Research Article

Effects of Pipe Roof Support and Grouting Pre-Reinforcement on the Track Settlement

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Based on the first shallow tunnel passing below an active railway station in the loess area in China, studies on the tunnel deformation and track settlement during tunneling are performed by using FLAC3D. It is found that, without adopting other reinforcement measures, the maximum track settlement has far exceeded engineering requirements. To reduce deformations induced by the tunneling, the combined presupport technique of the pipe roof and grouting reinforcement is presented and optimal construction parameters are provided. It is concluded that the installation of the pipe roof support plays an important role in controlling tunnel crown settlement and track settlement. The optimal pipe diameter is 159 mm, and the optimal arrangement area of the pipe roof is 150°. Grouting could improve soil strength and reduce deformations. The optimal thickness of the grouting reinforcement ring is 2 m. When the optimal parameters of the combined presupport technique are adopted, calculation results show that the maximum track settlement would reach 13.8 mm, which realized the settlement control goal of a maximum value of 15 mm. At last, the combined presupport technique proposed has been well validated in the “Railway Station” of Metro Line 4.

1. Introduction

In the past few decades, increasing demands on infrastructures increase attention on shallow soft ground tunneling methods in many urbanized areas. Many surface and subsurface structures make underground excavation works very delicate to the influence of deformation, which should be definitely limited to tolerable values [1]. The influence of underground construction on surface and subsurface structures should be accurately predicted, and corresponding remedial measures have to be put forward and taken prior to excavation.

Many efforts have been contributed to minimizing the negative effect due to underground construction [2–11]. Hasanpour et al. [12] investigated the effects of pipe roofing on surface settlements and evaluated the settlements associated with the twin tunnels in the Istanbul Metro by using numerical, semiempirical, and measured values. Yu et al. [13] evaluated the influence of blasting vibrations on the tunnel in soft soils in the city of Shanghai. Liu et al. [14] suggested to use the pile-beam-arch method to control the surface settlement induced by metro tunnel excavation. Sadaghiani and Dadizadeh [15] introduced the concrete-arch presupporting system in the metro underground station in Tabriz, Iran. Kivi et al. [16] carried out a numerical analysis on surface settlement using the central beam column structure. For tunneling in the loess area, Zhao et al. [17] systematically summarized the technical characteristics and main problems of the large-section loess tunnels in China’s speed railway, including classification of the surrounding rock, design of the supporting structure, surface settlement and cracking control, and safe and rapid construction methods. Li et al. [18] discussed the effects of the three-bench seven-step excavation method (TSEM) on the displacement characteristics for high-speed railway (HSR) tunnels. Qiu et al. [19] investigated the response of the metro tunnel under the local dynamic water environment. However, the above research studies have not involved the influence of tunneling on track settlement in the loess area and not provided effective solutions as well.
Based on the first shallow tunnel passing below an active railway station in the loess area in China, this paper deals with tunnel deformation and track settlement during tunneling by using FLAC3D. In order to meet engineering requirements, the combined pre-reinforcement technique is presented and optimal supporting parameters are further investigated. This paper could provide useful guidance for similar projects.

2. Engineering Background and Numerical Model

2.1. Background. “Railway Station” of Xi’an Metro Line 4 is the first shallow metro tunnel with a large cross section passing below an active railway station in the loess area in China, which is the critical project of Metro Line 4. Layout of “Railway Station” of Metro Line 4 is shown in Figure 1(a). The model size is adopted over three times the tunnel size, and the top surface is free, while other five surfaces are completely constrained. In the following numerical analysis, six types of pipes are simulated to investigate the effect of pipe parameters (R: diameter; s: thickness; Sc: effective area of concrete; S: effective area of the steel pipe; Ic: moment of inertia of the steel pipe; I: moment of inertia of concrete; E: elastic modulus of the grouting steel pipe; and ρ: density of the grouting pipe) on deformation, and their computing parameters are shown in Table 2. It is worth noting that the numerical model demonstrates the rationality and effectiveness of the numerical model. From Figure 3(b), it can be observed that the maximum track settlement has far exceeded 15 mm, and thus, it is pretty necessary to take remedial measures.

3. Pipe Roof Support

The pipe roof support technique has been widely applied as one of the important auxiliary methods for shallow tunnel excavation. The pipe roof support can consolidate the ground stress and disperse the ground stress and reduce the excavation release stress, which effectively limits the tunnel crown settlement or prevent ground settlement.

3.1. Selection of Pipe Type. Currently, steel pipes with a diameter between 89 mm and 186 mm are more applied in practical engineering. Modulus and density of the steel pipe are 210 GPa and 2700 kg/m³, respectively, with those of the grouting material being 23 GPa and 2200 kg/m³, respectively. In the following numerical analysis, six types of pipes are simulated to investigate the effect of pipe parameters (R: diameter; s: thickness; Sc: effective area of concrete; S: effective area of the steel pipe; Ic: moment of inertia of the steel pipe; I: moment of inertia of concrete; E: elastic modulus of the grouting steel pipe; and ρ: density of the grouting pipe) on deformation, and their computing parameters are shown in Table 2. It is worth noting that the pipe roof supports all range from 0° to 90°.

Tunnel deformation and maximum track settlement using different types of pipes are provided in Table 3. Comparing with the results in Figure 3, it could be found that the installation of the pipe roof plays an important role in controlling deformation. Stiffness of the grouting pipe has a close relationship with pipe diameter. The grouting pipe with a larger diameter possesses greater stiffness, which means stronger antideforming capability. In the shallow tunnel, it is indicated that vertical pressure acting on the lining is far more than horizontal pressure and crown settlement is the main form of tunnel deformation. Therefore, based on the results in Table 3, it could be explained that crown settlement is more sensitive to pipe parameter changes, but peripheral convergence is not.

3.2. Determination of Arrangement Area. Arrangement area of the pipe roof is one of the important construction parameters. In this study, in order to obtain the optimal arrangement area, four schemes are designed and shown in Figure 4.

From Table 4, it can be seen that the arrangement area of the pipe roof also has an impact on deformations. With increasing area, deformations all exhibit a decreasing trend.
Figure 1: (a) Layout and (b) geology of "Railway Station" of Metro Line 4.

Figure 2: Illustration of the numerical model.
### Table 1: Calculation parameters [20].

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (m)</th>
<th>Density (kg/m³)</th>
<th>Elasticity modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Cohesion (kPa)</th>
<th>Internal friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscellaneous soil</td>
<td>2.04</td>
<td>1600</td>
<td>9</td>
<td>0.41</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Plain filling soil</td>
<td>2.56</td>
<td>1800</td>
<td>12</td>
<td>0.38</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>New loess (above the water level)</td>
<td>3.75</td>
<td>1800</td>
<td>15</td>
<td>0.34</td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td>Saturated soft loess</td>
<td>4.83</td>
<td>1750</td>
<td>8</td>
<td>0.32</td>
<td>38.2</td>
<td>19.5</td>
</tr>
<tr>
<td>New loess (under the water level)</td>
<td>3.09</td>
<td>1900</td>
<td>22</td>
<td>0.31</td>
<td>40</td>
<td>20.5</td>
</tr>
<tr>
<td>Paleosol</td>
<td>10.96</td>
<td>2010</td>
<td>33</td>
<td>0.23</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Silty clay</td>
<td>57.78</td>
<td>2100</td>
<td>40</td>
<td>0.23</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Track</td>
<td>0.07</td>
<td>2800</td>
<td>21</td>
<td>0.2</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Track bed</td>
<td>0.15</td>
<td>2400</td>
<td>19</td>
<td>0.2</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>0.35</td>
<td>2800</td>
<td>19</td>
<td>0.24</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Primary lining</td>
<td>0.3</td>
<td>2300</td>
<td>2000</td>
<td>0.26</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Secondary lining</td>
<td>0.5</td>
<td>2500</td>
<td>2700</td>
<td>0.2</td>
<td>100</td>
<td>35</td>
</tr>
</tbody>
</table>

### Table 2: Cross section parameters of the grouting steel pipe.

<table>
<thead>
<tr>
<th>Number</th>
<th>R (mm)</th>
<th>s (mm)</th>
<th>(S_y) (m²)</th>
<th>(S_x) (m²)</th>
<th>(I_1) (m⁴)</th>
<th>(I_2) (m⁴)</th>
<th>E (GPa)</th>
<th>(\rho) (kg/m³)</th>
<th>Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>89</td>
<td>5</td>
<td>2.35e⁻²</td>
<td>2.72e⁻³</td>
<td>6.36e⁻⁷</td>
<td>1.49e⁻⁸</td>
<td>27.29</td>
<td>2371.25</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>108</td>
<td>6</td>
<td>3.46e⁻²</td>
<td>3.96e⁻³</td>
<td>1.36e⁻⁶</td>
<td>7.04e⁻⁸</td>
<td>32.17</td>
<td>2369.44</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>127</td>
<td>8</td>
<td>4.75e⁻²</td>
<td>6.18e⁻³</td>
<td>2.90e⁻⁶</td>
<td>2.49e⁻⁷</td>
<td>37.69</td>
<td>2390.86</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>159</td>
<td>8</td>
<td>7.54e⁻²</td>
<td>7.79e⁻³</td>
<td>5.85e⁻⁶</td>
<td>1.59e⁻⁶</td>
<td>62.92</td>
<td>2354.17</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>178</td>
<td>9</td>
<td>9.45e⁻²</td>
<td>9.81e⁻³</td>
<td>9.24e⁻⁶</td>
<td>3.92e⁻⁶</td>
<td>78.68</td>
<td>2354.90</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>186</td>
<td>10</td>
<td>1.03e⁻¹</td>
<td>1.14e⁻²</td>
<td>1.17e⁻⁵</td>
<td>5.49e⁻⁶</td>
<td>82.90</td>
<td>2364.24</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: Deformations using different types of pipes.

<table>
<thead>
<tr>
<th>Number</th>
<th>Crown settlement (mm)</th>
<th>Peripheral convergence (mm)</th>
<th>Maximum track settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>149.2</td>
<td>15.2</td>
<td>44.7</td>
</tr>
<tr>
<td>2</td>
<td>124.4</td>
<td>14.4</td>
<td>38.1</td>
</tr>
<tr>
<td>3</td>
<td>108.0</td>
<td>13.1</td>
<td>33.2</td>
</tr>
<tr>
<td>4</td>
<td>93.2</td>
<td>12.2</td>
<td>30.4</td>
</tr>
<tr>
<td>5</td>
<td>88.3</td>
<td>11.9</td>
<td>29.5</td>
</tr>
<tr>
<td>6</td>
<td>86.9</td>
<td>10.6</td>
<td>29.0</td>
</tr>
</tbody>
</table>

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Figure 3: Comparison between numerical results and in situ data. (a) Tunnel crown settlement. (b) Track settlement.
Maximum track settlement drops quickly when area ranges from 120° to 150°. Specially, peripheral convergence declines sharply from 11.3 mm to 3.2 mm, and afterwards, there is no distinct reduction with pipe roof area reaching 150°. So 150° should be adopted as the optimal parameter for the pipe roof area. In such a case, requirements for maximum track settlement still could not be satisfied and other control measures need to be taken.
4. Grouting Pre-Reinforcement

In the loess area, grouting pre-reinforcement is an ideal measure for reducing tunnel deformation during underground excavation. Studies show grouting pre-reinforcement could significantly improve performance of bearing capacity of soft surrounding rock and form a reinforcement ring around the tunnel. Thus, the stress state of the lining could be adjusted and tunnel stability enhanced. In this section, the effect of grouting pre-reinforcement on deformations is investigated.


In the construction site, five sampling points are determined and displayed in Figure 5(a). In order to obtain soil parameters after grouting, experiments for density, cohesion, and internal friction angle are carried out, as shown in Figure 5(b). Test results are shown in Figures 6(a)–6(c), respectively.

Figures 6(a) and 6(b) show that both density and cohesion $c$ of soil obviously increase after grouting. By comparison, internal friction angle $\phi$ increases slightly in
Figure 6(c). The average of each parameter after grouting is calculated and determined to be a simulation parameter for the grouting reinforcement ring and listed in Table 5.

4.2. Determination of Thickness of Grouting Reinforcement Ring. In order to determine reasonable thickness of the grouting reinforcement ring, as shown in Figure 7, thicknesses of 1 m, 2 m, and 3 m are planned to be calculated in numerical analysis, respectively. Here, the scheme of GP-0 is displayed to facilitate discussion on the grouting pre-reinforcement effect.

As shown in Figure 8(a), the curve for volume of the plastic zone with different reinforcement ring thicknesses is plotted. It is clear that grouting pre-reinforcement could significantly reduce the volume of the plastic zone in surrounding soil. If grouting pre-reinforcement is not adopted, volume of the plastic zone would reach about 1133 m³, which is 1.5 times that in the condition of 1 m reinforcement thickness. By comparison, this downtrend of volume of the plastic zone becomes more gentle with reinforcement thickness changing from 1 m to 3 m.

Figures 8(b) and 8(c) show the tunnel crown settlement and track settlement with different reinforcement ring thicknesses. Obviously, both crown settlement and track settlement are greatly affected by grouting pre-reinforcement. Remarkably, thickness of 2 m is a critical parameter for the grouting reinforcement ring because there is a little change in both crown settlement and track settlement after thickness reaches 2 m, and maximum track settlement could satisfy control requirements of this project when thickness of 2 m is being adopted. Therefore, it could be concluded that the grouting reinforcement ring of 2 m is optimal.

Based on the above analysis, optimal parameters for the combined presupport technique have been determined. Through the practical application in Xi’an Station of Metro Line 4, as shown in Figure 9, good effects are obtained. Therefore, for tunnels excavated in the loess area, the combined presupport technique of the pipe shed support and grouting reinforcement is very effective in reducing tunnel deformation and control track settlement.

5. Conclusions

Based on the first shallow tunnel passing below an active railway station in the loess area in China, the studies on the tunnel deformation and track settlement are carried out. To guarantee the safe operation of the railway station during underground excavation, safety evaluation of track settlement is performed and remedial measures of the combined presupport of the pipe roof and grouting reinforcement are presented.

The optimal support parameters are investigated as well. The following conclusions were notable:

(a) Without adopting other reinforcement measures, the maximum track settlement has far exceeded engineering requirements.

(b) The installation of the pipe roof support plays an important role in controlling tunnel crown settlement and track settlement. The optimal pipe diameter is 159 mm, and the optimal arrangement area of the pipe roof is 150°.

(c) Grouting could improve soil strength and reduce deformations. The optimal thickness of the grouting reinforcement ring is 2 m.
Figure 9: Field tests in Xi’an Station of Metro Line 4.
**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

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**References**


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