Three-dimension numerical analysis of large-span bridges’ pile foundation adjacent to an existing tunnel

Keguo Sun1*, Zhifei Xiao1, Xu Liu1, Yiqin Hong1 and Zonghao Hou1

1College of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
1E-mail: sunkeg@126.com

Abstract. In the process of urban transportation construction, it is inevitable that the new bridges will be adjacent to the existing tunnels. According to the spatial relationship between the new bridge and the existing tunnel, a three-dimension finite differential model of the pile-tunnel interaction is established by a numerical simulation method. The influence of the upper load of the new bridge on the adjacent tunnel is simulated, with the results of the numerical simulation method and the Boussinesq method are compared. It is found that the results of numerical simulation are verified by the Boussinesq method, with the deviation less than 10%. Moreover, the horizontal deformation of the tunnel is central-symmetrically distributed, and the symmetrical point of the horizontal deformation and the position of maximum vertical deformation are both near the midpoint of the two cushion caps. Besides, the deformation of the tunnel is mainly vertical. Last but not least, the influence of the construction and operation of the pile foundation of the bridge on the rails in the existing tunnel meets the control criteria. Therefore, the methods of analysis and parameters in this paper can provide a reference for similar projects.

1. Introduction
The approaching construction of the pile foundation of bridges and the existing tunnels has become one of the popular spots of construction research recently. The construction of the pile foundation and the upper load will change the stress state of the nearby soil, causing displacement and deformation of the underground structure around the pile area[1-2]. Consequently, some scholars have studied the approaching construction of the underground structure[3-5]. For instance, Lv Baowei and others used numerical simulation software to analyze the influence of the approaching construction of the pile foundation of bridges on the internal force and displacement of the tunnels’ structure[6-8]. Yan Jingya et al. divided the whole life of the pile foundation into three parts: the construction of the pile, the application of the upper load, and the period of operation to explore the influence of a new pile foundation on an adjacent tunnel[9]. In this paper, FLAC3D simulation software is used to figure out the influence of the upper load of a new bridge on the adjacent existing railway tunnel.

2. Project Overview
Haikou Ring Road, Meilan Airport to the Yingfeng Section E-Road Bridge crosses the east section of Hainan Island High-speed Railway. The intersection angle between the bridge and the railway center line is 71°, and the east line of the high-speed railway in Hainan Island is the passenger line. The line railway has a design speed of 250km/h and a line spacing of 4.6m. This section adopts a ballastless track.
3. Model Establishment

3.1. Simulation Model
The model mainly consists of 2 diaphragm walls, 2 cushion caps, 2 sets of pile foundation (1.5m diameter, 4m spacing, and 53m length) and an existing tunnel. The centerline of the 1# and 2# cushion caps intersects with the tunnel centerline at an angle of 71°. The minimum distance between 1#, 2# cushion caps and the tunnel is 9.91m and 9.46m respectively, and the tunnel depth is 3m, as shown in figure 1. Plus, the top surface of the model is ground, with 116m in the x-direction, 60m in the y-direction, and 65m in the z-direction. In addition, the side and bottom of the model are constrained in the normal direction, while the top surface of the model is free.

![Figure 1. The diagram of the simulation model.](image)

3.2. Physical Parameters
The physical and mechanical parameters used in this simulation are shown in table 1.

| Name                      | Weight (kN/m³) | Cohesive Force (kPa) | Internal Friction Angle(°) | Young Modulus(MPa) | Poisson’s Ratio |
|---------------------------|----------------|----------------------|---------------------------|--------------------|----------------|
| Silty clay 1              | 17.8           | 42.5                 | 8.8                       | 31.43              | 0.28           |
| Gravelly sand             | 18.5           | 25.0                 | 12.5                      | 30.24              | 0.35           |
| Silty clay 2              | 17.1           | 27.0                 | 4.2                       | 27.72              | 0.30           |
| Silty clay 3              | 18.2           | 31.2                 | 6.0                       | 34.93              | 0.30           |
| Cushion caps/Pile foundation | 25.0        | /                    | /                         | 3.15e4             | 0.20           |
| Lining                    | 25.0           | /                    | /                         | 3.15e4             | 0.20           |

3.3. Conditions of Simulation
The load on the top of the cushion caps is equivalent to the uniform load on the top surface of the caps under various working conditions. The loads of 1# and 2# caps under each working conditions are shown in table 2.

| Conditions | Upper load of 1# Cushion Cap(kPa) | Upper load of 2# Cushion Cap(kPa) |
|------------|-----------------------------------|-----------------------------------|
| A          | 226.67                            | 366.15                            |
| B          | 298.77                            | 482.63                            |
| C          | 332.95                            | 537.85                            |
4. Analysis, Comparison, and Verification of the Outcome

The influence of new-bridge construction and upper load on existing tunnels is mainly manifested by the additional stress and deformation of the tunnel. Hence, the deformation law of the tunnel under different upper loads is analyzed. Beyond that, in terms of the settlement of the cushion caps, the consequences of numerical simulation and theoretical calculation are compared, in order to verify the accuracy of the numerical simulation.

4.1. Analysis of Calculation Results

After the pile foundation is loaded, the displacement of the soil near the pile side causes the tunnel to undergo vertical deformation and horizontal deformation (the deformation at the left and right rail), as shown in figure 2 and figure 3.

![Figure 2. Vertical deformation curve of the bottom plate of the frame.](image1)

![Figure 3. Horizontal deformation curve of the bottom plate of the frame.](image2)

It can be seen from figure 2 that the maximum settlement of the tunnel under three conditions occurs near the midpoint (x=30) of the connecting line of the 1# and 2# cushion caps, and the settlement curve is reversed at x=10 and x=50, which indicates that the affected length of the tunnel is about 40m. Then, it can be seen from figure 3 that the horizontal deformation of the tunnel is all symmetrically distributed under three working conditions, and the three horizontal deformation curves are all intersected near the midpoint (x=30) of the connecting line of the 1# and 2# cushion caps. Finally, comparing figure 2 and figure 3, it can be seen that the maximum vertical deformation of the tunnel is 7.866 mm, while the maximum horizontal deformation is 0.81 mm, which is much smaller than the vertical deformation, indicating that the deformation of the tunnel is dominantly vertical. Moreover, the simulation results are evaluated according to the requirements of the specification. As a result, the influence of the construction and operation of the pile foundation on the rails in the existing tunnel conforms with the control criteria (regard the deformation of the bottom plate of the tunnel as the rail’s deformation), as shown in table 3.

| Items               | Index of the standard | Result of calculation |
|---------------------|-----------------------|-----------------------|
| Vertical Deformation| Within 2mm            | 0.132mm               |
| Horizontal Deformation| Within 2mm          | 0.097mm               |

4.2. Comparison and Verification of Simulation Results

The stratified summation method is currently the most commonly used method to calculate the foundation settlement. According to relevant specifications, Boussinesq calculation method (which is equivalent to the stratification sum method) (formula 1) is adopted to calculate the final settlement of the pile foundation under three conditions, which is shown in table 4. Besides, the diagram of the calculation of the pile foundation settlement is shown in figure 4[10].

![Figure 4. Diagram of the calculation of the pile foundation settlement.](image3)
The depth of the pile foundation settlement calculation is calculated according to formula (2):

\[ s = \psi - \psi_e - s = \psi - \psi_e - \sum_{j=1}^{m} P_{0j} \sum_{l=1}^{n} z_l \alpha_{l} - z_{l-1} \alpha_{l-1} \frac{E}{E_0} \]  

(1)

The depth of the pile foundation settlement calculation is calculated according to formula (2):

\[ \sigma_z = \sum_{j=1}^{m} \alpha_j P_{0j} \leq 0.2 \sigma_c \]  

(2)

Table 4. The final settlement at the top of the pile foundation.

| Conditions | The additional stress at the bottom of the cushion cap(kPa) | Depth of the settlement calculation(m) | Average settlement of the points(mm) | The average settlement at the cap-pile intersection(mm) |
|------------|-----------------------------------------------------------|----------------------------------------|-------------------------------------|------------------------------------------------------|
| Condition A | 226.67                                                    | 5.9                                    | 7.14                                | 21.44                                                |
| Condition B | 298.77                                                    | 5.9                                    | 10.10                               | 30.35                                                |
| Condition C | 332.95                                                    | 5.9                                    | 11.51                               | 34.58                                                |

Figure 5 is a comparison of the numerical method with Boussinesq method. As a result, it can be seen from figure 5 that the results of the two methods are consistent as the deviation is within 10%, indicating that the simulation is reliable.

5. Conclusion

In this paper, FLAC3D simulation software is used to analyze the influence of the upper load of a new bridge on an adjacent existing railway tunnel, and the result is compared with the outcome of Boussinesq method. The following conclusions are drawn:

(1) The numerical calculation method is correct, the parameters are reasonable, and the deviation is within 10%, verified by Boussinesq method.

(2) Under the three conditions, the maximum horizontal deformation of the tunnel is central-
symmetrically distributed. The symmetry point of the horizontal deformation and the position of the maximum vertical deformation are near the midpoint of the two cushion caps. Besides, the vertical deformation of the tunnel is dominating.

(3) The influence of construction and operation of the new bridge pile foundation on the rails in the existing tunnel meets the control criteria. Therefore, the analytical methods and parameters in this paper can provide a reference for similar projects.

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References
[1] Yang, M., Jin, J.W. (2016) Research progress on the interaction between pile foundation and existing subway tunnels. Journal of Building Structures, 37(08): 90-100.
[2] Ding, Z., Zhang, W., Zhou, L.Y., Chen Z.H. (2018) Research and Prospect of Interaction between Close Distance Bridge Piles and Subway Tunnels. Journal of Zhejiang University(Engineering Science), 52(10): 1943-1953+1979.
[3] Sun, K.G., Xu, W.P., Qiu, W.G. (2018) Study on the Characteristics of Safety Distribution Changing with Buried Depth for Metro Station in Upper-Soft and Lower-Hard Stratum. Advances in Civil Engineering, 2018:1-14.
[4] Wang, H.J., Xu, W.P., Zhao, C.X., Yang, P., Xiao, Z.F. (2019) Prediction of the Influence of Superstructure on Metro Stations in Complex Strata. Urban Rail Transit Research, 22(07): 21-26.
[5] Lu, P., Zheng, G. (2013) Study on the influence of overpass pile foundation construction and operation period on existing tunnels. Geotechnical Engineering, 35(S2):923-927.
[6] Lv, B.W. (2017) Numerical and Actual Analysis of Influence of Supercritical Bridge Pile Foundation Construction on Existing Tunnels. Railway Standard Design, 61(03):103-107.
[7] Gong, L., Ma, X.F., Kong, C., Liang, Z.N., Wu, J.L. (2018) Numerical Simulation Analysis of Bridge Piles Adjacent to Existing Tunnels. Railway Standard Design, 62(12):125-130.
[8] Ding, Z., Zhang, X. (2019) Numerical Analysis of Influence of Pile Foundation Construction on Adjacent Existing Metro Tunnels. Journal of Central South University,50(02):390-399.
[9] Yan, J.Y., Zhang, Z.X., Huang, H.W., Wang, R.L. (2008) Finite element analysis of the influence of pile foundation load on adjacent existing tunnels. Rock and Soil Mechanics, 09:2508-2514.
[10] The People's Republic of China Industry Standard. Technical Specifications for Building Pile Foundations. (JGJ94-2008), 2008.