Applicability of stress release method in soft rock tunnel with high geostress

Chen Xu
Institute of Rock Mechanics, Ningbo University, Ningbo, China
Ningbo Key Laboratory of Energy Geostructure, Ningbo, China

Lingxiao Zheng
Institute of Rock Mechanics, Ningbo University, Ningbo, China

Gecheng Zhang
Institute of Rock Mechanics, Ningbo University, Ningbo, China

Qing Yao
Institute of Rock Mechanics, Ningbo University, Ningbo, China

Shikang Qin
College of Civil Engineering, Tongji University, Shanghai, China

ABSTRACT: The Deformation Reserved (DR) method is a commonly used stress release method in the construction of weak rock tunnel with high geostress. The excavated tunnel section is usually larger than its design size, a space is reserved outside the design excavation boundary of the tunnel. The behavior of the double-layer support structure was investigated through theoretical derivation, and the applicability of the DR method in controlling the large deformation of soft surrounding rock during tunnel construction in high geostress was discussed. The calculated results by proposed method were verified by the in-situ monitoring data of field test. It is found that the DR method is capable of releasing the high geostress when tunnelling in squeezing rocks, and the double-layer support structure is necessary to resist the high ground stress.

Keywords: large deformation, in-situ monitoring, multi-layer support, Deformation Reserved method, stress release.

1 INTRODUCTION

Tunnel engineering has advanced towards larger sections and greater burial depths, particularly in central and western regions (Xu et al., 2021a). Many tunnels traverse areas of soft, broken rock with high in-situ stress, where they are impacted by the substantial deformation caused by the high ground stress of the soft rock (Kang et al., 2022, Guo et al., 2022, Wang, 2022). Soft rock tunnels under high ground stress undergo significant deformation, which can persist for extended periods and seriously impact construction progress and safety (Xu & Xia, 2021, Xu et al., 2021b, Ding et al. 2017). In response to the challenge of constructing tunnels in high ground stress soft rock with large deformation, both domestic and foreign scholars have undertaken corresponding studies. As early as 1998, Ortlepp and Stacey (1998) suggested that the use of higher strength support structures to resist large deformations in soft surrounding rocks is impractical and requires higher costs. Cantieni and Anagnostou (2009) pointed out that using yielding support to allow for displacement of surrounding rock is an effective way to deal with large deformations during tunnel excavation. Stress in the surrounding rock is partially released as it is displaced. Typically, this stress release is achieved by installing a yielding support system and allowing a certain amount of over-excavation and reserved deformation (Cui et al. 2021).

The reserved deformation space method is a stress relief approach that involves over-excavating the tunnel section so that the surrounding rock has a certain amount of deformation space and then waiting until the surrounding rock is displaced to a predetermined position before applying support. This method is widely used for tunnel support including the Wushaoling Tunnel, Maoyushan Tunnel, and Muzhailing Tunnel (Lei et al., 2008, Li, 2011, Liu et al., 2005). Some researchers have conducted field experiments and theoretical derivations on this construction method. Zhang et al. (2014) conducted experiments on both small and large section reserved deformation space methods and obtained satisfactory results. Xia et al. (2022) established elastoplastic solutions based on classical elastoplastic theory for different stress release methods.

Most existing theoretical studies have focused on single-layer support structures, with few considering the situation of multi-layer support structures. In this paper, based on elastoplastic theory, we develop a mechanical model of the double-layer reserved deformation space method and derive an elastoplastic solution for tunnel support using this method.

2 DEFORMATION RESERVING METHOD

The Deformation Reserved (DR) method is a commonly used stress release method during the construction of weak rock tunnel with high geostress (Xu et al., 2022). The excavated tunnel section is usually larger than its designed size, a space is reserved outside the design excavation boundary of the tunnel. The surrounding rock shrinks to the free face after excavation. The ground does not contact with the support at first. When the deformation of surrounding rock reaches the predetermined value, the ground contacts with the support. The mechanical model of a circular tunnel with double-layered support excavated by DR method is shown in Figure 1, where, R_1 is the radius of the excavation, R_0 is the distance from the inner wall of the initial support to the center of the tunnel, d_1 and d_2 are the thicknesses of the first and the second layer of the initial support, respectively. Besides, deformation spaces are reserved outside each layer, Δu_1 and Δu_2 are the reserved deformations outside the first and second layer of support, respectively. The initial support is assumed to be elastic-plastic satisfying the Treace yield criterion. It is specified that the tensile stress is positive and the displacement direction pointing to the center of the circle is positive.

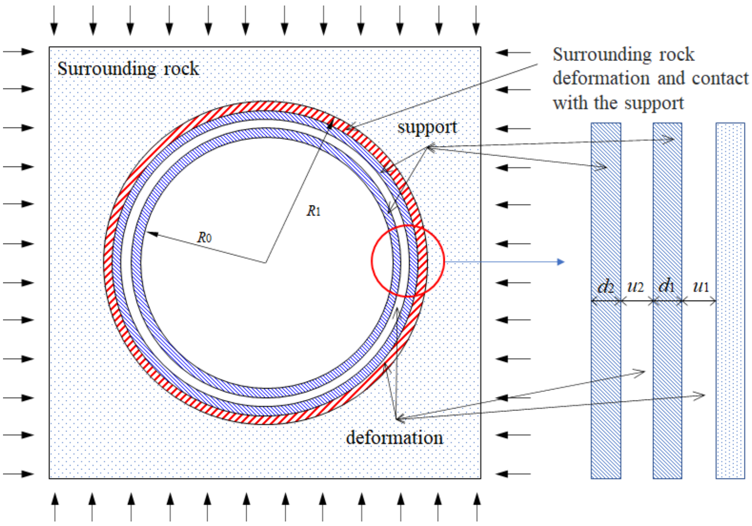

Figure 1. Mechanical model of a circular tunnel with double-layered support excavated by DR method.

The first layer of support structure starts to work when the surrounding rock deformation occupied the first part of the reserved deformation Δu_1. After that, the first layer of support structure and the surrounding rock will deform together until it touches the second layer of support structure. Since the deformation reserved between the two layers of support structure is usually very large, so the first layer of support structure yields as the rock continues deforming, the second part of the reserved deformation Δu_2 would be also occupied, then the second layer of support structure contacts with the first layer, i.e., the second layer of support structure starts to work. During this process, the ground stress borne by the first layer of support structure is directly calculated according to the yielding condition. Assuming that the contact pressure between the second and the first layer of support is σ_r^2 , the yield stress of the first layer of support is σ_s^1, and the contact stress between the surrounding rock and the support structure is σ_r^0. The relationship between the three stresses is as follows:

$$\sigma_r^2 = \sigma_r^0 - \sigma_s^1 \tag{1}$$

Elastoplastic calculations are performed for the second support structure, and assumed that the second layer of support structure consists of ideal elastoplastic material. According to the classical solution for thick-walled cylinders in elastic mechanics and Tresca yield criterion the relationship between the stress on the support and the yield strength σ_s of the material can be deduced as follows.

$$\sigma_\theta^\mathrm{L} - \sigma_r^\mathrm{L} = \sigma_\mathrm{s} = \frac{2\left(R_0 + d_2\right)^2 R_0{}^2}{r^2 d_2\left(2R_0 + d_2\right)}\sigma_2 \tag{2}$$

Assume that the existence of an elastoplastic boundary radius inside the second layer support structure is r_p, the boundary radius and the equivalent radial stress q at the elastoplastic boundary are deduced from the Tresca yield criterion as：

$$r_\mathrm{p} = \left[\frac{2\sigma_2\left(R_0 + d_2\right)^2 R_0{}^2}{\sigma_\mathrm{s} d_2\left(2R_0 + d_2\right)}\right]^{0.5} \tag{3}$$

$$q = \sigma_\mathrm{s}\left(r_\mathrm{p}{}^2 - R_0{}^2\right)/\left(2R_0{}^2\right) \tag{4}$$

Suppose that $r_\mathrm{p} \le R_0$, the displacement of the second layer support structure can be calculated using the elastic method. Referring to the elastoplastic solution proposed by Xu et al. (2022) for the deformation and stress of the surrounding rock and supporting structure, and combined with the mechanical model proposed in this paper, the equation for the displacement of the outer boundary of the second layer of the support structure can be obtained as follows:

$$u_r^\mathrm{L}\Big|_{r=R_0+d_2} = \frac{R_0{}^2\left(R_0 + d_2\right)\left(1 - \nu^\mathrm{L}\right)}{G^\mathrm{L} d_2\left(2R_0 + d_2\right)}\sigma_r^2 \tag{5}$$

Where, ν^L and G^L are the Poisson's ratio and shear modulus of the initial support, respectively. The deformation of the surrounding rock in the plastic zone and the stress equation are as follows.

$$u_r^\mathrm{rock}\Big|_{R_1} = \frac{(p_0 + c\cot\varphi)R_1\sin\varphi}{2G} \times \left(\frac{(p_0 + c\cot\varphi)(1 - \sin\varphi)}{\sigma_r^0 + c\cot\varphi}\right)^{(1-\sin\varphi)/\sin\varphi} \tag{6}$$

$$\left.\begin{aligned}
\sigma_r^\mathrm{rock} &= \left(r/R_1\right)^{2\sin\varphi/(1-\sin\varphi)}\left(\sigma_r^0 + c\cot\varphi\right) - c\cot\varphi \\
\sigma_\theta^\mathrm{rock} &= \left(r/R_1\right)^{2\sin\varphi/(1-\sin\varphi)}\left(\sigma_r^0 + c\cot\varphi\right)\left(1 + \sin\varphi\right)/\left(1 - \sin\varphi\right) - c\cot\varphi
\end{aligned}\right\} \tag{7}$$

Where: p_0 is the initial ground stress, c is the cohesive force of the surrounding rock, φ is the internal friction angle of the surrounding rock.

The contact stress between the surrounding rock and the support structure σ_r^0 can be obtained by the boundary conditions between the surrounding rock and tunnnel support.

If $R_0 \le r_p \le R_0 + d$, it indicates that the deformation calculation of the second layer of support structure needs to consider both elastic and plastic zone deformation. When calculating the elastic-plastic deformation of the support, the support deformation can be equated to the deformation of the elastic zone of the support. Specifically, the deformation of the outer boundary of the support can be simplified using the elastic solution of the thick-walled cylinder, which can be expressed as follows:

$$u_r^{\mathrm{L2}}\Big|_{r=R_0+d_2} = \frac{R_0^{\ 2}\left[\left(1+v\right)\sigma_r^2 r_p^{\ 2} + \left(1-v\right)\sigma_r^2\left(R_0+d_2\right)^2 - 2qr_p^{\ 2}\right]}{\mathrm{E}^{\mathrm{L}}\left[\left(R_0+d_2\right)^2 - r_p^{\ 2}\right]} \tag{8}$$

If $r_p > R_0 + d$, the double-layer support structure has undergone yielding. At this point, the resistance of the surrounding rock can be characterized by the yield stress of the two-layer support structure.At this point, the resistance of the surrounding rock is the yield stress of the two-layer support structure, so as to find the deformation of the surrounding rock, and through the deformation of the surrounding rock and support structure coordination conditions to find the amount of support deformation.

3 ENGINEERING APPLICATION

The Liancheng Mountain Tunnel has a maximum burial depth of approximately 700 m. The lithology of the surrounding rock revealed by the excavation is chlorite mica schist, which has a flake structure, low strength, fractured rock, fissure development, and very poor self-stabilization ability.

Following excavation of the tunnel, the surrounding rock exhibited rapid deformation and a large deformation rate. The initial support deformation continued to increase without convergence, resulting in the cracking and damage of the support shotcrete, as well as partial distortion deformation of the steel arch, as shown in Figure 2. This deformation also encroached on the second lining space.

Figure 2. Severe extrusion and deformation of initial support.

A double-layer support structure with H20b steel arch and C25 concrete of 28cm thickness, is employed as the initial support to control the large deformation and avoid the destruction of the support structure. The reserved deformation of the first layer is 120cm and the reserved deformation of the second layer is 60cm. The deformation diagram of the site monitoring section is shown in Figure 3. It indicates that the initial support deformation exhibits slow development after the second layer of support structure is applied. The deformation finally stabilizes at approximately 500mm, the support deformation is effectively controlled. The calculated support displacement at the cave wall was determined to be 635.5 mm by the proposed method, thereby indicating that support deformation was well controlled. Deformation and stress in the plastic zone of the surrounding rock are illustrated in Figure 4.

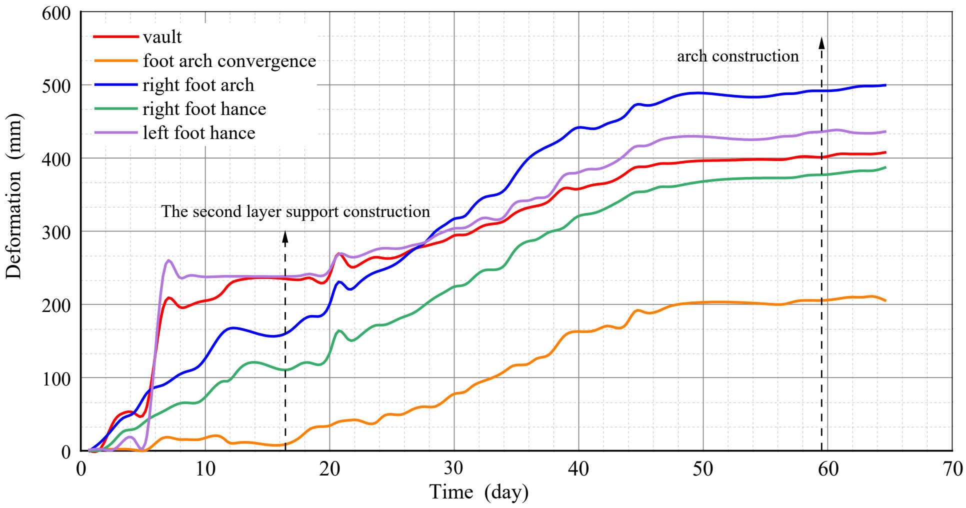

Figure 3. Accumulated deformation of initial support.

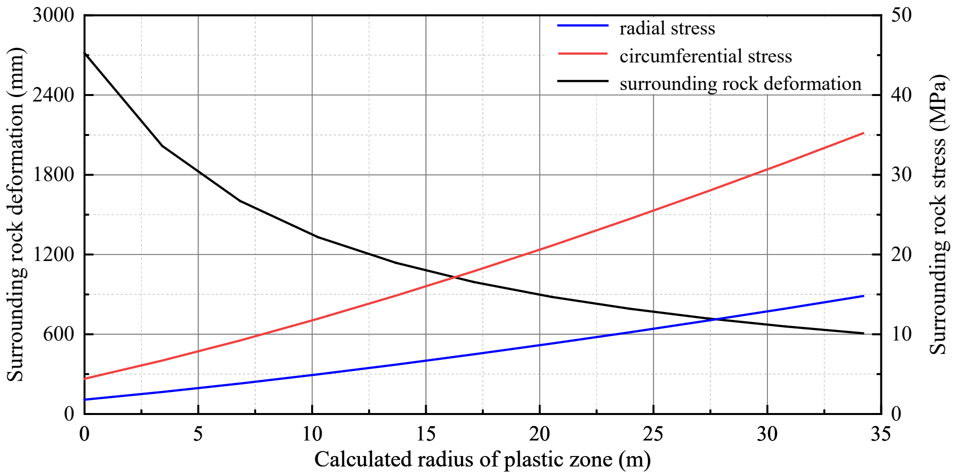

Figure 4. Deformation and stress diagram of surrounding rock in plastic zone.

4 DISCUSSION AND CONCLUSION

This paper presents an elastic-plastic solution for a double-layer support structure based on the theoretical derivation of the analytical solution of the single-layer support structure by the reserved deformation method, focusing on the deformation control effect of the double-layer support structure on the high ground stress soft rock section. The analytical solution of the double -layer support structure is derived using the reserved deformation method, which serves as the basis for the theoretical analysis.

Combining the theoretical analysis results and actual engineering monitoring data, it is confirmed that the double-layer pre-deformed support structure can well control the support deformation and ensure the construction safety and construction progress in the high ground stress soft rock surroundings.

In light of the complexity of the actual engineering environment conditions, it is essential to consider all factors, including the construction process, that can influence the deformation size of the support structure.Considering the complexity of the actual engineering environment conditions, it is essential that all factors including the construction process will affect the deformation size of the support structure. While the pure theoretical derivation results can only provide guidance to the engineering construction, they may not fully capture the intricacies of the actual engineering situation. And this is what needs to be discussed and studied in depth.

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