Nonlinear Analysis on Mechanical Characteristics of Jointed Rock Mass in Tunnels

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Abstract. The underground cavern excavation results in stress redistribution of the surrounding rock mass in tunnels. The joints and cracks will be developed in the process of excavation unloading and stress redistribution. The results show that the surrounding rock mass have stronger nonlinear characteristics. The Mohr-Coulomb strength Criterion, which widely adopted in engineering, will not be used to study the mechanical character of surrounding rock mass. Based on the nonlinear character of rock mass, the mechanics characteristics of jointed rock mass have been analyzed with the nonlinear failure criterion. The relationships between the stress state in plastic zone, the range of plastic zone and the nonlinear parameters is established, which are illustrated by an example.

Keywords: jointed rock mass, plastic zone; nonlinear, mechanical characteristics.

1. Introduction

The mechanical characteristics of the surrounding rock have widely caused concerns in designing and construction of tunnels. Because of the complexity of the natural characteristics, the imperfection of mechanical characteristics and special engineering properties of surrounding rock, in most cases, the theoretical results are not coincide with project results if the traditional linear analysis methods are adopted to analyze the mechanical characteristics of the surrounding rock(Gao Zheng-xia et al.2003).

After excavation of tunnels, the joints and cracks of surrounding rock mass are usually resulted from the unloading eustress and stress redistribution, which is a complicated and uncertain physical and mechanical process. In order to analyze the stability of surrounding rock mass to ensuring the safety, it is of great significance in studying the mechanical characteristics of jointed rock mass. At present, many researchers (Liu HY, et al,2009)in China and abroad have studied the mechanical properties of tunnels after excavation, but these researches are mainly based on the linear failure criterion, such as linear Mohr-Coulomb failure criterion, linear D-P criterion and so on, and the effect of nonlinear failure is rarely considered. But the nonlinearity of rock mass can be more reflected its inherent characteristics to describe the jointed rock mass through nonlinear failure criterion, and more embodied that the joints, cracks and stress state influence on the strength of surrounding rock mass (Yang Xiaoli, ET al.2004). In this paper, based on the nonlinear failure criterion: Hoek-Brown criterion, the mechanical characteristics of jointed rock mass in tunnels will be analyzed. In the meantime, it is analyzed the mechanical characteristics in plastic zone and plastic zone range, and the relationship between the stress, range in plastic zone and nonlinear parameters of surrounding rock mass in tunnels. In the final part of the paper, the rationality of analyzed results has been validated based on results of an engineering example, which can be a reference on engineering practice.

2. Nonlinear theoretical analysis on mechanical characteristics of jointed rock mass

2.1. A brief introduction of nonlinear strength criterion on rock mass.

In the existing engineering analysis, the Mohr-Coulomb failure criterion that depicts in formula 1 is widely adopted in the engineering researches.

$$\sigma_1 = q_p + M_p \sigma_3 \quad (1)$$

Where, $q_p = \dfrac{2c\cos\varphi}{(1-\sin\varphi)}$ $M_p = \dfrac{1+\sin\varphi}{1-\sin\varphi}$

Based on the Mohr-Coulomb failure criterion and a lot of the triaxle test results, the nonlinear failure criterion (Hu Wei-dong, et al, 2007; Lin song, 2008) will be obtained if considering the nonlinear characteristics of rock and soil.

$$\sigma_1 = q_p + M'_p(\sigma_3 / q_p)^\alpha \quad (2)$$

Where, M'_p α can be determined through lots of triaxle tests.

Based on lots of the triaxle test results of different types of rock mass, Hoek and Brown put forward an experience of failure criterion (Hock E, et al, 1998; Hock E, et al, 2002)that is suitable for rock mass in 1980 if considering the nonlinear characteristics of rock mass.

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_3\sigma_c + s\sigma_c^{\ 2}} \quad (3)$$

Where, σ_c is the uniaxial compressive strength of rock (MPa)? The constants m and s are the rock mass constants which are related to litholgic and structural plane, and considering the soft and hard degree, crush degree of rock respectively. The values of them can be obtained by RMR (Zhao Ming-jie, 2011).

For the disturbed rock mass,

$$m / m_0 = \exp\left(\frac{RMR-100}{14}\right) \qquad s = \exp\left(\frac{RMR-100}{6}\right)$$

For the undisturbed rock mass,

$$m / m_0 = \exp\left(\frac{RMR-100}{28}\right) \qquad s = \exp\left(\frac{RMR-100}{9}\right)$$

The value of m_0 is related to the type of rock. Its value can be obtained by following methods.

(1) The value of m_0 equals 7 for carbonate with joints development, for example, dolomite, limestone, and marble.

(2) The value of m_0 equals 10 for argillaceous cemented rock, for example, mudstone, siltstone, shale and slate.

(3) The value of m_0 equals 15 for psammite with strong crystallization and crystal cleavage nondevelopment, for example, sandstone and quartzite.

(4) The value of m_0 equals 17 for fine multimineral magmatite, for example, andesite, dolerite, dolerite, and rhyolite.

(5) The value of m_0 equals 25 for coarse multimineral magmatism and metamorphic, for example, amphibolite, gabbro, gneiss, granite.

2.2 Nonlinear theoretical analysis on mechanical characteristics of jointed rock mass.

In order to simplify the calculation model and the proof during the analyzing mechanical characteristic of surrounding rock after excavation of tunnel, in this paper, the cross-section shape of tunnel is supposed to be circular, and the length of tunnel must have enough to be simplified as plane strain problem. In the meantime, the value of lateral pressure coefficient equals 1.

(1) Nonlinear analysis on stress state in plastic zone of tunnel

The radial stress σ_{rp} will be released gradually; the circumferential stress σ_{tp} will be increased until the surrounding rock is completely destructed by shear failure during the process of construction in tunnel. Set the excavation radius as a, the following formula 4 will be obtained by the Hoek—Brown failure criterion.

$$\sigma_{tp} = \sigma_{rp} + \sqrt{m\sigma_c\sigma_{rp} + s\sigma_c^{\ 2}} \quad (4)$$

Considering the symmetry of structure and loads and ignoring the body forces of surrounding rock, the equilibrium equation of the surrounding rock in plastic zone will be obtained by the elastic theory.

$$\frac{d\sigma_{rp}}{dr}+\frac{\sigma_{rp}-\sigma_{tp}}{r}=0 \tag{5}$$

According to the formula 4 and formula 5, the following formula 6 can be obtained.

$$\frac{d\sigma_{rp}}{\sqrt{m\sigma_c\sigma_{rp}+s\sigma_c^{\ 2}}}=\frac{dr}{r} \tag{6}$$

Let's just integrate both sides and use the boundary condition $\sigma_{rp}\big|_{r=a}=0$, the following formula 7 can be obtained.

$$\frac{2}{3m\sigma_c}\left(m\sigma_c\sigma_{rp}+s\sigma_c^{\ 2}\right)^{\frac{3}{2}}=\ln\frac{r}{a}+\frac{2}{3}\frac{\sigma_c^{\ 2}}{m}s^{\frac{3}{2}} \tag{7}$$

So, $$\sigma_{rp}=\frac{1}{m\sigma_c}\left[\left(\frac{3m\sigma_c}{2}\ln\frac{r}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{2}{3}}-s\sigma_c^{\ 2}\right] \tag{8}$$

Let's take formula 8 into formula 4, the formula 9 will be obtained.

$$\sigma_{tp}=\sigma_{rp}+\left(\frac{3}{2}m\sigma_c\ln\frac{r}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{1}{3}} \tag{9}$$

The formula 8 and formula 9 are the equations that can depict stress distribution state of the surrounding rock in plastic zone based on the Hoek—Brown failure criterion.

(2) Nonlinear analysis on plastic zone range of the tunnels

According to the hypothesis of the elastic-plastic region, boundary condition and the lateral pressure coefficient equals 1, let's suppose the applied stress of the elastic-oplastic interface is σ_{r_0}, the stress state equation of surrounding rock in elastic zone will be obtained by the elastic theory.

$$\sigma_{re}=\gamma H\left(1-\frac{r_0^{\ 2}}{r^2}\right)-\sigma_{r_0}\frac{r_0^{\ 2}}{r^2} \tag{10}$$

$$\sigma_{te}=\gamma H\left(1+\frac{r_0^{\ 2}}{r^2}\right)+\sigma_{r_0}\frac{r_0^{\ 2}}{r^2} \tag{11}$$

According to the boundary condition of the elastic-plastic interface, that is $\sigma_{rp}\big|_{r=r_0}=\sigma_{re}\big|_{r=r_0}=\sigma_{r_0}$ and $\sigma_{tp}\big|_{r=r_0}=\sigma_{te}\big|_{r=r_0}$ .The following formula 12, formula 13 can be obtained.

$$\sigma_{rp}\big|_{r=r_0}=\frac{1}{m\sigma_c}\left[\left(\frac{3m\sigma_c}{2}\ln\frac{r}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{2}{3}}-s\sigma_c^{\ 2}\right]=\sigma_{r_0} \tag{12}$$

$$\sigma_{tp}\big|_{r=r_0}=\sigma_{rp}\big|_{r=r_0}+\left(\frac{3}{2}m\sigma_c\ln\frac{r}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{1}{3}}=2\gamma H-\sigma_{r_0} \tag{13}$$

So, the formula 14 can be obtained by utilizing the formula 12 and formula 13.

$$\frac{2}{m\sigma_c}\left[\left(\frac{3m\sigma_c}{2}\ln\frac{r_0}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{2}{3}}-s\sigma_c^{\ 2}\right]+\left(\frac{3m\sigma_c}{2}\ln\frac{r_0}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{1}{3}}=2\gamma H \tag{14}$$

Set $A=\left(\frac{3m\sigma_c}{2}\ln\frac{r_0}{a}+\sigma_c^{\ 3}s^{\frac{3}{2}}\right)^{\frac{1}{3}}$, then formula 14 can be simplified the following formula 15.

$$\frac{2}{m\sigma_c}A^2+A-2\left(\frac{s}{m}\sigma_c+\gamma H\right)=0 \tag{15}$$

Solving the equation 15, the following formula 16 will be obtained.

$$A = m\sigma_c\left(\sqrt{\frac{1}{16}+\frac{s}{m^2}+\frac{\gamma H}{m\sigma_c}}-\frac{1}{4}\right) \tag{16}$$

So, $$\left(\frac{3m\sigma_c}{2}\ln\frac{r_0}{a}+\sigma_c^{\frac{3}{2}}s^{\frac{3}{2}}\right)^{\frac{1}{3}} = m\sigma_c\left(\sqrt{\frac{1}{16}+\frac{s}{m^2}+\frac{\gamma H}{m\sigma_c}}-\frac{1}{4}\right) \tag{17}$$

The radius r_0 of plastic region can be obtained by formula 17.

$$r_0 = a\exp\left\{\frac{2}{3m\sigma_c}\left[m\sigma_c\left(\sqrt{\frac{1}{16}+\frac{s}{m^2}+\frac{\gamma H}{m\sigma_c}}-\frac{1}{4}\right)\right]^3-\sigma_c^{\frac{3}{2}}s^{\frac{3}{2}}\right\} \tag{18}$$

3. Analysis of examples

In order to analyze the nonlinearity of the jointed rock mass effect on the stability of the tunnel, the plastic zone range that results from the nonlinear characteristics of surrounding rock has been analyzed by a practical example, and the results are made comparisons with the results that will be calculated by existing the Mohr—Coulomb strength criterion.

Based on the Mohr—Coulomb strength criterion, the range of plastic zone (Guan Bao-shu.1993) can be gained by following equation 19.

$$r_0' = a\left[\frac{2}{\varepsilon+1}\cdot\frac{\gamma H(\varepsilon-1)+\sigma_c}{\sigma_c}\right]^{\frac{1}{\varepsilon-1}} \tag{19}$$

Where $\varepsilon = \dfrac{1+\sin\varphi}{1-\sin\varphi}$

The level of surrounding rock is the Ⅲ in an underground project. The excavation cross-section approximates circular. The radius of the tunnel is a cohesion of rock mass is 1.1 MPa, the internal friction angle is 45°. The uniaxial compressive strength of rock is 60 MPa. The original rock stress in present site is 7.2 MPa, and RMR=51 $m_0 = 17$. According to the above the data, let's take relevant parameters into the formula 18 and formula 19, the radius of plastic region will be obtained.

$r_0 = 0.7955a$, $r_0' = 0.8524a$

Therefore, the range of the plastic region in tunnel will be diseased when considering the nonlinear characteristics of the surrounding rock. Which is consistent with the changing orders of the plastic region in practical engineering.

4. Conclusion

(1) Based on the nonlinear empirical strength criterion-Hoek—Brown criterion, the mechanical characteristic of surrounding rock in plastic region is analyzed by considering the nonlinear characteristics of the rock mass, and the calculating formula of the nonlinear stress state and range in plastic regions are obtained. The processing of analysis is preciseness. It is can be used in analysis on the mechanical properties of the plastic regions in tunnel.

(2) The results calculated with the real cases demonstrate that the nonlinearity of the rock mass is important influence on the physical and mechanical characteristics. It can be decreased the plastic zone range of the surrounding rock when considering the nonlinearity.

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