ISSN 0021-8944, Journal of Applied Mechanics and Technical Physics, 2019, Vol. 60, No. 1, pp. 176–185. © Pleiades Publishing, Ltd., 2019.
Original Russian Text © Q. Yan, C. Zhang, W. Wu, Y. Zhang, T. Ma.

ANALYTICAL SOLUTION FOR THE EXTERNAL STRESS ACTING ON THE LINING IN A DEEP-BURIED CIRCULAR TBM TUNNEL CONSIDERING THE SEEPAGE FIELD

Q. Yan[a], C. Zhang[a,b], W. Wu[a], Y. Zhang[a], and T. Ma[c]

UDC 658.2

Abstract: Based on the elastic theory and the seepage flow theory, a new analytical solution with consideration of the seepage force is proposed to determine the external stress on the lining of a circular TBM tunnel. According to this solution, the relationships between the permeability coefficient of rock masses and the maximum allowable drainage flow are studied. The influence of the controlled drainage flow and the elastic modulus of surrounding rocks on the external stress is discussed. Moreover, in order to validate the results obtained from the elastic analytical solution developed in this paper, a comparison between the results obtained from the solution considering the seepage force and that without consideration of the seepage force is performed.

Keywords: TBM tunnel lining, groundwater, controlled drainage, external loading, seepage force, elastic solution.

DOI: 10.1134/S0021894419010218

INTRODUCTION

Tunnels, particularly, long and deep-buried tunnels are usually placed under the groundwater level, which forms a high water head, creating problems such as water leakage and lining collapse [1]. In general, there are three methods for dealing with groundwater: full drainage, full sealing, and controlled drainage [2]. However, full drainage may bring about serious environmental problems [3]. If full sealing is implemented, the tunnel lining has to sustain high water pressure, which may accelerate structural deterioration and consequently increase the risk of leakage, making the TBM tunnel difficult to design [4]. As a matter of fact, controlled drainage with the allowable discharge consistent with the environment should be adopted [5]. However, it seems much more difficult to adopt conventional drainage measures to reduce and control high water pressure, particularly, in deep-buried TBM tunnels, where the peripheral drainage system is no longer valid. A special drainage method is required. Tunnel experts have made attempts to figure out effective solutions to the problem. Among them, the pin drain method can be an alternative measure, which was successfully applied to the Storebalt railway tunnel in Scandinavia [6]. Moreover, some experts made further investigations on the effects of a pin drain system by using numerical methods, and the research results provided useful information for the design of the pin drain system [7]. In addition, Yan et al. [8, 9] proposed a feasible and effective design solution of the drainage lining structure, which is to bore release holes on the segmental

[a]Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, 610031, Chengdu, China; yanqixiang@home.swjtu.edu.cn; ⊠zhangchuan@my.swjtu.edu.cn; wuwang@my.swjtu.edu.cn; yanyang.zhang@swjtu.edu.cn. [b]Smart Material and Structure Laboratory, Department of Mechanical Engineering, University of Houston, Houston, TX 77204, USA. [c]China Railway Eryuan Engineering Group Co. Ltd, 610031, Chengdu, China; tingtingmaswjtu@163.com. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 60, No. 1, pp. 205–215, January–February, 2019. Original article submitted August 1, 2017; revision submitted May 15, 2018; accepted for publication May 28, 2018.

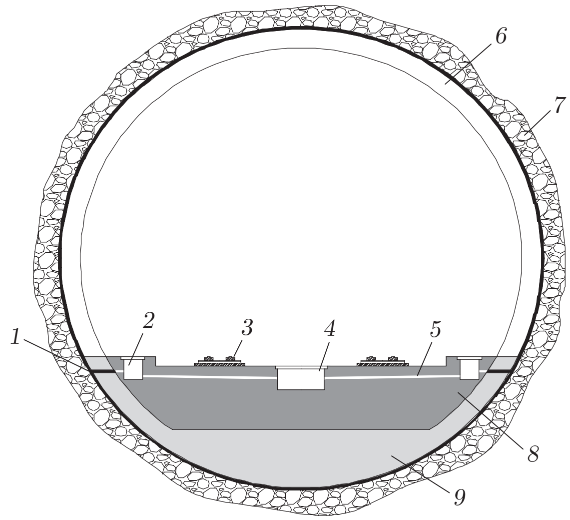

Fig. 1. Typical drainage system of the water drainage segmental lining: (*1*) drainage pipe; (*2*) side ditch; (*3*) track bed; (*4*) central ditch; (*5*) division pipe (gradient 2%); (*6*) cast-in-place concrete lining; (*7*) rock mass; (*8*) concrete component; (*9*) pre-fabricated invert segment.

lining to reduce and control high water pressure. Based on this solution, the relationships between the distribution characteristics of the external water pressure and the water discharge flow were further studied by the combination of similar model tests and numerical simulations [8, 9]. Figure 1 shows a typical drainage system of the water discharge segmental lining.

For TBM tunnels under a high water head, controlled drainage is a suitable option.

Generally, the external loading acting on the lining is the total stress, which consists of the effective stress and the pore water pressure. Analytical solutions of the pore water pressure for the steady seepage field around deep-buried tunnels were obtained in previous studies. Based on the principle of the image method, Harr [10] derived a formula for calculating the pore water pressure as applied to deep-buried circular tunnels under high hydraulic conditions [10].

Bobet [11] studied the lining stress with and without water conditions through analytical models. Tani [12] presented an analytical solution of the groundwater inflow based on the Mobius transformation and Fourier series [12]. Park et al. [13] performed comparisons of the existing analytical solutions for the steady-state groundwater inflow into a drained circular tunnel in a semi-infinite aquifer and obtained analytical solutions for two different boundary conditions by using the conformal mapping technique. As we can see, most of these studies concerning the analytical solution of the pore water pressure on the lining were derived from the seepage theory. However, the actual external loading acting on the lining including the effective stress failed to be taken into account. In addition, based on the assumptions that circular tunnels are excavated in elastic-plastic homogeneous rock masses under hydrostatic stress conditions, a series of analytical or semi-analytical solutions of displacements and stresses of surrounding rocks were studied without considering the seepage force [14].

The study and analysis of the lining stress considering the interaction of the surrounding rock stress and the seepage force are of great theoretical and engineering value.

Based on the earlier studies of Yan et al. [8, 9] taking the drainage segmental lining of a deep-buried circular TBM tunnel as a research object, this paper presents an elastic analytical solution for the external loading on the lining considering the effect of the seepage field on the stress field of surrounding rocks. On the basis of this solution, the relationship between the discharge flow and the external loading on the lining is discussed. Furthermore, the analytical solution is compared with a simplified solution in which the far-field loading is taken as a boundary force.

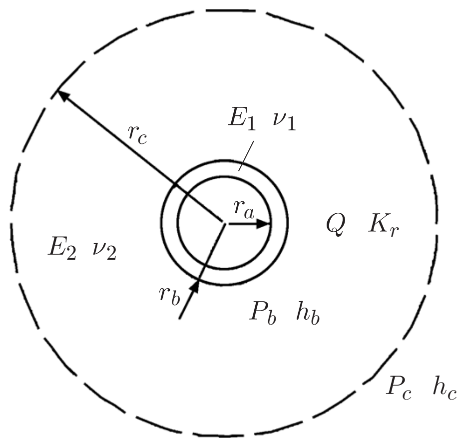

Fig. 2. Analytical model of the ground seepage field.

1. ANALYTICAL SOLUTION CONSIDERING THE SEEPAGE FORCE

1.1. Basic Assumptions

In order to derive an analytical solution for the proposed problem, the following assumptions are made.

1. Both the surrounding rocks and the lining remain homogeneous, isotropic, and elastic materials.

2. The plane strain condition is assumed at any cross section of the circular TBM tunnel, and the axisymmetric condition is considered, in which all quantities are independent of the angle θ in the plane polar coordinates. In this regard, the plane shearing stress $\tau_{r\theta}$, the strain $\gamma_{r\theta}$, as well as the circumferential displacement μ_θ are taken as zero.

3. The liquid (water) is incompressible, and Darcy's law is applicable. A steady state for the flow is assumed. In addition, the permeability coefficient of the surrounding rocks is assumed to be same in all directions, and the main seepage flow is along the radial direction.

4. The TBM tunnel is deep-buried so that the diameter of the circular tunnel is negligible as compared to the burial depth of the tunnel; thus, the contour of the water pressure around the lining can be regarded to be circularly axisymmetric.

5. The lining is assumed to be impermeable, and the water head inside the tunnel is zero.

1.2. Analytical Solution for the Seepage Force

As shown in Fig. 2, a calculation model was built to study the analytical solution of the seepage force in the surrounding rocks (r_a is the inner radius of the lining, r_b is the outer radius of the liner, r_c is the radius of the far field, which is the outer boundary of the problem, h_b and h_c are the water heads on the lining and on the boundary of the far field, respectively, Q is the drainage flow through the release holes, K_r is the permeability conductivity of the surrounding rocks, P_b is the effective stress on the interface between the lining and the rock masses, P_c is the effective stress on the outer boundary of the far field, E_1 and ν_1 are Young's elasticity modulus and Poisson's ratio of the segmental lining, and E_2 and ν_2 are Young's elasticity modulus and Poisson's ratio of the surrounding rocks).

For the axisymmetric problem of the steady seepage flow, the governing differential equation can be written as follows [15]:

$$\frac{\partial^2 H(r)}{\partial r^2} + \frac{1}{r}\frac{\partial H(r)}{\partial r} = 0; \tag{1}$$

$$Q(r)\Big|_{r=r_b} = Q, \qquad H(r)\Big|_{r=r_c} = h_c. \tag{2}$$

Thus, solving the governing differential equations (1) and (2), we can obtain

$$h_b = h_c + \frac{Q}{2\pi K_r} \operatorname{Ln}\Big(\frac{r_b}{r_c}\Big); \tag{3}$$

$$H(r) = h_c + \frac{Q}{2\pi K_r} \operatorname{Ln}\Big(\frac{r}{r_c}\Big). \tag{4}$$

Differentiating Eq. (4), we obtain

$$F_r = -\gamma_w \frac{d(\xi h)}{dr} = -\gamma_w \xi\Big(\frac{Q}{2\pi K_r}\frac{r_c}{r}\frac{1}{r_c}\Big) = -\frac{\gamma_w \xi Q}{2\pi K_r r}, \tag{5}$$

where F_r denotes the seepage body force, ξ is the effective coefficient of pore water pressure, and γ_w represents the unit weight of water.

1.3. Analytical Solution for Stresses and Displacements

Considering the seepage force as a body force, the equilibrium differential equation for the axisymmetric plane strain problem can be expressed as

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} - \frac{\gamma_w \xi Q}{2\pi K_r r} = 0, \tag{6}$$

where σ_r and σ_θ are the radial stress and the hoop stress of the rock masses. In this case, the relationships among the strains, displacements, and stresses are expressed as

$$\varepsilon_r = \frac{\partial U_r}{\partial r} = \frac{1}{E}(\sigma_r - \nu\sigma_\theta), \qquad \varepsilon_\theta = \frac{1}{r}\frac{\partial U_\theta}{\partial \theta} + \frac{U_r}{r} = \frac{1}{E}(\sigma_\theta - \nu\sigma_r).$$

The boundary conditions have the form

$$(\sigma_r)\Big|_{r=r_b} = -P_b, \qquad (\sigma_r)\Big|_{r=r_c} = -P_c. \tag{7}$$

The formulated boundary-value problem can be solved by using the Airy stress function method [16]. Thus, the radial displacement of the surrounding rocks on the outer surface of the lining $U_r\Big|_{r=r_b}$ is

$$U_r\Big|_{r=r_b} = \frac{-A_1 + A_2 r_c^2/r_b^2}{r_c^2/r_b^2 - 1} r_b + \frac{(A_1 - A_2) r_c^2}{(2\nu_2 - 1)(r_c^2/r_b^2 - 1)} \frac{1}{r_b} + \frac{(1+\nu_2)(1-2\nu_2)}{E_2(1-\nu_2)} \frac{\gamma_w \xi Q}{4\pi K_r} r_b \operatorname{Ln} r_b, \tag{8}$$

where

$$A_1 = \frac{(1+\nu_2)(1-2\nu_2)}{E_2}\Big[-\frac{\gamma_w \xi Q}{4\pi K_r}\Big(\frac{\operatorname{Ln} r_b}{1-\nu_2} + 1\Big) - P_b\Big],$$

$$A_2 = \frac{(1+\nu_2)(1-2\nu_2)}{E_2}\Big[-\frac{\gamma_w \xi Q}{4\pi K_r}\Big(\frac{\operatorname{Ln} r_c}{1-\nu_2} + 1\Big) - P_c\Big].$$

The displacement U_r is obviously related to Q, P_c, and unknown pressure P_b. For the lining structure, its displacement on the outer surface with a radial radius u_r denoted as $r = r_b$ can be obtained by using the calculation model of a thick-walled cylinder subject to the uniform axisymmetric external pressure (Fig. 3):

$$u_r\Big|_{r=r_b} = \frac{r_b}{E_1'(r_b^2 - r_a^2)}\Big[-r_b^2(1-\nu_1')q_b - r_a^2(1+\nu_1')q_b\Big]$$

$$= \frac{-r_b[r_b^2(1-\nu_1') + r_a^2(1+\nu_1')]}{E_1'(r_b^2 - r_a^2)}\Big[P_b + \gamma_w\Big(h_c - \frac{Q}{2\pi K_r}\operatorname{Ln}\frac{r_c}{r_b}\Big)\Big]. \tag{9}$$

Here $E_1' = E_1/(1-\nu_1^2)$ and $\nu_1' = \nu_1/(1-\nu_1)$.

Let us assume that the lining is in close contact with the surrounding rocks. In this case, we have

$$U_r\Big|_{r=r_b} = u_r\Big|_{r=r_b}. \tag{10}$$

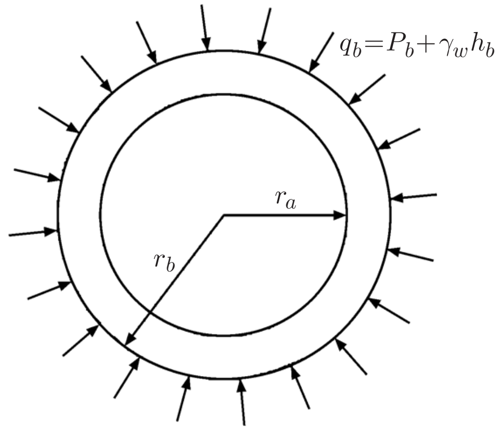

Fig. 3. Model of lining loading.

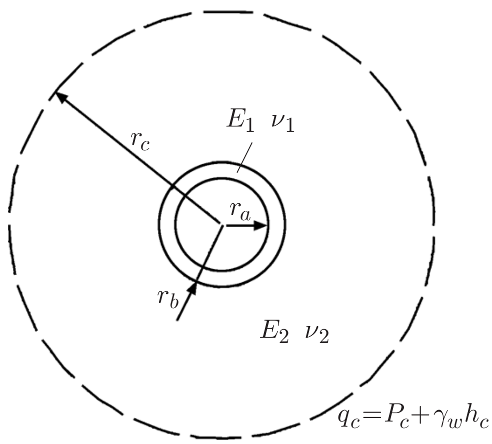

Fig. 4. Calculation model without consideration of the seepage force.

Substituting Eqs. (8) and (9) into equality (10), we obtain the expression for the effective stress on the interface between the surrounding rocks and the lining

$$P_b = \frac{K_1 + K_2K_3K_4 + K_5K_6 + K_7K_5K_8}{K_2K_3 - K_7K_5}, \tag{11}$$

where

$$K_1 = (2\nu_2 - 2)A_2r_c^2, \quad K_2 = r_c^2 - (2\nu_2 - 1)r_b^2, \quad K_3 = (1 + \nu_2)(1 - 2\nu_2)/E_2,$$

$$K_4 = -\frac{\gamma_w \xi Q}{4\pi K_r}\Big(\frac{\mathrm{Ln}\, r_b}{1 - \nu_2} + 1\Big), \quad K_5 = (2\nu_2 - 1)(r_c^2 - r_b^2), \quad K_6 = \frac{(1 + \nu_2)(1 - 2\nu_2)}{E_2(1 - \nu_2)}\,\frac{\gamma_w \xi Q}{4\pi K_r}\,\mathrm{Ln}\, r_b,$$

$$K_7 = \frac{[r_a^2 + r_b^2(1 - 2\nu_1)](1 + \nu_1)}{E_1(r_b^2 - r_a^2)}, \quad K_8 = \gamma_w h_c - \frac{\gamma_w Q}{2\pi K_r}\,\mathrm{Ln}\,\frac{r_c}{r_b}.$$

As is known, the radial contact stress on the interface between the surrounding rocks and the lining is equal to the effective stress plus the pore water pressure:

$$q_b = P_b + \gamma_w h_b. \tag{12}$$

2. SIMPLIFIED ANALYTICAL SOLUTION WITHOUT CONSIDERATION OF THE SEEPAGE FORCE

Without consideration of the seepage force in the rock masses, the proposed problem can be simplified as the calculation model of a thick-walled cylinder subject to the radial uniform pressure, in which the external stresses on the lining and the outer boundary of the far field, respectively, denoted as q_b and q_c, are regarded as surface forces (Fig. 4). It is assumed that there are no shear stresses between the contacts. Thus, the general solutions for the stress and displacement are expressed as

$$\sigma'_r = \frac{A'}{r^2} + 2D', \quad \sigma'_\theta = -\frac{A'}{r^2} + 2D', \quad u_r = \frac{1}{E'_1}\Big[-(1+\nu'_1)\frac{A'}{r} + 2(1-\nu'_1)D'r\Big],$$

where A' and D' are constants to be determined, σ'_r and σ'_θ are the radial stress and the hoop stress of the lining, and u_r denotes the radial displacement of the lining. In the plane strain problem, we have

$$E'_1 = E_1/(1-\nu_1^2), \qquad \nu'_1 = \nu_1/(1-\nu_1);$$

$$(\sigma'_r)\Big|_{r=r_b} = -q_b, \qquad (\sigma'_r)\Big|_{r=r_a} = 0. \tag{13}$$

Considering the boundary conditions (13), we obtain

$$A' = \frac{r_a^2 r_b^2 q_b}{r_b^2 - r_a^2}, \qquad D' = \frac{r_b^2 q_b}{2(r_a^2 - r_b^2)}.$$

For the surrounding rocks, the general solutions for the stress and displacement are expressed as

$$\sigma_r = A/r^2 + 2D, \qquad \sigma_\theta = -A/r^2 + 2D; \tag{14}$$

$$U_r = [-(1+\nu'_2)\,A/r + 2(1-\nu'_2)Dr]/E'_2,$$

where A and D are constants to be determined, σ_r and σ_θ are the radial stress and the hoop stress of the rock masses, and U_r denotes the displacement of the lining. The following relations are valid in the plane strain problem:

$$E'_2 = E_2/(1-\nu_2^2), \qquad \nu'_2 = \nu_2/(1-\nu_2).$$

The constants in Eqs. (14) are determined from the following boundary conditions:

$$(\sigma_r)\Big|_{r=r_c} = -q_c, \qquad (\sigma_r)\Big|_{r=r_b} = -q_b.$$

By considering the boundary conditions in Eqs. (14), we have

$$A = \frac{r_b^2 r_c^2 (q_b - q_c)}{r_b^2 - r_c^2}, \qquad D = \frac{r_c^2 q_c - r_b^2 q_b}{2(r_b^2 - r_c^2)}. \tag{15}$$

The following condition is valid at the interface between the surrounding rocks and the lining structure:

$$(U_r)\Big|_{r=r_b} = (u_r)\Big|_{r=r_b}.$$

Using this condition, we can determine the external stress on the outer surface of the lining

$$q_b = \frac{2dq_c r_c^2 N_3}{N_1 + dN_2N_3},$$

where

$$d = \frac{r_b^2 - r_a^2}{r_c^2 - r_b^2}, \quad N_1 = \frac{r_a^2 + r_b^2(1-2\nu_1)}{1-\nu_1}, \quad N_2 = \frac{r_c^2 + r_b^2(1-2\nu_2)}{1-\nu_2}, \quad N_3 = \frac{E_1}{1-\nu_1^2}\,\frac{1-\nu_2^2}{E_2}.$$

3. ANALYSIS AND DISCUSSION

Based on the above-proposed solutions, the relationships between the drainage capacity of the lining and the external total stress on the lining were further analyzed and discussed. The results were compared to the analytical solution without consideration of the seepage force. For the analysis and discussion of the results, a sample tunnel with the following geometrical, mechanical, and hydraulic parameters was considered: $r_a = 4.65$ m, $r_b = 5.05$ m, $r_c = 30.0$ m, $\nu_1 = 0.20$, $\nu_2 = 0.25$, $\xi = 1.0$, $E_1 = 33.5$ GPa, $E_2 = 16.0$ GPa, $\gamma_w = 10.0$ kN/m^3, and $P_c = 10.0$ MPa.

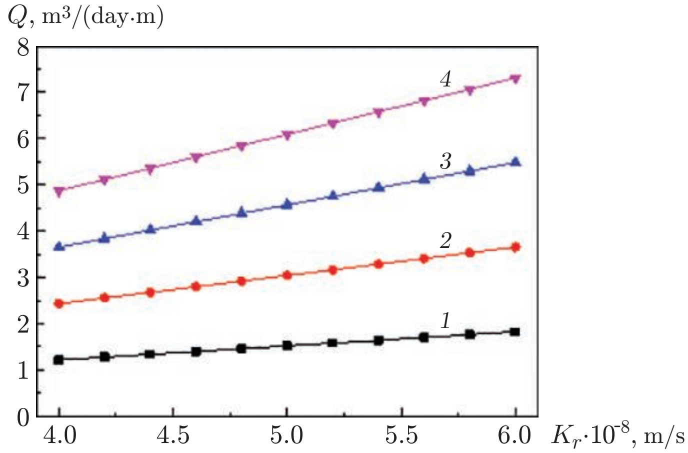

Fig. 5. Maximum allowable drainage flow versus the permeability coefficient of rock masses for different values of the far-field water head: $h_c = 100$ (*1*), 200 (*2*), 300 (*3*), and 400 m (*4*).

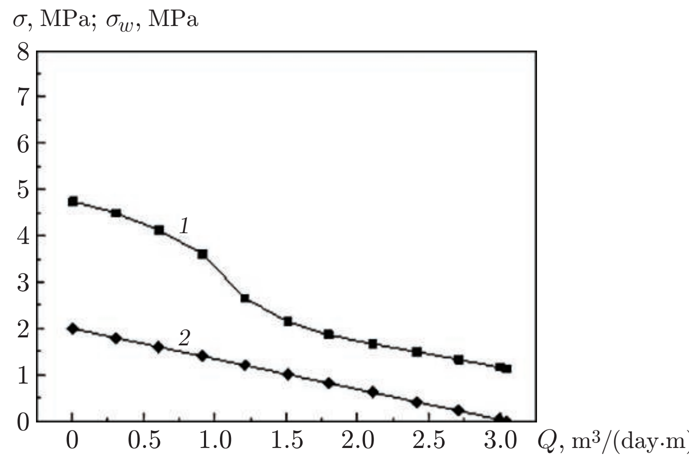

Fig. 6. Trends of the external stress σ (*1*) and water pressure on the lining σ_w (*2*) versus the controlled drainage flow.

3.1. Relationships between the Permeability Coefficient of Surrounding Rocks and the Maximum Allowable Drainage Flow

The maximum allowable drainage flow depends on the maximum water discharge capacity, which allows the water head to be reduced to the minimum at a certain drainage outlet in the tunnel. Obviously, the water discharge capacity of the segmental lining is related to the drainage flow velocity and the size of the drainage hole. The latter depends on the maximum allowable drainage flow. Based on Eq. (3), the relationships between the permeability coefficient of the rock masses and the maximum allowable drainage flow under the conditions of different far-field water heads ($h_c = 100$, 200, 300, and 400 m) were studied.

The calculated drainage flow Q is plotted in Fig. 5 as a function of the permeability coefficient K_r. The maximum allowable drainage flow increases linearly with the growth of the rock permeability coefficient for an unchanged far-field water head. For a constant permeability coefficient, the higher the far-field water head, the larger the maximum allowable drainage flow.

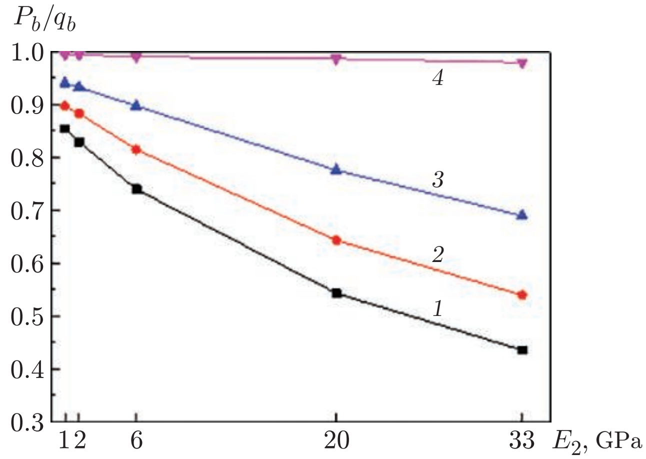

Fig. 7. Ratio P_b/q_b versus Young's modulus for different values of the drainage flow: $Q = 0$ (*1*), 1 (*2*), 2 (*3*), and 3 $m^3/(day \cdot m)$ (*4*).

3.2 Relationships between the External Stress on the Lining and the Drainage Flow

As is known, drainage outlets can reduce the external stress on the lining, which consists of the water pressure as well as the ground effective stress on the lining considering the effect of the seepage force. Based on Eqs. (11) and (12), the relationships between the external total stress on the lining and the drainage flow (ranging from zero to the maximum allowable drainage flow) were analyzed in the case with $K_r = 5 \cdot 10^{-8}$ m/s and $h_c = 200$ m. Figure 6 depicts the trends of the external total loading and the water pressure on the lining with the controlled drainage flow. As can be seen from the figure, with an increase in the controlled drainage flow, the water pressure decreases linearly, while the external total stress shows a nonlinear decreasing tendency. As the controlled drainage flow Q increases from 0 to 1.25 $m^3/(day \cdot m)$, the external stress decreases sharply with a growing decrement rate. At 1.25 $m^3/(day \cdot m) < Q <$ 1.50 $m^3/(day \cdot m)$, the decrement rate slightly decreases before it finally levels off. On this occasion, the trend of the external stress shows a similar linear tendency to that of the water pressure, which further illustrates that the effective stress basically remains constant at $Q > 1.5$ $m^3/(day \cdot m)$.

3.3. Effect of the Rock Mass Condition on the Effective Stress and Contact Stress on the Lining

Figure 7 shows the ratio of the effective stress to the external total stress on the lining P_b/q_b as a function of Young's elasticity modulus of the rock masses for different values of the drainage flow Q. The dependences are obtained by using Eqs. (11) and (12) of the elastic problem with $K_r = 5 \cdot 10^{-8}$ m/s and $h_c = 200$ m. It is seen in Fig. 7 that the ratio P_b/q_b significantly depends on Young's modulus of the rock masses. For a fixed value of Young's modulus, the ratio P_b/q_b decreases as the drainage flow is enhanced. With an increase in the modulus of elasticity of the rock masses, there is a downward trend of the ratio P_b/q_b. Moreover, the smaller the controlled drainage flow, the sharper the decreasing trend. Thus, the effective stress of the rock masses acting on the lining accounts for a smaller percentage of the total stress at high values of Young's modulus of elasticity.

3.4. Effect of the Seepage Force on the External Loading on the Lining

To analyze the effect of the seepage field on the external loading acting on the lining, the results obtained from the elastic analytical solution considering the seepage force [Eqs. (11) and (12) denoted as solution 1)] were compared to that derived from the simplified solution without consideration of the seepage force [Eqs. (15) denoted

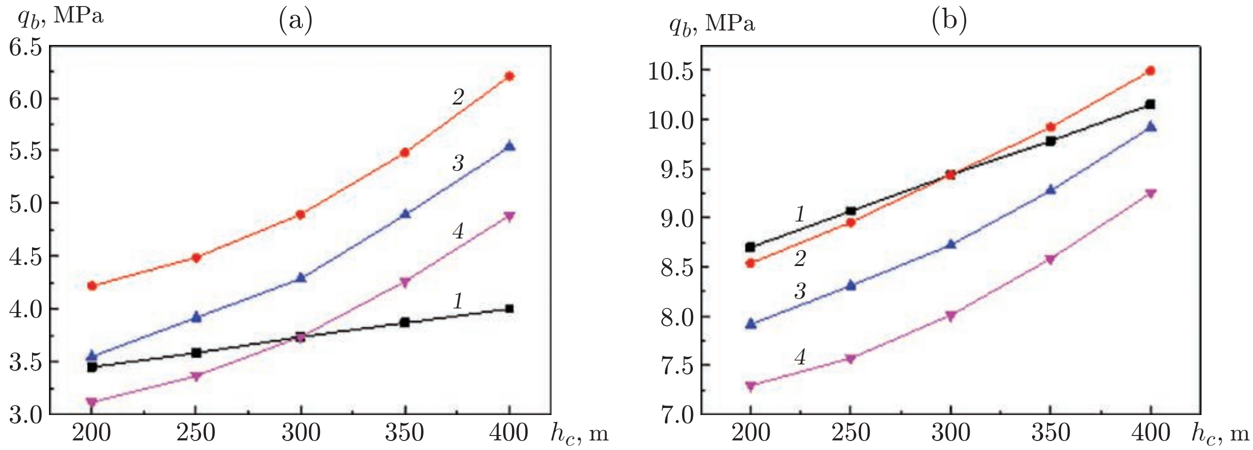

Fig. 8. External stress versus the far-field water head for $E_2 = 16$ (a) and 4 GPa (b); curve *1* refers to solution 1 calculated at $Q = 0$, and curves *2*–*4* refer to solution 2 calculated at $Q = 1$ (*2*), 2 (*3*), and 3 $m^3/(day \cdot m)$ (*4*).

as solution 2]. The solutions were obtained based on the following parameters: $K_r = 5 \cdot 10^{-8}$ m/s, $E_2 = 16$ and 4 GPa, and $Q = 1$, 2, and 3 $m^3/(day \cdot m)$. Figure 8 shows the external stress curves calculated by the two different solutions with the variation of the far-field water head. According to the figures, the external stress on the lining derived from solution 1 increases linearly with an increase in the far-field water head, while the external stress obtained from solution 2 goes up sharply with an increasing growth rate. It is found from Fig. 8a that the simplified solution without consideration of the seepage force largely underestimates the external stress as compared to the results obtained from the solution considering the seepage force, especially in the situation where the controlled drainage flow is relatively small. The result obtained from solution 1 can be almost twice as large as that obtained from solution 2 in the case with $E_2 = 16$ GPa, $Q = 1$ $m^3/(day \cdot m)$, and $h_c = 400$ m. As is shown in Fig. 8b, when the rock elastic modulus is smaller (in this case, $E_2 = 4$ GPa), the results obtained from solution 2 are much greater than those obtained from solution 1. The larger the drainage flow, the greater the difference between the results calculated by these two different solutions.

CONCLUSIONS

In order to better calculate the external stress on the lining in the TBM tunnel, based on the elastic theory as well as the theory of the seepage flow, this paper proposes a new analytical solution considering the effect of the seepage force. Based on this solution, the relationships between the permeability coefficient of the rock masses and the maximum allowable drainage flow were studied. In addition, the influence of the controlled drainage flow and Young's elasticity modulus of the surrounding rocks on the external stress acting on the lining were discussed. The results obtained from the solution considering the seepage force were compared with those obtained from the solution without consideration of the seepage force.

The main conclusions can be summarized as follows.

The maximum allowable drainage flow shows a linear upward trend with the growth of the rock permeability coefficient. The higher the far-field water head, the larger the maximum allowable drainage flow.

The external total stress on the lining drops dramatically with a change in the controlled drainage flow from 0 to 1.25 $m^3/(day \cdot m)$. Then the rate of decreasing gradually slows down and levels off when the drainage flow is larger than 1.5 $m^3/(day \cdot m)$. The decreasing trend of the external stress shows a similar linear tendency to that of the water pressure. This trend leads us to the conclusion that the variation of the controlled drainage flow has a large impact on the calculated results of the external stress when the drainage flow is relatively small. However, when the drainage flow is large enough, it has a very limited effect on the effective stress of the surrounding rocks.

With an increase in Young's modulus of the rock masses, there is a downward trend of the ratio P_b/q_b; the smaller the controlled drainage flow, the sharper this trend. Based on the elastic solution derived in this paper, it can be indicated that the geological conditions have a considerable impact on the ratio P_b/q_b. The higher Young's modulus of the surrounding rocks, the lower the ratio P_b/q_b.

Whether to consider the effect of the seepage force or not greatly affects the calculated external total stress value. The simplified solution without consideration of the seepage force may largely underestimate or overestimate the external stress compared to the results obtained from the solution considering the seepage force. The comparisons show that the elastic solution considering the effect of the seepage force in this paper provides relatively satisfactory results.

The research was supported by the National Natural Science Foundation of China (Grant No. 51678500). The authors also gratefully acknowledge the financial support provided by the China Railways Corporation (Grant No. 2014G004-H).

REFERENCES

1. J. X. Wang, B. Feng, L. S. Hu, et al., "Model Test of the Tunnel Subjected to High Water Pressure in Jinping Second Cascade Hydropower Station, China," Sci. China Technol. Sci. **54** (1), 192–198 (2011).
2. H. Aj, "Report on the Damaging Effects of Water on Tunnels during Their Working Life," Tunnell. Underground Space Technol. **6** (1), 11–76 (1991).
3. P. Lunardi and A. Focaracci, "Action to Reduce the Hydrogeological Impact Produced by Underground Works," in *Progress in Tunnelling after 2000, Proc. of the AITES-ITA 2001 World Tunnel Congress, Milan (Italy), 10–13 June 2001* (Sci. Committee, 2001), pp. 509–515.
4. J. H. Shin, D. M. Potts, and L. Zdravkovic, "The Effect of Pore-Water Pressure on NATM Tunnel Linings in Decomposed," Canad. Geotech. J. **42** (6), 1585–1599 (2005).
5. Y. Huang, Z. Fu, J. Chen, et al., "The External Water Pressure on a Deep Buried Tunnel in Fractured Rock," Tunnell. Underground Space Technol. **48**, 58–66 (2015).
6. S. R. Doran, D. J. Hartwell, N. Kofoed, and S. Warren, "Storebaelt Eastern Railway Tunnel-Denmark: Design of Cross Passage Ground Treatment," in *Proc. of the 11th Europ. Conf. on Soil Mechanics and Foundation Engineering, Copenhagen (Denmark), May 28 to June 1, 1995* (Danish Geotech. Soc., Copenhagen, 1995).
7. H. S. Shin, D. J. Youn, S. E. Chae, and J. H. Shin, "Effective Control of Pore Water Pressures on Tunnel Linings Using Pin-Hole Drain Method," Tunnell. Underground Space Technol. **24** (5), 555–561 (2009).
8. Q, Yan, Z. Meng, and C. Xi, "Study of Model Test for Water Pressure Distribution Character behind Drainage Segment Lining," Chinese J. Rock Mech. Eng. **32** (S1) 2617–2623 (2013) (in Chinese).
9. Q. X. Yan, X. Cheng, J. Zheng, and C. He, "Analysis on Fluid-Structure Interaction of Drainage Segment Lining under Different Drainage Schemes," J. China Railway Soc. **34** (6), 95–100 (2012) (in Chinese).
10. M. E. Harr, *Groundwater and Seepage* (McGraw-Hill, New York, 1962), pp. 249–255.
11. A. Bobet, "Effect of Pore Water Pressure on Tunnel Support during Static and Seismic Loading," Tunnell. Underground Space Technol. **18** (4), 377–393 (2003).
12. M. E. Tani, "Circular Tunnel in a Semi-Infinite Aquifer," Tunnell. Underground Space Technol. **18** (1), 49–55 (2003).
13. K. H. Park, A. Owatsiriwong, and J. G. Lee, "Analytical Solution for Steady-State Groundwater Inflow into a Drained Circular Tunnel in a Semi-Infinite Aquifer: A Revisit," Tunnell. Underground Space Technol. **23** (2), 206–209 (2008).
14. E. T. Brown, J. W. Bray, B. Ladanyi, and E. Hoek, "Ground Response Curves for Rock Tunnels," J. Geotech. Eng. **109** (1), 15–39 (1983).
15. J. Bear, *Dynamics of Fluids in Porous Media* (Dover, New York, 1988), pp. 222–235.
16. J. Wu, *Elasticity* (Higher Educat. Press, Beijing, 2001), pp. 151–159 (in Chinese).