The influence of stiffness coefficient of steel support on supporting effect and its optimization

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Abstract. The stiffness coefficient of steel support plays an important role in controlling the deformation of foundation pit, but the influence of various parameters in the stiffness coefficient on the supporting effect of foundation pit is still unclear, resulting in the unreasonable value of the stiffness coefficient. By means of theoretical analysis and numerical simulation, this paper makes a comprehensive and in-depth study on the influence law and optimization of the stiffness coefficient of steel support on the supporting effect. Based on the calculation of the stiffness of steel support, the calculation formula of the stiffness of steel support under the uniform radial load is derived by using the basic definition of stiffness calculation; the change rules of horizontal displacement and surface subsidence of the support structure under different parameters were analyzed by numerical simulation method, and the original scheme was optimized. The results show that: (1) in the stiffness coefficient, the steel support spacing and wall thickness have a great influence on the supporting effect; (2) with the increase of the rigid support spacing and the decrease of the steel support wall thickness, the horizontal displacement value and surface settlement value of the support structure both become larger. However, when the steel support spacing is 3.00-3.10m and the steel support wall thickness is 14mm-16mm, the horizontal displacement value and surface settlement value of the support structure do not change much, and they are all within the monitoring and warning value; (3) the original design scheme was optimized from 3.00m steel support spacing and 16mm steel support wall thickness to 3.10m steel support spacing and 14mm steel support wall thickness in the original scheme, which reduced the engineering cost and improved the construction efficiency.

Keywords: steel support, stiffness coefficient, horizontal displacement, the surface subsidence
1. The introduction

With the acceleration of urbanization, the foundation pit has been applied more and more widely, and is developing towards the direction of "big and deep". This requires more and more control of foundation pit. However, due to the relatively early formulation of relevant standards, there is a certain lag, resulting in the design of steel support stiffness coefficient is too conservative, resulting in the stiffness coefficient is too high, resulting in a series of problems such as increased budget, low construction efficiency. Therefore, it is necessary to study the influence of horizontal stiffness coefficient of steel support on the deformation of supporting structure.

Chunyan Wang [1] studied the algorithm of ring support system; Wenting Wang [2] compared the calculation results and actual monitoring data of MidasGTS and lizheng foundation pit software, and carried out engineering verification to verify the accuracy of the formula; Yuan H Y et al [3] compared the Plaxis 2D numerical simulation results with the actual situation on site, and analyzed the deformation of the support structure under different supporting stiffness; Chen T et al [4] proposed the rationality analysis method of the support system through theoretical analysis and finite element calculation; Hou G Y et al [5] studied the method of using finite element method to calculate the sample training RBF neural network; Xinquan Wang et al [6] studied the load-bearing characteristics of grid support structure and common support structure through field tests, and analyzed the deformation rules of different positions of the horizontal displacement of the wall under the support conditions; Hao Deng [7] analyzed the influence of the support stiffness on the horizontal displacement of the occluded pile through a variety of research methods; Shushen Chen [8] studied the formula of supporting stiffness of retaining pile;

Yingwei Song [9] derived the formula for calculating the horizontal stiffness of the support under the two conditions of plane symmetry problem and plane asymmetry problem, and proposed the formula for calculating the horizontal stiffness of the support under both the inclined and the opposed supports; Tao Chen [10] studied the internal support stiffness of the horizontal support system of the complex truss structure; Huimin Wang et al [11] analyzed the influence law of ratio of axial force and stiffness of support on supporting pile; Min Yang [12] studied the calculation method of horizontal stiffness coefficient of separate pile top ring beam, internal support system and external pull bolt; Yabing Jin [13] deduced the analytical solution of the horizontal stiffness coefficient of the fulcrum and proposed the calculation formula of the horizontal stiffness coefficient of the internal support structure; Hankai Liu [14] put forward a general formula for calculating the horizontal stiffness coefficient of counterbrace, diagonal brace, Angle brace and vertical diagonal brace, and verified it with the finite element method; Gordon et al [15] used the finite element method to analyze the main factors affecting the deformation of support structure and proposed a new calculation method; Addenbrooke[16] proposed the concept of displacement flexibility and studied the relationship between displacement and its change; Meilin Liu [17] studied the rigidity of the support system and proposed an expression for the rigidity of the support system; Xuanneng Gao [18] studied the influence of support arrangement on lateral stiffness; Xiaoli Liu et al. [19] analyzed the factors influencing the numerical calculation of equivalent stiffness coefficient of four typical types of in-plane support structures.

Although many scholars at home and abroad have used a variety of research methods to study the impact of steel support stiffness on the deformation of the supporting structure in the foundation pit support system. However, there are obvious problems in the mechanism of the stiffness coefficient of steel support and the value of the stiffness coefficient of steel support. In the design of steel support, for the sake of safety, the value of the stiffness coefficient of steel support is too conservative, which not only results in a small improvement in the effect, but also causes a significant increase in the cost. Therefore, it is necessary to study the influence law and optimization of the stiffness coefficient of steel support on the deformation of the support structure.
2. Mechanism of adjusting steel support coefficient

2.1. Calculation of stiffness coefficient of support
In a regular foundation pit, steel support is generally arranged along the long side, and diagonal support is set on the corner of the foundation pit [20]. For this type of foundation pit, the value of steel support stiffness is as follows:

\[ K_s = \frac{2 \cdot \alpha \cdot E_Z \cdot S_a}{S \cdot \sin \theta} \]  

*Figure 1. Schematic diagram of force on steel support structure*

Type:
- \( \alpha \) - Support relaxation coefficient;
- \( E_Z \) - Elastic modulus of steel support material;
- \( S_a \) - Section area of steel supported member;
- \( L \) - Compression length of steel supported member;
- \( S \) - Horizontal spacing of steel supports;
- \( \theta \) - The included Angle between the Angle brace and the waist beam is \( =90^\circ \) for the brace.

The horizontal spacing of the steel support and the thickness of the steel support wall have great influence on the supporting effect of the steel support. In this paper, these two parameters are selected to study the influence of the stiffness coefficient of the steel support on the surface settlement and horizontal displacement.

3. Project overview
Based on Beijing's new airport period of inter-city rail link Ming dig tunnel DK42 + 038 ~ DK42 + 138 miles of foundation pit as the research object, the mileage of a total of 100 m, the 2.5 m the top of the foundation pit slope, foundation pit excavation depth of 14 m were set up three steel support, three steel supports and distance of the ground is 0.5 m, 4 m, respectively to 9 m, steel support horizontal spacing for 3 m, 609 mm diameter, steel support 16 mm wall thickness. The construction technology of anchor net support is as follows:

*Figure 2. Arrangement of three steel supports*
4. Numerical simulation

4.1. Establishment of the model

In this model, FLAC3D software was used to simulate the horizontal displacement and surface subsidence of the support structure under different steel support spacing and wall thickness conditions. FLAC3D can provide multiple constitutive models and improve the accuracy of simulation.

The width and depth of foundation pit excavation were 18m and 14m respectively. The established FLAC3D calculation model selected an area with a length, width and height of 80m×60m×70m. The model is shown in figure 4.

(2) Model hypothesis

1) Consider the foundation pit as infinity and ignore the corner effect.
2) The soil mass before excavation is regarded as the consolidation state.
3) In the process of simulation, the relevant physical and mechanical parameters of soil can be regarded as fixed values, and the influence of precipitation and underground seepage on it need not be considered.

4.2. Model calculation

The x, y and z directions are taken as the horizontal direction, axial direction and height direction of the foundation pit respectively to establish a numerical simulation coordinate system. Based on the
relevant materials, the relevant parameters of the simulation calculation are shown in the following table.

(1) Soil layer division and parameters

| Name of the geotechnical | Thickness H(m) | Cohesion c(KPa) | Internal friction angle (°) | Density ρ(kg/m³) | Bulk modulus K (MPa) | Shear modulus G(MPa) |
|--------------------------|-------------|--------------|----------------------------|-----------------|---------------------|---------------------|
| Grain filling            | 5           | 10           | 8                          | 1910            | 17.92               | 3.16                |
| Silty sand               | 3           | 23           | 15                         | 1920            | 21.64               | 9.57                |
| Silt                     | 4           | 26           | 18                         | 1720            | 29.07               | 14.06               |
| Fine sand                | 4           | 30           | 25                         | 1970            | 52.19               | 21.52               |
| Silty clay               | 15          | 43           | 27                         | 2050            | 62.75               | 39.59               |
| Clay                     | 20          | 75           | 22                         | 2200            | 74.81               | 49.07               |

Table 2. Calculation parameters of underground continuous wall

| name                | Elastic Modulus E(GPa) | Poisson's ratio | Density ρ(kg/m³) |
|---------------------|------------------------|-----------------|-----------------|
| Diaphragm Wall      | 35                     | 0.18            | 2600            |

Table 3. Calculation parameters of steel support

| Dame               | Poisson's ratio | Moment of inertia (m⁴) | Elastic Modulus (GPa) | Sectional area (m²) | Polar moment of inertia (m⁴) |
|--------------------|-----------------|------------------------|----------------------|---------------------|-----------------------------|
| Steel support      | 0.3             | 0.0018                 | 210                  | 0.0292              | 0.0036                      |

4.3. Applicability verification of the calculation model

With the excavation of soil, due to the disappearance of the earth pressure on the supporting structure and the different forces on both sides of the supporting structure, the horizontal displacement of the supporting structure of the foundation pit is generated, which is the most important index to characterize the deformation of the foundation pit. Foundation pit excavation will also cause disturbance to the surrounding soil, resulting in surface settlement, which is also the most important indicator to characterize the impact of foundation pit excavation on the surrounding environment [21]. This paper carries out numerical simulation on the foundation pit of Beijing new airport: 1) numerical simulation was carried out by FLAC3D software to analyze the deformation of support structure and surrounding environment under different steel support spacing and wall thickness conditions; 2) verify the correctness of the numerical simulation by comparing the measured and simulated values. FIG. 4 shows the cloud diagram of horizontal displacement deformation of the support structure. FIG. 5 and 6 show the comparison between the measured and simulated values of the horizontal displacement and surface subsidence of the envelope structure.
Figure 5. Cloud diagram of horizontal displacement deformation of support structure

Figure 6. Comparison of simulated and measured horizontal displacement of support structure

Figure 7. Comparison of measured and simulated surface subsidence values after excavation
5. Influence of mechanical parameters of steel support on deformation of foundation pit support structure

The supporting structure and the steel support jointly constitute the foundation pit support system, which includes the steel support and the support structure, and the steel support stiffness is an important factor to control the deformation of the foundation pit [22]. By means of numerical simulation, the supporting effect of steel support under different stiffness was studied. By adjusting the spacing and wall thickness of steel support, the variation rules of horizontal displacement and surface settlement of support structure under different stiffness were studied.

![Graph showing horizontal displacement of supporting structure with different steel support wall thickness and diameter](image)

**Figure 8.** Horizontal displacement of supporting structure with different steel support wall thickness and diameter

FIG. 8 shows the horizontal displacement of the support structure with different wall thickness and different steel support spacing. With the decrease of the steel support spacing and the increase of the steel support wall thickness, the horizontal displacement of the control support structure is improved less. On the contrary, after the steel support interval changed from 3.00 to 3.10, the horizontal displacement of the support structure changed little, and the three curves were very close to each other. When the spacing between steel supports is 3.15, the horizontal displacement changes obviously, and the cumulative displacement is close to the warning value. After the thickness of the steel support wall changed from 16mm to 14mm, the horizontal displacement of the support structure changed little, and the distance from the early warning value was far. When the steel support wall thickness is 12mm, the
horizontal displacement changes obviously, and the horizontal displacement value is large, which is close to the warning value. According to the above analysis, increasing the steel support spacing and decreasing the steel support wall thickness in a certain range have little influence on the horizontal displacement of the restricted support structure. Moreover, the increase of steel support stiffness is accompanied by a substantial increase in cost. Therefore, on the premise of satisfying the foundation pit safety, the supporting stiffness can be reduced to reduce the cost and play a role in reducing the budget.

Figure 9. Surface subsidence at different steel support wall thicknesses and diameters

Figure 9 shows the surface settlement with different wall thickness and different steel support spacing. Compared with the steel support wall thickness of 14mm and 16mm, the two curves are relatively close, and the surface settlement of the steel support wall thickness of 14mm is far from the early warning value. When the steel support wall thickness is 12mm, compared with the steel support wall thickness of 14mm, the surface settlement changes greatly, and it is close to the warning value. Compared with 3.00, the surface settlement did not change significantly and was far from the warning value. When the steel support spacing is 3.15, the surface settlement is relatively large, which is close to the warning value. It can be seen that increasing the steel support distance and decreasing the steel support wall thickness in a certain range have little influence on limiting the surface settlement.
Figure 10. Horizontal displacement and surface settlement value of support structure with different steel support spacing

Figure 11. Maximum horizontal displacement and surface subsidence of the support structure under different steel support wall thickness

Figure 10 and 11 show the relevant parameters of horizontal displacement and surface subsidence of the support structure with different steel support spacing and wall thickness. When the thickness of the steel support wall is 14 ~ 16mm and the spacing is 2.95-3.10mm, the horizontal displacement of the support structure and the maximum value of surface settlement change little, and the support effect does not increase significantly with the increase of the stiffness coefficient. Therefore, there is room for optimization in the original design.

6. Steel support design scheme optimization

Through the above studies, we know that the original design is too conservative. In the original design, both the surface subsidence value and the horizontal displacement value are far less than the monitoring and warning value. The horizontal displacement value is only 72.44% of the monitoring and warning value, and the surface subsidence value is only 50% of the monitoring and warning value. So there is room for optimization. We can optimize the original scheme on the premise of ensuring the quality of the project. The rigidity of the steel support can be adjusted by adjusting the spacing and wall thickness of the steel support. The optimization list of various parameters is shown in table 4.

Table 4. Steel support parameter optimization table

| Project    | Steel support wall thickness / mm | Steel support spacing / m |
|------------|---------------------------------|--------------------------|
| Original plan | 16                             | 3.00                     |
| Optimization | 14                             | 3.10                     |
By means of numerical simulation, the horizontal displacement and surface subsidence of the support structure of the optimized scheme are studied to study the feasibility of the optimized scheme. The comparison of the horizontal displacement and surface subsidence of the original scheme and the optimized scheme is shown in FIG. 12. The figure shows that horizontal displacement of retaining structure of foundation pit a maximum of 19.37 mm before optimization, optimization of the maximal displacement of 21.88 mm, after a 12.96% increase, the ground settlement around the surface subsidence in a maximum of 7.50 mm before optimization, the optimized settlement is 10.52 mm, increased 40.26%, the horizontal displacement of retaining structure and the surface subsidence has increased, but the total variation and the extent of change in the monitoring and early warning value of less than, can guarantee the engineering quality and construction safety, and reduce steel support, transportation cost of raw materials, lifting, artificial cost.

![Figure 12. Comparison of horizontal displacement and surface subsidence of support structures in different construction cases](image)

**Table 5. Monitoring alarm value**

| Monitoring items                  | Cumulative alarm value (Level 1 alarm) | Cumulative warning value (Secondary warning) |
|----------------------------------|----------------------------------------|---------------------------------------------|
| Horizontal displacement of supporting structure | 45mm                                  | 25mm                                        |
| Settlement around the surface    | 25mm                                  | 15mm                                        |

7. **The conclusion**

1) In the stiffness coefficient, the steel support spacing and wall thickness have a great influence on the supporting effect.

2) Through the FLAC3D numerical simulation, calculate the steel support 609 mm diameter, wall thickness to 16 mm spacing were 2.95 m, 3.00 m, 3.05 m, 3.10 m, 3.15 m at the time of the supporting structure and the surface subsidence, horizontal displacement, according to the results of the steel support spacing of 3.00 m, 3.05 m, 3.10 m when the horizontal displacement of retaining structure and the surface settlement difference is very small, and in monitoring and early warning value; in addition, the horizontal displacement and surface subsidence of the support structure were calculated when the steel support was up to 609mm in diameter, the steel support spacing was 3.00m, and the wall thickness was 12mm, 14mm, 16mm and 18mm. The results showed that the horizontal displacement and surface subsidence of the support structure were very little different when the steel support wall thickness was 14mm and 16mm, and they were all within the monitoring and warning value.
According to the results of numerical simulation, the steel support construction scheme was optimized from the original plan of 3.00m steel support spacing and 16mm steel support wall thickness to 3.10m steel support spacing and 14mm steel support wall thickness. The horizontal displacement of the support structure was changed from 19.37mm to 21.88mm, with an increase of 12.96%. The maximum value of the surrounding surface subsidence was changed from -7.50mm to -10.52mm, which increased by 40.26%. However, both the cumulative change and the range of change were within the monitoring and warning values, and a large amount of budget was reduced.

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