Numerical simulation on ground deformation characteristics during double-line shield tunnel crossing airport runway

Wenqi Ding\textsuperscript{1,2}, Zhili Shao\textsuperscript{1,2}, Xingbang Lu\textsuperscript{1,2,*} and Yafei Qiao\textsuperscript{1,2}

\textsuperscript{1}Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China
\textsuperscript{2}Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai, 200092, China
\textsuperscript{*}Corresponding author’s e-mail: 1610160@tongji.edu.cn

Abstract: Using Peck empirical formula and superposition method, the variation of ground settlement, uneven settlement and ground curvature caused by single-line and double-line shield tunnel are obtained. The finite element numerical simulation method is used to analyze the construction process of shield tunnel below the airport runway. Considering the existence of the runway structure and the successive excavation effects of the left and right line, the comparison of simulation and empirical formula is analyzed. Based on this, the deformation Characteristics of the runway is derived under different buried depths and different ground loss ratios.

1. Introduction
Shield tunnels have been widely used in municipal engineering. Due to the particularity of the airport runway, the ground disturbance should be strictly controlled during the crossing construction. In the theoretical study of shield tunnel construction disturbance, Zhang \cite{1} carried out research on the engineering properties of disturbed soils; Ding \cite{2} studied the material behavior and staged numerical simulation of the staged process of underground engineering construction. In the finite element simulation of shield tunnel construction disturbance, some scholars have carried out research on the long-term effects of shield construction \cite{3}\cite{4}.

There are few studies on the disturbance effects of shield tunnels crossing the airport runway \cite{5}. This paper is based on risk control project for crossing construction of Shanghai Pudong Airport. Firstly, the superimposed Peck empirical formula is used to study the ground deformation caused by the excavation of the double-line shield tunnel. Comparing the empirical method and simulation result, the deformation characteristics of the double-line shield tunnel crossing the airport runway is obtained.

2. Empirical formula for deformation of double-line shield tunnel

2.1. Peck formula
Peck \cite{6} proposed that, in the undrained condition, the volume of the ground settlement trough formed by tunnel excavation should be equal to the volume of the formation loss. Based on a large number of monitoring data, it is pointed out that the settlement curve caused by the tunnel construction has a Gaussian normal distribution (Figure 1). The calculation of the surface settlement distribution is shown in Equation (1) and Equation (2).
Figure 1. Settlement curve caused by single-line tunnel construction.

\[ S(x) = \sqrt{\frac{\pi v_i D^2}{4i}} \exp \left( \frac{-x^2}{2i^2} \right) \]  
\[ S_{\text{max}} = \sqrt{\frac{\pi v_i D^2}{4i}} \]

Where:
- \( S_{\text{max}} \) is the maximum surface settlement caused by tunnel excavation (m);
- \( v_i \) is the ground loss ratio caused by shield tunnel construction;
- \( x \) is the distance from the center line of the tunnel (m);
- \( i \) is the width coefficient of settlement curve (m), which represents the distance from the tunnel center to the inflection point of the settlement curve in Figure 1.

2.2. Superposition method

Based on the Peck formula, the settlement curves caused by the excavation of the single-line tunnels are respectively obtained, and then the two results are superimposed to derive the whole subsidence curve with a W shape, as shown in Figure 2. This superposition method is applicable to two parallel shield tunnels with long distance. In addition, the influence of the tunnel spacing and the non-Gaussian normal distribution of the settlement curve can be considered [7]. The expression is as follows:

\[ S(x) = S_{\text{max1}} \exp \left( \frac{-(x - 0.5L)^2}{2i^2} \right) + S_{\text{max2}} \exp \left( \frac{-(x + 0.5L)^2}{2i^2} \right) \]

Figure 2. Settlement of double-line tunnel by superposition method.

Where: \( L \) is the axis spacing (m) of the left and right line.

2.3. Ground deformation of double-line tunnel

The existing research mainly focuses on the ground settlement during shield tunneling crossing airport runway. In fact, in addition to the surface settlement, the uneven settlement and curvature of the runway also have strict control standards. We assume \( S \) represents ground settlement, \( K \) represents uneven settlement of ground and \( C \) represents curvature of ground, where \( K=\frac{dS}{dx} \) and \( C=\frac{d^2S}{dx^2} \). In this project, \( D=7.3m \) and \( L=2D \). The ground loss ratio \( v_i \) is 0.5\%. According to Equation (1) and (3), the single-line and double-line settlement curves under different buried depths are shown in Figure 3.

From Figure 3, it can be seen clearly that the shape of the double-line settlement curve is related to the buried depth. When the buried depth is shallow, the mutual influence of the two lines excavation is small, and the settlement curve is W-shaped. With the increase of buried depth, the maximum settlement gradually decreases while the influence width is growing conversely. And the settlement curve is
changed from “W-shape” to “U shape” or “V shape”, which indicates that the mutual disturbance of the two lines excavation is more significant. When $H=5D$, the settlement curves of two lines are combined into one, and the ground deformation finally reaches twice the settlement value of the single-line tunnel.

![Figure 3](image.png)

**Figure 3.** Settlement of single-line and double-line tunnels under different depths.

### 3. Numerical analysis for deformation of double-line shield tunnel

#### 3.1. Numerical model establishment

The plane strain model was established by finite element software Plaxis 8.5 for numerical simulation (Figure 4). In this model, we calculate the settlement, uneven settlement and curvature of airport runway induced by the double-line shield tunnel. The vertical displacement is shown in Figure 5. We assume $D=7.3m$ and $L=2D$, which is the same as the actual situation. The soil constitutive model is the Hardening Soil-Small Strain model, and the soil layer parameters are shown in Table 1. This tunnel is simulated by a plate of linear elastic material, where the thickness of the plate is 0.4m, the modulus of elasticity is $2.76\times10^4$MPa, and the weight $\gamma$ is 24kN/m$^3$. 

| Transverse position (m) | Single line | Double line |
|-------------------------|-------------|-------------|
| $S$ (mm)                |             |             |
| $C$ ($10^{-4}m^{-1}$)   |             |             |
| $K$ ($10^{-3}$)         |             |             |
Table 1. Values of soil layer parameters.

| Number | Layer            | Thickness /m | γ /kN·m⁻³ | $E_{50}$ /MPa | $E_{oed}$ /MPa | $E_{ur}$ /MPa | c/kPa | $\phi^o$  | ν  | m | $\gamma_{o7}$ /10⁻⁴ | G₀ /MPa |
|--------|------------------|--------------|-----------|---------------|---------------|---------------|-------|-----------|----|---|---------------------|---------|
| 1      | Clay             | 1.7          | 18.4      | 8.7           | 7.3           | 43.6          | 8     | 29        | 0.2| 0.8| 2.7                 | 174     |
| 1-2    | Clay             | 2.65         | 18.2      | 6.8           | 5.6           | 33.8          | 9     | 28        | 0.2| 0.8| 2.7                 | 135     |
| 2-3    | Sandy soil       | 3.45         | 18.4      | 9.7           | 8.1           | 48.4          | 5     | 32        | 0.2| 0.8| 2.7                 | 194     |
| 3-1    | Muddy silty clay | 1.26         | 17.6      | 3.0           | 2.5           | 21.2          | 12    | 21        | 0.2| 0.8| 2.7                 | 85      |
| 3-2    | Sandy soil       | 1.84         | 18.3      | 10.5          | 8.8           | 73.7          | 4     | 31        | 0.2| 0.8| 2.7                 | 295     |
| 4      | Muddy clay       | 10.6         | 16.7      | 2.0           | 1.7           | 14.3          | 14    | 12        | 0.2| 0.8| 2.7                 | 57      |
| 5-1    | Clay             | 11.3         | 17.7      | 3.0           | 2.5           | 15.1          | 17    | 15        | 0.2| 0.8| 2.7                 | 60      |
| 7-1    | Clayey silt      | 8            | 18.9      | 12.1          | 10.1          | 60.4          | 1     | 32        | 0.2| 0.5| 2.7                 | 242     |
| 7-2    | Silt             | 19.2         | 19        | 14.1          | 11.8          | 70.6          | 1     | 33        | 0.2| 0.5| 2.7                 | 282     |

In the numerical simulation, considering the coordinate deformation of the runway structure and the foundation soil, the elastic modulus of the cement concrete slab and the gravel base layer of the runway are respectively 30,000 MPa and 5000 MPa.

We assume the left line tunnel is firstly constructed, and then the right-line tunnel construction is carried out. The soil excavation is simulated by killing the soil unit in the lining, and the lining unit is simultaneously activated to generate the tunnel lining.

3.2. Influence of the runway structure
Considering the existence of the runway structure and the successive excavation effects of the left-line and right-line, the deformation characteristics of the runway surface is derived where buried depths is 7.3m and ground loss ratio is 0.4%.

Figure 6 shows the runway settlement, uneven settlement and curvature for different stages of construction by numerical simulation. It can be seen that the construction of the left and right tunnels is less disturbing and the settlement is asymmetric.

Comparing the simulation results with empirical results of the settlement of the double-line tunnel, it can be concluded that the influence the runway structure on the subsidence curve shape is significant. The runway structure has a “gentle” effect on the surface settlement curve, which is changed from “W shape” to “U shape” or “V shape”. Due to the different shapes of the settlement curves, the uneven settlement and curvature between the simulation results and empirical results are also different.
3.3. Influence of tunnel depths and ground loss ratios
The runway settlement curves under different buried depths are shown in Figure 7, where the ground loss ratio is 0.6%. And the Figure 8 shows the variation of runway with ground loss ratio when the buried depth is 7.3m. As the buried depth increases, the runway settlement curve is closer to the Gaussian normal curve with reduced settlement value. The mutual influence of the two tunnels is gradually increasing, which is consistent with the empirical formula.

As the ground loss ratio decreases, the central part of the settlement curve tends to be gentle. When the burial depth increases and the ground loss ratio decreases, the width of the settlement trough increases continuously.

4. Conclusion
(1) Using the superimposed Peck empirical formula, it is indicated the settlement curve is changed from “W shape” to “U shape” or “V shape as the burial depth increases.
(2) Comparing the simulation results with empirical results, the runway structure has a “gentle” effect on the surface settlement curve. The presence of the runway structure and the reduction in ground loss ratio can control the runway deformation.
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