Transversal deformation mechanism of shield tunnels caused by micro-disturbance grouting

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Abstract. Micro-disturbance grouting has been widely used in the control of transversal deformation of shield tunnel. It is proved that the grouting not only effectively controls the further deformation in the future but also reduces the existing large deformations. However, the study on grouting mechanism is relatively limited. By using the analytical model with the soil expressed by the Mohr-Coulomb yield criterion, the nonlinear relationship between soil stress and displacement in elastic-plastic zone of the grouting area are derived based on cavity expansion theory. The grouting pressure and required volume for different grouting distance between grouting holes and tunnel linings, and the grouting depth are given. The analytical results are compared with the monitoring data to validate the proposed model. According to the comparison results, the construction sequence of grouting hole can be optimized which can avoid short-time stress superposition to squeeze the tunnel segments and produce structural diseases. Moreover, the optimal grouting volume can effectively keep the effect of the reduction of the tunnel deformation by micro-disturbance grouting technology. The proposed micro-disturbance grouting and its associated optimized construction scheme can be quite helpful to the practical control of the large deformation.

1. Introduction
With rapid urbanization development, the subway has become an important means of urban public transportation. As the foundation of subway operation, the durability and safety of tunnel structure is particularly critical. In soft soil area, shield is often used in subway tunnel construction. There are many joints in shield tunnel, and the strength of joints will be reduced, especially for the continuous seam tunnel. When there is nearby disturbance caused by the loading or lateral unloading, the tunnel is easy to produce large lateral deformation. as the lining deformation increases, it inevitably will lead to the segment damage, joint cracking, leakage, and other diseases, which will eventually affect the normal operation of the metro line [1-3]. In 2019, there are many cases of excessive tunnel deformation caused by foundation pit excavation in Shanghai. For example, the transverse deformation of the corresponding tunnel in Xu Jiahui central Project is 68mm larger than the design value, far exceeding the design requirements of 5 ‰ D (D is the outer diameter of the tunnel, D=6.2m) [4]. In order to solve this problem, micro-disturbance grouting technology has been successfully applied to the above case [5], the transverse deformation of the tunnel is reduced accordingly. However, there are some problems in the construction. On one hand, with the passage of time, one-third of the reduction by grouting leads to rebound, which makes the tunnel return to a high-risk state; on the other hand, the grouting volume and pressure are based on the condition that the grouting hole is 3m away from the tunnel. However, when the traffic condition above the deformed tunnel is too critical to maintain the requirement of the distance of 3m between grouting hole to the tunnel, the
grouting pressure and volume will be largely discounted and subsequently the effect of reduction of large deformation due to grouting will be limited.

Many scholars worldwide have done a lot of researches on compaction grouting. Zou, J.F., et al. [6] based on the theory of cavity expansion, the fracture grouting pressure is studied in the case of large deformation, and analytical solutions of the stress, strain and displacement fields for cavity expansion are presented with the non-associated flow rules for the shear dilatation characteristics. Wang, G.G., et al. [7] studied the influence range of compaction grouting, the distribution law of excess pore water pressure and the law of strength growth based on the theory of cavity expansion. It is believed that with the dissipation of excess pore water pressure caused by grouting, the surrounding soil is compacted and the strength is improved. Zhou, M.R., et al. [8] analyzed the stress and deformation of elastic and plastic zone by combining the theory of cavity expansion and the modified Cam-clay model, and proposed a calculation method which suitable for collapsible loess area. However, the above researches mainly focused on the compaction grouting, while the mechanism of the micro-disturbance grouting might not belong to this type of grouting. But there are quite few studies on this subject.

Hence, in view of the above limitations, in this paper, combined with the existing research results, the cavity expansion theory is applied to study transverse deformation mechanism of shield tunnels caused by micro-disturbance grouting. The influence range, stress and lateral displacement under different grouting pressure are analyzed; the required grouting pressure and volume are given in the case of different grouting depth and position, which is important to both the theoretical researches and the application of grouting.

2. Problem description and analytical model

The technology of micro-disturbance grouting at the side of the tunnel is shown in Figure 1. Under the action of initial opening pressure, the soil will be split. With the increase of grouting volume, the soil is compacted and diffused outward, and divided into plastic zone and elastic zone according to the stress. The mechanical model is shown in Figure 2. $\sigma_r$ is the radial stress, $\sigma_\theta$ is the circumferential stress, $\sigma_{rp}$, $\sigma_{ru}$ are the radial stress and displacement at the elastic-plastic interface; $P_0$, $P_e$, $P_u$ are the lateral earth pressure, ultimate elastic pressure and ultimate grouting pressure; $r_0$, $r_p$, $r_e$ are the initial radius, plastic radius and elastic radius. In order to guide the grouting, the influence range, the maximum grouting pressure and the minimum grouting amount are solved as follows.

2.1. The influence range

When $r$ is greater than $r_p$ and less than $r_e$, the soil is in elastic state. Considering that the grouting position is generally deep, it is assumed that the soil does not produce vertical displacement and is plane strain. According to the cavity expansion [9], and boundary conditions, the expressions of stress
and displacement in elastic zone can be achieved as equation (1). Where \( r \) is the distance from grouting centre, \( \nu \) is the Poisson's ratio of soil, \( E \) is the elastic modulus of soil.

\[
\begin{align*}
\sigma_r &= \frac{r^2 - r_p^2}{r_e^2 - r_p^2} \sigma_0 + \frac{r^2 - r_e^2}{r_e^2 - r_p^2} \sigma_e \\
\sigma_\theta &= \frac{r^2 - r_p^2}{r_e^2 - r_p^2} \sigma_0 + \frac{r^2 + r_p^2}{r_e^2 - r_p^2} \sigma_e \\
u &= \frac{(1 + \nu)}{E} 
\left[ \frac{(1 - 2\nu)}{r_e^2 - r_p^2} \sigma_e - \frac{r_e^2 \sigma_0 - \sigma_e}{r} \right]
\end{align*}
\]

(1)

When \( r=r_e \), the displacement at the boundary of elastic zone is zero, the ultimate elastic pressure can be obtained as equation (2) based on equation (1).

\[
p_e = \frac{(1 - 2\nu) \sigma_e + \sigma_0}{2(1 - \nu) \sigma_e - \sigma_0}
\]

(2)

In elastic limit state, soil failure obeys the Mohr-Coulomb yield condition, and its relationship is expressed as equation (3).

\[
(\sigma_r - \sigma_\theta) = (\sigma_r + \sigma_\theta) \sin\varphi + 2c \cos\varphi
\]

(3)

When \( r=r_p \), combining equation (1) with equation (3), and the initial stress is considered [10], the ultimate elastic pressure in elastic zone can be obtained as equation (4).

\[
p_e = \frac{(1 - 2\nu) \sigma_e + \sigma_0}{\frac{1}{(1 - 2\nu) \sigma_e - \sigma_0} \left( \frac{p_0 \sin\varphi + c \cos\varphi}{} \right)}
\]

(4)

From equation (2) and (4), the elastic radius can be calculated by equation (5).

\[
r_e = \left( \frac{1}{2} \frac{(3 - 2\nu) \sin\varphi + 2(1 - \nu) c \cos\varphi}{(1 - 2\nu) \sigma_e + \sigma_0} \right)^{1/2}
\]

(5)

It can be seen from equation (5), the elastic radius is related to soil parameters, lateral earth pressure and the plastic radius. By controlling the grouting pressure and volume, the radius of plastic zone is equal to the distance between grouting hole and tunnel, the influence range of grouting can be uniquely determined according to the soil parameters when the buried depth of the tunnel is determined. According to the influence range, the construction can be guided to avoid short-term superimposed influence, which makes the transverse deformation of the tunnel too large and causes tunnel structural diseases.

2.2. The grouting pressure

When \( r \) is greater than \( r_0 \) and less than \( r_p \), the soil is in plastic state. Combining equation (3), the equilibrium differential equation of plane strain axisymmetric problem is expressed as equation (6).

\[
\frac{d\sigma_e}{dr} + \frac{2 \sin\varphi}{1 + \sin\varphi} \frac{\sigma_e}{r} + \frac{2c \cos\varphi}{1 + \sin\varphi} \frac{1}{r} = 0
\]

(6)

The radial stress and circumferential stress in the plastic region are obtained as equation (7), by solving the first order linear differential equation. Where \( c \) is the cohesive strength, and \( \varphi \) is the internal friction angle.
When \( r = r_p \), from equation (1) and (7), the ultimate grouting pressure is obtained as equation (8).

\[
p_u = \left( \frac{(1-2\nu)r_e^2(1+\sin\varphi)}{1-2\nu} \right) \left( \frac{p_o + c\cot\varphi}{r} \right) \frac{2\sin\varphi}{1+\sin\varphi - c\cot\varphi}
\]

\[
\sigma_r = \left( p_o + c\cot\varphi \right) \frac{r_p}{r} \frac{2\sin\varphi}{1+\sin\varphi - c\cot\varphi}
\]

\[
\sigma_\theta = \left( p_o + c\cot\varphi \right) \frac{r_p}{r} \frac{2\sin\varphi}{1+\sin\varphi - c\cot\varphi}
\] (7)

2.3. The optimal grouting volume

In the plastic region, the radial and circumferential total strain includes elastic strain and plastic strain [11, 12], as shown in equation (9).

\[
e_r = \frac{\varepsilon_f}{\varepsilon_r} + \epsilon_e^r, \quad e_\theta = \frac{\varphi}{\varphi} + \epsilon_e^\theta
\] (9)

Where \( e_r, e^p_r, \epsilon_e^r \) represent the total radial strain, plastic radial strain and elastic radial strain; and \( e_\theta, e^p_\theta, \epsilon_e^\theta \) represent the total circumferential strain, plastic circumferential radial strain and elastic circumferential radial strain.

A non-associated flow is adopted, and assumed that the elastic strain in the plastic zone is very small relative to the plastic strain. The relationship between the plastic deformation of radial strain and circumferential strain under the condition of plane strain can be written as equation (10).

\[
h \epsilon^p_r + k \epsilon^p_\theta = 0, \quad h = (1 - \sin\psi) / (1 + \sin\psi)
\] (10)

Where \( \psi \) is the dilation angle of soil, which is generally half of the friction angle[13]. For cavity expansion, \( k \) is taken as 1; for spherical cavity expansion, \( k \) is taken as 2.

According to Hooke's law, the relationship between stress and strain in plane strain can be shown in equation (11).

\[
\begin{align*}
\epsilon^r_e &= \frac{1-\nu^2}{E} (\sigma_r - \frac{r}{r_p} \sigma_r) \\
\epsilon^\theta_e &= \frac{1-\nu^2}{E} (\sigma_\theta - \frac{r}{r_p} \sigma_\theta)
\end{align*}
\] (11)

Combining equation (10) and (11), the relationship between the radial and circumferential total strain is obtained as equation (12).

\[
h \frac{\text{d}u}{\partial r} + \frac{u}{r} = \frac{1-\nu^2}{E} \left[ h - \frac{\nu}{1-\nu} \sigma_r + \frac{1-h}{1-\nu} \sigma_\theta \right]
\] (12)

According to the boundary condition of elastic-plastic interface, the displacement of plastic zone can be obtained as equation (13).

\[
\begin{align*}
u &= Ar^{1-\sin\varphi} + Br + Cr^\frac{-1}{h}, \\
A &= \frac{1-\nu^2}{E} \left[ h - \frac{\nu}{1-\nu} \right] \left( \frac{1-\sin\varphi}{1+\sin\varphi} \right) \left( p_o + c\cot\varphi \right) \frac{2\sin\varphi}{1+\sin\varphi - c\cot\varphi}, \\
B &= \frac{1-\nu^2}{1-\nu} \left( p_0 - c\cot\varphi \right), \\
C &= \frac{(1+\nu) r_e^2}{(r_e^2 - r_p^2) E} \left( p_0 - p_e + (1-2\nu) \left( \frac{p_o - r_p^2}{r_p^2} p_e \right) \right) \frac{2\sin\varphi}{1+\sin\varphi - c\cot\varphi} \left( p_o + c\cot\varphi \right) r_0^{1-\sin\varphi} - Br^{1-\sin\varphi} - Ar_c^{1-\sin\varphi}
\end{align*}
\] (13)
The expansion range can be obtained by adding the initial radius and displacement. In order to maintain the grouting effect, it is necessary to fill the expansion range, and the amount required is the optimal grouting volume. It not only reduces the amount of grouting material, but also makes the maximum elastic deformation.

3. Verification of mechanical model by field data

3.1. Project introduction

In order to validate the correctness of the model, the project of Pingliang 22nd block is selected. In this case, large deformation of the shield tunnel (from Ring S620 to Ring S760,) is caused by foundation pit excavation. The maximum transverse deformation is 68mm (i.e., 10 % D) larger than the design value, far exceeding the design requirements of 5 % D. After the discovery of the defects, the repair plan was launched immediately. The grouting of Row1, as shown in Fig.3, was conducted first from January 19 to March 11, 2017, and the grouting of Row2 was conducted from May 23 to July 5, 2017, due to the impact of traffic constraint on the ground surface. Layout of the grouting arrangement is presented in Figure 3., and the soil layer and grouting profile is shown as Figure 4. The grouting parameters used are shown in Table 1. The horizontal displacement of tunnel is not considered in the early stage of grouting. Since February 18, the horizontal displacement measurement of tunnel has been increased. Figure 5. shows the horizontal displacement curve of tunnel during grouting, and the deformation is 5-8mm until the grouting of Row1 completed on March 11.

![Figure 3. Plan view of grouting.](image)

![Figure 4. Soil layer and grouting profile.](image)

![Figure 5. The horizontal displacement curve of tunnel during grouting.](image)

### Table 1. Grouting parameters.

| Parameters                              | Range       |
|-----------------------------------------|-------------|
| Water-cement ratio                      | 0.6-1.0     |
| Flow rate of cement slurry              | 14-16L/min  |
| Flow rate of sodium silicate            | 5-10L/min   |
| Volume ratio of cement slurry to sodium sulfate | 2-3        |
| Lifting rate of grouting pipe           | 10cm/min    |

3.2. Monitoring data analysis

In order to study the influence of single grouting hole on surrounding soil, Ring S767 and S755 are selected for analysis, which were grouted on the first day. The grouting time of Ring S767 is 22:50 ~ 23:55, January 19, 2017; Ring S755 is 23:55 ~ 00:54. The curve of tunnel transversal deformation during grouting was shown in Figure 6.and Figure 7.
It can be seen from Figure 6 and Figure 7, during the grouting period of Ring S761 (22:50 ~ 23:55), the transversal deformation of Ring S762 is 3 ~ 4mm, and the deformation of Ring S759 is 1 ~ 2mm, while the diameter of Ring S756 is basically unchanged. When the grouting surface is located at the bottom of the tunnel (22:50 ~ 23:00), the transversal deformation of Ring S762 is small; when the grouting surface is 1m away from the tunnel centre (23:00 ~ 23:35), the transverse deformation of the tunnel caused by grouting is large, and the deformation is about 3-4mm. The same as Ring S755 grouting (23:55 ~ 00:54), the transversal deformation of Ring S754 and S756 is 3 ~ 4mm, while the diameter of Ring S751 is basically unchanged. Under the grouting parameters mentioned in this paper, it can be considered that grouting influences the adjacent two rings.

### 3.3. Theoretical calculation and analysis

The parameters of soil corresponding to the tunnel centre are selected for calculation, and the soil parameters are shown in Table 2. The coefficient of lateral earth pressure at rest \( k_0 \) is equal to 0.53, and the initial radius is 0.6m [14].

| Soil   | \( c \) / kPa | \( E \) / MPa | \( \varphi \) / (°) | \( \psi \) / (°) | \( \nu \) | \( \gamma_s \) / (kN·m\(^{-3}\)) |
|--------|--------------|--------------|-------------------|-------------|-----|---------------------|
| 51Clay | 13           | 15           | 13                | 6.5         | 0.33 | 18.5                |

Taking the Ring S761 as an example, the lateral earth pressure at the centre of the tunnel is 0.2MPa. According to equation (4) and equation (5), the ultimate elastic pressure is 0.24MPa, and the radius of the influence area is 4.02m. According to equation (8), the ultimate grouting pressure is 0.48MPa. The calculation results are shown in Figure 8., and the stress and displacement curve of elastic-plastic zone is shown in Figure 9.
When Ring S761 has been treated by the grouting, the tunnel displacement is 10.8mm according to the calculation method in this paper, which is equal to the sum of measured transversal deformation (3-5mm) and horizontal displacement (5-6mm). If a circle according to the calculated influence radius (4.02m) is drawn, the influence range is just two rings on the left and right sides, which is consistent with the measured results.

As shown in Figure 8., the expansion radius of the hole formed after grouting is 0.95m, the optimal grouting volume is 1486L calculated by 10% mixing ratio, but the actual grouting volume is 1248L, that is the reason why the rebound occurs after grouting.

The tunnel deformation caused by grouting pipe at different depths is shown in the Figure 10. Taking the tunnel bottom as the datum plane, when the grouting surface is either lower than 0.8m or higher than 5.04m, grouting has little effect on the transverse deformation of the tunnel. The effect is best when the grouting surface is located at the centre of the tunnel. The main reason is that when the grouting position is determined, with the lifting of the grouting surface, the actual distance between the grouting hole and the tunnel is the closest to the waist, so the deformation of the tunnel waist caused by grouting is large. Therefore, the grouting range can be reduced from 5.2m to 4.2m.

![Figure 10. Variation of tunnel diameter during grouting.](image)

![Figure 11. Stress curve of elastic-plastic zone at different depth.](image)

Taking the grouting distance is 3m away from the tunnel as an example, the grouting pressure and stress curves are shown in Figure 11. With the increase of lateral earth pressure, the required limit grouting pressure and elastic limit pressure are increased, but the elastic influence range decreases.

When the lateral earth pressure is 0.2MPa, the recommended grouting pressure and influence range under different grouting distances are shown in Figure 12. And the grouting volume and effect are shown in Figure 13.

![Figure 12. Stress and displacement curve of elastic-plastic zone with different grouting distance.](image)

![Figure 13. Grouting volume and effect.](image)
With the increase of grouting distance, the theoretical maximum grouting pressure increases simultaneously, which not only increases the tunnel deformation, but also increases the influence range. From Figure 13, it can be concluded that the effect is best when the distance is 2m, it can not only avoid the damage of tunnel caused by excessive pressure, but also can use less grouting materials.

4. Conclusion

Based on the cavity expansion theory combined with Mohr-Coulomb yield criterion, the expressions of stress and displacement in the elastic and plastic zone under the influence of grouting are obtained, and the grouting pressure and required volume for different distance and depth are given. Some key conclusions can be summarized as follows:

1) The influence range of grouting is related to soil parameters, soil lateral earth pressure and the plastic radius. By assuming the radius of plastic zone, the grouting pressure and grouting volume can be calculated according to the tunnel buried depth and soil parameters.

2) With the increase of depth, the lateral earth pressure increases. The required limit grouting pressure and elastic limit pressure are increased, but the elastic influence range decreases, which makes the grouting pressure increase, but the elastic influence range decreases.

3) The grouting pressure can be obtained by combining the depth of tunnel, soil parameters and grouting position, it can not only avoid the damage of tunnel caused by excessive pressure, but also can use less grouting materials. Under the condition of existing technology, 2~3m away from the tunnel is more suitable.

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