FEM analysis of induced ground settlement of tunneling side-crossing high-voltage rod foundation considering reinforcement measures

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Abstract: Taking the actual working conditions of the Wuhan Guanggu 1st/Gaoxin 4th drainage channel project as the research object, Finite Element Method (FEM) is used to analyse the effectiveness of reinforcement measures to control surface settlement deformation around poles during tunnel propulsion. Calculations prove that as the tunnel advances, the displacement around the high-voltage rod gradually increases and tends to stabilize; The numerical simulation study of the combined engineering conditions of different reinforcement measures shows that the pile foundation reinforcement and the pile top beam reinforcement both can effectively reduce the surface settlement, and the reinforcement effect in pile top beam is far greater than that in pile foundation; The numerical results of both the two reinforcement measures involved are compared with the actual monitoring data, and the results are in good agreement. Then the correctness of the numerical model is verified. Therefore, the two reinforcement measures in this area show great effectiveness by studying the four different engineering conditions. The reinforcement measures have certain reference value for related engineering design in this area.

1. Introduction
With the rapid development of Chinese transportation, there are more and more engineering construction projects in the red clay area, which poses a major challenge to the safe construction and operation of infrastructure construction.

Red clay is formed by weathering of carbonate rocks. As one of the special soils in actual engineering, it is widely distributed in China[1]. Red clay is a high liquid plastic limited clay with high viscosity, high void ratio, low density, low compaction, high shear strength, strong impermeability and great bearing capacity[2]. Considering the special physical and chemical properties of red clay, it is inevitable
that the urban underground tunnel will contain more insecure factors. For example, the tunnel construction will disturb the soil and cause the ground to move. Uneven settlement of the foundation of the building (structure) and additional deformation of the superstructure may even lead to cracking, destruction and collapse of the building (structure). When the tunnel passes through the red clay stratum, it is necessary to reinforce the surrounding structures to reduce the influence of settlement deformation. Ouyang Lian[3] took the strong tamping method in the construction of subgrade engineering as the research object, and carried out micro and macro analysis on the red clay reinforcement mechanism. Liu Can et al[4] conducted a systematic analysis of the stratum structure of the red clay tunnel and studied the grouting effect of the pipe shed. Zhou Leping[5] studied the reinforcement mechanism of the red clay tunnel arch foundation.

In general, the research on the impact of the tunnel propulsion process on the surrounding environment is mainly carried out by means of empirical methods, analytical methods, numerical calculation methods and engineering measurement methods, focusing on tunnel excavation to surface settlement, residential or commercial buildings, and underground construction, etc[3-5].

In terms of current research, most researchers focus on the reinforcement of red clay foundation and the deformation of the ground caused by tunnel construction, but there are few research on the reinforcement measures of the overlying structures of red clay tunnels. In this paper, tunnel with double-side drift method side through the high-voltage rod, a typical engineering situation of the Wuhan Guanggu 1st/Gaoxin 4th drainage channel project is taken as an engineering example. The PLAXIS software is used to explore the influence of surface settlement around the high-voltage rod under different reinforcement measures to verify the effectiveness of reinforcement measures in controlling the ground settlement. The correctness of the numerical model can be verified by comparing the results of both the two reinforcement measures involved in the numerical simulation with the field monitoring data, then summarize the different reinforcement measures and explore the influence of that on the settlement of the surface around the high-voltage rod. Finally, more experience will be accumulated in the design and construction of subsequent tunnel projects in Wuhan.

2. Project Overview

The total length of the drainage channel of Wuhan Guanggu 1st/Gaoxin 4th Road is 2300m, of which 720m is shallow-buried tunnel. The shallow-buried tunnel passes through special soil sections such as red clay, and the geological conditions are complex. The test site area is plain fill, red clay and limestone from top to bottom. Considering the unique engineering properties of red clay, the tunnel is excavated under the geological conditions, and the surrounding rock is prone to large deformation. If the support method is unreasonable, it will even lead to collapse. This paper focuses on the surface settlement deformation around the pole caused by the tunnel crossing the high-voltage rod. Figure 1(a) shows the geological distribution of the construction section of double-side drift method. This section is based on the Quaternary plastic-hard plastic old clay and red clay with poor self-stability and common side collapse. The surrounding rock mass of the tunnel has water softening, shrinkage and deformation. The surrounding rock grade is V-VI.

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The step-by-step construction process of the double-side guide tunnel is carried out according to the actual construction sequence, just as the figure 1(b) shows. Firstly, the guiding tunnels are excavated in sequence in the order of ①, ②, ③, ④, ⑤ and ⑥. At the same time, lining and the anchor rod are laid after the corresponding guiding tunnel is excavated. Finally, the lining and the temporary support should be removed until the previous work is over. The length of each excavation in the longitudinal direction is 1m.
3. Calculation and analysis

3.1. Numerical model and calculation parameters

In order to verify the effectiveness of pile foundation reinforcement measures and pile top reinforcement beam reinforcement measures to control the settlement of the ground surface, numerical models under four different combinations of reinforcement measures is set up: no reinforcement measures, pile foundation reinforcement measures, pile top reinforcement beam reinforcement measures and both the two reinforcement measures involved.

The numerical model soil layer is composed of plain fill, red clay and limestone from top to bottom, respectively. The model adopts Cartesian coordinate system and the coordinate axis determination method: horizontal direction (X axis); the tunneling direction (Y axis) is the positive direction; the vertical direction (Z axis) is positive. The horizontal clearance between the high-voltage rod and the tunnel is about 7.709m, the depth of the pole foundation is 12m, the buried depth of the tunnel is 13.5m, and the diameter of the high-voltage rod is 0.8m. According to the influence of tunnel construction on the soil as well as the principle of Saint-Venans, the size of selected model has a range of 3-5 times the diameter of the tunnel. Therefore, the proposed model size is 50m×20m×50m.

In the process of the tunneling, the initial support and the temporary support include anchors and they are arranged in the form of plum piles, which are difficult to simulate separately. In this paper, equivalent simulation is used to simulate anchors, etc. The strength of the equivalent reinforcement area can be obtained as follows:

\[ E_{\text{red}} \cdot V_{\text{red}} + E_{\text{anchor}} \cdot V_{\text{anchor}} = E_{\text{eq}} \cdot V_{\text{eq}} \]  (1)

\[ V_{\text{red}} + V_{\text{anchor}} = V_{\text{eq}} \]  (2)

Where, \( E_{\text{red}} \) is the elastic modulus of red clay; \( V_{\text{red}} \) is the volume of red clay in the anchor reinforcement area. \( E_{\text{anchor}} \) is the elastic modulus of anchor. \( V_{\text{anchor}} \) is the volume sum of all reinforcement zone anchors. \( E_{\text{eq}} \) is the equivalent elastic modulus of the reinforced area. \( V_{\text{eq}} \) is the volume of the reinforcement area.

Then the equivalent elastic modulus can be obtained and its value is 28.7 Mpa.

For the pile foundation reinforcement measures, it mainly considers the foundation above the tunnel and below the pile. The depth of grouting is to the bottom of the pile. The grouting adopts ordinary Portland cement, the cement adopts 42.5 grade, and the water-cement ratio is 0.6-1.0, which can infiltrate an appropriate amount of additives. The diffusion radius is 2.0 m. According to “Concrete structure
engineering construction quality acceptance specification”, the strength of the reinforcement zone is determined to be 34.1 Mpa.

The advanced pipe shed support is considered by an equivalent method. The elastic modulus of steel is converted to shotcrete by the following formula:

$$E = E_0 + \frac{S_s \times E_g}{S_c}$$  \hspace{1cm} (3)

Where, $E$ is the converted concrete modulus; $E_0$ is the original concrete modulus; $S_s$ is the cross-section area of steel; $E_g$ is the elasticity modulus of steel. $S_c$ is the cross-section area of concrete.

For the pile top coupling beam reinforcement measures, the pile-retaining structure is added to the periphery of the high-voltage rod, and the pile-top beams are arranged to form a steel frame structure, especially the horizontal and vertical joints, thereby enhancing anti-interference of the high-voltage rod. The pile top beams in both directions are orthogonal and their length is 5 m. The row piles are parallel to the poles, connected to the pile top beams, and inserted into the soil. The length of the row pile is 11.4 m. Both the high-voltage rod and the row pile are simulated by the embedded beam element, and the pile-top coupling beam is simulated by the general beam element.

Moor-Coulomb Criterion is used to describe the physical and mechanical processes of soil. Linear elastic model is used for the primary lining, temporary support and secondary lining. The soil and material parameters are shown in Table 1, and the structural element parameters are shown in Table 2.

The model is divided by automatic meshing technology. The soil is simulated by solid elements. The primary, secondary and temporary supports are simulated by plate elements. In order to obtain more accurate results, the mesh around the excavated tunnel is properly encrypted.

| Soil layer          | $\gamma_{unsat}$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | $E$ (MPa) | $\nu$ | $c$ (kPa) | $\phi$ (°) | $k_0$ (m/d) | $H$ (m) |
|---------------------|------------------------------|---------------------------|-----------|------|----------|----------|------------|--------|
| Prime fill          | 17.6                         | 17.6                      | 15        | 0.35 | 8        | 8        | 0.552592e-1 | 2      |
| Red clay            | 17.8                         | 19.0                      | 20        | 0.2  | 22       | 15       | 0.551728e-3 | 20     |
| 7-1 limestone       | 23.0                         | 27.0                      | 11400     | 0.17 | 26       | 56       | 0.12789e-2  | 28     |
| Advance reinforcement zone | 22                    | 22                        | 25        | 0.2  | 32.4     | 15       | 0.551728e-3 | -      |
| Equivalent reinforcement zone | 20                  | 20                        | 28.7      | 0.2  | 41.6     | 19.2     | 0.551228e-3 | -      |

| Material               | $d$ (m) | $\gamma$ (KN/m) | Attributes                   | $E$ (MPa) | $\nu$ |
|------------------------|---------|-----------------|------------------------------|-----------|------|
| First lining           | 0.2     | 22              | Linearity, isotropy          | 5e3       | 0.2  |
| Temporary support      | 0.0227  | 22              | Linearity, isotropy          | 5e3       | 0.2  |
| Secondary lining       | 0.6     | 22              | Linearity, isotropy          | 5e3       | 0.2  |

| Structure              | $E$ (MPa) | $\gamma$ (kN/m$^3$) | $D$ (m) | $A$ (m$^2$) | $I_2$ | $I_3$ | $T_{start}$ | $T_{end}$ | $F_{max}$ |
|------------------------|-----------|---------------------|---------|------------|------|------|-----------|-----------|----------|
| high-voltage rod       | 3e4       | 24                  | 0.8     | 0.5027     | 0.02 | 0.02 | 200       | 500       | 10000    |
| Pile top beam          | 3e4       | 24                  | -       | 1.131      | 0.02 | 0.02 | -         | -         | -        |
| Row pile               | 3e4       | 24                  | 1.2     | 1.131      | 0.1018| 0.1018| 200       | 500       | 10000    |

A vertical displacement constraint is applied to the bottom of the model, and the y-direction displacement constraints are applied to the front and rear sides, and the x-direction displacement
constraints are applied to the left and right sides. Models of tunnel side-through high-voltage rod under four different conditions (hidden soil) are shown in Figure 2.

![Models of tunnel side-through high-voltage rod](image)

(a) No reinforcement measures  
(b) Pile foundation reinforcement measures  
(c) Pile top coupling beam reinforcement measures  
(d) Both the reinforcement measures involved

Figure 2. Three-dimensional model of tunnel side-through voltage pole under four different conditions

3.2. Result analysis

3.2.1. Analysis of monitoring results

The partial layout of the construction site is shown in Figure 3. From December 11, 2017 to March 7, 2019, more than one year of settlement monitoring was carried out on the soil layers around the high-voltage rod (DXG1-1, DXG1-2, DXG1-3, and DXG1-4).

![Construction site monitoring point layout](image)

Figure 3 Construction site monitoring point layout

![The surface settlement around the monitoring point](image)

Figure 4 The surface settlement around the monitoring point

This section is mainly based on the analysis of the settlement monitoring data over time and the cumulative settlement. Figure 4 shows the variation of the settlement at four monitoring points of DXG1-1, DXG1-2, DXG1-3 and DXG1-4 over time. It can be seen from the comparative analysis in the figure that the settlement monitoring amount is gradually accumulated with time, and the maximum cumulative amount is 8.89mm, 9.91mm, 10.32mm and 10.01mm, respectively.
3.2.2. Numerical calculation result analysis

In order to be consistent with the monitoring point arrangement of the actual construction site, corresponding monitoring points are set in the four numerical models for comparison. During the tunnel propulsion process, the displacement of the surface is always recorded at the monitoring point in the numerical model. Figure 5 is a view showing the position distribution of the monitoring points in the numerical model.

As for the spatial location distribution of the structures in the model, DXG1-2 and DXG1-4 are the closest to the tunnel and the farthest from the tunnel, while DXG1-1 and DXG1-3 are both in the center. In order to verify the effectiveness of the reinforcement measures, this section focuses on the analysis of the settlement deformation of the two monitoring points of DXG1-1 and DXG1-2.

Figure 6(a) is the settlement amount at the DXG1-1 around the utility pole under the four working conditions with the tunneling step. It can be seen from the figure that as the tunnel advances, the displacement of the monitoring point gradually increases and tends to be stable. At the same time, it can be known that the maximum settlement is 7.39mm without reinforcement measures, and the maximum settlement stays 7.01mm in the pile foundation reinforcement measures. The maximum settlement lies 5.31mm in the pile top coupling beam reinforcement measures. The maximum settlement of both reinforcement measures is 5.15 mm, which is consistent with the actual monitoring. Comparing the four different working conditions, the pile foundation reinforcement measures and the pile top coupling beam reinforcement measures can effectively reduce the settlement deformation of the surrounding stratum of the pole, but the reduction of the surface settlement is more obvious when the reinforcement is used in the pile top coupling beam, which is reduced by 28.12%. The pile foundation reinforcement measures reduced the ground settlement by only 5.14%, and both reinforcement measures were reduced to 30.31%.

Figure 6(b) shows the settlement amount at the DXG1-2 around the utility pole under the four different conditions with the tunneling step. It can be seen from the figure that the variation settlement is consistent with that of DXG1-1. However, the maximum settlement is 10.1 mm when there is no reinforcement, and the maximum settlement lies 9.72 mm in the pile foundation reinforcement measures. The maximum settlement is 8.72mm in the pile top coupling beam reinforcement measures. The maximum settlement of both reinforcement measures stays 7.64mm, which is consistent with the actual monitoring situation. The pile foundation reinforcement measures and the pile top coupling beam

![Figure 5 Position distribution of monitoring points in numerical model](image1)

![Figure 6(a) DXG1-1](image2)

![Figure 6(b) DXG1-2](image3)

Figure 6 The settlement under the four engineering conditions with the tunneling steps.
reinforcement measures can effectively reduce the settlement deformation of the surrounding strata of the pole. Among them, the situation in the pile foundation reinforcement measures applied is reduced by 3.76%, the situation the pile top coupling beam reinforcement measures applied is reduced by 13.67%, and the situation the two reinforcement measures applied is 24.36%.

4. Conclusions
Based on the Wuhan Guanggu 1st/Gaoxin 4th drainage channel project, combined with on-site monitoring data analysis and finite element simulation, this paper analyses the displacement and deformation of ground displacement caused by tunnel through the high-voltage rod. The conclusion is obtained as follows:

(1) As the tunnel advances, the displacement around the pole gradually increases and tends to stabilize.

(2) Numerical simulation studies on four working conditions show that the reinforcements can effectively reduce the surface settlement. The pile top coupling beam reinforcement measures is much larger than that in the pile foundation reinforcement measures. The two combined measures have the best effect on the reduction of surface settlement. Among them, the settlement of DXG1-1 in the pile foundation reinforcement measures is reduced to 5.14%, the reinforcement in the pile top coupling beam is 28.12%, and the two combined measures are 30.31%. The settlement of DXG1-2 in the pile foundation reinforcement measures is reduced to 3.76%, the reinforcement in the pile top coupling beam reinforcement measures is 13.67%, and the two combined measures are 24.36%.

In this paper, three-dimensional numerical simulation method is used to study the tunnel with double-side drift method. For the tunnel lining and anchor reinforcement and other structures, the equivalent simulation method of local soil strength increasing is adopted, so the simulation is not accurate enough, and the subsequent simulation research of the red clay tunnel will continue.

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