Analysis of Mechanical Characteristics and Anchoring Effect of Bolt in shallow-buried Loess Tunnels

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Abstract. Based on the current situation of design and construction in loess tunnels, the methods of mechanical monitoring and mechanical characteristics is used for the anchoring effects of bolts in shallow loess tunnels studied in depth. The on-site monitoring results show that for large-section shallow buried loess tunnels, after the bolts are removed from the arch, the construction time of each process can be shortened, which is better for controlling the surrounding rock deformation than the setting of the bolts; the result of theoretical analysis shows that the pattern of displacement distribution in the tunnel arch and the side wall is significantly different. The gradient of displacement from the tunnel vault to the surface is small, the surrounding rock of the arch is mainly sinking, the displacement of the side wall is relatively small, and the attenuation of displacement within the range of the bolt is faster than the arch. The research results will provide a theoretical basis for future advanced support design of loess tunnels.

1. Introduction
Regarding the role of bolts in supporting system of loess tunnel, there are currently three main viewpoints: one view is that systematic bolts in loess tunnel has no effect on stability of tunnel, and can be cancelled. The second view is that it is important to control the overall subsidence in the construction of the loess tunnel; considering the effect of the arch bolt is small, and the side bolt can withstand the shearing effect, which can strengthen the effect of controlling the arching of the arch, the arch bolt should be eliminated and the side bolt should be retained. The third view is that the systematic bolts of the loess tunnel plays a key role in tunnel stability and should be set. These controversies not only bring great difficulties to the design of the loess tunnel, but also cause confusion in the construction support of the loess tunnel.

In the past research based on ordinary section of loess tunnel, the engineering characteristics of loess, the design and construction technology of loess tunnel, the anchorage mechanism of loess layer and the effect of system bolting of tunnel, have been deeply studied. However, in the large-section loess tunnel, there are doubts whether the worse the surrounding rock is, the denser and longer bolts should be adopted in the design, and the more easily the surrounding rock deformation can be controlled, the better the effect of the systematic bolts can be obtained.

For the rock bolts, the scholars have made great research achievement in the past. Foreign scientists have carried out groundbreaking work, such as Freeman (1978)[4], who proposed the concept of neutral point, bolt length and drawing load by observing the loading process and stress distribution of the bolt. Regarding the position of the neutral point and the magnitude of the shear stress on both sides, many experts and scholars have put forward their own research results[5-10]. In China, Chen Jiangong[9] studied the propagation laws and characteristics of stress waves of different damage bolts through
theoretical research, laboratory model tests, numerical simulation experiments, field tests and modern signal processing techniques, and established a nondestructive testing theory for detecting the damage model of bolt, and quantitatively analyze the bolt quality by using modern intelligent mathematics theory, and the technology of real-time monitoring and large-area census of systematic bolts was established. You Chun'an[11] used the displacement solution of Mindlin problem to derive the elastic solution of the full-length bonded bolt, and discussed the force characteristics of the anchor and its influence factors, which provided a kind of design and calculation for theoretical basis of the anchor. In general, there are few studies on the mechanical mechanism of anchors in loess tunnels.

Based on the on-site monitoring and theoretical analysis of large-section loess tunnels, this paper studies the mechanism of anchors in large-section loess tunnel. We adopt the research method based on on-site comparative test and theoretical analysis to make deep study of mechanical state of the bolt and the effect of reinforcing the surrounding rock. According to the current norm, the bolts with similar parameters are used in the design of large-section loess tunnels. During the construction, the bolts are fully grouted and the installation angle is correct.

2. Action mechanism of bolts

2.1 Mechanism of Bolt action

Bolt is one of the important supporting means for maintaining the stability of surrounding rock and ensuring construction safety during tunnel construction. Guan Baoshu[12] proposed a variety of mechanisms to explain the support effect of bolts, such as supporting surrounding rock, strengthening surrounding rock, combined beam action and suspension.

2.2 Mechanism of systematic bolts in shallow-buried loess tunnels

The mechanism of the bolts in shallow-buried loess tunnels is studied in a similar way to the analysis of the mechanism of bolts in deep-buried loess tunnels. Based on the condition 1 for setting the bolts, the axial force of the bolt in the shallow-buried loess tunnel is generally small[7], the maximum value of the arch is less than 12kN, and it is basically under pressure; the maximum value of the side wall is generally about 10kN, only one point reaches 37kN, and are basically in tension. Judging from the condition 1, the basic conditions for setting bolt cannot be satisfied.
Figure 2. Relationship curve of vault settlement and arch settlement and arch in shallow tunnel with systematic bolt

As shown in Fig. 2 and Fig. 3, whether the systematic bolts are set or not, the vault settlement and the arch settlement are basically the same. In the section of the tunnel from the vault to the arch, there is no relative deformation due to differential settlement, which will make the bolts of vault unable to function.

3. Analysis of bolt force

3.1 Displacement model of the surrounding rock in loess tunnel

If the surrounding rock is deformed due to excavation rather than external force applied, bolts placed in the underground opening will constrain the surrounding rock. In this way, internal force of bolt is generated by deformation of the surrounding rock. Therefore, exploring the deformation of surrounding rock after excavation is the key to solve the internal force of the bolt.

As described in the literature [4], assume that the section of the loess tunnel of Zhengxi high-speed railway is circular, and calculate the radial displacement of the surrounding rock when there is no support in the tunnel under the elastic condition:

$$u = \frac{1+\mu}{2E}\left[p_0\left(1+\lambda\right)\frac{R_0^2}{r} - 4\left(1-\mu\right)\left(1-\lambda\right)\frac{R_0^2}{r}\cos2\theta + \left(1-\lambda\right)\frac{R_0^4}{r}\cos2\theta\right]$$

Where: $\mu$ is the Poisson's ratio of the surrounding rock, $p_0$ is the initial stress of the surrounding rock, calculated as $p_0=\gamma H$, $\gamma$ is the surrounding rock gravity; $E_r$ is the elastic modulus of the surrounding rock; $\lambda$ is the lateral pressure coefficient of the surrounding rock, $\lambda=\mu/(1-\mu)$; $R_0$ is the tunnel radius, and $r$ is the distance from any point in the surrounding rock to the center of the tunnel.

In formula (1), when $r=R_0$, the displacement of the vault is obtained:

$$u_o = \frac{1+\mu}{2E}p_0R_0\left[(1+\lambda)-(3-4\mu)(1-\lambda)\cos2\theta\right]$$

In order to verify whether the surrounding rock displacement formula based on circular tunnel can be applied to the large-section loess tunnel well, the relevant parameters can be substituted into formula (2). When $\theta=90^\circ$, the obtained $u_o$ is the vault displacement. Compare the calculated value with the monitored value to see if the two values can be well matched.

- Shallow-buried loess tunnel

Taking the test section of Hejiazhuang Tunnel as the analysis object, when $r=R_0$, the relevant surrounding rock parameters and buried depth $H=35m$, $R_0=7.5m$, $\mu=0.31$, $E_r=240MPa$ are substituted into the formula (2), and get:

$$u_o = \frac{1+\mu}{2E}p_0R_0\left[(1+\lambda)-(3-4\mu)(1-\lambda)\cos2\theta\right]=0.0324m=32.4mm$$
Comparing the average vault settlement (44 mm) of all sections with or without systematic bolts in Fig. 4 and 5, the calculated values are basically consistent with the measured values, so the calculation method can be applied to shallow-buried large-section loess tunnels.

For the Hejiazhuang tunnel, when $\theta=90^\circ$, the relevant parameters are substituted into (2), and the radial displacement formula of the surrounding rock above the vault is obtained:

$$u(x) = 0.1 \left( \frac{1.45 + 0.55}{8 + x} \right) \left[ \frac{56.25}{(8 + x)^2} - 2.76 \right]$$  \(\text{(3)}\)

For the Hejiazhuang tunnel, when $\theta=0^\circ$, the relevant parameters are substituted into (2), and the radial displacement formula of the surrounding rock at the side wall is obtained:

$$u(x) = 0.1 \left( \frac{1.45 + 0.55}{8 + x} \right) \left[ \frac{56.25}{(8 + x)^2} - 2.76 \right]$$  \(\text{(4)}\)

According to the formula (3) and (4), the displacements of the arch and the wall side at different depths along the Hejiazhuang tunnel are extracted, and the displacement reduction curves of the two places are obtained, as shown in Fig. 4. As can be seen from the figure, compared with the displacement deformation law of the surrounding rock of the deep-buried loess tunnel, the reduction of the surrounding rock displacement of the side wall in the shallow-buried loess tunnel is faster than that of the vault, and it is obvious.

3.2 Shear stress distribution of bolt

• Shear stress distribution between the proximal and neutral points of the bolt

C. Li (1999) \cite{14} proposed a set of derivation formulas for the action mechanism and stress of bolts in geotechnical engineering. According to above mentioned method, Yao Xianchun \cite{15} used the axial force of the neutral point as the concentrated force, and through the Mindlin solution of the semi-infinite body subjected to the concentrated force, obtained the distribution of the shear stress at the bolt interface inside the neutral point; by comprehensively analyzing the shear stress distribution before and after the neutral point, the axial force distribution of the full-length bonded bolt is obtained. According to the research idea, the rock bolt restrains the surrounding rock deformation, and can cause the increase of the axial force, i.e., the load is applied to the bolt due to the deformation of the surrounding rock. Fig. 5 shows the shear stress distribution of bolts in the rock mass. The surrounding rock deformation will produce shear stress at bolt interface. Because the surrounding rock is deformed greatly at the proximal end of bolt, the shear stress generated in this part tends to pull the bolt to the wall. Therefore, the shear stress at the far end of the bolt should consist of two parts: (1) shear stress caused by deformation of surrounding rock; (2) shear stress which is caused by the shear stress of proximal end of the bolt draws the far end of the bolt. Based on above viewpoint, a mechanical model of the bolt can be established in this study. Fig. 6 shows a bolt setting in a rock mass.
Assuming that the influence range of a single bolt is half of the distance between the bolt and the adjacent bolt, an anchoring micro-body $d_{x}$ is taken to study the interaction between the bolt and the surrounding rock, as shown in Fig. 7. Before the bolt is set, the deformation of the surrounding rock $d_{x}$ is $d_{u}$; after the bolt is set, the deformation of the surrounding rock $d_{x}$ is $d_{u_{b}}$. According to the results of the pull-out test of the loess tunnel, the surrounding rock and the bolt rod are deformed together before the bolt is destroyed, that is, the elongation of the bolt is also $d_{u_{b}}$. Therefore, the $d_{u_{b}}$ can be calculated as the elongation of the bolt. The reduction in the deformation of the surrounding rock, $d_{u_{r}}$, is due to the effect of the bolt, which increases the stress of the surrounding rock by $\Delta \sigma_{r}$. Obviously, $d_{u}=d_{u_{r}}+d_{u_{b}}$, i.e.:

$$d_{u} = d_{u_{b}} + d_{u_{r}} = \frac{\sigma_{s}}{E_{b}} dx + \frac{\Delta \sigma_{r}}{E_{r}} dx \quad (5)$$

For the left vertical plane, according to the static equivalent principle, we get:

$$\sigma_{b} A = \Delta \sigma_{r} S \quad (6)$$

Where: $A$ is the cross-sectional area of the bolt, and $S$ is the influence range of the bolt, which is numerically equal to the area enclosed by the four adjacent bolts.

Substitute formula (6) into formula (5), and get:

$$\sigma_{b}(x) = \xi G_{r} \frac{d_{u}}{dx} \quad (7)$$

$$\Delta \sigma_{r}(x) = \xi G_{r} \frac{A d_{u}}{S dx} \quad (8)$$

where, $\xi = \frac{2(1+u)SE_{r}}{AE_{b} + SE_{r}}$, $G_{r} = \frac{E_{r}}{2(1+u)}$, $E_{b}$ is the modulus of elasticity of the bolt rod body and $E_{r}$ is the modulus of elasticity of the surrounding rock.

According to the overall balance, get:

$$\tau_{b_{1}}(x) = -\frac{A}{\pi l_{b}} \frac{d\sigma_{b}}{dx} = -\xi G_{r} \frac{A}{\pi l_{b}} \frac{d^{2}u}{dx^{2}} \quad (9)$$

Where: $d_{b}$ is the diameter of the bolt and $x$ is the distance from the micro-unit to the bolt.

The shear stress $\tau_{b_{1}}(x)$ of the wall can be obtained by the formula (9). Due to unloading caused by tunnel excavation, the elastic modulus of the surrounding rock near the tunnel wall is reduced, and the surrounding rock converges and deforms into the tunnel cave. This part of the surrounding rock
deforms greatly, which will generate a large shear stress at the bolt interface. The farther away from the wall, the deformation of the surrounding rock begins to decrease, the radial displacement begins to decrease, and the shear stress applied to the bolt decreases. The shear stress decreases exponentially to zero, i.e., the neutral point. The shear stress at the bolt interface can be expressed as:

$$\tau_a = \tau_{01} \left(1 - \frac{x}{L} e^{\alpha x}\right)$$  \hspace{1cm} (10)

Where: \(\tau_a\) is the shear stress of the proximal end of the bolt; \(L\) is the length of the bolt; \(\alpha\) is the attenuation coefficient. When \(\tau_a = 0\), the distance \(x_1\) from the neutral point to the tunnel wall can be obtained.

By integrating (10), the distribution of the axial force of the bolt along the bolt rod in the range of \(0 \leq x \leq x_1\) is obtained as below:

$$P(x) = \int_0^x \tau_a(x) \pi d_x dx = \pi d_x \int_0^x \tau_a(1 - \frac{x}{L})dx = \pi d_x \tau_a \left(1 - \frac{e^{\alpha x}}{2L} x^2\right)$$  \hspace{1cm} (11)

- Shear stress distribution between the far end and the neutral point of the bolt

After the neutral point, the radial displacement of the surrounding rock continues to decrease, and the bolt enters the transition zone of the surrounding rock. The shear stress is reduced due to the deformation of the surrounding rock. At this time, due to the drawing action of the outward shear stress of the bolt interface generated by the loosening zone on the bolt rod, a large drawing shear stress that faces away from the tunnel wall is generated at this area. The combined effect of above mention two stresses causes the bolt interface under the shear stress away from the tunnel wall. In this area, the shear stress of the bolt away from the wall will gradually increase until the bolt enters the stabilization zone of the surrounding rock.

After entering the stabilization zone of the surrounding rock, the surrounding rock deformation is reduced further, and at the same time, the drawing action on the outward shear stress weakens, which is caused by the inward shear stress at the bolt interface in the transition zone. Therefore, the inward shear stress of the bolt interface in the stabilization zone is rapidly attenuated until the bolt end.

Therefore, after the neutral point, the interface shear stress withstood by the bolt should consist of two parts: one is the shear stress generated by the deformation of the surrounding rock, which is directed to the tunnel wall, and the other is the shear stress directed to the far end of the bolt and caused by the drawing action on the bolts within the neutral points, which is applied by outward shear stress between the tunnel wall and the neutral point. For the inward shear stress of the bolt generated by drawing, the axial force on the neutral point is first calculated, and then the ordinary differential equation for shear stress \(\tau_{b2}\) at the bolt interface within the neutral points can be derived from the Mindlin solution of the semi-infinite body subjected to the concentrated force. The ordinary differential equation is:

$$\tau_{b2} + kr\tau_{b2} + rk\tau_{b2} = 0$$  \hspace{1cm} (12)

with

$$k = \frac{4\pi G}{(3-2\mu)E_A A}$$  \hspace{1cm} (13)

Where: \(G\) is the shear modulus of the surrounding rock and \(\mu\) is the Poisson's ratio of the bolt.

Solve the above differential equation and use the boundary conditions \(r \rightarrow \infty, \tau_{b0} = 0\). Finally, the shear stress of the bolt, which is distributed along the rod body, can be obtained:

$$\tau_{b2} = \frac{N}{\pi a} \left(1 - \frac{1}{2} t^2\right) \exp\left(-\frac{1}{2} t^2\right)$$  \hspace{1cm} (14)

Where: \(a\) is the radius of the bolt body, \(N\) is the axial force of the neutral point of the bolt, and \(t\) is a constant, which can be taken as follows:
\[
I = \frac{1}{(1+\mu)(3-2\mu)a^2} \left( \frac{E_s}{E_i} \right)
\]

Therefore, the shear stress \( \tau(x) \) of the bolt interface after the neutral point can be obtained:

\[
\tau(x) = \tau_{n1}(x) + \tau_{n2}(x) = 2N \cdot \frac{1}{2} \left[ t(x-x_1) \right] e^{-\frac{1}{2}(x-x_1)^2} - \xi G \frac{A}{\pi d} \frac{d^2u}{dx^2}
\]

Where: \( x_1 \) is the distance from the neutral point to the tunnel wall.

Integrate (6) to obtain the axial force distribution of \( x_1 < x < L \) bolt along the bolt body:

\[
P(x) = N - \int_{x_1}^{x} \tau_{n1}(x) \pi d \, dx
\]

\[
P_1(x) = N - \int_{x_1}^{x} \pi \tau_{n2} \, dx = N e^{-\frac{x-x_1}{2}}
\]

\[
P_2(x) = \int_{x_1}^{x} \tau_{n2} \pi d \, dx
\]

\[
P(x) = P_1(x) + P_2(x)
\]

4. Calculation and analysis of the internal force of the bolt

According to Fig 8, determine the position of neutral point, and then calculate the internal force of the bolt in the deep tunnel as shown in Fig. 9, adopting the same calculation process as that of the deep tunnel.

![Figure 8. Measured axial force of bolt in shallow tunnel](image1)

![Figure 9. Calculated internal force of bolt in shallow tunnel](image2)

As can be seen from the calculation result, the bolt in the shallow tunnel has the similar force law as that of bolt in deep tunnel, as follows:
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• The vault bolt bears a small force, of which the maximum axial force is 4.1kN (tension); the bolt of the side wall is subject to a large force, of which the maximum tensile force is 35.6kN. The force of the side wall bolt is much larger than the axial force of the vault bolt. It can be found by theoretical calculation that it is difficult to utilize the tensile strength of the vault bolt in the shallow buried large-section loess tunnel.

• The vault bolt has small shear stress, of which the outer end shear stress is 205.9 kPa, and the inner end shear stress is 66.6 kPa; the outer end shear stress of the side wall bolt is 244 kPa, and the inner end shear stress is 576.8 kPa, which are also much larger than the shear stress at the corresponding points of the vault bolt, that is, the shearing capability of the side wall bolt can be utilized.

5. Conclusion

Through the study on the force mechanism of the bolt in the large-span shallow-buried loess tunnel, it can be concluded as follows:

• The results of on-site comparison test show that for the shallow-buried large-section loess tunnel, removal of the vault systematic bolt can shorten the construction duration of each process, and it’s also better for control of the surrounding rock deformation.

• Theoretical analysis shows that for large-section loess tunnels, there is a significant difference in the displacement distribution patterns of tunnel vault and side walls. The displacement of the arch is large, the gradient from the tunnel vault to the surface displacement is small, and the surrounding rock of the vault has an integral settlement deformation (which has been proved by the displacement test); The displacement of the side wall is smaller than that of the vault, but the displacement in the function range of the bolt is reduced more rapidly than that in the arch.

• In the large-section loess tunnel, due to the short time of the collapse arch in the loess tunnel, and even no collapse arch existing, the arch bolt does not play the role of suspension and bearing. It is not that the longer the bolt is, the more load it bears, nor that the denser the bolts are, the more effective they will be. Therefore, in the design of large-section loess tunnel, it is better not to install bolts within 120° of the arch; from below the range of 120° to the wall side, wall bolts and feet-lock bolts are set to use the shear resistance ability of the bolt.

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