Surface Settlement Analysis of Double-Line Shield Passing Through a Power Tunnel and Directly Cutting Pile Foundation

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Abstract. Three-dimensional numerical simulation was conducted to investigate the influence of shield directly cutting the pile foundation of surface settlements using the Hangzhou Metro Line 4 shield passing through a power tunnel. The thrust force of the tunnel working face and grouting pressure are used as the tunneling parameters for the numerical simulation, from which field monitoring data is obtained and analyzed. The simulation results are verified to a certain extent by comparing them with the monitoring data. The power tunnel with high stiffness acts as a beam in the soil and can effectively reduce soil settlement, making the settlement curve affected by the power tunnel no longer axisymmetric. The final surface settlement value decreases with the increase of thrust force of the tunnel working face and grouting pressure. In the influence range of the power tunnel, the thrust of the tunnel working face has a significant effect on the width of the settlement trough, while the effect of grouting pressure on the width of the settlement trough is not as significant as with the thrust.
1. Introduction

When building subway shield tunnels in dense urban areas, due to the limitation of tunnel line design or the difficulty of using ground pile extraction technology, the shield machine encounters reinforced concrete pile foundation from time to time\cite{1,2}. Direct shield cutting pile foundation technology has negligible impact on the surrounding environment, low cost, short construction period, etc., with design safety allowance in pile foundation bearing capacity design. Hence, direct shield cutting pile foundation technology research and analysis are very valuable for engineering applications. At present, the technology of direct shield cutting pile foundation is not mature. There are few studies on the surface settlement caused by shield directly cutting underground tunnel pile foundation. Based on the Tianjin subway, Feng\cite{3} analyzed the influence of the lines excavated first on the characteristics of the lines excavated later from the perspective of tunnel excavation deformation and surface settlement and verified the superposition effect of the surface settlement caused by the shield construction of the double-line tunnel. Qiu\cite{4} studied the evolution law of ground deformation caused by shield tunneling of a double-track tunnel in combination with numerical simulation and field measured data. The results showed that the distribution of surface settlement curve during the construction of double-track tunnel changes from deep V-shape, shallow V-shape, U-shape, shallow W-shape, deep W-shape, and two independent V-shape with the change of the near- and far-distances of the double-line tunnel. Based on dynamic monitoring and analysis of the building group 9-13 in a residential area in Shenzhen during the process of shield crossing, Zhang\cite{5} reported that the cumulative settlement accounted for more than 60% of the total settlement from the time when the cutter head entered the house to the time when the shield tail left the house. Taking the shield cutting pile foundation of building 9-13 in a residential area of Shenzhen as a case study, Wang\cite{6} conducted a finite element numerical simulation, wherein the results showed that the settlement rate was fast and the shield cutting pile foundation and the settlement in this stage accounted for about 70% of the total settlement. Tang and Lin\cite{7} conducted theoretical analysis and finite element numerical simulation on the background of direct shield cutting pile foundation in Guangzhou Metro, studied the influence of negative friction resistance on residual pile bearing capacity, and provided a calculation method for estimating the bearing capacity of the residual piles. Zhou\cite{8} carried out theoretical analysis and numerical simulation based on shield passing through the Wanquan River viaduct of Beijing Metro Line 16. The results showed that the differential settlement and inclination of the bridge in the direction of the cross-section are larger than that in the direction of the longitudinal section, and the differential settlement is related to the relative position of pile foundation and tunnel on the horizontal plane. The differential settlement is the largest when one pile foundation is directly above the tunnel and the other is far away from the tunnel. There are many other examples of similar projects\cite{9-13}. Unlike the buildings mentioned in the above article, power tunnels are underground structures. Above the power tunnel is a municipal highway; if the surface settlement is too large, it will inevitably impact road traffic, residents' lives, etc. Based on this, this study mainly focuses on the surface settlement induced by the direct shield cutting pile foundation of a power tunnel;
and the influence of thrust force and grouting pressure on the width of the settlement trough is analyzed. This study can provide valuable references for similar future projects.

2. Project profile
The shield tunneling method is used to construct the section tunnel between Hanggang Station and Gongkang Road Station in Hangzhou Metro Line 4. According to the design plan and the scene investigation, when the shield tunnel passes through the power tunnel, two settlement reducing piles with a diameter of 600 mm, constructed with C35 concrete, should be cut off. The main formation calculation parameters of the soil are shown in Table 1. In addition, the spatial relationship of the existing power tunnel and the new metro tunnels is established in Figure 1.

**Table 1. Physical properties of the soil.**

| Soil Type          | K₀  | γ   | Thickness (m) | E  | ν  | c   | φ   |
|--------------------|-----|-----|---------------|----|----|-----|-----|
| Fill               | 0.5 | 18.6| 1.25          | 1.8| 0.33 | 10.0| (12.0) |
| Silty clay         | 0.56| 18.9| 1.61          | 1.8| 0.36 | 17.0| 14.5  |
| Clay               | 0.45| 19.5| 5.4           | 4.92| 0.31 | 35.0| 16.0  |
| Sand clay with silt| 0.53| 18.8| 8.2           | 2.37| 0.35 | 17.0| 19.0  |
| Clay               | 0.45| 19.7| 8.7           | 5.85| 0.31 | 40.0| 15.0  |
| Silty clay         | 0.45| 20.0| 7.84          | 4.38| 0.31 | 30.0| 18.0  |

**Figure 1.** Schematic diagram of shield cutting pile foundation.

3. Three-dimensional (3D) numerical modeling

3.1. Finite element modeling
This study uses Midas GTS's finite element analysis software to simulate the surface settlement before and after the direct shield cutting pile foundation. According to the engineering data, the outer diameter of the tunnel is 6.48 m, the buried depth of the new tunnels is −17.52 m, and the segment thickness is 0.35 m. The pile bottom elevation is −21.2 m. The minimum horizontal net distance between the shield and power tunnels is about 1.33 m, and the minimum vertical net distance is 4.74 m. Considering the impact range of tunnel construction on soil and power tunnel, the model size was chosen as 103 m × 48 m × 33 m. The model adopted a standard constraint, which only restricts the corresponding horizontal displacement in the horizontal direction, while the fixed constraint is adopted at the bottom to
restrict the vertical and horizontal displacements. The formations are based on the classic Mohr-Coulomb model; the tunnel lining structure materials are C50 concrete, the perfusion pile material is C35 concrete, and the elastic structure model is used. The formation is simulated using a 3D solid unit, the lining structure is simulated using a 2D plate unit, and the perfusion pile is simulated using a 1D beam unit. See Figure 2.

![Figure 2. Schematic diagram of the 3D model.](image)

3.2. Comparative analysis of measured data and simulation results
According to the monitoring scheme, appropriate monitoring points are arranged on the surface, as shown in Figure 3 and Figure 4.

![Figure 3. Layout of surface monitoring points](image)

![Figure 4. Layout of site surface monitoring points](image)

According to the measured data, the final settlement values of the surface monitoring points DBC44, DBC45, DBC46, and DBC47 are −3.36 mm, −1.74 mm, 0.35 mm, and −4.17 mm. The simulation results show that the final settlement values of the surface monitoring points DBC44, DBC45, DBC46, and DBC47 are −1.35 mm, −1.77 mm, −2.57 mm, and −3.93 mm respectively. The errors of the simulation results are −2.01 mm, 0.03 mm, 2.92 mm, and −0.24 mm. The accuracy of the numerical simulation is verified to a certain extent because there are assumptions in the numerical simulation, such as uniform formation distribution, no overcut clearance, and the grouting amount being exactly equal to the clearance of shield tail, so the error is within allowable limits of most engineering projects.

3.3. Analysis of the law of surface settlement
To explore the influence of power tunnel structure and pile cutting on surface settlement, the surface settlement curves of 1-1, 2-2, 3-3, and 4-4 sections intercepted, as shown in Figure. 5. The 1-1 section (y = 44 m) is the area without the influence of the power tunnel, the 2-2 section (y = 26 m) is the area affected by the power tunnel, the 3-3 is the section along the right tunnel axis, and 4-4 is the section along the left tunnel axis.

The Figure.6 and Figure.7 reveal the influence of power tunnel on the transverse surface settlement curve. The surface settlement curve 1-1 shows that the surface settlement conforms to the Peck\cite{14} settlement curve when the right tunneling is over. The width of the settlement trough gradually widened to the left during the excavation of the left line, and the surface settlement curve showed an axisymmetric "U" shape when the left tunneling is over. The maximum settlement value is −6.40 mm at the right tunnel axis. The 2-2 surface settlement curve shows that the power tunnel structure with high stiffness acts as a beam in the soil, effectively reducing the soil's settlement above it. When the left tunnel is tunneling for 24 m, the settlement value of 1-1 settlement curve at the surface corresponding to the left tunnel axis is −6.04 mm, and the settlement value of 2-2 settlement curve is −1.07 mm, indicating an
82.29% decrease. The settlement value at the right tunnel axis is −6.38 mm and −3.85 mm, respectively, decreasing by 39.66%. The different proportion of surface settlement reduction is that the spatial position of the new left and right tunnels and the power tunnels are different. The reducing piles are arranged in the middle of the power tunnel in large numbers, reducing the surface settlement when the left tunnel passes through from the middle of the power tunnel. When the left tunnel is tunneling for 36 m, the surface settlement value above the cut piles 1 and 2 increased significantly, indicating that the cutting pile foundation had a significant effect on surface settlement. When the left tunnel tunneling is completed, the settlement value on the surface of the left tunnel is −1.74 mm, the settlement value of the right tunnel is −3.76 mm, and the settlement curve is nonaxisymmetric in the range affected by the power tunnel structure.

![Figure 8](image1.png)  
**Figure 8** Surface settlement curve of 3-3 section
The Figure 8 and Figure 9 reveal the influence of power tunnel on the longitudinal surface settlement curve. The surface settlement curve 3-3 shows that when the right line is tunnelled 12 m and 24 m, the surface settlement behind the excavation is larger, the surface settlement is smaller in the range 3D before the excavation (D is the tunnel excavation diameter), and a slight rise in the surface outside the 3D range of the excavation face front is experienced. When the right line is tunnelled for 36 m, the surface settlement behind the excavation to the power tunnel is relatively moderate due to the influence of the power tunnel. After the right line tunneling, the settlement curve is high in the middle and low on both sides. The settlement value of the area affected by the power tunnel is about −3.6 mm, and the maximum settlement value is −6.29 mm, which further proves that the power tunnel structure can reduce the settlement of the soil above it. The surface settlement curve 4-4 shows that the right line tunneling causes a slight surface settlement of the left tunnel axis. At the end of the right line tunneling, the maximum settlement value of the left tunnel axis is −0.57 mm. When the left line is tunnelled for 12 m, the surface settlement curve is similar to the right tunnel. When the left line is tunnelled for 24 m, the surface settlement before the excavation is very small due to the influence of the power tunnel, and the settlement curve has an obvious turning point. After the left-line tunneling, the settlement curve was also high in the middle and low on both sides. The settlement value of the area affected by the power tunnel is about −1.5 mm, and the maximum settlement value is −6.59 mm. Compared with the 3-3 settlement curve, the
settlement value of the area affected by the power tunnel in the 4-4 curve is significantly smaller, which proves that the reducing pile can considerably reduce the surface settlement.

4. Analysis of construction parameter

The thrust force of the tunnel working face and grouting pressure are selected as key parameters of construction simulation for variable analysis. Three thrust groups were selected, which are 100%, 115%, and 130% lateral earth pressure (163.3kPa, 187.8kPa, and 212.3kPa) at the tunnel axis, respectively. In addition, three groups of grouting pressure (200kPa, 300kPa, 400kPa) are selected. The influence of thrust and grouting pressure on the surface settlement is analyzed by comparing the simulation results under different working conditions.

4.1. Analysis of the influence of thrust on settlement

Figures 10, 11, and 12 are surface settlement diagrams at the end of left-line tunneling under different thrust conditions. When the grouting pressure of 300 kPa is kept constant, the final settlement value decreases with the increase of the thrust force. The data shows that outside the impact range of the power tunnel, the width of the settlement trough generated by the
tunneling of the double-line tunnel under various working conditions is about ±28 m in the middle line of the double-line tunnel. The change of the thrust force has little influence on the width of the settlement trough in this zone. Within the influence range of the power tunnel, the width of the settlement trough is about ±28 m in the middle line of the double-line tunnel at a thrust of 163.3 kPa. At a thrust of 187.8 kPa and 212.3 kPa, the width of the settlement trough is about ±25 m in the middle line of the double-line tunnel and the width of the settlement trough is significantly affected by the thrust.

4.2. Analysis of the influence of grouting pressure on settlement

Figures 13, 14, and 15 are the surface settlement diagrams at the end of left-line tunneling under different grouting pressure conditions. When the thrust is maintained at 163.3 kPa, the final settlement value decreases with increasing grouting pressure. The data show that outside the impact range of the power tunnel, the width of the settlement trough generated by the tunneling of the double-line tunnel under various working conditions is about ±28 m in the middle line of the double-line tunnel. Thus, grouting pressure changes have little influence on the width of the settlement trough in this zone. However, within the impact range of the power tunnel, under grouting pressures of 200 kPa, 300 kPa, and 400 kPa, the widths of the settlement trough are about ±28 m, ±28 m, ±25 m in the middle line of the double-line tunnel,
respectively. Thus, the width of the settlement trough within this range can be significantly reduced under the condition of higher grouting pressure, and the effect of the grouting pressure on the width of the settlement trough is not as significant as that of thrust.

5. Conclusion

This study analyzes and summarizes the influence of shield tunneling through power tunnels and directly cutting pile foundations on surface settlement and draws the following conclusions:

(1) According to the measured data, the final settlement values of the surface monitoring points DBC44, DBC45, DBC46, and DBC47 are $-3.36 \text{ mm}$, $-1.74 \text{ mm}$, $0.35 \text{ mm}$, and $-4.17 \text{ mm}$, and the simulation results show that the final settlement values of the surface monitoring points DBC44, DBC45, DBC46, and DBC47 are $-1.35 \text{ mm}$, $-1.77 \text{ mm}$, $-2.57 \text{ mm}$, and $-3.93 \text{ mm}$ respectively. The simulation errors were $-2.01 \text{ mm}$, $0.03 \text{ mm}$, $2.92 \text{ mm}$, and $-0.24 \text{ mm}$. The accuracy of the numerical simulation is verified to a certain extent because there are assumptions in numerical simulation, such as uniform formation distribution, no overcut clearance, and the grouting amount being exactly equal to the clearance of shield tail; hence, the error is within allowable limits of engineering projects.

(2) Power tunnel structure acts as a beam in the soil and effectively reduces the surface settlement. The surface settlement corresponding to the right tunnel is reduced by 39.66%. Due to the reducing pile, the surface settlement corresponding to the left tunnel is reduced by 82.29%, and the reduction effect is very significant. The surface settlement curve is not axisymmetric in the range affected by the power tunnel structure. Along the tunnel axis, the final surface settlement curve is “high in the middle and low on both sides”.

(3) The final settlement value of the surface decreases with the increase of the thrust force or the grouting pressure. The width of the settlement trough beyond the influence range of the power tunnel is about ±28 m in the middle line of the double-line tunnel, and the change of the thrust force or grouting pressure has little influence on the width of the settlement trough in this zone. Within the impact range of the power tunnel, the width of the settlement trough is significantly affected by thrust. When the thrust is increased to 187.8 kPa, the width of the settlement trough can be reduced to ±25 m in the middle line of the double-line tunnel. The effect of grouting pressure on the width of the settlement trough is not as significant as the thrust. The width of the settlement trough can be reduced to ±25 m in the middle line of the double-line tunnel under a higher grouting pressure (400 kPa).

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