Study on Surface Settlement Law of Shield Construction in Mudstone Stratum

Song Xiangshuai¹,a*, Xiong Dongdong²,b

¹ CCC Second Harbor Engineering Company Ltd, Hubei Wuhan, China
² CCC Second Harbor Engineering Company Ltd, Hubei Wuhan, China
*aemail:songxiangshai@163.com,bemail: 06317xidoo@sina.com

Abstract: In order to explore the influence of groundwater on the surface settlement law of shield construction under mudstone with different weathering degrees, this paper studies the influence of buried depth on surface settlement under different weathered mudstone, and the influence law of groundwater in stratum and different depths of water level on settlement of shield construction using a three-dimensional(3D) numerical model establish by finite element software based on the engineering background of Chengdu Metro Line 18. The results show that: (1) With the increase of buried depth, the range of lateral settlement trough on the surface gradually increases, but the maximum settlement gradually decreases. By analyzing the buried depth and the maximum surface settlement, it is found that the buried depth ratio has a logarithmic relationship with the corresponding maximum surface settlement. (2) The construction settlement increases obviously when there is groundwater in the stratum compared with when there is no groundwater. (3) The depth of water level above the vault and the maximum settlement caused by shield construction basically conform to the linear law. For every 1m increase in the depth of water level above the vault, the maximum settlement value can increase by about 0.43 mm. Compared with the field monitoring data, the calculation results are basically consistent, which shows the reliability of the calculation. This paper aims to provide experience for similar projects.

1. Introduction

In recent years, with the rapid increase of urban scale and population, the ground transportation has been overburdened, and the urban rail transit, especially the shield method, has ushered in the development climax. The influence of shield construction on the surrounding environment is mainly reflected in the surface settlement. Due to the particularity of the upper environment of the subway tunnel, the settlement control requirements are strict. With the increase of subway construction scale and the extension of construction period, the difference of groundwater level caused by seasonal rain has gradually become an uncertain factor in the control of ground settlement. In recent years, collapse and water leakage accidents of different scales have occurred in Guangzhou, Fuzhou, Foshan and Hangzhou. The reasons are basically related to groundwater, and the groundwater pressure caused by different water levels will increase Structure construction. However, the settlement law of shield construction in different strata has its own characteristics. Therefore, it is necessary to analyze and study the surface settlement law of specific strata affected by groundwater.
At present, some scholars have carried out the research on the influence of tunnel depth, groundwater and other factors on the ground settlement. Zhang Ajin [1] analyzed the influence law of different tunnel diameters and buried depths on the instability mode of excavation face by ABAQUS analysis software. Huang Zhaomei, Cao Guangyong et al. [2] analyzed the influence of buried depth and soil loss rate on the change law of surface settlement by shield overbreak model test. Ruan Lei, Jian Yunqi, etc. [3] studied the beam structure, track line and pile foundation displacement of bridges under different buried depths by ANSYS software relying on Wuhan Metro Line 3. Yang Ziqi [4] simulated the construction process of the two tunnels, and established numerical models with or without fluid-structure coupling respectively to obtain the influence of groundwater on tunnel excavation by FLAC3D fluid-structure coupling calculation model. Zong Zhenyu [5] revealed the important influence of groundwater seepage in tunnel construction on stratum deformation based on the passage project of Changchun Metro Line 1. Zhang Dongmei, Liu Yin et al. [6] emphatically analyzed the pore water pressure distribution and the long-term settlement development law of stratum and tunnel under different seepage conditions based on the mapping transformation of complex variable function and considering the lining effect. Xin Li [7] studied the instability evolution law and failure characteristics of the excavation face under different water cover depths, cohesion and internal friction angles by establishing a numerical model of the cross-river shield tunnel taking the cross-river tunnel as the engineering background. At present, the research on the influence law of buried depth and groundwater mainly focuses on the excavation face. However, there is little research on the characteristics of surface settlement law. In addition, because groundwater has obvious influence on mudstone with different weathering degrees, this paper analyzes the influence law of different buried depth and groundwater level on surface settlement in shield construction under different weathering mudstone strata, and provides experience for similar projects based on Chengdu Metro Line 18.

2. Project Introduction
The terrain traversed by shield tunnels from Airport South Station to T3T4 Station of Chengdu Metro Line 18 is mostly hilly, and the ground fluctuation varies greatly. According to field investigation, the maximum buried depth of the ground is 29.3m, and the minimum is 5.14m. The ground structures traversed by the tunnel are mainly dense houses, iron towers and roads, so it is necessary to strictly control the surface settlement. According to the hydrogeological data of the interval, the buried depth of the static groundwater level in the shield interval is about 0.1~18.5m. Under natural ecological conditions, the normal buried depth of the groundwater level in the wet season is about 5m, and the annual variation of the groundwater level is about 1.0~4.0m.

3. Calculation Model and Parameter Formulation
3.1. Establishment of calculation model
The analytical model of 60m $\times$ 45m (25rings) $\times$ 42m was established in order to analyze the influence of tunnel excavation on surface settlement. The diameter of the excavation face is 8.6m, the outer diameter of the segment is 8.3m, the inner diameter of the segment is 7.5m, and the width of the segment is 1.8m. After excavation, the interval between the segment and the soil is 0.15m. The ring of the shield tail gap is filled with synchronous grouting equivalent layer. Considering the timeliness of slurry hardening, a staggered hardening process is adopted, i.e. when one ring is excavated, a ring of segment and thin slurry with smaller elastic modulus are assembled, and the previous ring of thin slurry is hardened.
3.2. Selection of calculation parameters

Mohr-Coulomb elastic-plastic model is adopted for soil, and the seepage parameters of soil are set by "Permeability". The lining is made of reinforced concrete, and its strength is higher than that of the surrounding soil. During the whole excavation and unloading process, it is basically in the elastic deformation stage, so the linear elastic model is adopted and it is assumed to be impermeable. In order to simulate the change of water level, the saturation of soil above water level is assumed to be "0" and "C3D8R" 3D stress element is adopted. It is considered that the soil below the water level is completely saturated, and the "C3D8P" element considering the influence of pore water pressure is adopted. In addition, the corresponding pore water pressure boundary condition is set on the boundary of soil below the water level, and the boundary condition of pore water pressure of "0" is set on the water level height, while only the displacement boundary condition is set on the soil above the water level.

See Table 1 for the selection of calculation parameters of the analysis model. The formation permeability coefficient refers to the corresponding engineering geological parameters, and the permeability coefficient of segment and slurry is $5 \times 10^{-13}$ m/s.

| Strata and materials       | Severe (kN/m$^3$) | Modulus of deformation (MPa) | Poisson's ratio | Internal friction angle (°) | Cohesion (kPa) | Permeability coefficient (m/s) | Porosity |
|----------------------------|-------------------|-----------------------------|----------------|-----------------------------|----------------|--------------------------------|----------|
| Silty clay                 | 19.5              | 24.8                        | 0.28           | 15                          | 34             | $1.1 \times 10^{-5}$            | 0.67     |
| Strongly weathered mudstone| 22.1              | 50.0                        | 0.25           | 30                          | 30             | $1.1 \times 10^{-9}$            | 0.67     |
| Moderately weathered mudstone| 23.5           | 134                         | 0.22           | 33                          | 300            | $1.1 \times 10^{-12}$           | 0.67     |
| Shield shell               | 78.0              | $2.10 \times 10^5$         | 0.20           | —                           | —              | 0                              | —        |
| Segment lining             | 31.0              | $2.93 \times 10^4$         | 0.20           | —                           | —              | $5 \times 10^{-11}$             | —        |
| Dilute slurry              | 21.0              | 1.00                        | 0.26           | —                           | —              | 0.001                          | —        |
| Hard grout                 | 21.0              | 50.0                        | 0.25           | —                           | —              | $5 \times 10^{-11}$             | —        |

3.3. Simulation process of shield tunnel excavation

The actual process of shield tunnel excavation includes working face excavation, lining ring assembly and shield tail synchronous grouting. The dynamic excavation process of shield tunnel is simulated by using the element birth and death technology of finite element. The specific steps are as follows:

1) Dead weight is applied to the stratum, initial in-situ stress field is established, initial displacement is obtained and cleared;

2) Excavate the first and second ring soil bodies, apply the corresponding shield shell structure, apply the soil bin pressure in the normal direction of the working face, and the distribution form and
value of the soil bin pressure are respectively set according to different conditions;

(3) Excavate the soil with the length of the first ring segment (1.8m) in front, apply the corresponding shield structure, and apply the soil bin pressure in the normal direction of the working face. At the same time, remove the first ring shield structure and apply the first ring segment structure;

(4) Repeat step (3) until the excavation is completed.

4. Analysis of Influencing Factors

4.1. Influence of buried depth on surface settlement of mudstone stratum

Figure 2 and 3 are graphs of lateral and longitudinal settlement of the surface under different buried depth ratios. The curve analysis in the figure shows that with the increase of buried depth ratio, the lateral settlement of the surface gradually decreases; and the deformation range of settlement tank increases with the increase of buried depth ratio. The main reason for this phenomenon is soil settlement caused by soil loss and consolidation settlement, among which soil loss is the main factor. The deformation law of soil loss is that the farther away from the excavation face, the smaller the deformation, and the deformation range increases with the increase of the distance from the excavation face.

Comparing the maximum surface displacement settlement under different buried depth ratios, the curve relationship between the maximum surface displacement settlement and buried depth ratio under different buried depth ratios is obtained, as shown in Figure 4.

![Figure 2 Graph of lateral settlement of surface at y=18m](image1)

![Figure 3 Settlement curve of the measuring point of the surface central axis at y=18m](image2)

![Figure 4 Graph of the relationship between the maximum settlement of the surface and the ratio of buried depth](image3)
The curve analysis in Figure 4 shows that with the increase of buried depth, the maximum displacement settlement of the surface gradually decreases, which indicates that the buried depth ratio has a logarithmic relationship with the corresponding maximum settlement of the surface. When the tunnel passes through the undulating stratum, it is necessary to properly control the parameters such as silo pressure and cutter head thrust to ensure reasonable settlement, especially in shallow stratum due to the difference of buried depth.

4.2. Influence of groundwater on surface settlement

In order to study the influence of groundwater on the surface settlement of shield tunnel, it is necessary to consider the key factor of whether the excavation face is drained. When the pressure of the soil bin is sufficient, the pressure of the soil bin can resist the water and soil pressure of the excavation face, and it can be considered that the excavation face is not drained at this time; When the propulsion force of the shield machine is insufficient, the groundwater in front of the shield machine will flow back to the pressure chamber. At this time, it can be considered that the excavation face is drained. The set analysis conditions are shown in Table 2.

| Conditions | Distance between groundwater level line and surface (m) | Drainage condition of excavation face | Uppermost silo pressure (kPa) | Lowest silo pressure (kPa) |
|------------|--------------------------------------------------------|-------------------------------------|-----------------------------|--------------------------|
| Condition 1 | No groundwater                                         | —                                   | 104.890                     | 236.362                  |
| Condition 2 | 0                                                      | Partial drainage                    | 179.890                     | 354.362                  |
| Condition 3 | 5                                                      | Undrained                           | 154.890                     | 329.362                  |
| Condition 4 | 5                                                      | Free drainage                       | 154.890                     | 329.362                  |
| Condition 5 | Partial drainage                                       |                                     | 154.890                     | 329.362                  |
| Condition 6 | 10                                                     | Partial drainage                    | 129.890                     | 304.362                  |

(1) Analysis of calculation results under different drainage conditions of excavation faces

Figure 5 (a)~(c) are the cloud pictures of pore water pressure distribution when the excavation face is excavated to y=28m under different drainage conditions. The analysis shows that when the drainage conditions of excavation face are different, the permeability coefficient of mudstone stratum is small, which leads to poor seepage of groundwater in stratum. Figure 5 (a) shows that when the excavation face is undrained, due to the low permeability of mudstone and undrained excavation face, the change of groundwater pore water pressure is relatively uniform and basically presents stratification phenomenon. Figure 5 (b) shows the partial drainage of the excavation face. When the pore water pressure of the excavation face is set to 75% of the corresponding initial pore water pressure [9], local...
drainage occurs and a certain degree of pore water pressure fluctuation occurs near the excavation face. When the excavation face is set to free drainage, a limit state is simulated at this time, and groundwater in the stratum flows towards the excavation face, especially the air pressure near the excavation face changes obviously.

Figure 6 shows the lateral settlement curve of the surface when the excavation face is excavated to \( y=28 \text{m} \) under different drainage conditions.

As can be seen from the lateral settlement curves of the surface of different excavation faces in Figure 6, when the excavation face is not drained, the maximum settlement of the surface is 7.53mm, the influence range of the surface settlement is about 3.0D, and the settlement of each point of the surface outside the settlement groove is about 0.5mm. When the excavation face is partially drained, the maximum displacement settlement of the surface is 9.79mm, the influence range of surface settlement is about 3.0D, and the settlement of each point of the surface outside the settlement groove is about 0.5mm. When the excavation face is completely drained, the maximum displacement settlement of the surface is 16.83mm, the influence range of surface settlement is about 3.0D, and the settlement of each point on the surface outside the settlement groove is about 1.0mm. With the reduction of the pressure of the excavation face, the maximum displacement settlement of the surface gradually increases, and the calculation results are basically consistent with Li Xiao's [9] law on the drainage of the excavation face to the surface settlement, i.e. the drainage of the excavation face is unfavorable to the surface settlement during the excavation process, and the drainage of the excavation face should be strictly controlled during the construction to reduce the leakage of groundwater on the excavation face.

(2) Analysis of calculation results of different groundwater level lines

When the tunnel is excavated on site, the excavation face is generally affected by construction factors, which makes the excavation face unable to completely guarantee undrained water. Setting the pressure of the excavation face to 75% of the corresponding initial pore water pressure to simulate the partial drainage of the excavation face, and analyzing different groundwater levels such as condition 1 (not considering groundwater), condition 2 (the distance between the groundwater level and the surface is 0m), condition 5 (the distance between the groundwater level and the surface is 5m), and condition 6 (the distance between the groundwater level and the surface is 10m).
Figure 7 (a)–(c) is a nephogram of pore water pressure distribution when excavation under different groundwater level lines reaches \( y = 28 \text{m} \). The analysis shows that, because the distance between the groundwater level and the ground surface decreases, the overlying water depth of the tunnel gradually decreases, and the excavation face set during the tunnel excavation is partially drained, the influence of tunnel excavation on the stratum disturbance is increasing, and the groundwater pore water pressure appears to some extent. Fluctuation.

Figure 8 shows the lateral settlement curve of the surface when the excavation face is excavated to \( y = 28 \text{m} \) under different groundwater level lines. The analysis shows that the greater the overlying water depth, the greater the maximum surface settlement and the influence range of surface settlement. This is because after the tunnel is excavated, the pore water pressure inside the segment decreases, and the groundwater around the tunnel infiltrates into the tunnel under the drive of hydrodynamic pressure, which causes the consolidation settlement of the soil. When the groundwater level rises, the pore water pressure increases, and the change of pore water pressure around the tunnel will cause greater consolidation settlement. When seepage is not considered, there is no consolidation settlement of soil, so the maximum settlement and the influence range of surface settlement are relatively small. The greater the overlying water depth, the greater the hydrodynamic pressure and the larger the seepage disturbance zone caused by tunnel excavation. It can be considered that the influence range of surface settlement is completely determined by stress field when seepage is not considered. When seepage is considered, the influence range of surface settlement is mainly determined by seepage disturbance zone caused by tunnel excavation.

The curve analysis in Figure 9 shows that the depth of water level above the vault and the maximum surface settlement caused by shield construction basically conform to the linear law. The maximum settlement value can increase by about 0.43mm for every 1m increase in water level depth above the vault.
vault. With the increase of water level depth above the vault, the maximum displacement settlement of the surface gradually increases, and the calculation results are basically consistent with the research on the law of groundwater on surface settlement by Lin Zhibin and Li Yuanhai [10].

5. Comparative Analysis of Calculation Results and Monitoring Data

By comparing the surface settlement of the excavation to y=17m in the numerical simulation process with the on-site monitoring section YDK68+790, as shown in Figures 10 and 11.

![Figure 10 Settlement tank curve of surface cross-section of YDK68+790 section](image1)

![Figure 11 Displacement settlement curve of surface measuring point DBY68+790](image2)

The curve analysis of Figure 10 and 11 show that when considering groundwater and buried depth, the change trend is basically consistent with the law reflected by the field measured data by the results of numerical analysis, which indicates the reliability of the analysis results and provides experience for subsequent similar projects.

6. Conclusions

The influence of buried depth under mudstone stratum and groundwater on the displacement and settlement of stratum and surface is emphatically discussed, and the following conclusions are obtained through the analysis of shield construction in mudstone stratum in Chengdu:

(1) With the increase of the buried depth ratio, the scope of the lateral settlement trough of the surface gradually increases, but the maximum displacement settlement of the surface gradually decreases. The relationship between the buried depth ratio and the maximum displacement settlement of the surface satisfies $y=2.5931\ln(x)-6.7784$. The relationship between the buried depth ratio and the corresponding maximum surface settlement is approximately logarithmic.

(2) Whether the excavation face is drained or not is an important link that affects the law of stratum displacement. When the excavation face is free to drain, the displacement disturbance of the stratum caused by tunnel excavation is greater, and when the excavation face is not drained, the displacement settlement value of the stratum is smaller. It shows that with the decrease of the pressure of the excavation face, the maximum displacement settlement of the surface gradually increases, that is, during the excavation process, the drainage of the excavation face is unfavorable to the surface settlement, and the drainage of the excavation face should be strictly controlled during the construction.

(3) The construction settlement increases obviously when there is groundwater in the stratum compared with when there is no groundwater. The depth of water level above the vault and the maximum surface settlement caused by shield construction basically conform to the linear law. When the depth of water level above the vault increases by 1m, the maximum settlement value can increase by about 0.43 mm, which indicates that the greater the overlying water depth of the tunnel, the greater the maximum settlement of the surface and the influence range of the surface settlement. In order to ensure reasonable settlement during construction, the tunnel construction should be carried out in dry season as far as possible to reduce the disturbance influence on the stratum.

(4) By analyzing the influence law of tunnel buried depth and groundwater on surface settlement, the
risk of uneven surface settlement caused by groundwater level difference caused by seasonal rainfall is reduced, which provides technical support for surface settlement control in construction. In addition, it provides experience for similar strata or projects.

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