001) Big tunnels in bad rock. J Geotech Geoenviron 127(9):726–740
Kolymbas D, Fellin W, Kirsch A (2006) Squeezing due to stress relaxation in foliated rock. Int J Numer Anal Met 30(13):1357–1367
Meng LB, Li TB, Jiang Y, Wang R, Li YR (2013) Characteristics and mechanisms of large deformation in the Zhegu mountain tunnel on the Sichuan-Tibet highway. Tunn Undergr Sp Tech 37:157–164
Mezger F, Ramoni M, Anagnostou G, Dimitrakopoulos A, Meystre N (2017) Evaluation of higher capacity segmental lining systems when tunnelling in squeezing rock. Tunn Undergr Sp Tech 65:200–214
Mezger F, Ramoni M, Anagnostou G (2018) Options for deformable segmental lining systems for tunnelling in squeezing rock. Tunn Undergr Sp Tech 76:64–75
Moritz B (2011) Yielding elements–requirements, overview and comparison. Geomech Tunn 4(3):221–236
Ngoc-Anh D, Dias D, Oreste P (2015) 3D numerical investigation on the interaction between mechanized twin tunnels in soft ground. Environ Earth Sci 73(5):2101–2113
Scussel D, Chandra S (2014) New approach to the design of tunnels in squeezing ground. Int J Geomech 14(1):110–117
Tian HM, Chen WZ, Yang DS, Wu GJ, Tan XJ (2016) Numerical analysis on the interaction of shotcrete liner with rock for yielding supports. Tunn Undergr Sp Tech 54:20–28
Tian HM, Chen WZ, Tan XJ, Yang DS, Wu GJ, Yu JX (2018) Numerical investigation of the influence of the yield stress of the yielding element on the behaviour of the shotcrete liner for yielding support. Tunn Undergr Sp Tech 73:179–186
Vrakas A, Anagnostou G (2016) Ground response to tunnel re-profiling under heavily squeezing conditions. Rock Mech Rock Eng 49(7):2753–2762
Wang C, Wang Y, Lu S (2000) Deformational behaviour of roadways in soft rocks in underground coal mines and principles for stability control. Int J Rock Mech Min 37(6):937–946
Wang H, Chen WZ, Tan XJ, Tian HM, Cao JJ (2012) Development of a new type of foam concrete and its application on stability analysis of large-span soft rock tunnel. J Cent South Univ 19(11):3305–3310
Wang H, Chen W, Wang Q, Zheng P (2016) Rheological properties of surrounding rock in deep hard rock tunnels and its reasonable support form. J Cent South Univ 23(4):898–905
Wu GJ, Chen WZ, Dai YH, Yang JP, Tan XJ, Tian HM (2017) Application of a type of strain block FBG sensor for strain measurements of squeezing rock in a deep-buried tunnel. Meas Sci Technol 28(11):115001
Zeng KH, Xu JX (2013) Unified semi-analytical solution for elastic-plastic stress of deep circular hydraulic tunnel with support yielding. J Cent South Univ 20(6):1742–1749
Zhao WS, Chen WZ, Tan XJ, Huang S (2013) Study on foamed concrete used as seismic isolation material for tunnels in rock. Mater Res Innov 17(7):465–472