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Stress characteristics of surrounding rocks for inner water exosmosis in high-pressure hydraulic tunnels

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Abstract: Seepage and stress redistribution are the main factors affecting the stability of surrounding rock in high-pressure hydraulic tunnels. In this work, the effects of the seepage field were firstly simplified as a seepage factor acting on the stress field, and the equilibrium equation of high pressure inner water exosmosis was established based on physical theory. Then, the plane strain theory was used to solve the problem of elasticity, and the analytic expression of surrounding rock stress was obtained. On the basis of criterion of Norway, the influences of seepage, pore water pressure and buried depth on the characteristics of the stress distribution of surrounding rocks were studied. The analyses show that the first water-filling plays a decisive role in the stability of the surrounding rock; the influence of seepage on the stress field around the tunnel is the greatest, and the change of the seepage factor is approximately consistent with the logarithm divergence. With the effects of the rock pore water pressure, the circumferential stress shows the exchange between large and small, but the radial stress does not. Increasing the buried depth can enhance the arching effect of the surrounding rock, thus improving the stability.

Key words: high pressure hydraulic tunnel; inner water exosmosis; physical theory; seepage factor; stress redistribution; plane strain theory

1 Introduction

From the development of design theory and engineering practice of pressure tunnels, for tunnels buried deeply in the high head water-enriched zone or under a high head internal pressure, the influence of seepage on the surrounding rock stress field cannot be ignored. Seepage factor caused by seepage fundamentally changes the stress field of surrounding rock in high-pressure hydraulic tunnels. In addition, after excavation, the phenomenon of surrounding rock stress redistribution will occur, and the stress will adjust to a new equilibrium state. Visible seepage and stress redistribution are the two important factors influencing the surrounding rock stress field. At present, due to the large number of pumped storage power station constructions, pressure tunnel construction is becoming more and more widespread, the current scale of which is far beyond the scope of application of the existing norms, therefore, the objective response of the stress distribution of surrounding rocks for inner water exosmosis in high-pressure hydraulic tunnels under the influence of seepage and stress redistribution has become a major issue which must be solved in current hydroelectric development.

In the analysis of previous studies, NAM and BOBET [1], BOBET [2], DAHLO and NILSON [3] and others derived the analytical solution of the supporting structure of surrounding rock considering the action of water, and analyzed the stability problem. EL TANI [4], KYUNG et al [5], KOLYMBAS and WAGNER [6], FAHIMIFAR and ZAREIFARD [7] and others derived the analytical solution of groundwater seepage under different project situations, and pointed out the difference among the flow predictions. KELSALL et al [8] studied the influence of tunnel excavation on the permeability of surrounding rock. LEE et al [9] studied

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the influence of tunnel excavation on the ground settlement, considering the effects of seepage force. These studies have provided a certain guiding role to the tunnel construction buried deeply in high head water-enriched zones, but the results are only suitable for the analysis of the outer water exosmosis phenomenon, and not for the analysis of the problem of inner water exosmosis of high-pressure hydraulic tunnels.

In view of the problem of inner water exosmosis of high-pressure hydraulic tunnels, few researchers have been involved so far. This work is based on the plane strain theory, with the phenomenon of inner water exosmosis of high-pressure hydraulic tunnels as the research background. Consideration is given to the effect of seepage and stress redistribution on the surrounding rock stress field, to explore the influence law between the two in the Norway criterion. The innovation points of the work are as follows: Establishing equilibrium equation of inner water exosmosis of high-pressure hydraulic tunnels, and considering the impact of seepage and stress redistribution on the surrounding rock stress field.

2 Surrounding rock stress field for inner water exosmosis of high-pressure hydraulic tunnels

2.1 Establishment of equilibrium equation

The main characteristic of high-pressure hydraulic tunnels is that the surrounding rock stress field changes with the process of inner water exosmosis, and seepage mainly occurs along the radius direction [10−11]. Inner water exosmosis is fully carried out after a certain period of time of hydraulic tunnel normal operation, and seepage enters the stable state, thus its influence on the surrounding rock stress field can be regarded as a constant. Therefore, the solution of the steady seepage field stage can be regarded as a problem of axisymmetric steady seepage. To solve this problem, the force balance of the radial and hoop direction at any point in the external of tunnel is free of the shear stress component, which plays a leading and controlling role in the force balance. In addition, inner water exosmosis of high-pressure hydraulic tunnels occurs mainly along the radial direction, which does not consider the effects of buoyancy caused by the seepage factor. According to the stress state as shown in Fig. 1, we use the physical theory to establish the force equilibrium differential equation:

$$\sum F_r = 0 \tag{1}$$

$$(\sigma_r + \mathrm{d}\sigma_r + P_{\mathrm{w}} + \mathrm{d}P_{\mathrm{w}})r\mathrm{d}\theta - [(\sigma_r + P_{\mathrm{w}})(r+\mathrm{d}r)\mathrm{d}\theta + 2\sin\frac{\mathrm{d}\theta}{2}(\sigma_\theta + P_{\mathrm{w}})\mathrm{d}r] = 0 \tag{2}$$

When $\mathrm{d}\theta$ is small enough, $\sin\frac{\mathrm{d}\theta}{2} = \frac{\mathrm{d}\theta}{2}$ is obtained. Therefore, Eq. (2) can be altered to the following form:

$$\frac{\mathrm{d}\sigma_r}{\mathrm{d}r} - \frac{\sigma_r + \sigma_\theta}{r} + f_r = 0 \tag{3}$$

where f_r is the seepage factor, which can be described by Eq. (4); and σ_θ and σ_r are the hoop stress and radial stress at any point r of the surrounding rock, respectively.

$$f_r = \frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}r} - \frac{2P_{\mathrm{w}}}{r} \tag{4}$$

where $\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}r}$ is the body force of seepage; and P_{w} is the seepage force, as can be seen from Fig. 1; P_{w}, σ_θ and σ_r have the same unit of MPa.

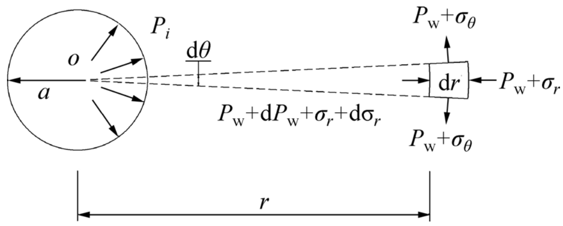

Fig. 1 Force diagram of element in surrounding rock

For the axisymmetric steady seepage problem, BIAN et al [12] gave the solution of seepage field, as follows:

$$H = \frac{1}{\ln\alpha}\left(h_a \ln\frac{\alpha a}{r} + h_0 \ln\frac{r}{a}\right) \tag{5}$$

where H is the water head at any point r of the surrounding rock, of which the unit is m; a is the radius of tunnel; and α represents the radius ratio of the circular boundary where the far head h_0 and wall head h_a are located.

The relationship between the body force of seepage and the water head is shown as

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}r} = -\gamma_{\mathrm{w}}\frac{\mathrm{d}(\xi H)}{\mathrm{d}r} \tag{6}$$

Combining Eqs. (5) and (6) yields the following:

$$\frac{\mathrm{d}P_{\mathrm{w}}}{\mathrm{d}r} = \frac{\gamma_{\mathrm{w}}\xi(h_a - h_0)}{r\ln\alpha} \tag{7}$$

where γ_{w} is the water density, of which the unit is kN/m^3. Seepage changes the stress state of the surrounding rock, in turn altering the permeability of the rock mass. Considering the rock pore characteristics, the rock equivalent coefficient of pore water pressure ξ is introduced into Eq. (6).

Integrating Eq. (7), the seepage factor expression can be obtained as

$$f_r=\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{r\ln\alpha}\left(1-2\ln r\right) \tag{8}$$

Therefore, the equilibrium differential equation can be changed into the following form:

$$\frac{\mathrm{d}\sigma_r}{\mathrm{d}r}-\frac{\sigma_r+\sigma_\theta}{r}-\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{r\ln\alpha}\left(2\ln r-1\right)=0 \tag{9}$$

2.2 Solution of problem

2.2.1 Surrounding rock stress caused by seepage

As shown in Fig. 2, tunnel excavation radius is a. When the hydraulic tunnel is buried deeply, the tunnel excavation is consistent with the plane strain assumption. Seepage is in a stable state after inner water exosmosis is fully carried out, and assuming the wall internal pressure is P_a, and the far field pressure is P_0, then the two constitute the boundary condition of the surrounding rock stress. σ_θ and σ_r are the hoop stress and radial stress, respectively, at any point of the surrounding rock in polar coordinates (r, θ).

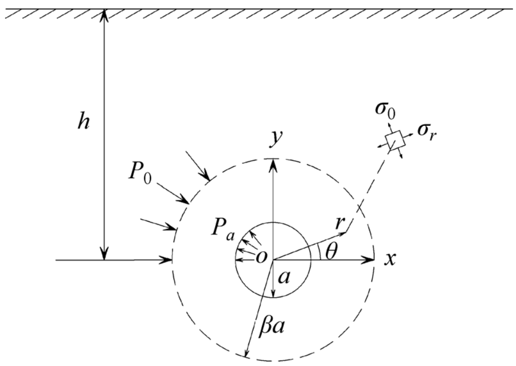

Fig. 2 Calculation sketch of hydraulic tunnel

In the plane strain problem, the physical equation using displacement represents stress is as follows:

$$\begin{cases}\sigma_\theta=\lambda\left(\dfrac{1-\upsilon}{\upsilon}\cdot\dfrac{u}{r}+\dfrac{\mathrm{d}u}{\mathrm{d}r}\right)\\ \sigma_r=\lambda\left(\dfrac{1-\upsilon}{\upsilon}\cdot\dfrac{\mathrm{d}u}{\mathrm{d}r}+\dfrac{u}{r}\right)\end{cases} \tag{10}$$

where λ is the first Lame parameter, and it is expressed as $\lambda=\dfrac{E\upsilon}{\left(1+\upsilon\right)\left(1-2\upsilon\right)}$, of which the unit is MPa. E is the elastic modulus of the rock mass; υ is the Poisson ratio of the rock mass; and u is the radial displacement of the surrounding rock.

Using Eqs. (9) and (10) simultaneously, and combining with the boundary conditions of the stress as $\begin{cases}\sigma_{r|r=a}=-P_a\\ \sigma_{r|r=\beta a}=-P_0\end{cases}$, the displacement field of the surrounding rock can be obtained, and the stress field of the surrounding rock can be solved as follows:

$$\sigma_r=\frac{\lambda}{\upsilon}\cdot\left[\frac{M_1}{\beta^{n_2-1}-\beta^{n_1-1}}\cdot\left(\frac{a}{r}\right)^{1-n_1}+\frac{M_2}{\beta^{n_1-1}-\beta^{n_2-1}}\cdot\left(\frac{a}{r}\right)^{1-n_2}\right]+\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{\ln\alpha}\left[\frac{2\upsilon^2+5\upsilon-2}{\left(2+\upsilon\right)^2}-\frac{2}{2+\upsilon}\ln r\right] \tag{11}$$

$$\sigma_\theta=\frac{\lambda}{\upsilon}\cdot\left[\frac{n_1''}{n_1'}\cdot\frac{M_1}{\beta^{n_2-1}-\beta^{n_1-1}}\cdot\left(\frac{a}{r}\right)^{1-n_1}+\frac{n_2''}{n_2'}\cdot\frac{M_2}{\beta^{n_1-1}-\beta^{n_2-1}}\cdot\left(\frac{a}{r}\right)^{1-n_2}\right]+\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{\ln\alpha}\left[\frac{2-\upsilon-2\upsilon^2}{\left(2+\upsilon\right)^2}-\frac{2}{2+\upsilon}\ln r\right] \tag{12}$$

where M_1 and M_2 are constant parameters, and can be described by the following formulae:

$$M_1=\frac{\left(1+\upsilon\right)\left(1-2\upsilon\right)}{E}\cdot\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{\ln\alpha}\cdot\left[\frac{2\upsilon^2+5\upsilon-2}{\left(2+\upsilon\right)^2}\cdot\left(1-\beta^{n_2-1}\right)+\frac{2}{2+\upsilon}\left(\beta^{n_2-1}\ln a-\ln\beta a\right)\right]+\frac{\left(1+\upsilon\right)\left(1-2\upsilon\right)}{E}\left(P_0-P_a\beta^{n_2-1}\right) \tag{13}$$

$$M_2=\frac{\left(1+\upsilon\right)\left(1-2\upsilon\right)}{E}\cdot\frac{\gamma_{\mathrm{w}}\xi\left(h_a-h_0\right)}{\ln\alpha}\left[\frac{2\upsilon^2+5\upsilon-2}{\left(2+\upsilon\right)^2}\cdot\left(1-\beta^{n_1-1}\right)+\frac{2}{2+\upsilon}\left(\beta^{n_1-1}\ln a-\ln\beta a\right)\right]+\frac{\left(1+\upsilon\right)\left(1-2\upsilon\right)}{E}\cdot\left(P_0-P_a\beta^{n_1-1}\right) \tag{14}$$

The correlation coefficients of the formulae are as follows:

$$\begin{cases}n_1''=\dfrac{\upsilon}{1-\upsilon}n_1+1\\ n_2''=\dfrac{\upsilon}{1-\upsilon}n_2+1\\ n_1'=n_1+\dfrac{\upsilon}{1-\upsilon}\\ n_2'=n_2+\dfrac{\upsilon}{1-\upsilon}\\ n_1=\dfrac{\kappa+\sqrt{\left(\kappa+4\right)^2-28}}{2}\\ n_2=\dfrac{\kappa-\sqrt{\left(\kappa+4\right)^2-28}}{2}\\ \kappa=\dfrac{1}{1-\upsilon}+1\end{cases} \tag{15}$$

In order to obtain the solution of the surrounding rock stress, the finite radius of ba is used to represent infinity, the value of which meets the engineering requirements; through analysis, this value is typically b=30.

In the initial water-filling stage, the internal pressure can be regarded as the wall surface force, due to the fact that the seepage field cannot be formed in a short period of time. By using the surface force theory, i.e., the thick-walled cylinder theory with only inner pressure, the surrounding rock stress of the first water-filling can be obtained in the basic assumption of elasticity as follows:

$$\sigma_r = \left[\frac{1}{\beta^{n_1-n_2}-1}\left(\frac{a}{r}\right)^{1-n_1} + \frac{1}{\beta^{n_2-n_1}-1}\left(\frac{a}{r}\right)^{1-n_2} \right] P_a \tag{16}$$

$$\sigma_\theta = \left[\frac{n_1''}{n_1'}\cdot\frac{1}{\beta^{n_1-n_2}-1}\left(\frac{a}{r}\right)^{1-n_1} + \frac{n_2''}{n_2'}\cdot\frac{1}{\beta^{n_2-n_1}-1}\left(\frac{a}{r}\right)^{1-n_2} \right] P_a \tag{17}$$

2.2.2 Influence of stress redistribution

The excavation of the hydraulic tunnel leads to the redistribution of the surrounding rock stress. When it is buried deeply, the influence of excavation can be regarded as the axisymmetric case, and the classical elastic solution can be obtained as follows:

$$\begin{cases} \sigma_r = q\left(1-\dfrac{a^2}{r^2}\right) \\ \sigma_\theta = q\left(1+\dfrac{a^2}{r^2}\right) \end{cases} \tag{18}$$

where q is the initial stress of the rock mass. To distinguish from the third stress field, $\sigma_r^{(2)}$ and $\sigma_\theta^{(2)}$ are used to represent the secondary stresses caused by excavation.

2.3 Third stress field of surrounding rocks of high pressure hydraulic tunnel

The surrounding rock stress of the high pressure hydraulic tunnel can be solved by the superposition principle [11], and seepage and stress redistribution are considered in the superposition process. Therefore, the third stress field of the surrounding rock of the high pressure hydraulic tunnel is as follows:

$$\begin{cases} \sigma_r^{(3)} = \sigma_r^{(2)} + \sigma_r \\ \sigma_\theta^{(3)} = \sigma_\theta^{(2)} + \sigma_\theta \end{cases} \tag{19}$$

where $\sigma_r^{(2)}$, $\sigma_\theta^{(2)}$ and σ_r, σ_θ are the secondary stresses caused by excavation and surrounding rock stress generated by internal water pressure after water-filling, respectively. The surrounding rock stress is calculated according to Eqs. (15) and (16) in the initial water-filling stage, and according to Eqs. (11) and (12) in the steady seepage field stage correspondingly.

3 Validation of analytical solution

For the convenience of data analysis, the providing pressure is positive. At the same time, σ_{rf}, $\sigma_{\theta f}$ and σ_{rs}, $\sigma_{\theta s}$ represent the surrounding rock stresses in the initial water-filling stage and steady seepage field stage, respectively.

In the verification, a=3 m, E=2000 MPa, υ=0.25, α=30, β=30 (the same as below), and the seepage factor is removed from the formulae of the steady seepage field, to produce the following diagram.

From Fig. 3, we can see that, without considering seepage factor, the distribution of the surrounding rock stress of steady seepage field is consistent with the first water-filling. In addition, the stress field converges to the far field stress, which is in accordance with the general rules of Tunnel Mechanics [13], explaining that the derivation of the analytic solution is correct, and that the model shown in Fig. 1 is reasonable.

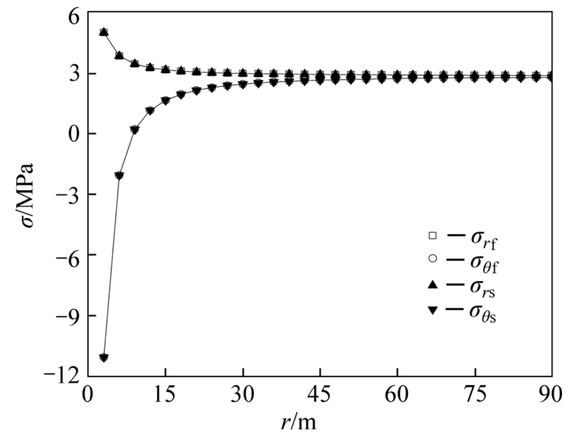

Fig. 3 Stress distribution in two stages

4 Stress characteristics of surrounding rocks

4.1 Effect of seepage

The inner pressure of an unlined hydraulic tunnel is applied to the wall directly; therefore, it is necessary to ensure that there is enough buried depth in the tunnel, i.e., the rock cover thickness of the tunnel is greater than the minimum overburden. The well-known Norway criterion is adopted to determine the minimum cover of hydraulic tunnels. The Norway criterion is an experience rule, which requires that the gravity of the tunnel overburden is not less than the inner pressure. Determining values of parameters according to the Norway criterion: the far field pressure is 1 MPa, wall internal pressure is 5 MPa, far field head is 50 m, wall head is 250 m, buried depth is 120 m, and water density is 9.8 kN/m^3, rock equivalent coefficient of pore water pressure is 1. Then, make the distribution of the surrounding rock stress before and after inner water undergo exosmosis.

With the expansion of inner water exosmosis, the surrounding rock stress of the first water-filling develops toward the steady seepage field stage. From Fig. 4, it can be seen that the hoop stress in the tensile region around tunnel will be smaller, but the value of it in the pressure region which goes deep into the surrounding rock will be larger. Under the circumstance that the radial stress is pressure, the strength of the surrounding rock would increase in the steady seepage field stage based on “the confining pressure effect”, and tends to be more stable. In the circumferential direction, the conversion of the mechanical property will occur, which creates tension around the tunnel, but this is gradually manifested as pressure with the going-deep-into the surrounding rock. From Fig. 4, we can see that the tensile region in the initial water-filling stage is significantly greater than the size in the steady seepage field stage. It is found that the first water-filling plays a decisive role in the stability of the surrounding rock; however, with the expansion of inner water exosmosis, the effect of the seepage is highlighted, the confining pressure of surrounding rock is increased, and the arching effect is enhanced. Thereby, the stability of the tunnel surrounding rock would be improved, thus dredging the formation of the seepage field could make the surrounding rock stable.

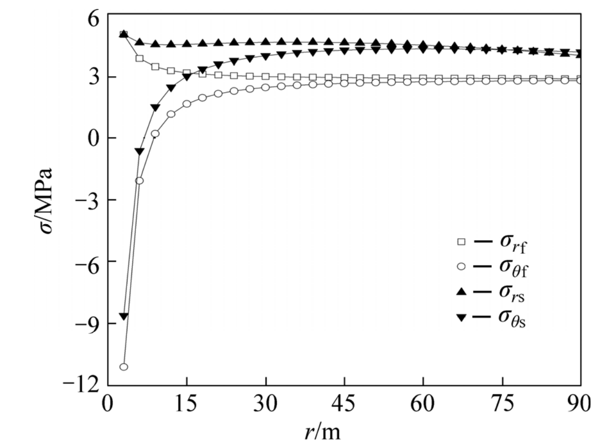

Fig. 4 Comparison of calculation results in two stages

From Fig. 4, it is seen that the stress curve is convergent (i.e., the values of α and β have a slight impact on the surrounding rock stress). In addition, the difference values of the convergence in the radial and hoop directions in the two stages are not equal to the values of the third item in the formulas of the steady seepage field, the third item possesses divergence in the logarithmic form due to no convergence. As found in the influence of the seepage, not only is it found that there is an increase of the third item, but the coefficients of the first two items are highly correlated with it. This is the reflection of the effect of the seepage, and the influence of seepage on the surrounding rock stress is reflected in the seepage factor. Therefore, next we discuss the change regulation of the seepage factor in the Norway criterion.

From Fig. 5, it can be seen that the influence of the seepage on the surrounding rock stress is relatively complex, which can be understood as being due to the change of the seepage factor is approximately consistent with the logarithm divergence from the analysis of the analytical expressions. Reflecting occurs when decreasing sharply in the circumferential direction and increasing rapidly in the radial direction around the tunnel, but the change in the deep surrounding rock is relatively slow. It is found that the influence of the seepage on the stress field around the tunnel is the greatest. The seepage factor of the two orthogonal directions shows the exchange of large and small at 5 and 21 times tunnel radius in the Norway criterion. In addition, the value in the radial direction is larger than that in the circumferential direction in the internal of this region, and the situation is opposite outside the region.

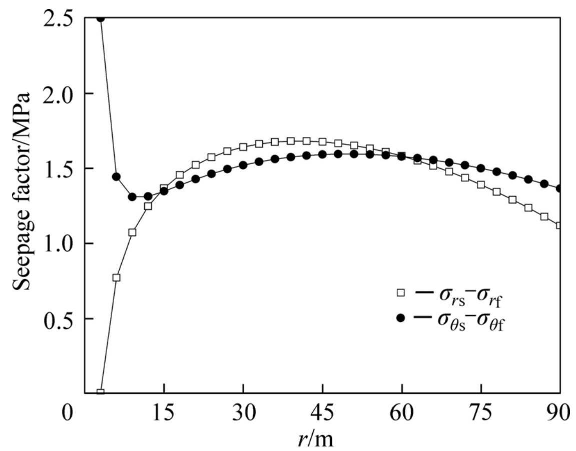

Fig. 5 Effect of seepage factor on surrounding rock stress

4.2 Rock pore water pressure

Similarly, the values of the parameters are consistent with those described above. From the above analysis, we can also see that the variation of the seepage factor is relatively complex, and rock pore water pressure is the main factor, thus, the relationship between the rock pore water pressure and surrounding rock stress field requires further exploration. Now, regarding the calculated results in the initial water-filling stage as the benchmark of the comparison, we produce charts and relative analysis tables, as shown in Fig. 6 and Tables 1 and 2.

From Fig. 6 and Tables 1 and 2, we can see that when ξ=0.2, i.e., the pore water pressure is relatively small, the stress field of the going-deep-into surrounding rock is close to the initial water-filling stage, but there is great variation in the values around the tunnel. When ξ=1.0, i.e., the pore water pressure is relatively large,

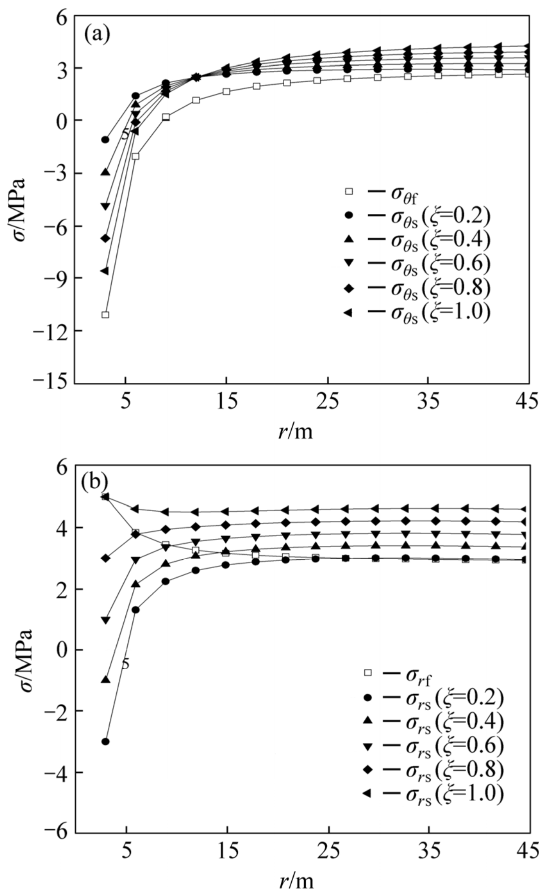

Fig. 6 Relationship between surrounding rock stress field and pore water pressure: (a) Hoop stress; (b) Radial stress

Table 1 Relative analysis of hoop stress (%)

r/r_a	ξ=0.2	ξ=1.0
1	−90	−23
3	936	633
5	60	81
7	32	66
9	22	63
11	16	61
13	13	61
15	10	60

Table 2 Relative analysis of radial stress (%)

r/r_a	ξ=0.2	ξ=1.0
1	−160	0
3	−35	31
5	−12	43
7	−4	50
9	0	54
11	0	56
13	0	57
15	0	57

then the stress field around the tunnel is close to the initial water-filling stage, but the value of the going-deep-into surrounding rock is gradually deviated from it. This is sufficient to see that the influence of the pore water pressure on the surrounding rock stress field is extremely great.

Considering the effects of rock pore water pressure, the hoop stress field would show the exchange of large and small at four times the tunnel radius, i.e., it does not change with the change of the pore water pressure at four times the tunnel radius. Furthermore, the hoop stress decreases with the decrease in the rock equivalent coefficient of the pore water pressure at the internal of four times the tunnel radius, and the final result is changed into pressure; the hoop stress increases with the increase in the rock equivalent coefficient of the pore water pressure outside four times the tunnel radius, and finally tends to be stable. When the radial stress field does not show the exchange of large and small, it increases with the increase in the rock equivalent coefficient of the pore water pressure. In addition, when the pore water pressure is relatively small, the radial stress around the tunnel becomes tensile; it changes greatly compared with the initial water-filling stage, which is most likely to appear in the form of the hydraulic fracturing phenomenon.

4.3 Buried depth

The Norway criterion requires that the rock cover thickness of tunnel is greater than the minimum overburden, and also requires exploring the influence of the buried depth of the high pressure hydraulic tunnel on surrounding rock stress under it. From the analytical expression, we can see that the sensitivity of the buried depth in the two stages is similar, thus we select the steady seepage field stage as the research object, as shown in Fig. 7.

From Fig. 7, we can see that increasing the buried depth in the Norway criterion, the influence of the stress redistribution on the surrounding rock stress field is more outstanding. It shows a linear increase in the stress values in the two orthogonal directions, as well as a linear decreasing in the radius of the tensile region, and gradually transits to the pressure by the tension, such as increasing 5/3 times of the buried depth shown in Fig. 7. It only reflects the seepage factor in the wall, due to the effect of the boundary conditions in the radial direction. This is sufficient to see that increasing the buried depth can make the tensile region decrease, and enhance the arching effect as well. Therefore, increasing the buried depth in the Norway criterion will contribute to the stability of the surrounding rock.

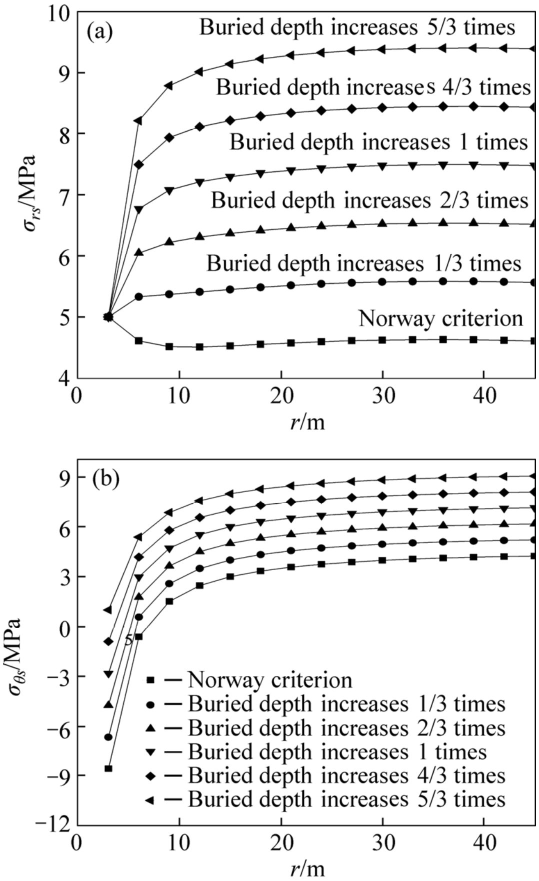

Fig. 7 Relationship between stress field and buried depth: (a) Radial stress; (b) Hoop stress

5 Conclusions

1) The first water-filling plays a decisive role in the stability of the surrounding rock, but with the expansion of inner water exosmosis, the strength of the surrounding rock is increased and the arching effect is enhanced. In addition, the influence of seepage on the stress field around the tunnel is the greatest, and the change of the seepage factor is approximately consistent with the logarithm divergence.

2) The influence of rock pore water pressure on the surrounding rock stress field is extremely great. The hoop stress field shows the exchange of large and small, while the radial stress field does not.

3) Increasing the buried depth in the Norway criterion may make surrounding rock stress increase linearly (in addition to the radial stress in the wall), and decrease linearly in the radius of the tensile region. Further increasing the buried depth in the Norway criterion will contribute to the stability of the surrounding rock.

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