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Calculation of ground settlement by considering building structural stiffness

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ABSTRACT: By analyzing the interaction mechanism of foundation-foundation-superstructure and considering the constraint effect of building structural stiffness on the stratum, the equivalent subsidence principle is used to propose the ground settlement prediction formula which considering the structural rigidity of the building to the stratum constraints, and verified its correctness through indoor model test. The results show that: 1) the structural stiffness has obvious restraining effect on the soil layer, so that the settlement curve caused by tunnel excavation tends to be uniform; 2) the greater the structural rigidity of the building, the more obvious the constraint on the soil layer, the surface settlement tank The wider and shallower; 3) The settlement prediction curve is close to the measured curve, and has good engineering applicability and practicability.

Keywords: Surface building; Peck formula; Indoor model test; Relative stiffness

I. INTRODUCTION

With the acceleration of urbanization and the increasing tension of urban areas, the original infrastructure can no longer meet the daily commuting requirements of the growing urban population. Under the condition of low surface tension, the development of underground rail transit has become the mainstream trend of urban development. At present, shield method has increasingly become the main construction choice for urban subway construction because of its many advantages, such as less interference by weather factors, less disturbance to the stratum, high degree of mechanization and less impact on surface traffic and surrounding residents [1]. However, due to the functional requirements of subway track construction, its line is generally selected in the prosperous section with large pedestrian flow, which inevitably needs to pass through the core area with dense buildings. Therefore, it is of great engineering significance to study the deformation of the surface and adjacent buildings caused by shield tunnel excavation and put forward an economic and reliable deformation prediction method.

There are many existing studies on surface deformation and displacement caused by tunnel excavation. The research methods mainly include empirical formula method, theoretical analysis method and numerical simulation method. In 1969, Peck [2] put forward the famous empirical formula to describe the surface settlement trough by summarizing and analyzing a large number of monitoring data of surface settlement; Polish scholar J. litviniszyn regarded rock and soil mass as a random medium and put forward the random medium theory in the 1950s. Chinese scholars (Yang Junsheng, Liu Baochen, 1998 [3]; Yang Junsheng, Liu Baochen, 2002 [4]; Shi Chenghua, Peng Limin, Liu Baochen, 2003 [5]) further improved and developed it, It is widely used to calculate the surface settlement caused by underground mining and urban subway tunnel excavation; By establishing the soil movement model of shield tunnel, Wei Gang [6] gave the general calculation formula and upper and lower limit solutions of the maximum ground settlement above the tunnel axis; Burland [7] proposed "elastic deep beam model", which is widely used in the calculation of building deformation due to surface settlement; Liao Shaoming et al. [8] studied the example of Shanghai Metro, comprehensively used the boundary element method and Mindlin solution, and gave the prediction method of surface settlement during shield tunneling; Zhang Xiaozhi, Cao Guangyong and others [9] used FLAC3D software to conduct three-dimensional finite element simulation, and proposed the influence range of shield machine crossing on the surface; Tao Longguang, Liu Bo et al. (2003) [10] Taking Guangzhou Metro 3# line as the engineering background, FLAC3D was used to simulate the station passing construction of shield double tunnel under different working conditions and analyze its impact on the ground.

The above research mainly focuses on the

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surface deformation caused by tunnel excavation, but in fact, the surface settlement deformation is the result of the interaction and interaction of foundation foundation building structure. The result obtained by simply considering the surface settlement caused by tunnel excavation is too large, which will cause unnecessary waste in the actual project construction. Therefore, It is necessary to further study the surface settlement and deformation under the influence of foundation superstructure interaction.

In this paper, considering the constraint effect of the structural stiffness of surface buildings on the formation deformation, the "equivalent stiffness method" is used to convert the structural stiffness of buildings that restrict the formation deformation into the overburden under the equivalent stiffness, and the surface settlement formula under the equivalent conversion stiffness is obtained based on peck formula.

II. CALCULATION AND ANALYSIS OF GROUND SETTLEMENT CONSIDERING THE STIFFNESS OF BUILDING STUCTURE

Tunnel excavation is bound to cause soil loss and stratum settlement and deformation. When considering the interaction of foundation foundation building structure, the three should meet the deformation coordination equation in deformation and the stress balance condition in internal force. According to the analysis of reference [11]: in the tunnel excavation stage, considering the interaction principle between foundation soil and building structure, the buildings with large upper stiffness have the functions of transmission, coordination and restraint, so as to restrict the stratum deformation caused by tunnel excavation; Because of the continuity of the stratum, its stiffness is uniformly distributed, and the constraint of the building structure on the stratum also shows continuity and uniformity; The greater the stiffness of the building, the stronger its constraint on the stratum deformation, and the more flat and uniform the foundation deformation, that is, the width of the settlement tank increases and the maximum settlement decreases.

Structural stiffness of buildings refers to the ability of buildings to resist deformation. Sun Jiale et al. [12] believe that how much the building stiffness can play in the process of structural deformation is closely related to the size of foundation deformation under the corresponding "joint work". According to Saint Venant's principle, the influence height of foundation deformation on superstructure is limited, and its influence range is related to the size of deformation The structure is related to the foundation stiffness ratio and the beam column linear stiffness ratio. Under the joint action of tunnel soil building structure, only part of the building structure stiffness plays a role. The stiffness that can play a role is called "play stiffness", which is actually the effective stiffness that plays a role in this process. In fact, because the structural stiffness of the building is much greater than that of the soil layer, in the process of settlement and deformation of the building with the ground layer, The building can be regarded as a rigid body, that is, the building only produces the soil layer deformation under the joint action of tunnel soil building structure, and the small deformation of the building itself can be ignored. Therefore, this paper considers that the part of the structure stiffness that the building can play in the process of restricting the soil layer deformation is only limited to the part in contact between the building and the stratum, That is, the basic part of the building structure.

The calculation of effective stiffness in this paper is based on the following assumptions:

1) Only the deformation of buildings caused by tunnel excavation in two-dimensional case is considered, that is, the length of buildings along the axial direction of the tunnel is irrelevant;

2) The influence of pile-soil interaction and pile group effect on effective stiffness is ignored;

3) The included angle between most buildings and tunnel line is generally zero or vertical, so the influence of the included angle between buildings and tunnel on settlement is ignored [11].

4) Only the influence of structural foundation stiffness is considered;

According to the discussion in reference [14], for multi-storey and high-rise buildings with n > 3, the shear stiffness of the building mainly affects the settlement deformation caused by tunnel excavation; According to the simplified method of building stiffness by maie and Taylor [13], it is assumed that the building structural foundation giving full play to the structural stiffness consists of N parts. Considering the influence of actual building structural foundation construction technology and other factors, the effective shear stiffness of the building shall be multiplied by a stiffness reduction coefficient, and the equivalent shear stiffness of the structural foundation can be calculated by the following formula:

$$G = \zeta \frac{\sum_{i=1}^{n} t_i G_i A_i}{a \cdot b} \quad (1)$$

Where： G_i Building foundations part i shear modulus of effective member materials, unit

Pa；

The relationship G_i and E_i is, $G_i = \frac{E_i}{2(1+\upsilon)}$ υ Is Poisson's ratio, and the Poisson's ratio of reinforced concrete is taken as 0.2;

A_i Is the cross-sectional area of part i effective

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member material on the building section, unit m^2;
ζIs the reduction coefficient of structural foundation stiffness;
a is the length of the building;
b is the width of the building;
t_i iss the thickness of building structure foundation。
For the superstructure with thickness of t and structural stiffness of M, its constraint effect on stratum deformation can be equivalent to the effect of overlying soil layer with thickness h_s and stiffnessM_s , namely:

$$t \cdot M = h_s \cdot M_s \quad (2)$$

According to the results of numerical analysis [14], the influence of structural stiffness on formation loss can be ignored. According to the numerical calculation research results of franzius et al. [15], the influence of building load on formation loss rate is very small and can also be ignored. According to peck formula, the formula of surface settlement caused by tunnel excavation on natural surface is:

$$s = \frac{A \cdot V_l}{\sqrt{2\pi}Kz} \exp\left[\frac{-y^2}{2K^2z^2}\right] \quad (3)$$

Where: K is the width coefficient of settlement tank;z is the buried depth of tunnel axis; A is the excavation area of the tunnel; Is the formation loss rate; Considering the constraints of buildings on surface deformation, after converting to the equivalent overburden layer with thickness, the surface settlement curve formula caused by tunnel excavation in simultaneous equations (1), (2) and (3) is: $s =$

$$\frac{A \cdot V_l}{\sqrt{2\pi}K\left(z+\frac{\zeta\frac{\sum_{i=1}^{n} t_i G_i A_i}{a \cdot b}}{M_s}\right)} \exp\left[\frac{-y^2}{2K^2\left(z+\frac{\zeta\frac{\sum_{i=1}^{n} t_i G_i A_i}{a \cdot b}}{M_s}\right)^2}\right] \quad (4)$$

$$i = Kz_0 \quad (5)$$

For circular section tunnel, if the section shrinkage radius is ΔR, the formation loss rate V_l can be expressed as:

$$V_l = \frac{2R \cdot \Delta R - \Delta R^2}{R^2} \approx \frac{2\Delta R}{R} \quad (6)$$

$$\Delta R = \alpha G_p + U_{3d} + \omega \quad (7)$$

Where: G_p refers to the gap between shield machine and lining, which shall be multiplied by a grouting filling reduction factor α ; Yang Guantian et al. [16] pointed out that for sandy soil, α = 0.1 ~ 0.3, for clay, α = 0.2～0.4 ; It is the three-dimensional elastic-plastic deformation of the soil in front of the shield machine and the construction factor.ω
In conclusion, the surface settlement deformation curve caused by tunnel excavation is:

$$s = \frac{A \cdot \frac{2(\alpha G_p + U_{3d} + \omega)}{R}}{\sqrt{2\pi}K\left(z+\frac{\zeta\frac{\sum_{i=1}^{n} t_i G_i A_i}{a \cdot b}}{M_s}\right)} \exp\left[\frac{-y^2}{2K^2\left(z+\frac{\zeta\frac{\sum_{i=1}^{n} t_i G_i A_i}{a \cdot b}}{M_s}\right)^2}\right] \quad (8)$$

III. INDOOR TEST EQUIPMENT AND PRINCIPLE

The model box is to be fully welded and assembled with 201 stainless steel with a thickness of 3mm. The specific size of the box is: the size of the internal small box (length) × wide × Height) 2.0m × 1.2m × 1.0m; External large box size (L) × wide × Height) 2.2m × 1.4m × 1.0m; Dimension of bottom plate (length) × (width) 2.2m × 1.4m; There is no capping on the model box. In order to simulate the water level boundary during foundation pit excavation, evenly drill holes on all sides of the model box to make the water in the water supply interlayer between the two boxes penetrate into the soil evenly. At the place 50cm from the bottom of the two box interlayer, a fully welded anti-seepage water barrier is set to separate the upper and lower water layers of the water supply interlayer. The upper part simulates formation phreatic water and the lower part simulates confined water. The three-dimensional schematic diagram of the model boxis shown in Figure **1.**

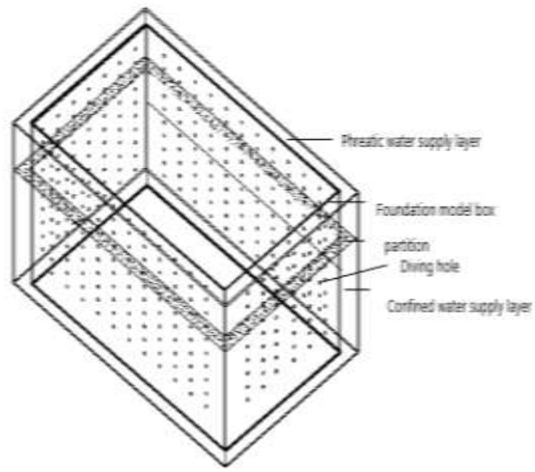

Fig.1 overall schematic diagram of model box

The geometric similarity ratio of the experimental model is 1:40. According to the similarity theory, the physical and mechanical parameters are deduced and calculated. The experimental similarity ratio is: bulk density similarity ratio: C γ= 1 ; Poisson's ratio, strain and friction angle similarity ratio: C μ= C ε= C φ= 1 ; Similarity ratio of compressive strength, stress, cohesion and elastic modulus: Cr = C σ= CC = CE = 20 the tunnel has an inner diameter of 3.6m and an

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outer diameter of 4.0m, so the tunnel Jing excavated in the model test is 100mm.

According to the above similarity ratio calculation results, the experimental materials are selected as follows:

(1) Soil material. The mechanical parameters of the prototype soil layer are: ES = 36Mpa, C = 6kpa, γ= 22.3kN/m3， φ = 36°。 The materials used in the model are barite powder, fly ash, coarse river sand, quartz sand, engine oil and water mixed according to a certain mix proportion. (the cohesion, compression modulus, internal friction angle and bulk density of the model material are measured through geotechnical test to meet the requirements of similarity ratio)

(2) Segment lining material. The segment lining structure is made of aluminum alloy, each ring segment is 5cm wide, and is composed of four wedge-shaped aluminum alloy segments connected by bolts, with an outer diameter of 205mm. PVC pipe is proposed to replace aluminum alloy segment lining to facilitate the experiment.

(3) Treatment of rich water. According to the prototype soil, the pore water pressure is obtained. Then, the stable water pressure column is used for continuous water injection.

(4) Simulation of buildings. According to the above geometric similarity ratio, the size of the building is simulated. The material used in the model is concrete and processed into a building corresponding to the actual project. If the influence of building load needs to be considered, weights can be hung on the building to achieve the load effect.

As for both sides of the building model 2D away from the tunnel central axis (D is the tunnel excavation width) and 2.5D away from the tunnel inlet, six earth pressure boxes are evenly arranged at both ends of the model box at the buried depth of 40cm, and four earth pressure boxes are evenly arranged at both ends of the model box at the buried depth of 70cm. Before the experiment, the strain gauge is powered on and preheated for 20 ~ 30min, and the earth pressure box reading is recorded after connecting the line, Set up the dial indicator frame, place the pointer on the surface of the building, record the initial sub meter readings, and conduct the excavation simulation of the shield tunnel after the soil, building and water rich conditions are stable. For each segment width (5cm) excavated by the shield, apply the segment lining at the tail. During lining, the PVC segments are connected with latex. For each ring of excavation, the PVC segments are hammered slowly with a rubber hammer to simulate the lining. After each segment length is excavated, the readings of dial gauge and strain gauge are recorded after 30min until the excavation is completed.

IV. TEST RESULTS AND DATA ANALYSIS

According to literature [17], take the average value α = 0.23, the outer diameter of the shield shell is generally 102% of the outer diameter of the lining segment [18]. Therefore, considering the deformation modulus of the prototype soil, Poisson's ratio, building elastic modulus E = 3000mpa, take[11] for sandy pebble stratum. According to the discussion in literature [14], the shear stiffness of buildings is the main factor affecting the settlement deformation caused by tunnel excavation; For the convenience of analysis, only the influence of building foundation structure stiffness on surface settlement is considered. Assuming that the building width is 10m, it is easy to obtain the predicted value of surface settlement under various conditions with the help of MATLAB. Now the experimental values and the predicted values of different foundation structures are summarized in Table 1.

Table 1 Comparison of measured values with the solution in this paper and the solution of Peck formula

distance（m）		0	0.2z	0.4z	0.6z	0.8z	z
Peck solution（mm）	/	72.1	57.7	29.6	9.8	2.1	0.3
Paper solution（mm）	Strip foundation	44.1	40.6	31.6	20.8	11.6	5.5
	Independent foundation	36.2	34.2	28.9	21.9	14.8	8.9
	Plie	28.9	27.9	25.0	20.9	16.3	11.8

	foundation						
	Raft foundation	30.1	28.9	25.8	21.2	16.2	11.4
	Box foundation	26.0	25.2	23.1	20.0	16.4	12.6
Measured value（mm）	Pile foundation	26.63	24.76	19.88	17.23	12.76	12.1

Note: the Z value in the table is the buried depth of the tunnel (the same below);
The thickness of strip foundation is 0.5m;
The independent foundation is taken as the building, and only one row is arranged per linear meter in the longitudinal direction;
For the pile foundation, only one row is arranged per linear meter in the longitudinal direction of the building, and the buried depth of the pile foundation is 3m;
The buried depth of raft foundation is 2m;
The side wall thickness of box foundation is 0.2m and the buried depth is 3m;

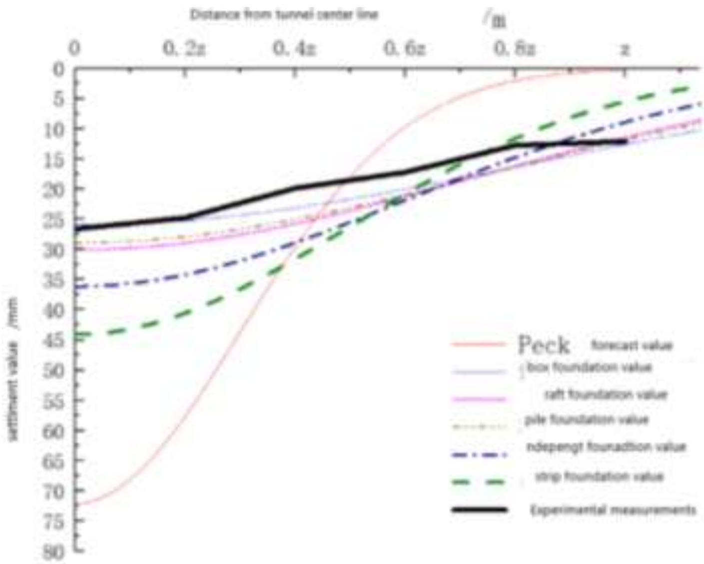

Fig.2 predicted and measured building settlement curve

As can be seen from Figure 2 above, the settlement prediction curve of peck formula is significantly larger than the settlement curve predicted and measured in this paper, while the settlement groove width is significantly smaller than the settlement groove width predicted and measured in this paper, indicating that the constraint of building structural stiffness on surface settlement is obvious, and its structural stiffness can homogenize the surface settlement curve; The measured building settlement curve is close to the settlement curve predicted in this paper, which shows that the settlement prediction formula in this paper is close to the actual settlement curve, so its correctness is verified. The predicted curve in the figure is slightly lower than the measured curve. The main reason may be that the influence of the building stiffness embedded in the soil layer is not considered, resulting in the large predicted value in this paper; It can be seen from the above figure that different foundations have different constraints on stratum settlement. Pile foundation and box foundation can effectively inhibit the settlement of buildings. For high-rise and super high-rise buildings with strict settlement control, pile foundation or box foundation is recommended for building foundation, and the foundation burial depth is increased by comprehensively considering economy and building use purpose.

V. CONCLUSION AND DISCUSSION

By analyzing the settlement mechanism of buildings, this paper puts forward the settlement prediction curve considering the structural stiffness of buildings, and verifies the correctness of the prediction curve through indoor model test. The main conclusions for building settlement prediction are as follows:

1) The effect of building structure stiffness on surface settlement is as follows: constraining the longitudinal development of settlement, correspondingly, the width of surface settlement trough increases, that is, under the action of building structure, the settlement curve presents the characteristics of shallow and wide;

2) Under the influence of structural stiffness, the width of settlement trough is much larger than that of natural surface settlement trough, and the greater the structural stiffness, according to the principle of equivalent stiffness, the greater the thickness of equivalent soil layer, the greater the width of settlement trough;

3) Pile foundation and box foundation have a good effect on restraining stratum settlement. These two kinds of building foundations are recommended for buildings sensitive to settlement control;

4) The settlement prediction curve proposed in this paper is close to the actual measured settlement curve, which shows that the settlement prediction curve in this paper is correct and has strong engineering applicability and practicability.

It should be specially pointed out that this paper only studies the case that the boundary of the building is parallel to the center line of the tunnel. When using the equivalent stiffness method, the influence of the structural stiffness of the foundation part embedded in the soil is ignored. For the oblique intersection of the building and the tunnel axis with a certain angle and the influence of the structural stiffness embedded in the soil layer, further research is needed. The settlement prediction curve in this paper can predict the settlement of surface buildings in the early stage of engineering construction. For more detailed analysis, it can be combined with numerical simulation and field monitoring.

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