

# Mechanical analysis about the influence of tunnel excavation on vertical effect of adjacent bridge pile

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**Abstract:** Tunnel excavation will bring additional deformation and internal force of adjacent bridge piles, if the deformation is large, it will threat the upper structure safety of the bridge. According to the complexity of the existing three - dimensional numerical simulation modeling and the time - consuming calculation, a two - stage analysis method of tunnel excavation based on Winkler foundation model was proposed. Firstly, Loganathan and Polous solutions were used to obtain the vertical displacement of the soil free field at the pile position when tunnel excavated, and the corresponding polynomial fitting displacement curve was taken. Secondly, the differential equation was established by means of the equilibrium condition of micro - element physical force and considering the pile group effect. Then, through the logical derivation, the calculation expressions of the tunnel excavation on the effect of the adjacent bridge pile (settlement, axial force and friction resistance) were obtained. Finally, based on the background of the tunnel project of Yanxing Door Station ~ Xianning Road Station in Xi'an Metro Line 3, the feasibility and applicability of the proposed method were proved by comparing the calculated values with the numerical simulation values. It provides theoretical guidance for the effective analysis about the influence of tunnel excavation on the adjacent pile foundation effect.

## 1 Introduction

Located in the bustling areas and special areas of the city, due to the impact of existing buildings, underground engineering had to be built in the vicinity of the existing bridge pile. When the tunnel constructed near the existing pile, the surrounding soil will cause disturbance, so that the original initial stress field will be destroyed. However, the deformation of the soil will be transmitted to the adjacent pile foundation through the pile and soil interaction, which will lead to deformation of the pile foundation<sup>[1]</sup>, reduce its bearing capacity, and even to failure. When it comes to this problem, most scholars focus on both experimental studies<sup>[2-3]</sup> and numerical simulations<sup>[4-5]</sup>. The finite element simulation can take into account the interaction between pile and soil, pile and pile. And the stress release of the soil is completed by applying the reduced boundary nodal force at the periphery of the tunnel, which is in accordance with its construction mechanics behavior, but it is very different from the actual soil displacement field<sup>[6]</sup>, in addition, the need to establish a complex spatial model and the calculation of time-consuming, combined with the uncertainty of geotechnical media and tunnel excavation diversity, resulting in existing researches have some limitations, it is difficult to popularize all related projects. Located in the middle of the Weihe River Basin is the world famous ancient city, Xi'an. The nature of the soil is complex, doping collapsible loess, soft loess, etc., the adverse geological environment caused the Xi'an subway tunnel settlement more complex, and now little research on this subject. Therefore, this article relies on the tunnel project of Yanxing Door Station ~ Xianning Road Station in Xi'an Metro Line 3. Firstly, based on the two-stage analysis method, the



influence of tunnel excavation on the single pile effect was studied by using the shear displacement model. Then, considering the effect of pile group effect, the differential equation of pile group subsidence was established by using the equilibrium condition of micro – element, and found out its analytical solution. Finally, the feasibility of the theoretical method was verified by the numerical simulation and the measured data. It provides some theoretical guidance and technical support for the safety protection about the pile foundation of other construction of Xi'an subway.

## 2 Establishment and Solution of Differential Equation for Single Pile Settlement

The influence of tunnel excavation on the single pile settlement is studied by two-stage method: In stage 1, the vertical displacement of soil free field at pile position is determined. In stage 2, the differential equation of single pile settlement is established by Winkler foundation model.

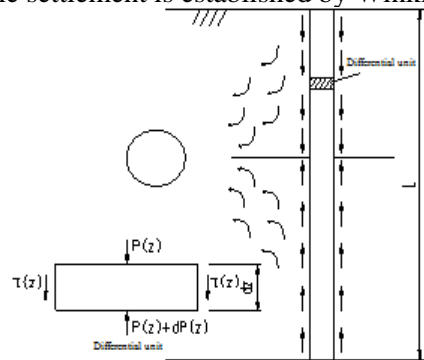


Fig.1 Simplified single pile calculation diagram

Establishing the passive pile displacement equation:

$$d^2w(z)/dz^2 - u_p \tau(z)/(E_p A_p) = 0 \quad (1)$$

In the literature<sup>[7]</sup>, according to the Winkler foundation model, the load displacement expression of the pile-side soil is assumed:

$$w(z) = \frac{\tau(z) r_0}{G_s} \cdot \ln\left(\frac{r_m}{r_0}\right) \quad (2)$$

Combining (1) and (2):

$$\begin{aligned} d^2w(z)/dz^2 - u_p G_s w(z)/E_p A_p r_0 [\ln(r_m) - \ln(r_0)] = \\ -u_p G_s s(z)/E_p A_p r_0 [\ln(r_m) - \ln(r_0)] \end{aligned} \quad (3)$$

Introduce the parameters  $k_z$  and  $\lambda^2$ , the simplified formula (3) is:

$$d^2w(z)/dz^2 - \lambda^2 w(z) = -\lambda^2 s(z) \quad (4)$$

$$\lambda^2 = \frac{2\pi G_s}{A_p E_p \ln(r_m/r_0)} \quad (5)$$

$$k_z = \frac{2\pi G_s}{\ln(r_m/r_0)} \quad (6)$$

From the formula (4), the vertical displacement of the pile can be solved:

$$w(z) = c_1 e^{\lambda z} + c_2 e^{-\lambda z} + w^*(z) = c_1 e^{\lambda z} + c_2 e^{-\lambda z} + \frac{e^{\lambda z}}{2} \int s(z) d e^{-\lambda z} + \frac{e^{-\lambda z}}{2} \int s(z) d e^{\lambda z} \quad (7)$$

$c_1, c_2$  are determined by boundary conditions:

$$\begin{aligned} -E_p A_p \frac{dw(z)}{dz} \Big|_{z=0} &= P(0) \\ -E_p A_p \frac{dw(z)}{dz} \Big|_{z=L} &= P(L) = w(L) 4 \cdot r_0 \cdot G / (1 - \mu) \end{aligned} \quad (8)$$

$w^*(z)$  is a special solution, Loganathan and Polous solutions are used to calculate the free displacement of soil  $s(z)$  at a pile position, simplified by using  $s(z) = \sum_{i=0}^n a_i z^i$ .  $s(z)$  a polynomial, and  $w^*(z)$  is also a polynomial, that is  $w^*(z) = \sum_{j=0}^n b_j z^j$ , the relationship between  $b_j$  and  $a_i$  is obtained by the recursive principle<sup>[8]</sup>.

### 3 establishment And Solution Of Differential Equation For Pile Group Settlement

#### 3.1 Displacement calculation of mutual influence of double piles

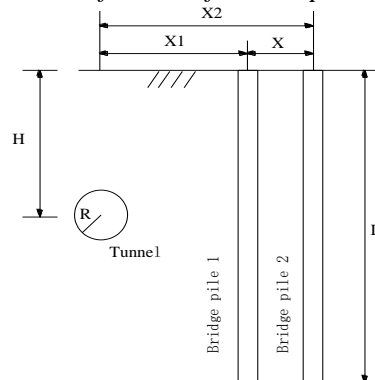


Fig.2 Simplified double piles calculation diagram

According to the shear displacement, it is possible to obtain the soil cover displacement of bridge pile 1 to bridge pile 2.

$$\begin{aligned} s_{21} &= \psi(x) \cdot (w_1 - s_1) \\ &= \frac{\ln(r_m - x)}{\ln(r_m - r_0)} \cdot (w_1 - s_1) \quad (r_0 \leq x \leq r_m) \end{aligned} \quad (9)$$

Settlement control equation of bridge pile 2 under the action of bridge pile 1:

$$\frac{d^2 w_{21}}{dz^2} - \lambda^2 (w_{21} - s_{21}) = 0 \quad (10)$$

Substituting equation (9) into equation (10)

$$\frac{d^2 w_{21}}{dz^2} - \lambda^2 [w_{21} - \psi(x) \cdot (w_1 - s_1)] = 0 \quad (11)$$

$$w_1 - s_1 = \sum_{i=0}^n A_{1,i} \cdot z^i - \sum_{i=0}^n a_{1,i} \cdot z^i = \sum_{i=0}^n (A_{1,i} - a_{1,i}) \cdot z^i = \sum_{i=0}^{n-2} A_{11,i} \cdot z^i \quad (12)$$

$w_1$ : The settlement value of pile 1 due to the soil settlement;

$s_1$ : The settlement value of arbitrary soil depth at the location of bridge pile 1 caused by tunnel excavation.

The settlement of the bridge pile 2, which is due to the masking effect of the bridge pile 1:

$$w_{21}(z) = A_{21} e^{\lambda z} + B_{21} e^{-\lambda z} + \frac{\lambda \cdot \psi(x)}{2} z (-e^{\lambda z} A_{11} + e^{-\lambda z} B_{11}) + w_{21}^* \quad (13)$$

$w_{21}^*$  is a special solution:

$$w_{21}^* = \sum_{i=0}^{n-2} A_{21,i} \cdot z^i \quad (14)$$

$A_{21}, B_{21}$  determined by the boundary condition of the bridge pile 2:

$$p_{21}^t = 0; \quad w_{21}^b = \frac{p_{21}^b (1 - \mu)}{4r_0 G_s} \left(1 + \frac{2r_0}{\pi s}\right) \quad (15)$$

$p_{21}^t, w_{21}^b, p_{21}^b$  are the top axial force, the bottom displacement and the axial force of bridge pile 2, which are caused by the influence of bridge pile 1 on bridge pile 2.

### 3.2 Displacement calculation of pile group interaction

Set the spacing of  $n$  bridge piles to  $x$ , the displacement of the  $i$ -th bridge pile (regardless of the influence of the group pile) is:

$$w_{ii}(z) = A_{ii} e^{\lambda z} + B_{ii} e^{-\lambda z} + w_{ii}^* \quad (16)$$

$w_{ii}^*$  is a special solution:

$$w_{ii}^* = \sum_{k=0}^n A_{i,k} \cdot z^k \quad (17)$$

The displacement of the  $i$ -th bridge pile (affected by the  $j$ -th root bridge pile) is:

$$w_{ij}(z) = A_{ij} e^{\lambda z} + B_{ij} e^{-\lambda z} + \frac{\lambda \cdot \psi(X)}{2} z (e^{\lambda z} A_{ij} - e^{-\lambda z} B_{ij}) + w_{ij}^* \quad (18)$$

$w_{ij}^*$  is a special solution:

$$w_{ij}^* = \sum_{k=0}^{n-2} A_{ij,k} \cdot z^k \quad (19)$$

The settlement of the  $i$ -th bridge pile can be obtained by the superposition principle:

$$w_i(z) = \sum_{j=1}^n w_{ij} \quad (20)$$

Axial force:

$$P_i(z) = -E_p A_p \frac{dw_i(z)}{dz} \quad (21)$$

Friction resistance:

$$\tau_i(z) = \frac{E_p A_p}{u_p} \frac{dw_i^2(z)}{dz^2} \quad (22)$$

#### 4 Case Analysis

Taking Yanxing Door Station ~ Xianning Road Station in Xi'an Metro Line 3 as an example, each pier has 4 piles,  $2 \times 2$  isometric layout, pile length is 45m, pile diameter is 1.5m.

##### 4.1 Analysis of theoretical results

1 ~ 4 # pier foundations of the east second ring interchange are selected for analysis. Because the distance between the pier 1# and 3# is almost equal to the tunnel spacing, so 1 # pier and 2 # pier are only considered. Select 1-1 #, 1-2 # and 2-1 #, 2-2 # pile foundations to calculate.

As seen from Fig.3: The tunnel excavation causes the change of the adjacent pile group effect. 1 # Pier is closer to the tunnel, the soil displacement and pile effect changes greatly, and the maximum vertical displacement of the soil at the 1-1 pile position closest to the tunnel is 5.56mm; 2 # pier is far from the tunnel, soil displacement only minor changes, soil settlement of 2-1#, 2-2 # pile at the pile position is not more than 0.15mm, so the pile effect is also very small changes; If the displacement of the soil is larger than that of the pile, the pile will be dragged by soil, that is, the negative friction resistance of the pile will increase the axial force of the pile, and reduce the bearing capacity of the pile. When the displacement is equal, the friction is 0, where the axial force is the maximum.

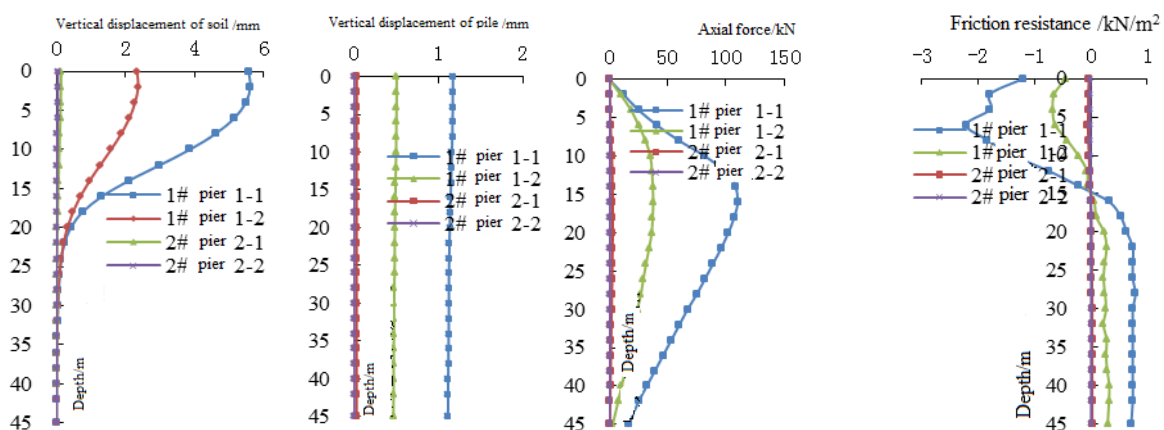


Fig.3 Schematic diagram of pile group effect distribution curve induced by tunnel excavation

##### 4.2 Validation of finite element results

Using FLAC3D to build bridge piles and tunnel location model, as seen from Fig.4. The subway tunnel is roughly parallel to the bridge. 1 #, 2 #, 3 #, 4 # bridge pile foundations are selected for

research.

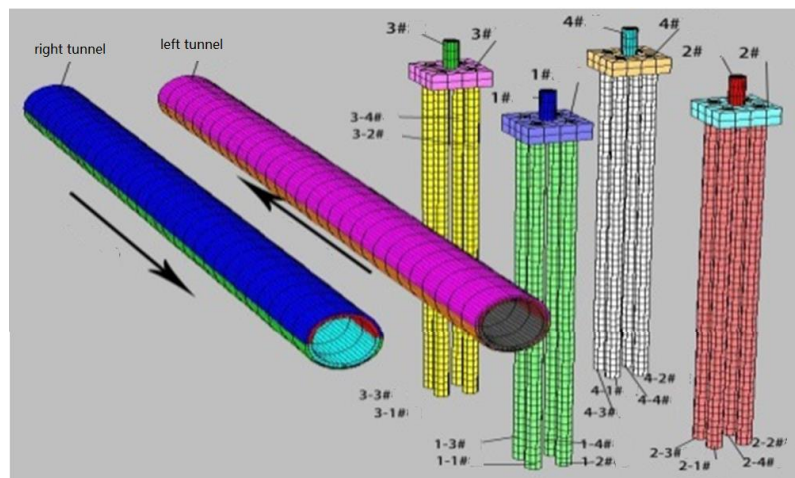


Fig.4 Three - dimensional model diagram about the relationship between subway and bridge pile

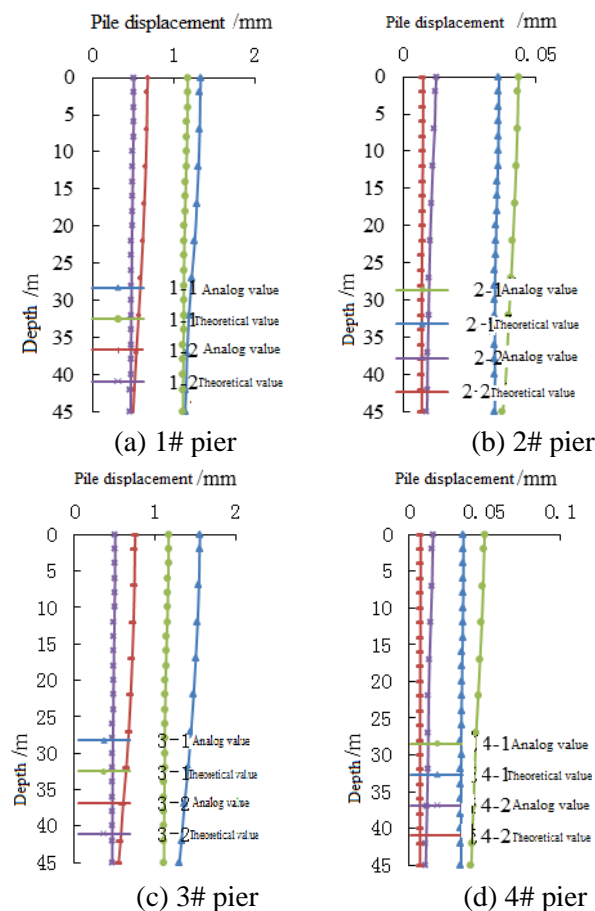


Fig.5 Bridge pile displacement comparison diagram

As seen from Fig.5: The closer to the tunnel, the larger 1#, 3# pier foundations are, however, the settlement of the pile foundation is smaller at the position of the 2,4 # pier, which are far from the tunnel, and the tunnel excavation has no effect on it; And because the actual pile foundation measurement is more difficult, only the top of the settlement value of the platform is known, so the

theoretical calculation and numerical values were compared: The theoretical calculation is consistent with the displacement distribution of the simulated numerical pile foundation, and the simulation value is larger than the theoretical value, the reason why is that the simulation considers the interaction between each position in the model.

## 5 Conclusion

Due to the complexity of 3D finite element modeling, and the computation is time consuming , therefore, in this paper, the influence of tunnel excavation on the vertical effect of bridge piles was studied by two-stage analysis method, which is based on winkler foundation model. Based on the balance of micro - element physical force, considering the pile group effect, the differential equation of pile settlement was established. The analytical expression of vertical effect of pile group caused by tunnel excavation was deduced. Combined with engineering examples, the rationality of the algorithm was verified by finite element numerical simulation. The method can quickly calculate the results, and provide theoretical guidance for similar projects.

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