Theoretical Analysis on the Effect of Tunnel Excavation on Building strip foundation

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Abstract: In this paper, according to the characteristics of the ground settlement troughs curves, the influence of tunnel excavation on the effect of strip foundation was studied by inverse analysis firstly. The differential equation of the synergistic effect of the strip foundation and foundation under the tunnel excavation was established by using the equilibrium condition of the micro-element physical force. Then, the conceptual definite initial parameter method was used to solve the corresponding homogeneous equation. According to the plane section assumption, combined with the basic theory of material mechanics, considering the differential characteristic of hyperbolic trigonometric function, and using matlabmathmatica software, the theoretical calculation expression of displacement and internal force which is about the tunnel passes through the strip foundation was obtained. Finally, combined with engineering case analysis, changes of the relative position between the tunnel and the foundation, the influences of the main parameters on the foundation effect were studied. The results show that: The influence scope of the tunnel on the foundation is [-0.5 \sim 1.5] times of the foundation length, and when the tunnel center at the end of the foundation, there exists the maximum settlement. The parameters about the soil loss rate, the excavation section and the buried depth of the tunnel have great influence on the foundation effect. The change of foundation height has a great influence on its internal force.

1 Introduction

Due to urban traffic pressure and construction land constraints, urban underground projects must be built under the foundation of existing buildings or near the side. And so far, many research scholars at home and abroad focus on the internal forces and deformation effect of the tunnel excavation on deep foundation\textsuperscript{[1-4]}, however, shallow foundation rarely involved in basic research. Assuming that the foundation stiffness is large, the influence of tunnel excavation on the vertical settlement of the shallow foundation that the upper part is brick and concrete structure was studied using numerical simulation by Feng Che\textsuperscript{[5]}. Moreover, there is no theoretical research in this field, and shallow foundation depth is shallow, the tunnel will have different effects on the foundation and the surface soil when crossing the different locations from the foundation. Therefore, the influence of the tunnel crossing position on the foundation effect is a worthy subject. In this paper, we first established the differential equation by using the equilibrium condition of the micro-element physical force, and then derived it through the rigorous mathematical theory, and got the theoretical solution of shallow foundation effect caused by tunnel excavation with the advanced software matlabmathmatica. Finally, combined with engineering case analysis, the influences of tunnels and foundation position changes, buried depth of tunnel, tunnel section size, the soil loss rate, soil parameters changes, and shallow
foundation of its own parameter changes on the foundation effect were studied. The research results of this paper have some theoretical guidance significance for the similar construction, whether it needs taken necessary safety measures and the measures taken in the surrounding area of the building or the structure or not.

2 Analysis on the effect of strip foundation initiated by tunnel excavation

2.1 Establishment of differential equation

Assume:
(1) The inverse effect of tunnel excavation is on the top of the strip foundation;
(2) The top surface of the strip foundation is acting on the surface, and the vertical displacement of the surface is solved by empirical formula;
(3) The bottom of the foundation beam is in close contact with the surface of the foundation.

The differential equation of the settlement of the strip foundation is obtained by the equilibrium condition of Fig.1:

\[ EI \frac{d^4 w(x)}{dx^4} + kbw(x) = kw_1(x) + qb \]

\[ w(x) \] settlement at any point on a strip foundation;
\[ w_1(x) \] settlement induced by tunnel excavation;
\[ q \] vertical uniform load of superstructure;
\[ k \] coefficient of subgrade reaction;
\[ b \] foundation width.

By the assumption (2)\(^6\)\(^7\)know

Fig.1. The relative position diagram between the tunnel and the strip foundation
\[ w(x) = S_{\text{max}} \exp\left[-\frac{x^2}{2\mu^2}\right] \]  

(2a) \[ S_{\text{max}} = \frac{V_0/2.5i = \sqrt[3]{2\pi V_0 D^3/i(0)} = 0.313 V_0 D^3/i(0)} \]

(2b) \[ i(0) = m[R + H \tan(45 - \phi/2)] \]

(2c) \( S_{\text{max}} \): Maximum surface settlement; \( i(0) \): Width of settlement trough; \( V \): Volume of settlement trough; \( \nu \): Stratum loss rate; \( \phi \): Soil friction angle; \( m = 0.45 - 0.50 \); \( R, H \): Tunnel section and buried depth.

The simultaneous equations (1) and (2a) can deduce the differential equations of the strip foundation settlement caused by tunnel excavation:

\[ EI\varphi'(x)/d\varphi + kbw(x) = kbS_{\text{max}} \exp\left[-\frac{x^2}{2\mu^2}\right] + qb \]  

(3)

2.2 Solving the differential equation

Equation (3) is consists of general solutions and special solutions, namely

\[ w(x) = w_0(x) + w_1(x) + w_2(x) \]  

(4)

The flexibility coefficient of elastic foundation beam is \( \alpha \), namely \( \alpha = \sqrt{kb/4EI} \). Then the general solution of \( w(x) \) is:

\[ w(x) = w_0\phi_1(\alpha x) + \theta_0\phi_2(\alpha x)/2\alpha - 2\alpha^2 M_{\phi_1}(\alpha x)/kb - \alpha Q_{\phi_1}(\alpha x)/kb \]  

(5)

The special solution of \( w_0(x) \) is:

\[ w_0(x) = q/kb \]  

(6)

The special solution of \( w_1(x) \) is:

\[ w_1(x) = \int_a^x S_{\text{max}} \exp\left[-\frac{(u - j)^2}{2(\mu^2)}\right] \phi_2(\alpha (x-u)) du \]

\[ = \frac{\pi}{\sqrt{32}} i(0)\alpha S_{\text{max}}(1+i) \exp\left[-\alpha (1+i)j(1+i)x+i(0)^2/\alpha f\right] \]

\[ \times \left\{ \begin{array}{l}
-\exp\left[2\alpha (j+i)x\right] \exp\left[-\frac{-j+x+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] - \exp\left[-\frac{-j+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] \\
+\exp\left[2\alpha x(i+(i+1)x+i(0)^2/\alpha f\right] \exp\left[-\frac{j-x+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] - \exp\left[-\frac{j+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] \\
+\exp\left[2\alpha x(i+(i+1)x+i(0)^2/\alpha f\right] \exp\left[-\frac{-j+x+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] - \exp\left[-\frac{-j+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] \\
+\exp\left[2\alpha x(i+(i+1)x+i(0)^2/\alpha f\right] \exp\left[-\frac{j-x+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] - \exp\left[-\frac{j+(1+i)i(0)^2\alpha}{\sqrt{2i(0)}}\right] \\
\end{array} \right\} \]

(7)

In order to obtain the basis of the corresponding corner, bending moment, shear force, material mechanics was used.

2.3 Determination of initial parameters

\( w_0, \phi_0, M_\phi, Q_\phi \) are the initial parameters, two of these parameters can be obtained directly by the two boundary conditions of the origin, and the other two parameters can be determined by the boundary
conditions at the other end. That is, both free ends of the strip foundation:

\[ M(x)|_{x=0} = 0; \quad Q(x)|_{x=0} = 0; \quad M(x)|_{x=L} = 0; \quad Q(x)|_{x=L} = 0. \]

3 Example analysis
Taking the 3# interval tunnel project of Xi’an Metro Tunnel as an example, foundation parameters: C30, \( L = 40m \), \( b = 1500mm \), \( h = 400mm \), \( q = 100kN/m^2 \), \( k = 40000kN/m^3 \); Tunnel parameters: \( D = 6m \), \( H = 12.85m \), \( V_r = 1% \), \( \phi = 15^\circ \). The influence of tunnel excavation on its foundation effect was studied.

3.1 The influence on the center of the tunnel deviates from the center of the foundation

(a)

(b)

(c)
As can be seen from Fig.2: When \( j \) is different, the maximum settlement is 24.3mm, the minimum settlement is 1.67mm, the maximum whole inclination is 0.00057\(<0.001\) \([8]\), and the maximum settlement of the measured surface of the tunnel is 21mm\(<30mm\) \([9]\). Foundation maximum angle is 0.132 degrees, the minimum angle is nearly 0 degrees. The maximum positive moment of the foundation is 175 kN·m, and the maximum negative moment is -79 kN·m. The maximum positive shear force of the foundation is 42.3 kN, and the maximum negative shear force is -42.3 kN. When \( j=0m \) and \( j=L \), that is, the tunnel eccentricity ratio is 0.5, the foundation settlement reaches the maximum at this position, and the upper structure is the most vulnerable. When \( j=20m \) (\( j=L/2 \), that is, the tunnel is not eccentric through the shallow foundation, the foundation settlement is "Gaussian curve" distribution, the settlement and bending moment are centroid symmetrical distribution about the foundation, and the angle and shear force are center antisymmetric distribution about the foundation. When \( j=60m \) (\( j=1.5L \)), the settlement value is very small, the foundation settlement is 1.67mm, and the settlement tends to be stable. Indicating that the impact of tunnel excavation is negligible, and settlement is only caused by the upper building.

Due to the constraints of the article length, parameters of the settlement and bending moments studied only when \( j=10m \).

### 3.2 The influence of stratum loss rate

As can be seen from Fig.3: The foundation deformation and internal force (\( j=10m \)) increase rapidly with the increase of soil loss rate, therefore, it can be reinforced by grouting to reduce the surface deformation caused by stratum loss for areas where the stratum loss rate is large. And in the actual construction process should pay attention to the timing and quality of simultaneous grouting. If the ground subsidence is too large, the construction process of horizontal jet grouting pile can be used. In the dug tunnel dome where to form a ring curtain body, and combined with advanced pre-grouting reinforcement support measures to ensure the stability of the excavation process. Control the tunnel dome settlement within 30mm, which can effectively control the ground subsidence. When the foundation distance from the tunnel axis exceeds 0.5L, the foundation effect curve tends to be stable.
3.3 The influence of tunnel section

![Fig.4](image)

As can be seen from Fig.4: The foundation deformation and internal force \( (j=10\text{m}) \) increase rapidly with the increase of the radius, the reason is that the larger the excavation section is, the larger the soil settlement is, and excavation methods and corresponding reinforcement measures should be selected reasonably for the large section tunnel. When the foundation distance is more than 0.5L from the tunnel axis, the foundation effect curve tends to be stable.

3.4 The influence of tunnel buried depth

![Fig.5](image)

As can be seen from Fig.5: The foundation deformation and internal force \( (j=10\text{m}) \) increase rapidly with the decrease of burial depth, the reason is that the deeper the buried depth is, the greater the surface disturbance, the greater the additional load applied on the foundation when inverse analysis. Concerned about ultra-shallow tunnel project case is needed. When the foundation distance is more than 0.5L from the tunnel axis, the foundation effect curve tends to be stable.

3.5 The influence of foundation height

![Fig.6](image)

As can be seen from Fig.6: The foundation settlement and the angle \( (j=10\text{m}) \) are affected slightly by the height. However, the foundation bending moment and the shearing force increase exponentially with the increase of the height. The main reason is that the increase of the height and the foundation stiffness, and the growth rate of stiffness is cube of height. When the distance between the foundation and the tunnel axis is more than 0.75L, the foundation internal force curve shape does not change.
3.6 The influence of coefficient of subgrade reaction

Fig.7 The curve about the influence of coefficient of subgrade reaction on the strip foundation effect
As can be seen from Fig.7: The foundation deformation (j=10m) decreases slightly with the increase of the coefficient of subgrade reaction, but has little effect on the internal force. When the distance between the foundation and the tunnel axis is more than 0.5L, the curve shape of the foundation angle, bending moment and shear remain unchanged.

3.7 The influence of foundation concrete strength grade

Fig.8 The curve about the influence of foundation concrete grade on the strip foundation effect
As can be seen from Fig.8: The foundation deformation and internal force are little affected by the strength grade of the concrete, so the C30 concrete is generally used on the strip foundation, and the main reason for adopting C30 is to increase the durability of the foundation itself and improve the moisture resistance of its own structure.

4 Conclusion

Based on the Winkler foundation theory, the ground subsidence caused by tunnel excavation was applied to the top of the strip foundation. Considering the cooperative principle of ground and foundation, the corresponding differential equation was established, and using the initial parameter method with clear and unique physical meaning to solve it. The error function expressions of additional displacement, angle, bending moment and shear force of the influence of tunnel excavation on strip foundation, which were deduced and simplified by means of the basic principle of higher mathematics distribution integral. And the influence of tunnel excavation on the shallow foundation effect of the building was studied theoretically by the parameter sensitivity analysis, and the following conclusions are drawn:

(1) The range about the influence of tunnel excavation on strip foundation is (-0.5 ~ 1.5) times of the foundation length.

(2) When the center of the tunnel is located at the end of foundation, its settlement is the largest. And the maximum uneven settlement value about the influence of the tunnel excavation on the strip foundation, which is at the position closest to the center line of the tunnel, that is, the location of the maximum settlement is only related to the tunnel eccentricity. Therefore, the tunnel excavation should be carefully considered the working condition of the nearest location about the strip foundation distance from the tunnel center line.

(3) When the tunnel axis is located at the center of the foundation, the vertical displacement curve of the strip foundation is Gaussian curve distribution, and symmetrical distribution with the center of
the foundation. Likewise, the bending moment is symmetrical distributed, the angle is antisymmetrically distributed, and the shear force is anti-symmetrically distributed, and the location of the bending moment and shear values are the largest.

(4) The effect of soil loss rate, tunnel depth and tunnel diameter on the maximum value of settlement is very significant. The foundation angle, the bending moment and the shear force also increase rapidly with the increase of the soil loss rate, the decrease of the buried depth and the increase of the diameter. The reason is that the soil loss rate, tunnel diameter, tunnel buried depth and other parameters directly affect the maximum stratum settlement value. The settlement is large, and the additional load applied is large during the inverse analysis. Therefore, engineering should first understand the engineering geological conditions, tunnel depth, tunnel excavation section and other conditions, a reasonable choice of construction technology and the corresponding reinforcement measures to control the settlement of ground soil, so as to ensure the safety of tunnels and foundations and ground buildings.

(5) The influence of the variation of the parameters on the foundation deformation is small, but it has a great influence on the internal force, and the most influential change is the foundation height.

References
[1] Fu Wen-sheng, Xia Bin, Luo Dong-mei. Comparison Research on the Effect of Shield Tunnel Traversing Adjacently under the Existing Pile Foundations[J]. Chinese Journal of Underground Space and Engineering, 2009,5(1):133-138.
[2] Zhao Jing-yang, Yang Shuang-su, Xu Jing etc. Optimization Design of Isolation Pile Parameters in Shield Tunneling for the Control of Deformation of High-Rise Buildings[J]. Journal of Taiyuan University of Technology, 2017,48(1):62-65
[3] Wu Bo, Liu Wei-Ning, Suo Xiao-Ming etc. A study on the reinforcement of a short-piled overpass foundation in the vicinity of metro construction[J].Civil Engineering Journal, 2006.7:99-103.
[4] Yang Guang-wu, Zhao Jiang-tao, Su Jie. Analysis of Bridge Pile Responses Caused by Subway Construction[J].Urban Rapid Rail Transit, 2014,6(3):70-74.
[5] Che Feng, Gong Quan-mei. Finite Element Analysis on the Deformation of Shallow Foundation Induced by Shield Tunnel Construction[J].Journal of East China Jiaotong University, 2015,32(6):74-81.
[6] PECK R B. Deep excavations and tunneling in soft ground[C]/Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering. Mexico: Balkema, 1969: 225-290.
[7] Wei Gang. Study On Calculation For Width Parameter Of Surface Settlement Trough Induced By Shield Tunnel[J]. Industrial Construction, 2009.39(12).
[8] Heng Chao-yang, Teng Yan-jing, Chen Xi-quan. Research of Allowable Deformation Value of the Building Foundation Soils above Metro Shield Tunnel[J]. Chinese Journal of Underground Space and Engineering, 2006,2(8): 1336-1340.
[9] Yao Xuan-de, Wang Meng-shu. Statistic analysis of guideposts for ground settlement induced by shallow tunnel construction[J]. Chinese Journal of Rock Mechanics and Engineering, 2006, 25(10): 2030-2035. (in Chinese).