Mechanical Characteristic and Length Optimization of System Anchor in Loess Tunnel Based on Field Measurement and Analytical Solution

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In this paper, field measurement is used to obtain the force of system anchor in its actual working condition and stress situation of system anchors in different parts of loess tunnel is analyzed based on field test results, indicating the reasons why values of measured axial force of system anchor are different in different parts of loess tunnel. Based on the displacement solution of Mindlin problem, this paper deduces the analytical solution to stress distribution of system anchors in the sidewall of loess tunnel under the pull-out force, analyzes the distribution forms and influencing factors of shear stress and axial force. At the same time, analytical solutions to system anchor stress and surrounding rock plastic zone radius are tentatively applied to the analysis of stress characteristics and length optimization of system anchor in loess tunnel. The research results are of great significance to understand the mechanical characteristics of anchors in loess tunnel and to optimize the design of anchors in the primary support system of loess tunnel, which leads to accelerated construction progress and low economically cost, especially in loess tunnels with large cross section and long span.

1. Introduction

China has the largest areas of loess, about 640000 square kilometers, in the world. The loess is mainly distributed in the provinces of Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, and the northwest of Henan. With the implementation of China’s Western Development Strategy and the Belt and the Road Strategic Plan, more and more high-speed railways and expressways have been or will be built in loess areas to stimulate economic potential and meet the needs of rapid increase of traffic volume [1–3].

Restricted by topography and geological conditions, more and more loess tunnels with large cross section and large-span have been or will be inevitably built in such regions. System anchor is the most common support type in loess tunnel construction, which can offer a kind of flexible support force, adjust the stress state of surrounding rock, and ultimately make good use of self-bearing capacity [4–7]. So, it is an important part of the primary support system in loess tunnel, and rationality of system anchor parameter design will directly affect the construction period and cost. Engineering practices show that the anchor has good applicability and can achieve good supporting effect in hard rock and soft rock [8–10].

However, low strength of loess, poor stability of large-span and large cross-section tunnel excavation, and large deformation of surrounding rock make the anchor design encounter key problems. Design and construction of loess tunnel and effect of system anchor in loess tunnel have been deeply studied in the last decades. Combined with a large-section shallow buried loess tunnel, scholars studied the effect of system anchor but did not deeply analyze the reasons why the arch system anchor was in the state of compression and its value of axial force was small, and why
the sidewall anchor was in the state of tension and its value of axial force was large [11]. Many experts and scholars have done a lot of research on mechanical characteristics of system anchor and its setting problems by means of numerical analysis, similar model test, and field measurement, which has played a positive role in promoting the understanding of its mechanical characteristics [12–18]. However, it is rare, from the perspective of theoretical analysis, to analyze the mechanical characteristics of system anchors in loess tunnel under the pull-out force [19–35]. Shear stress distribution and axial force distribution of system anchor obtained from the pull-out test are different from those obtained from the field tunnel system anchor in its actual working condition.

Based on axial force of full-length adhesive anchor measured in monitoring measurement of the rock highway tunnel, relationship between the maximum axial force of the anchor and radius of plastic zone and radius of loose zone of the surrounding rock is derived, but optimization of anchor length parameters has not been further studied. Many experts and scholars have analyzed mechanical characteristics of full-length adhesive anchors in rock tunnels and loess tunnels, but there is a lack of research on optimization of anchor length parameters based on the mechanical characteristics.

Taking into account previous research on the vertical pressure and horizontal pressure mode of surrounding rock, this paper, from the perspective of stress of system anchor, analyzed the reasons for the large difference of stress of system anchor in different parts of the Hejiazhuang loess tunnel located on Zhengzhou-Xi'an Passenger Dedicated Line. Based on the measured ultimate pull-out force of the anchor in the sidewall of the Longwangmiao loess tunnel in Kelan-Linxian expressway, mechanical characteristics of anchor under the pull-out force are analyzed from the perspective of theoretical analysis, and distribution forms of shear stress and axial force of system anchor are discussed under different soil properties. In addition, this paper attempts to analyze the optimization of anchor length parameters in loess tunnel based on the theoretical solution from two aspects of mechanical characteristics under the pull-out force and axial force measured at the neutral point of system anchor.

2. Project Profiles

Case 1. The Hejiazhuang tunnel, located in Sannmenxia City, Henan Province, is a large-section loess tunnel on Zhengzhou-Xi'an Passenger Dedicated Line. It is located in the loess tableland area with a buried depth of about 35 m, a total length of 1815 m, an excavation span of more than 15 m, and an excavation area of 170 m². The terrain on top of the tunnel is flat. The stratum passing through by the tunnel is mainly clayey loess (Q2), of which the structure is compact and the thickness is more than 30 m.

According to the geotechnical investigation report of the Hejiazhuang tunnel, the soil mechanical parameters used in the calculation and analysis are as follows: elastic modulus \( E = 120 \text{ MPa} \), Poisson’s ratio \( \mu = 0.3 \), density \( \rho = 1740 \text{ kg/m}^3 \), cohesion \( c = 80 \text{ kPa} \), and internal friction angle \( \phi = 24^\circ \). The adopted system anchor for the arch parts is \( \varphi \alpha_{22} \) with the length of 2.5 m, and for the sidewall parts is \( \varphi \alpha_{22} \) with the length of 3.5 m. The spacing of anchor is 1 m (circumferential) \( \times 1 \text{ m} \) (longitudinal). Construction sequences of the Hejiazhuang tunnel are shown in Figure 1, and site construction of the Hejiazhuang tunnel is shown in Figure 2.

Case 2. The Longwangmiao loess tunnel, as shown in Figure 3, is designed as a short tunnel with small clear distance between the left and right tunnel and located in Kelan-Linxian expressway. The right tunnel starts at K112 + 989 and ends at K113 + 248, with a total length of 259 m and a maximum buried depth of 57.7 m, while the left tunnel starts at ZK112 + 984 and ends at ZK113 + 258, with a total length of 274 m and a maximum buried depth of 64.3 m. Design of the tunnel is based on the speed of 80 km/h, with a clear width of 10.25 m and a clear height of 5 m. The designed excavation radius of the arch ring is 15.64 m. According to geological investigation report of the tunnel, the surrounding rock of the tunnel is grade V, which is composed of the tertiary Pliocene jingle formation silty clay and the Quaternary Pliocene Malan formation silt. The surrounding rock conditions of the tunnel face are shown in Figure 4. Elastic modulus of the loess soil and system anchor is 150 MPa and 210 GPa, respectively, Poisson’s ratio \( \mu \) is 0.3, diameter of system anchor A is 25 mm, and diameter of system anchor B is 22 mm. Length of system anchor is 3 m, and spacing of the anchor is 0.5 m (circumferential) \( \times 0.5 \text{ m} \) (longitudinal).

3. Monitoring of System Anchor Axial Force

3.1. Layout of Field Measuring Points and Daily Monitoring.

In the engineering and academic circles, the supporting effect of system anchor in loess tunnel has always been the focus of debate. Some scholars believe that system anchor has no effect on the stability of loess tunnel, so it can be cancelled; however, others insist that it plays a key role in the stability of loess tunnel and that it should be set. In order to further verify effect of system anchor in loess tunnel support, anchor axial force sensors are, respectively, set at the arch vault, haunch, and sidewall in DK243 + 009 section and DK243 + 897 section of the Hejiazhuang tunnel on Zhengzhou-Xi'an Passenger Dedicated Line. The schematic diagram of measuring points at different parts of the tunnel is shown in Figure 5. Field splicing and installation of anchor axial force sensor is shown in Figure 6. Field test line protection and daily monitoring axial force of system anchor is shown in Figure 7. The stable values measured for each system anchor are shown in Table 1.

3.2. Analysis of the Measured Results.

It can be seen from Table 1 that the arch anchors are under tension and compression, but most of them are under compression and the value is small, which indicates that the effect of the arch system anchor is not obvious, while most of the sidewall anchor is under tension and the value is large, which
illustrates that the effect of the sidewall anchor is drastically significant. Values of the measured points in Table 1 also show that the maximum axial force of each anchor is located at the measuring point near the free face of tunnel.

4. Reasons for the Difference of Axial Force of System Anchor

4.1. Distribution of Surrounding Rock Pressure. Wang et al. studied the calculation method of surrounding rock pressure of large cross-section loess tunnel and pointed out that the following two models can be used for the calculation of surrounding rock pressure in the vertical direction [31]. Considering that the pressure is symmetrical to the center line of the tunnel, when the pressure at the vault is \( q \), the pressure at 30° on the left and right sides of the tunnel is \( 1.5q \sim 2.0q \), and the pressure at 60°~90° on the left and right sides of the tunnel is \( 0.75q \). Assuming that distribution of the pressure is linear, the pressure distribution pattern is peak type as in Figure 8, (a) Mode 1. The measured surrounding rock pressure shows that its distribution is not uniform, but the difference is small. Theoretically, it can be considered as uniform pressure distribution as in Figure 8, (b) Mode 2.

The distribution model, as shown in Figure 9, can be used to calculate the pressure of surrounding rock in horizontal direction of the cross-section loess tunnel. Horizontal pressure at the arch vault is \( e \), and it increases linearly from the arch vault to the arch foot. Pressure at the arch foot reaches \( 1.5e \sim 2.0e \), while the pressure remains \( 1.5e \sim 2.0e \) from the arch foot to the wall foot, which are different from that in Specifications for Design of Highway Tunnels Section1 Civil Engineering (JTG 3370.1-2018).

4.2. Analysis of Axial Force Difference of System Anchor. Combined with the numerical simulation results of the Hejiazhuang tunnel, Boltzmann function is used to fit the radial displacement of arch and sidewall at different depths.

The fitting function of arch vault is as follows:

\[
u = 67.231 + \frac{10.261}{1 + \exp((x - 6.482)/2.077)}
\]

(1)

The fitting function of sidewall is as follows:
After the excavation of the shallow buried loess tunnel, the surrounding rock has a large deformation due to its low self-bearing capacity. Although the displacement patterns of vault and sidewall both conform to the law of inverse exponential function, the degree of attenuation to the depth of surrounding rock is different. The displacement of the surrounding rock at the arch decreases gently along the depth direction, and the gradient is very small; that is to say, the surrounding rock at the arch within a certain depth range has the trend of overall subsidence, while the displacement of the surrounding rock at the sidewall decreases rapidly along the depth direction, and the gradient is very large; that is to say, the surrounding rock at the sidewall does not move as a whole. The relative displacement of the sidewall anchor for the surrounding rock is greater than that of the vault anchor for the surrounding rock, and the shear force of the sidewall anchor is greater than that of the vault.

\[
u = -11.665 + \frac{79.122}{1 + \exp\left((x - 1.342)/1.113\right)}
\]  

Figure 5: Schematic diagram of system anchor and measuring points. (a) System anchor measuring points in different parts of the tunnel. (b) Distance between measuring points.

Figure 6: Field splicing and installation of anchor axial force sensor. (a) Field splicing. (b) Field installation.
anchor, so the axial force of the sidewall anchor is greater than that of the vault anchor. Therefore, different soil displacement patterns and horizontal pressure distribution are the reasons for the great differences in the axial forces of arch and sidewall anchors.

5. Analytical Solution to Shear Stress Distribution and Radius of Plastic Zone

5.1. Analytical Solution to Shear Stress Distribution in System Anchor. The soil around the anchor can be regarded as a semi-infinite plane. If a concentrated force $Q$, as in Figure 10, is applied at the depth $h$, the vertical displacement $\omega$ at point $B (x, y, z)$ can be determined by Mindlin’s displacement solution:

$$\omega = \frac{Q (1 + \mu)}{8\pi E (1 - \mu)} \left[ \frac{3 - 4\mu}{R_1^3} + \frac{(z - h)^2}{R_1^4} + \frac{8(1 - \mu)^2}{R_2^3} + \frac{(3 - 4\mu)(z + h)^2 - 2hz}{R_2^4} + \frac{6hz(z + h)^2}{R_2^5} \right],$$

(3)

where $E$ and $\mu$ are the Elastic modulus and Poisson’s ratio of soil, respectively:

$$R_1 = \sqrt{x^2 + y^2 + (z - h)^2};$$
$$R_2 = \sqrt{x^2 + y^2 + (z + h)^2}.$$

At the orifice of system anchor, due to $x = y = z = 0$, formula (3) can be simplified as follows:

$$\omega = \frac{Q(1 + \mu)(3 - 2\mu)}{2\pi Eh}.$$  

(5)

Assuming that the anchor embedded in the soil is semi-infinite and that the deformation between the anchor and the bonding material is in an elastic state, then the displacement of the soil at the orifice of system anchor is equal to the total elongation of the anchor:

$$\int_0^\infty \frac{(3 - 2\mu)\alpha}{2G} \frac{\tau}{z} dz = \int_0^\infty \frac{1}{E_a A} (Q - 2na) \int \frac{1}{\rho} r dz dz,$$

(6)

where $\alpha$ is the radius of system anchor, $G$ is the shear modulus of soil, $E_a$ is the elastic modulus of system anchor, $A$ is the cross-sectional area of system anchor, and $\tau$ is the shear stress.
After appropriate simplification, equation (6) can be reduced to a second-order homogeneous ordinary differential equation with variable coefficients as follows:

\[ \tau'' + k z \tau' + 2k \tau = 0, \quad (7) \]

\[ k = \frac{4\pi G}{(3 - 2\mu)E_aA} \quad (8) \]

The ordinary differential equation (7) can be transformed into Weber's equation. Considering the boundary conditions \( \tau|_{z=\infty} = 0 \), the analytical formula of shear stress distribution along the anchor body under the pull-out force can be obtained as the following formula:

\[ \tau = \frac{P}{\pi a} \left( \frac{1}{2} tz \right) \exp \left( \frac{-1}{2} tz^2 \right), \quad (9) \]

where \( P \) is the pull-out force at the orifice of system anchor, and \( t = (1/(1+\mu)(3 - 2\mu)a^2)(E/E_a) \).

Then, by integrating formula (9), the analytical expression of axial force distribution along the anchor body under the pull-out force can be obtained as the following formula:

\[ N = P \exp \left( \frac{-1}{2} tz^2 \right). \quad (10) \]

5.2. Analytical Solution to the Radius of Plastic Zone. Figure 11 shows the cross section of a circular tunnel. To simplify the calculation, it is assumed that the surrounding rock is elastic-plastic homogeneous, so it is an axisymmetrical plane strain problem.

Combined with the stress boundary conditions of the interface between the support and surrounding rock, when the support resistance is \( p_i \), the stress in the plastic zone can be obtained from the equilibrium equation and plastic equation of the plastic zone:

\[ \sigma^p_r = (p_i + C \cot \phi) \left( \frac{r}{r_0} \right)^{2\sinh(1 - \sin \phi)} - C \cot \phi, \]

\[ \sigma^p_\theta = (p_i + C \cot \phi) \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right) \left( \frac{r}{r_0} \right)^{2\sinh(1 - \sin \phi)} - C \cot \phi. \quad (11) \]

Then, the stress difference \( \sigma^p_\theta - \sigma^p_r \) on the elastoplastic interface is as follows:

\[ M = (p_i + C \cot \phi) \left( \frac{2 \sin \phi}{1 - \sin \phi} \right) \left( \frac{R_0}{r_0} \right)^{2\sinh(1 - \sin \phi)}. \quad (12) \]

Assuming that the surrounding rock and the anchor deform together, maximum axial force of the anchor can be expressed as in the following formula:

\[ N_{\text{max}} = \frac{k}{2} \left( \frac{M(R_0^2 - r_0^2)}{4G} \right) E_aA \left( \frac{1}{r_0^2} - \frac{1}{r_c^2} \right). \quad (13) \]

By substituting equation (12) into (13), the radius formula of plastic zone after support can be obtained as follows:

\[ R_0^2 = \left( \frac{A_R}{t(p_i + C_1 \cot \phi)} \right)^{1/(1+\mu)} \quad (14) \]
6. Pull-Out Force Test and Influencing Factors

6.1. Pull-Out Force Test of System Anchor. The pull-out test of the anchor is a test to check the anchoring effect, and the pull-out force is the maximum tension of system anchor.

Anchoring effect is affected by the strength of surrounding rock, the state of hole wall, and the anchoring method. It is particularly important to carry out the pull-out bearing capacity test of the anchor in the construction of loess tunnel. The test device is shown in Figure 12.

6.1.1. Pull-Out Equipment. Equipment commonly used for the system anchor pull-out force test is hydraulic jack, manual hydraulic pump, oil pressure gauge, and dial indicator.

6.1.2. Test Method. The designed hole depth is adopted in the sidewall of loess tunnel with grade V surrounding rock, and the anchor to be tested is appropriately lengthened to ensure that the hydraulic jack and anchor are concentric and to avoid eccentric tension. After the test anchor is installed normally, the hole opening is smoothed with mortar to facilitate the installation of bearing plate. Then, pressurize evenly by manual hydraulic pump (10 kN/min). The pull-out force of the anchor is calculated according to the piston area.

6.2. Pull-Out Force Influencing Factors. The pull-out force of system anchor in loess tunnel is related to the strength of anchor body, the cohesion between anchor body and mortar, and the cohesion between mortar anchor and surrounding soil. When system anchor of the sidewall is damaged, the anchor body is not affected in fact. The strength between the mortar anchor and the surrounding soil directly affects the effect of the system anchor. So, it should pay special attention to the construction quality, strengthen the anchoring strength between the anchor body and the surrounding soil, and improve the pull-out force of the system anchor. For the Longwangmiao tunnel, pull-out tests of system anchor A and B at the sidewall are carried out. The relevant test results are shown in Figure 13.

The theoretical results show the following:

(1) At the orifice, shear stress of anchor A and B is 0, and shear stress inside the orifice increases sharply. The maximum shear stress of anchor A is 501 kPa at 103 cm, then decreases gradually, and the shear stress decreases to 0 at 460 cm. At the depth of 73 cm, shear stress of anchor B reaches the maximum value of 790.401 kPa, and it gradually decreases to 0 at the depth of 440 cm.

(2) When the pull-out force of the anchor reaches a certain value, the shear stress near the orifice first exceeds the elastic limit of the bonding material and enters the plastic flow state.

(3) The axial force of the anchor is the largest at the orifice and then decreases along the depth direction. At the depth of 200 cm, the axial force of anchor A is only 0.46 kN. The axial force of anchor B is only 1.488 kN at the depth of 200 cm and 0.013 kN at the depth of 300 cm.

The attenuation rate of axial force of system anchor in loess tunnel is less than that of shear stress. The axial force of the system anchor at the depth of 200 cm in the V-grade surrounding rock is very small and basically cannot play its desired effect. Therefore, based on the field measured pull-out force of the system anchor in loess tunnel, the stress characteristics of the system anchor can be mastered, and the design length of system anchor in loess tunnel can be optimized on the basis of its axial force distribution.

6.3. Relationship between Stress Distribution of Anchor Body and $E/E_a$. It can be seen from analytical formula (8) that shear stress of the system anchor is directly proportional to the pull-out force of the anchor. The larger the pull-out force is, the larger the shear stress of the anchor body will be, but distribution form of the shear stress is the same.

In addition, the magnitude and distribution of shear stress and axial force under the pull-out force are also affected by $E/E_a$.

Figure 14 describes the relationship between $E/E_a$ and distribution of shear stress and axial force of the anchor.

It can be seen from Figure 14 that the smaller the $E/E_a$ value is, (that is to say, the softer the soil is) the smaller the maximum shear stress of the anchor 0069 s, but the more uniform the shear stress distribution is and the larger the range is, the slower the axial force of the anchor body decays along the length of the anchor. The larger the $E/E_a$ value is, (that is to say, the harder the soil is) the greater the maximum shear stress of the anchor is, the more concentrated the shear stress distribution is, and the smaller the range is,
and the faster the axial force of the anchor body decays along the length of the anchor. At the same time, it also shows that the setting of system anchor can follow the principle of “short and dense” in the tunnel constructed in the surrounding rock with relatively good geological conditions.

7. Optimization Analysis of Anchor Length under the Measured Axial Force

Taking the system anchor at a certain section of the Longwangmiao tunnel as the research object, $r = 18.64$ m and the measured displacement of tunnel wall is $4.2$ mm before anchoring. According to the geotechnical investigation report, the Elastic modulus and Poisson’s ratio of loess in grade V surrounding rock are determined, respectively, $E = 150$ MPa, $\mu = 0.3$. In order to accurately measure the cohesion and internal friction angle of soil, the undisturbed soil is taken as the test object, and three groups of tests with confining pressures of 50 kPa, 100 kPa, and 200 kPa are carried out by using TSZ-3 strain controlled triaxial apparatus, as shown in Figure 15, and the values of $c$ and $\phi$ are determined, respectively, $c = 91.81$ kPa, $\phi = 35.24^\circ$. Soil samples after the indoor experiment are shown in Figure 16. The earth pressure box embedded in the tunnel

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**Figure 12:** Device of pull-out test for the anchor.

**Figure 13:** Distribution curve of system anchor A and B. (a) Distribution curve of shear stress for system anchor A and B. (b) Distribution curve of axial force.
construction site is shown in Figure 17, and the field measurement shows that the pressure is 112.76 kPa between shotcrete and surrounding rock at the section.

P1/P2/P3/P4 are four monitoring points arranged in the full length of the anchor body to monitor the anchor axial force. P1 is near the free side of the tunnel, and P4 is near the inner side of the surrounding rock. The distance between monitoring points is shown in Figure 18. P2 is the neutral point of the anchor. According to the field measurement, the maximum axial force at P2 is 11.68 kN.

The radius of plastic zone of surrounding rock calculated by formula (14) is 17.51 m, which is less than the value of the sum of arch excavation radius (15.64 m) and designed system anchor length (3 m). The calculation shows that it is feasible to adopt the system anchor with the length of 3 m. However, \( R_0 - r_0 = 1.87 \) m, and this value is much smaller than the original designed anchor length, which indicates
that there is an optimization space on the length of system anchor. According to the calculation and analysis above, the length of the system anchor can be optimized to the suggested length 2 m.

8. Conclusions

Based on the field test results, this paper analyzes the stress situation of system anchors in different parts of loess tunnel, and based on the displacement solution of Mindlin problem, this paper deduces the elastic solution to the stress distribution of system anchors in the sidewall of loess tunnel under the pull-out force, analyzes the distribution forms and influencing factors of shear stress and axial force. At the same time, the theoretical solution to system anchor stress and the theoretical solution to radius of plastic zone of the surrounding rock are applied to the analysis of stress characteristics and length optimization of system anchor in loess tunnel. The following conclusions can be drawn:

(1) The vertical component of surrounding rock pressure at the arch is small, and the whole settlement movement of surrounding rock at the arch occurs within a certain depth range, and the radial displacement attenuation is gentle, which are the reasons why stress of the anchor is small in the arch of loess tunnel.

(2) The horizontal component of the surrounding rock pressure at the sidewall is not small, and in a certain depth range, the whole radial displacement of the surrounding rock of the sidewall does not occur, and the radial displacement decays rapidly, so that the tensile force of the anchor at the sidewall is larger.

(3) Under the pull-out force, the maximum shear stress of the system anchor appears in a certain position within the orifice, and the attenuation rate of the axial force is less than that of the shear stress. Based on the axial force distribution of the anchor, the design length of the anchor can be optimized. So, during the construction, attention should be paid to the construction quality of the system anchor to achieve the ideal anchoring effect.

(4) The magnitude and distribution form of shear stress and axial force of system anchor body are related to soil properties. The harder the soil is, the larger the shear stress value is, the denser the distribution is, and the faster the axial force decays along the anchor length; while the softer the soil is, the smaller the shear stress value is, the more uniform the distribution is, and the slower the axial force decays along the anchor length.

(5) The axial force attenuation rate of the system anchor is less than the shear stress attenuation rate under the pull-out force. Based on the axial force distribution of anchor body, the design length of system anchor can be optimized.

(6) The radius of plastic zone of surrounding rock in excavation and support of loess tunnel can be expressed as a function of the axial force of system anchor. The size of plastic zone of the surrounding rock can be back analyzed according to the measured axial force of system anchor, and then the designed length of system anchor can be optimized.

Data Availability

The data used to support the findings of this study are all included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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