International Journal of Mining Science and Technology 26 (2016) 401–407

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Theoretical analysis of a new segmented anchoring style in weakly cemented soft surrounding rock

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form 16 December 2015
Accepted 3 February 2016
Available online 15 March 2016

Keywords:
Weakly cemented soft rock
Segmented anchorage
Strain softening
Analytical model

ABSTRACT

According to the tensile failure of rock bolt in weakly cemented soft rock, this paper presents a new segmented anchoring style in order to weaken the cumulative effect of anchoring force associated with the large deformation. Firstly, a segmented mechanical model was established in which free and anchoring section of rock bolt were respectively arranged in different deformation zones. Then, stress and displacement in elastic non-anchoring zone, elastic anchoring zone, elastic sticking zone, softening sticking zone and broken zone were derived respectively based on neural theory and tri-linear strain softening constitutive model of soft rock. Results show that the anchoring effect can be characterized by a supporting parameter β. With its increase, the peak value of tangential stress gradually moves to the roadway wall, and the radial stress significantly increases, which means the decrease of equivalent plastic zone and improvement of confining effect provided by anchorage body. When β increases to 0.72, the equivalent plastic zone disappears, and stresses tend to be the elastic solutions. In addition, the anchoring effect on the displacement of surrounding rock can be quantified by a normalization factor δ.

1. Introduction

Roadway in the western mining area of China is mainly arranged in Cretaceous and Jurassic weakly cemented soft rock. The special diagenetic environment results in its unstable mechanical behavior with the characteristics of poor cementation and low strength. Even under low stress level, large deformation will be produced. In the anchorage system of this kind roadway, rock bolts often undergo tensile failure due to the large deformation of soft surrounding rock, or loosen to move due to the tensile fracture of rock mass at the end area of the anchorage body. These bring great challenges to the reinforcement of roadway. Hence, it is especially urgent to make clearly the anchoring mechanism and propose some new anchoring styles for soft rock engineering in the western mining area of China.

As an active support, the anchoring force of rock bolt is developed with the deformation of surrounding rock. For the interaction system between rock mass and anchorage body, it can better embody the essence of anchorage effect and the self bearing capacity of surrounding rock to study the anchoring effect from the strong perspective of rock mass.

In the past few decades, domestic and foreign scholars have established a series of theoretical models for anchorage body. According to the layer structure and broken rock mass, Zhu et al. analyzed the hardening behavior of shear strengths by respectively employing three kinds of constitutive models: Mohr Coulomb, Hoek Brown and Duncan Chang [1]. Actually, it is difficult to establish a unified analytical model due to the complicated interaction between rock bolt and rock mass as well as the diversity of constitutive models for different rock mediums. Currently, most of the analytical models were presented under the assumption of two-dimensional axial symmetry problem. Among them, some typical results were deduced on the basis of the ideal elastic–plastic model for rock mass by Tanimoto, Aydan, Graziani, and Labiouse [2–5]. Indraratna et al. respectively established the analytical model of anchored surrounding rock around circular roadway under the hydrostatic pressure field and emphatically discussed the mechanical response of rock bolt by employing elasto-brittle plastic model and strain softening model for rock mass, and the yield criterion of M–C as well as the empirical strength criterion of Hoek–Brown [6–18]. Afterwards, Bobet further presented the analytical model

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http://dx.doi.org/10.1016/j.ijmst.2016.02.006
2095-2686/

of axi-symmetric roadway under non-uniform stress field, regarding the anchored rock mass as isotropic elastic material and anisotropic elastic material respectively [19,20]. Ahmad put forward the finite difference solutions for circular roadway under hydrostatic pressure field from the angle of numerical solution [21]. Cai et al. established a series of equilibrium equations for rock bolt, surrounding rock and bolt-rock system considering the load transfer, and then carried out the decoupling analysis [22].

In view of the complexity of anchoring effect, many scholars have carried out some studies by experimental methods. Kilic et al. discussed the effect of bolt shape and grout property on the carrying capacity of anchorage body respectively [23–26]. Based on indoor tests, Yang et al. studied the strengthening effect of rock bolt on the stiffness and strength parameters of rock mass, and further analyzed the control effect on the plastic zone of surrounding rock [27]. Under the condition of non-anchorage and vertical anchorage, Sawwaf et al. drew the conclusion that the soil stiffness and pullout force of rock bolt would be significantly enhanced by anchorage body based on small-scale experimentations [28]. Zou et al. studied the anchoring effect in different rock mediums, and result showed that the weaker the lithology is, the better of anchoring effect [29]. Besides, Ding and Shen put forward the concept of anchored wall by simulating the action of a plurality of anchor cable in high slope engineering [30]. Li et al. discussed the anchoring effect on stress distribution and displacement of surrounding rock as well as the axial force in rock bolt by establishing the numerical model of a circular roadway [31].

The above results have laid a good theoretical basis for classifying the anchorage mechanism. However, the deficiency mainly includes as: the conclusions are only applicable to the end anchoring and full-length anchoring, which is not suitable for the new anchoring style proposed in this study. Moreover, little results are related to the anchoring effect of weakly cemented soft rock. Therefore, the mechanical model of a new segmented anchorage style was firstly established in this study according to the large deformation of soft rock, and then the analytical model was proposed based on elasto-plastic theory. Finally, the anchoring effect of the new style was discussed. The results of this study may lay a theoretical foundation for the further development of a new anchoring device according to the weakly cemented soft rock in western mining area.

2. Model of anchoring effect in weakly cemented soft rock

2.1. Mechanical model of a new segmented anchorage style

The fundamental cause of instability in surrounding rock is the broken zone. Tensile failure of rock bolt mainly occurs in this zone due to the superposition of anchoring load. For this reason, a new segmented anchorage style was proposed as follows: the free section was arranged in the broken zone, and the anchorage section was set in softening and elastic rock mass respectively. Moreover, the following assumptions were made for rock bolt: (1) the roadway is circular under the uniform stress field; (2) the layout of rock bolt is axial symmetry as shown in Fig. 1 where p_0 represents the original stress; (3) the length of rock bolt across broken zone, soften zone and elastic zone; and (4) no shear sliding exists between grout and surrounding rock.

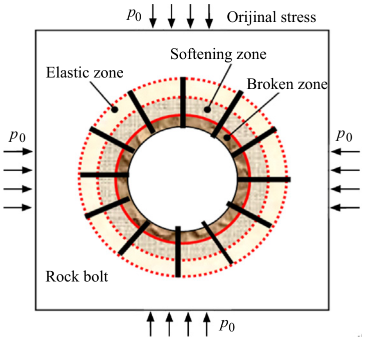

Fig. 1. Different deformation zones of soft rock and arrangement of rock bolts.

According to the different locations of neutral point, there are two kinds of mechanical model as shown in Fig. 2. When the neutral point is in the elastic zone, surrounding rock can be divided into the following five zones according to the deformation behavior: elastic non-anchoring zone, elastic anchoring zone, elastic sticking zone, strain softening zone and broken zone (Fig. 2a) where ρ_i ($i = f, s, p, a$) denotes the distance from different deformation zones to roadway center respectively. However, the strain softening zone will be divided into softening anchoring zone and softening sticking zone when the neutral point is in the strain softening zone (Fig. 2b).

Tao and Chen studied the mechanical feature of the full-length bonded rock bolt in surrounding rock with strain softening behavior, and put forward the following theoretical formula to determine the position of neutral point [32]:

$$\rho = \frac{L}{\ln(1 + L/a)} \tag{1}$$

where ρ is the distance from neutral point to roadway center, L the length of rock bolt, and a the radius of roadway.

2.2. Strain softening constitutive model of weakly cemented soft rock

Deformation behavior of surrounding rock has a great effect on the anchoring effect of supporting system. Weakly cemented soft rock often shows significant strain softening behavior under triaxial compression, even under uni-axial compression. Therefore, a simplified tri-linear strain softening model is employed here to describe the mechanical behavior (Fig. 3).

In Fig. 3, σ_c and σ_{rf} denote the peak strength and residual strength respectively. ε_1^c and ε_1^r refer to the axial strain at peak point and at residual point, respectively. Let the softening modulus at post-peak stage be λ, and the plastic dilatation coefficient at softening stage and residual stage be α_s and α_f respectively. Then the increment of plastic strain at strain softening zone and residual zone should meet following conditions:

$$\begin{aligned} &\varepsilon_3^p + \alpha_s \varepsilon_1^p = 0 \\ &\varepsilon_3^f + \alpha_f \varepsilon_1^f = 0 \end{aligned} \tag{2}$$

2.3. Quantification of anchoring effect on the stress distribution of surrounding rock

A micro element is extracted respectively along the radial direction of sticking zone and anchoring zone within one space. Fig. 4 shows the stress distributions. According to the neutral theory, the shear stress written as τ in the two models possesses opposite direction.

Let the frictional coefficient between the anchorage body and surrounding rock be f. Taking the model, shown in Fig. 4a, as an example, the shear force transferred from rock bolt to surrounding rock can be written as

$$dF_S = f\sigma_\theta \pi d dr \tag{3}$$

This is a decent proxy for the increase of body force in the radial direction of micro model as

$$dF_{Sv} = \frac{dF_S}{dv} = \frac{f\sigma_\theta \pi d dr}{r\theta dr n_a} = \beta \frac{\sigma_\theta}{r} \tag{4}$$