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Roof collapse of shallow tunnel in layered Hoek-Brown rock media

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Abstract. Collapse shape of tunnel roof in layered Hoek-Brown rock media is investigated within the framework of upper bound theorem. The traditional collapse mechanism for homogeneous stratum is no longer suitable for the present analysis of roof stability, and it would be necessary to propose a curve failure mode to describe the velocity discontinuity surface in layered media. What is discussed in the paper is that the failure mechanism of tunnel roofs, consisting of two different functions, is proposed for layered rock media. Then it is employed to investigate the impending roof failure. Based on the nonlinear Hoek-Brown failure criterion, the collapse volume of roof blocks are derived with the upper bound theorem and variational principle. Numerical calculations and parametric analysis are carried out to illustrate the effects of different parameters on the shape of failure mechanism, which is of overriding significance to the stability analysis of tunnel roof in layered rock media.

Keywords: layered rock; nonlinear failure criterion; tunnel roof

1. Introduction

The stability analysis of shallow tunnel is an important topic, and has been investigated by several scholars. Chen (1975) presented the upper and lower bound for slope stability factors, soil pressure of retaining walls, and bearing capacity of foundations, using the upper bound theorem and lower bound theorem. Since Davis *et al*. (1980) introduced limit analysis method to estimate the lower and upper bound stability solutions of tunnels by constructing a two dimensional failure mechanism, the limit analysis method had been used to analyze tunnel stability tunnel by many scholars. In order to obtain an upper solution, Leca and Dormieux (1990) developed three dimensional failure mechanisms of tunnels. Soubra *et al*. (2008) improved the failure mechanism of Leca and Dormieux (1980) by using a new three dimensional failure mechanism. Comparing the upper bound results by using the mechanism of Leca and Dormieux (1980), Soubra *et al*. (2008) claimed that the results calculated by improved mechanism were better. These works are focused on limit analysis method of tunnels with a linear Mohr-Coulomb (MC) failure criterion. Compared with the traditional limit equilibrium method, solutions derived from limit analysis are more rigorous for actual projects.

However, as the strength envelops are nonlinear in the normal and shear stress space in engineering (Hoek and Brown 1997, Yang and Pan 2015), the nonlinear failure criterion is more

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suitable to analyze tunnel problems than linear criterion. Since Hoek-Brown (HB) failure criterion was proposed in 1980, this nonlinear HB failure criterion had been widely applied in a variety of geotechnical engineering after modification and development (Serrano and Olalla 1998, 1999, Sofianos and Halakatevakis 2002, Sofianos 2003). With the nonlinear HB criterion, some researchers constructed different kinematically admissible failure mechanisms, and calculated the external work rate and internal energy dissipation of tunnel collapse blocks in the framework of upper bound theorem of limit analysis (Fraldi and Guarracino 2009, 2010). These works focus on the stability of tunnels in homogeneous and isotropic materials. In practices, tunnels are often excavated in layered stratum described by different material parameters. Consequently, a question, which arises in practice, is how to estimate the effects of layered rock stratum when the nonlinear HB criterion is employed.

To solve the problem, this paper proposes a failure mechanism which satisfies the kinematically admissible conditions. The tunnel roof is located in the two layered rock media. The failure mechanism consists of two different functions. Based on the proposed failure mechanism and nonlinear HB criterion, the energy dissipation is calculated by employing two integral calculations. According to the results of optimization calculation, the upper solutions of collapse shape of shallow circular tunnel are obtained. With the nonlinear HB failure criterion, this paper extends the work of Fraldi and Guarracino (2009, 2010) for single media to that for layered media. A study is conducted to investigate the effects of the parameters in the nonlinear failure criterion on collapsing tunnel in the layered rock stratum.

2. Hoek-Brown nonlinear failure criterion

Considering the nonlinear characteristics of rock materials, MC linear failure criterion is not perfect enough to analyze the intrinsic relationship between rock masses and the corresponding mechanical parameters, thus certain kinds of nonlinear criterion were employed to make up for the drawback of linear criterion. Typically, the HB nonlinear failure criterion is the one widely utilized to estimate the rocks from a new perspective of nonlinear way (Hoek and Brown 1997). Initially, it was established with the form of major and minor principal stresses, which is very suitable for tightly interlocked hard rock masses, as it was previously discussed and established on this type. The experiments and relevant investigation demonstrated that it can also be an appropriate formula as an alternative for very poor quality rock masses. Then another form was subsequently set up described by normal and shear stresses showing as follows, and it is convenient to calculate internal energy dissipation in engineering cases, such as working out energy dissipation generated by normal and shear stresses along with the velocity discontinuity surface (Fahimifar *et al*. 2015, Li *et al*. 2016, Yang and Yan 2015, Yang *et al*. 2016, Zhang and Wang 2015).

$$\tau = \mathrm{A}\sigma_c[(\sigma_n + \sigma_t)\sigma_c^{-1}]^B \tag{1}$$

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3. Upper bound analysis using the nonlinear criterion

3.1 Curve mechanism of shallow tunnels in the layered stratum

Based on the mechanical characteristic of deep tunnel, Fraldi and Guarracino (2009, 2010) firstly introduced an arch failure mechanism to establish work equation. According to the mechanical characteristic and actual failure situation of tunnels, Huang *et al*. (2012, 2013) introduced a curve failure mechanism for a homogeneous stratum. In the paper, a failure mechanism, consisting of two different functions, extends from circular tunnel roof to the ground is proposed, which is illustrated in Fig. 1. As it can be seen in Fig. 1, L_1 and L_3 are half width of the top and bottom of failure block respectively, and L_2 is half width of the layered position of failure block. Based on HB nonlinear criterion and associated flow rule, the energy dissipation along the failure surface can be calculated by employing integral calculation.

3.2 Upper bound solution of tunnel roof with the variational approach

Since the scope of the present work is to investigate the collapse of rock blocks on account of the gravitational field, the attention will be focused on admissible vertical velocity fields, v, which are assumed in the direction of the y-axis, see Fig. 1. Let the expression $y = g(x)$ and $y = f(x)$ indicate the set of the curves which define a possible collapsing block in the Cartesian

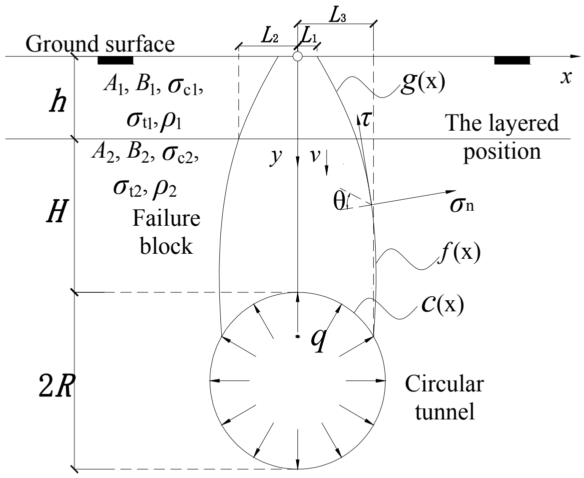


Fig. 1 Curve failure mechanism of tunnel roof in the layered rock media

reference frame x-y. $y = g(x)$ is the equation of velocity discontinuity surface of upper stratum and $y = f(x)$ is the equation of velocity discontinuity surface of the lower stratum.

By making reference to Fig. 1, from the first equation the normal component of stress can be written as a function of the HB mechanical parameters and of the first derivative of the unknown detaching curve $g'(x)$ and $f'(x)$, that is

$$\sigma_{n1} = -\sigma_{t1} + \sigma_{c1}\left[A_1 B_1 g'(x)\right]^{\frac{1}{1-B_1}} \tag{2}$$

$$\sigma_{n2} = -\sigma_{t2} + \sigma_{c2}\left[A_2 B_2 f'(x)\right]^{\frac{1}{1-B_2}} \tag{3}$$

where A_1, B_1, A_2 and B_2 are the material constants. At impending collapse the dissipation density of the internal forces on the detaching surface, $\dot{D}_{i1}$ and $\dot{D}_{i2}$ are expressed as

$$\begin{aligned}\dot{D}_{i1} &= \sigma_{n1}\dot{\varepsilon}_{n1} + \tau_{n1}\dot{\gamma}_{n1} \\ &= \frac{v}{w}\left[1+g'(x)^2\right]^{-\frac{1}{2}}\left[\sigma_{t1} - \sigma_{c1}(A_1B_1)^{\frac{1}{1-B_1}}(1-B_1^{-1})g'(x)^{\frac{1}{1-B_1}}\right]\end{aligned} \tag{4}$$

$$\begin{aligned}\dot{D}_{i2} &= \sigma_{n2}\dot{\varepsilon}_{n2} + \tau_{n2}\dot{\gamma}_{n2} \\ &= \frac{v}{w}\left[1+f'(x)^2\right]^{-\frac{1}{2}}\left[\sigma_{t2} - \sigma_{c2}(A_2B_2)^{\frac{1}{1-B_2}}(1-B_2^{-1})f'(x)^{\frac{1}{1-B_2}}\right]\end{aligned} \tag{5}$$

where ε_{n1} and ε_{n2} are normal plastic strain rate respectively, $\dot{\gamma}_{n1}$ and $\dot{\gamma}_{n2}$ are shear plastic strain rate respectively, w is the thickness of the plastic detaching zone. By integrating $\dot{D}_{i1}$ over the interval $[L_1, L_2]$ and integrating $\dot{D}_{i2}$ over the interval $[L_2, L_3]$, the energy dissipation along the velocity discontinuity surface is

$$\begin{aligned}D &= \int_{L_1}^{L_2}\dot{D}_{i1}w\mathrm{d}s + \int_{L_2}^{L_3}\dot{D}_{i2}w\mathrm{d}s \\ &= v\int_{L_1}^{L_2}[\sigma_{t1} - \sigma_{c1}(A_1B_1)^{\frac{1}{1-B_1}}(1-B_1^{-1})g'(x)^{\frac{1}{1-B_1}}]\mathrm{d}x \\ &\quad + v\int_{L_2}^{L_3}[\sigma_{t2} - \sigma_{c2}(A_2B_2)^{\frac{1}{1-B_2}}(1-B_2^{-1})f'(x)^{\frac{1}{1-B_2}}]\mathrm{d}x\end{aligned} \tag{6}$$

The work rate of failure block produced by weight can also be obtained by integral calculation

$$P_e = v\left\{\int_0^{L_3}\rho_2 c(x)\mathrm{d}x - \int_{L_1}^{L_2}\rho_1 g(x)\mathrm{d}x - \int_{L_2}^{L_3}\rho_2 f(x)\mathrm{d}x - (\rho_2 - \rho_1)L_2 h\right\} \tag{7}$$

in which ρ_1 and ρ_2 are the unit weights of the rock mass of upper layer and lower layer, respectively. $c(x)$ is the equation describing the circular tunnel profile which is given by

$$c(x) = h + H + R - \sqrt{R^2 - x^2} \tag{8}$$

where h is the height of upper stratum, $h + H$ and R are the buried depth and radius of the circular tunnel respectively. The power of supporting pressure of shallow tunnel is expressed as

$$P_q = -Rqv\arcsin\frac{L_3}{R} \tag{9}$$

where q is the supporting pressure of the circular tunnel. The solution calculated by the work equation is just an upper bound solution, rather than the real solution. Moreover, according to the upper bound theorem, the solution close to real solution is the extremum among these upper solutions which can be determined by optimization calculation. To obtain the optimum upper solution, it is necessary to construct an objective function which is composed of external rate of work and the internal energy rate of dissipation

$$\begin{aligned}\xi &= D - P_e - P_q \\ &= \xi_1 + \xi_2 + Rqv\arcsin\frac{L_3}{R} - v\int_0^{L_3}\rho_2 c(x)\mathrm{d}x - (\rho_2 - \rho_1)L_2 hv\end{aligned} \tag{10}$$

where

$$\xi_1 = v\int_{L_1}^{L_2}\Lambda_1[x, g(x), g'(x)]\mathrm{d}x \tag{11}$$

$$\xi_2 = v\int_{L_2}^{L_3}\Lambda_2[x, f(x), f'(x)]\mathrm{d}x \tag{12}$$

where $\Lambda_1[x, g(x), g'(x)]$ and $\Lambda_2[x, f(x), f'(x)]$ are functions which can be written as

$$\Lambda_1[x, g(x), g'(x)] = \sigma_{t1} - \sigma_{c1}(A_1B_1)^{\frac{1}{1-B_1}}(1 - B_1^{-1})g'(x)^{\frac{1}{1-B_1}} + \rho_1 g(x) \tag{13}$$

$$\Lambda_2[x, f(x), f'(x)] = \sigma_{t2} - \sigma_{c2}(A_2B_2)^{\frac{1}{1-B_2}}(1 - B_2^{-1})f'(x)^{\frac{1}{1-B_2}} + \rho_2 f(x) \tag{14}$$

The difficulty is how to find the extremum of the objective function ξ. It can be found that the objective function ξ is made up of two objective functions, ξ_1 and ξ_2. Assuming that the objective function ξ_1 and ξ_2 obtain the extremum, the objective function ξ. obtains the extremum. It also can be found that from Eqs. (11) and (12) that the ξ_1 is determined by Λ_1 and the ξ_2 is determined by Λ_2. Therefore, the upper bound solution of possible collapse is regarded as searching the minimum value of objective function Λ_1 and Λ_2. The expressions of Λ_1 and Λ_2 are functions which can be turned into two Euler's equations by variational calculation. The variational equations of Λ_1 and Λ_2 on stationary conditions can be expressed as follows

$$\frac{\partial\Lambda_1}{\partial g(x)} - \frac{\partial}{\partial x}\left[\frac{\partial\Lambda_1}{\partial g'(x)}\right] = 0 \tag{15}$$

$$\frac{\partial \Lambda_2}{\partial f(x)} - \frac{\partial}{\partial x}\left[\frac{\partial \Lambda_2}{\partial f'(x)}\right] = 0 \tag{16}$$

By substituting Eq. (13) into Eq. (15) and substituting Eq. (14) into Eq. (16), the two Euler equation of Λ_1 and Λ_2 are obtained

$$\rho_1 - \sigma_{c1}(A_1 B_1)^{\frac{1}{1-B_1}}(1-B_1)^{-1}[g'(x)]^{\frac{2B_1-1}{1-B_1}} g''(x) = 0 \tag{17}$$

$$\rho_2 - \sigma_{c2}(A_2 B_2)^{\frac{1}{1-B_2}}(1-B_2)^{-1}[f'(x)]^{\frac{2B_2-1}{1-B_1}} f''(x) = 0 \tag{18}$$

It is obvious that Eqs. (17) and (18) are two nonlinear second-order homogeneous differential equation which can be solved by integral calculation. Thus, expression of velocity discontinuity surface $g(x)$ and $f(x)$ are

$$g(x) = k_1\left(x - \rho_1^{-1} m_0\right)^{\frac{1}{B_1}} + m_1 \tag{19}$$

$$f(x) = k_2\left(x - \rho_2^{-1} n_0\right)^{\frac{1}{B_2}} + n_1 \tag{20}$$

where

$$k_1 = A_1^{-\frac{1}{B_1}}\left(\frac{\rho_1}{\sigma_{c1}}\right)^{\frac{1-B_1}{B_1}}, \qquad k_2 = A_2^{-\frac{1}{B_2}}\left(\frac{\rho_2}{\sigma_{c2}}\right)^{\frac{1-B_2}{B_2}} \tag{21}$$

m_0, m_1, n_0 and n_1 are integration constants, respectively, which can be determined by boundary condition.

According to the equilibrium equation of an element on the ground surface, the expression of shear stress of the element is derived. As there is no distribution of shear stress on the ground surface, the following equation is obtained

$$\tau_{xy}\left(x = L_1, y = 0\right) = 0 \tag{22}$$

Furthermore, it can be found from Fig. 1 that there are three geometric equations to be satisfied

$$g(x = L_1) = 0 \tag{23}$$

$$g(x = L_2) = h \tag{24}$$

$$f(x = L_3) = c(x = L_3) \tag{25}$$

Based on Eqs. (22) and (23), the values of constants m_0 and m_1 are determined. Substituting these constants into Eq. (19), the equation including unknown constant L_1 is obtained

$$g(x) = k_1 \left(x - L_1 \right)^{\frac{1}{B_1}} \tag{26}$$

At the interface of the two media, an equation should be satisfied as follows

$$g'(x = L_2) = f'(x = L_2) \tag{27}$$

By substituting Eqs. (20) and (26) into Eq. (27), it can obtain

$$\rho_2^{-1} n_0 = L_2 - Z \tag{28}$$

where

$$Z = \left[\frac{k_1}{k_2} \frac{B_2}{B_1} \left(L_2 - L_1 \right)^{\frac{1-B_1}{B_1}} \right]^{\frac{B_2}{1-B_2}} \tag{29}$$

By substituting Eq. (20) and Eq. (29) into equation $f(x = L_2) = h$, it can obtain

$$n_1 = h - k_2 Z^{\frac{1}{B_2}} \tag{30}$$

And the expression of $y = f(x)$ can be written as follows

$$f(x) = k_2 (x - L_2 + Z)^{\frac{1}{B_2}} + h - k_2 Z^{\frac{1}{B_2}} \tag{31}$$

The expression of ξ is determined by substituting Eqs. (11), (12), (13), (14), (26) and (31) into Eq. (10), which is written as

$$\begin{aligned} \xi = v\{ & \sigma_{t_1} (L_2 - L_1) + A_1^{-\frac{1}{B_1}} (1 + B_1)^{-1} \sigma_{c1}^{\frac{B_1 - 1}{B_1}} \rho_1^{\frac{1}{B_1}} (L_2 - L_1)^{\frac{1+B_1}{B_1}} \\ & + (\sigma_{t2} + \rho_2 h - \rho_2 k_2 Z^{\frac{1}{B_2}})(L_3 - L_2) + A_2^{-\frac{1}{B_2}} (1 + B_2)^{-1} \sigma_{c2}^{\frac{B_2 - 1}{B_2}} \rho_2^{\frac{1}{B_2}} [(L_3 - L_2 + Z)^{\frac{1+B_2}{B_2}} - Z^{\frac{1+B_2}{B_2}}] \\ & + Rq \arcsin \frac{L_3}{R} - \rho_2 L_3 (H + h + R) + \frac{\rho_2 L_3}{2} \sqrt{R^2 - L_3^2} + \frac{\rho_2 R^2}{2} \arcsin \frac{L_3}{R} + (\rho_2 - \rho_1) L_2 h \} \end{aligned} \tag{32}$$

Based on Eqs. (24) and (25) , two equations, including three unknown constants L_1, L_2 and L_3, are obtained

$$k_1 \left(L_2 - L_1 \right)^{\frac{1}{B_1}} = h \tag{33}$$

$$k_2 \left(L_3 - L_2 + Z \right)^{\frac{1}{B_2}} + h - k_2 Z^{\frac{1}{B_2}} = H + h + R - \sqrt{R^2 - L_3^2} \tag{34}$$

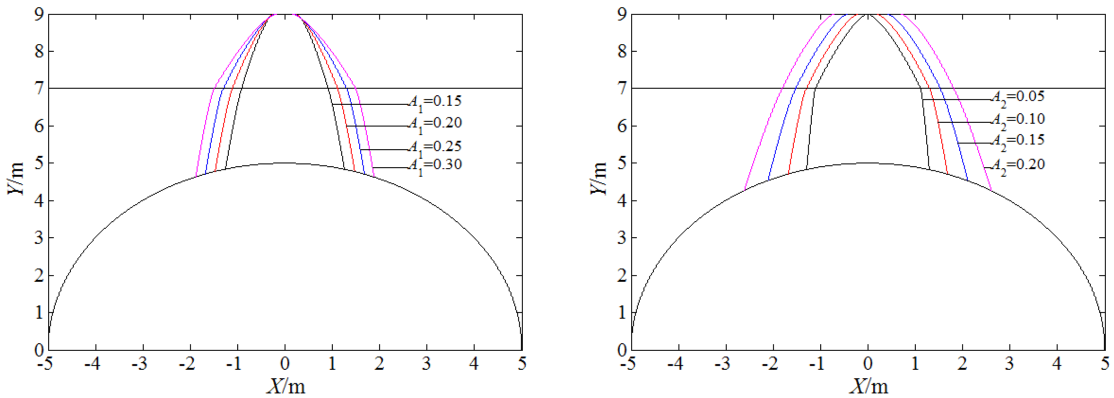
For the purpose of determining the values of L_1, L_2 and L_3, another equation which includes the two unknown constants is derived by equating external rate of work and the internal energy dissipation.

$$
\begin{aligned}
\xi = v\{ & \sigma_{t_1}(L_2 - L_1) + A_1^{-\frac{1}{B_1}}(1+B_1)^{-1}\sigma_{c1}^{\frac{B_1-1}{B_1}}\rho_1^{\frac{1}{B_1}}(L_2 - L_1)^{\frac{1+B_1}{B_1}} \\
& + (\sigma_{t2} + \rho_2 h - \rho_2 k_2 Z^{\frac{1}{B_2}})(L_3 - L_2) + A_2^{-\frac{1}{B_2}}(1+B_2)^{-1}\sigma_{c2}^{\frac{B_2-1}{B_2}}\rho_2^{\frac{1}{B_2}}[(L_3 - L_2 + Z)^{\frac{1+B_2}{B_2}} - Z^{\frac{1+B_2}{B_2}}] \\
& + Rq\arcsin\frac{L_3}{R} - \rho_2 L_3(H + h + R) + \frac{\rho_2 L_3}{2}\sqrt{R^2 - L_3^2} + \frac{\rho_2 R^2}{2}\arcsin\frac{L_3}{R} + (\rho_2 - \rho_1)L_2 h\} = 0
\end{aligned}
\tag{35}
$$

Combining the Eqs. (33), (34) and (35), the values of L_1, L_2 and L_3 can be solved by using numerical software. Based on L_1, L_2 and L_3, the final forms of detaching curve consisting of $y = g(x)$ and $y = f(x)$ are obtained, and the shape of failure surface can be drawn by Eqs. (26) and (31).

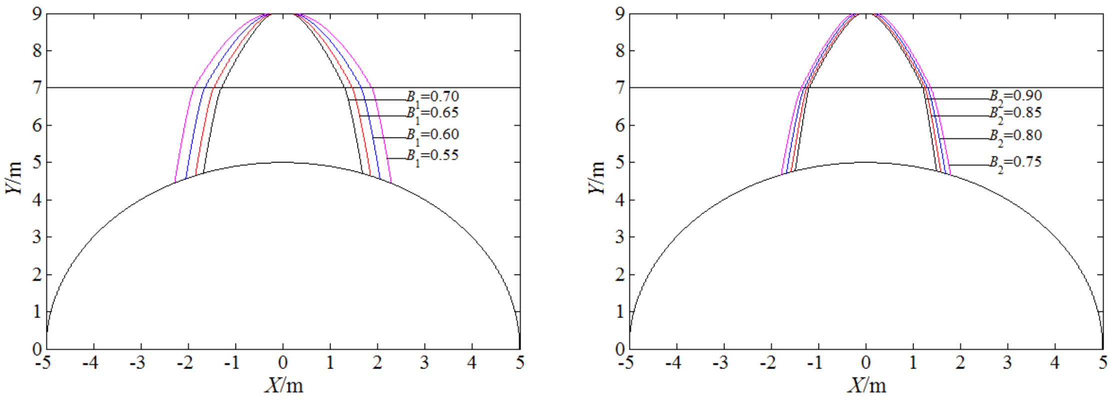
4. Numerical results and discussions

As the failure surface of shallow tunnel extends to the ground surface, the tunneling-induced surface subsidence and deformation may cause damage to existing structures. So the prediction of the collapse range of shallow tunnel is an issue with high engineering significance. Based on the analytical solutions of velocity discontinuity surfaces $g(x)$ and $f(x)$ expressed in Eqs. (26) and (31), the failure surfaces of shallow tunnel excavated in the layered stratum can be drawn for different parameters. To investigate the effect of parameters A_1, B_1, A_2 and B_2 on the shape of failure surface, the failure surfaces of the parameters corresponding to $\sigma_{c1} = \sigma_{c2} = 0.5$ Mpa, $\sigma_{t1} = \sigma_{c1}/100$, $\sigma_{t2} = \sigma_{c2}/100$, $\rho_1 = \rho_2 = 17.5$ kN/m^3, $q = 40$ kPa, $R = 5$ m, $h = 2$ m, $h + H = 4$ m, $A_1 = 0.15/0.30$, $A_2 = 0.05/0.20$, $B_1 = 0.75/0.9$ and $B_1 = 0.55/0.7$ are illustrated in Fig. 2. It is necessary to notice that, in the process of calculation, the relationships of size between A_1, B_1, A_2 A_2 and B_2 are $A_1 > A_2$ and $B_1 > B_2$. It can be seen from these figures that the failure surface extends form which form a funnel-shaped collapse block and each curve of failure surface is made up of two parabolic curves. With the increase of A_1, the top width of the failure block L_1 decreases. With the increase of width of L_2 and L_3, and the possible collapse of tunnel increases. With the increase of A_1, the possible collapse



(a) Effects of parameter A_1 (b) Effects of parameter A_2

Fig. 2 Shape of collapsing blocks of shallow tunnel for different rock parameters



(c) Effects of parameter B_1 (d) Effects of parameter B_2

Fig. 2 Continued

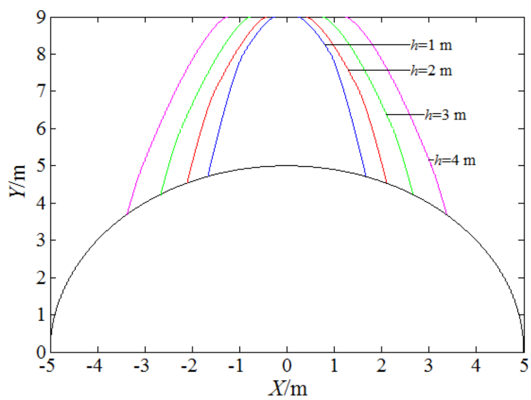


Fig. 3 Shape of collapsing blocks of shallow for different h

of tunnel also increases. Moreover, the possible shape of collapsing blocks of shallow tunnel decreases with the increase of B_1 and B_2. From the perspective of engineering this means that the shallow tunnel excavated in the layered stratum with A_1, B_1, A_2 and B_2 will contribute to controlling the size of failure block.

On the other hand, to study the effect of height of h on the failure mechanism, the collapsing blocks of rock parameters corresponding to $A_1 = 0.30$, $A_2 = 0.10$, $B_1 = 0.8$, $B_1 = 0.7$, $\sigma_{c1} = \sigma_{c2} = 0.5$ Mpa, $\sigma_{t1} = \sigma_{c1}/100$, $\sigma_{t2} = \sigma_{c2}/100$, $\rho_1 = \rho_2 = 17.5$ kN/m^3 and $q = 40$ kPa with h varying from 1m to 4m are illustrated in Fig. 3. As shown in Fig. 3, the possible shape of collapsing increases with the increase of height of first layer stratum.

5. Conclusions

Based on upper bound theorem in the framework of plasticity theory, the failure mechanism is proposed to estimate the effect of nonlinear HB failure criterion on tunnel roof in layered rock media. Therein, the failure mechanism of tunnel roofs consists of two different functions. The nonlinear failure criterion is incorporated into upper bound theorem, including the rate of gravity and internal energy dissipation. The solution for the shape of collapsing block in circular tunnel excavated in the layered rock media is obtained in the framework of the upper bound theorem of limit analysis. Based on the results, the shape of failure surface, which is made up of velocity discontinuity surface $g(x)$ and $f(x)$, is obtained. Employing the nonlinear HB failure criterion, this paper has extended the work of Fraldi and Guarracino (2009, 2010) for single media to that for layered media on the prediction of collapsing mechanism. According to the discussion above, some conclusions can be drawn:

(1) The different rock parameters have significant influence on the collapsing shape of rock mass in shallow circular tunnels excavated in layered HB rock media. It is found that the possible collapsing shape of the failure block increases with the increase of parameters A_1 and A_2, when the relationships, $A_1 > A_2$ and $B_1 < B_2$, are satisfied.
(2) The collapsing block magnitude decreases with the increase of parameters B_1 and B_1, when the relationships, $A_1 > A_2$ and $B_1 < B_2$, are satisfied.
(3) With $A_1 > A_2$ and $B_1 < B_2$, the increase of the height h of the first layer stratum results in the failure block increase.

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