Deep Loess Tunnel Foundation Grouting Reinforcement Effect Analysis

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Abstract: For lining crack problems in loess tunnel construction, combining with the topography characteristics, this paper studied the tunnel surrounding rock deformation characteristics and grouting reinforcement effect with the method of numerical simulation combined with field observations. The results shown that as surrounding rock stress redistribution after tunnel excavation, with the increase of buried depth, increasing plastic zone led to uneven subsidence of foundation, which cause lining crack. Grouting technique could improve the stress state of foundation and the inverted arch, which controlled plastic zone development and deformation of loess tunnel foundation effectively. Monitoring 3 typical section of the road center accumulative deformation, grouting reinforcement could control the deformation obviously, which satisfied the requirement of tunnel stability for a long time.

Introduction

Loess particles composition was given priority to silt and it contained sand and clay at the same time. Loose loess structure, developed porosity, and significant affected by groundwater level, which susceptibly led the instability of the basement, lining crack, large deformation, landslides and other diseases in the process of the loess tunnel construction. Aiming at the loess tunnel foundation disease, Wang Analysed construction vibration damage on the s initial support and the stability of surrounding rock relying on the Wangjiacha tunnel soil compaction pile construction scheme in tunnel entrance and hole, and put forward effective control measures(Hongkun Wang, 2013)[1]. Zhang focused on analysis of the loess tunnel foundation reinforcement method with high pressure jet grouting pile, and put forward the problems that should be paid attention to in the construction(Jianlin Zhang, 2013) [2]. Guo proposed cement compaction pile treatment measures combining engineering project, and reinforcement effect evaluation method was put forward(Jun Guo et al., 2007) [3]. Scholars at home and abroad had carried out a series of research work on the loess tunnel foundation reinforcement problem , but the research on the deep loess tunnel foundation grouting reinforcement technique was less[4-6].Given this, grouting reinforcement technology was analyzed in this paper relying on Qiaoyuan tunnel, aiming at the lining crack problems occurred in the tunnel construction. At the same time, treatment effect of loess tunnel foundation grouting reinforcement technology was analyzed by means of numerical simulation and field observation, and the results provided a theoretical basis and practical guidance in the application of loess tunnel foundation grouting reinforcement technology.

Loess Tunnel Surrounding Rock Deformation Characteristics

Qiaoyuan tunnel was located in the flat loess plateau, with developed gully, deep ditch and slope steep, where broken plateau were distributed in. Its micro geomorphology is loess gully, loess slope and loess beam, etc., with homogeneous soil, loose structure, developed large pore, insect hole, vertical joints in tunnel site. It is a typical loess tunnel, with maximum depth of 114.98m. After tunnel excavation, surrounding rock stress redistribution, due to the loess tunnel broken surrounding rock, low bearing capacity and short stable time ,the soil was highly vulnerable to disturbance and was deformed in the construction process, where was unable to form load-bearing arch with open joint. Soil deformation in vault and side wall would cause soil upward deformation at the tunnel bottom
furthermore, which resulted in occurrence of foundation instability, uneven subsidence of foundation, and the lining cracking.

10 days after tunnel excavation, crack started development from the arch foot at a certain angle along the lining, and stretched forward with tunnel continuous excavation and gradually ahead of heading face, with width and depth increasing gradually. A crack roughly parallel to the tunnel axial was appear in primary support spandrel area, and a through crack was even appeared in cable trench in some serious uneven subsidence tunnel section. Specific conditions was shown in figure 1 and figure 2.

Large finite element software been adopted to establish the two-dimensional model, this paper assumed the model was plane strain problem and surrounding rock deformation was isotropic. According to the relevant specification, discriminant standard for deep tunnel was shown in Eqs. (1):

$$H_p = (2.0 - 2.5) h_q$$  
(1)

The load equivalent height \( h_q \) could be determined by Eqs. (2):

$$h_q = 0.45 \times 2^{\frac{1}{1 - \nu}}$$  
(2)

\( h_q \) was determined by PU’s equilibrium arch theories. In computing, \( h_q \) was approximately equal to tunnel span 12.3 m. Buried deep 2.5 times to 6.5 times tunnel span model was set up. As tunnel buried depth increased, this paper researched deep tunnel foundation deformation, stress changes, and range of foundation soil plastic zone.

Soil sample was obtained by reconnaissance. After the direct shear test and triaxial compression test, the physical and mechanical parameters of the soil sample were obtained. The material parameter was shown in Tab.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>( E ) (GPa)</th>
<th>( v )</th>
<th>density (kg/m(^3))</th>
<th>( c ) (kPa)</th>
<th>( \phi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratum 1</td>
<td>1</td>
<td>0.35</td>
<td>1900</td>
<td>100</td>
<td>29</td>
</tr>
<tr>
<td>Stratum 2</td>
<td>0.8</td>
<td>0.3</td>
<td>1950</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>Stratum 3</td>
<td>0.7</td>
<td>0.33</td>
<td>1946</td>
<td>115</td>
<td>30</td>
</tr>
<tr>
<td>initial liner</td>
<td>28.5</td>
<td>0.22</td>
<td>2300</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>second lining</td>
<td>30</td>
<td>0.2</td>
<td>2500</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>rock bolt</td>
<td>210</td>
<td>0.3</td>
<td>7900</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>steel shotcrete</td>
<td>210</td>
<td>0.3</td>
<td>7900</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

As shown in Tab.2, with the increase of buried depth, deep loess tunnel foundation deformation and stress increased significantly. Simulation results of buried deep 6.5 times tunnel span tunnel foundation stress was shown in figure 3.

<table>
<thead>
<tr>
<th>Buried Deep/m</th>
<th>30.75</th>
<th>43.05</th>
<th>55.35</th>
<th>67.65</th>
<th>79.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation/mm</td>
<td>3.32</td>
<td>5.17</td>
<td>7.13</td>
<td>9.20</td>
<td>10.97</td>
</tr>
<tr>
<td>Stress /kPa</td>
<td>42.2</td>
<td>66.3</td>
<td>94.8</td>
<td>121.1</td>
<td>146.3</td>
</tr>
</tbody>
</table>
As was shown in Figure 4, with the increase of tunnel buried depth, foundation soil plastic zone range increased significantly. Plastic damage of soil resulted in severe foundation uneven subsidence, which caused lining crack diseases.

Loess Tunnel Foundation Reinforcement Technology

Tunnel foundation reinforcement measures mainly included pile foundation reinforcement and grouting reinforcement. Combined with site condition, pile foundation reinforcement required drill hole in the inverted arch of completed tunnel, which would cut of steel bar and steel frame and affect the integrity of the lining structure. Pile foundation scheme cannot effectively block influence of groundwater on the foundation, and it was difficult that large diameter pile foundation construction in field. Using grouting reinforcement foundation, the spread of the slurry could be utilized to fill surrounding rock fissure, which would improve the strength of the foundation and effectively prevent the erosion of tunnel bottom soil particles by the groundwater. After grouting Inverted arch and foundation could contact close, which could satisfy assumed conditions of numerical simulation.

Aiming at tunnel geological conditions, summarizing previous engineering experience, loess tunnel foundation reinforcement scheme was put forward. As shown in Figure 4, φ42 small tubes were used in grouting reinforcement, with 5m small tubes and spacing of 1.5m×1.5m. Grouting material used cement accelerator of (0.6~0.8):1, and grouting pressure was 0.5~1.0 MPa. After grouting, filling grouting hole with dry slurry.
conditions, which would evaluate treatment effect of grouting technology in loess tunnel foundation reinforcement comprehensively.

Monitoring inverted arch axial force and bending moment per 0.5m in inverted arch unit, results of numerical simulation was analysed. As shown in Tab.3, Figure 6, and Figure 7, for the grouting reinforcement foundation model(work condition 1) and unreinforced foundation model(work condition 2), the inverted arch axial force and bending moment were symmetric distribution in the tunnel axis. Maximum axial force was in the inverted arch 1/4 position in condition 1, while maximum axial force in the arch foot in condition 2. In condition 2, inverted arch axial force significantly decreased and inverted arch overall stress was good. Inverted arch foot withstood positive bending moment, while center of inverted arch withstood negative moment. In condition 2, inverted arch force decreased as a whole. Foundation mechanical properties analysis showed that compared with condition 1, foundation deformation decreased 1/3 and stress reduced 1/2 in condition 2.

**Tab.3  Foundation Deformation and Stress Changes**

<table>
<thead>
<tr>
<th>Working</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation/mm</td>
<td>10.97</td>
<td>7.30</td>
</tr>
<tr>
<td>Stress /kPa</td>
<td>146.3</td>
<td>78.9</td>
</tr>
</tbody>
</table>

**Figure 6: Inverted Arch Axial Force**

**Figure 7: Inverted Arch Bending Moment**

**Figure 8: Plastic Zone Range**

Compared with plastic zone of 2 kinds of working condition, as shown in Figure8, plastic zone range was about 0.5 times tunnel span in condition 1, while plastic damage only appeared at arch foot position in condition 2. The foundation bearing capacity and stability greatly improved.

**Loess Tunnel Foundation Grouting Reinforcement Technique Effect Analysis**

In the process of construction, with weak surrounding rock stability, inverted arch deformation was very obvious in the construction. Aiming at tunnel stability and effect of foundation grouting reinforcement, with inverted arch backfill completed, 3 typical sections was selected in foundation reinforcement. Steel nails as observation points were embedded in concrete at the center of the tunnel pavement, and continuous deformation observation sustained nearly 3 months.

As shown in figure 9, different section deformation of tunnel pavement were not the same, but the overall trend of deformation were basically same. Deformation mainly occurred in 30 days after pavement construction, and it accounted more than 80% of total deformation in this period. After 30
days the deformation rate gradually decreased, and deformation curve flattened. The analysis results showed that the effect of loess tunnel foundation reinforcement was obvious, with stronger foundation strength and resistance ability. The peak of the tunnel deformation value was less than 10 mm, which could satisfy the requirement of tunnel stability for a long time.

![Figure 9: Section Accumulative Deformation of Tunnel Pavement Center](image)

Conclusions

1) As surrounding rock stress redistribution after tunnel excavation, with the increase of buried depth, increasing plastic zone led to uneven subsidence of foundation, which was the main cause of lining crack.

2) Aiming at Qiao Yuan tunnel lining crack, this paper put forward the concrete implementation plan of the grouting, including the location, pressure, grouting amount, and grouting material, etc.

3) Grouting technique could effectively control the plastic zone development, improving the foundation and the inverted arch stress state, which could control the loess tunnel foundation deformation and disease.

4) Monitoring 3 typical section accumulative deformation at center of the road, the peak of the tunnel deformation value was less than 10 mm. Foundation strength and stability was improved after grouting reinforcement, which could satisfy the requirement of tunnel stability for a long time.

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References


