

Calculation Method of Bracing Stiffness in Foundation Pit: A Review

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Abstract

In the excavation engineering, the bracing stiffness is an important parameter reflecting the supporting performance of the inner bracing system. Bracing stiffness has great influence on the deformation of the retaining structure and the foundation pit, and its calculation method is the theoretical basis for the design and deformation analysis of the foundation pit. The limit equilibrium method, subgrade reaction method and finite element method used in the design, stability and deformation analysis are introduced in detail. Different calculation models and calculation methods of bracing stiffness are summarized in detail in each analysis method. The method of providing foundation pit retaining design standard and the optimization method proposed by scholars are introduced and analyzed in depth. It is suggested that the subsequent research should further establish a support stiffness calculation method taking influence of important parameters such as the difference of support stiffness and uneven support spacing.

Keywords

Excavation Engineering; Foundation Pit; Inner Support System; Inner-bracing; Bracing Stiffness.

1. Introduction

In the internal bracing system of excavation engineering, the support stiffness is one of the main factors affecting the deformation of foundation pit [1-2]. The support stiffness has great influence on the deformation of foundation pit and the internal force of enclosure structure [3], and its sensitivity is also very high [4]. The calculation method of internal bracing stiffness determines the rationality and accuracy of foundation pit retaining design, foundation pit stability and deformation analysis.

2. Basic Calculation Models of Inner Bracing

The basic methods for the design, stability and deformation analysis of inner bracing system include limit equilibrium method, subgrade reaction method and finite element method [5]. The basic calculation models of inner bracing in each method are different, and the calculation methods of stiffness are also very different. The limit equilibrium method [6] uses the load-structure model to solve the internal forces of the retaining structure according to the principle of force balance. The internal support is simplified as hinge support, and the support is set as infinity. Because the internal support deformation is neglected and the interaction between the supporting structure and the stratum cannot be considered, the calculation results of the internal force and deformation of the supporting structure are far from the actual ones. In subgrade reaction method [7], the co-deformation of the supporting structure and the strata in the passive zone is taken into accounting. Spring is used to simulate the constraint effect of the strata and the inner support on the retaining structure, and bracing is simplified as the spring

support [8]. The internal force and deformation of the inner support and retaining structure can be accurately calculated by this method. It has the double advantages of clear calculation mode and simple solution process. Reasonable stiffness value of inner support is an important guarantee to control the calculation accuracy of subgrade reaction method. Finite element method includes finite beam element method [9] and continuous medium finite element method [10]. In FEM modeling, the bracing is often simplified as beam element, hinge support or spring support, etc., and the solid modeling can also be carried out. When beam element or solid model is used in bracing, the finite element program can consider the supporting effect by itself, and does not involve the problem of calculating the bracing stiffness separately. However, when the bracing is simplified as a spring support, it is necessary to use other methods to calculate the bracing stiffness first, and then input the results into the finite element program. Therefore, both subgrade reaction method and part of finite element method are involved in the value of support stiffness. The research on the calculation method of bracing stiffness is of great value to further improve the stability and deformation analysis method of foundation pit.

3. Calculation Method of Bracing Stiffness

The calculation method of bracing stiffness is related to the dimension of the calculation model established. In the finite element analysis of three-dimensional modeling, the compressive stiffness of the spring used to represent the bracing is calculated based on the structure and material parameters of the bracing itself. When subgrade reaction method [11,12] or plane finite element method [13] is used for foundation pit supporting design or internal force and deformation analysis, the horizontal stiffness coefficient of bracing system needs to be input. Therefore, the analytical formulae (formula 1 and 2) for calculating the stiffness coefficient of elastic fulcrum in width are provided in the design standard for foundation pit retaining. It is suggested that the calculated results can be used as the horizontal stiffness coefficient of bracing system. In formula 1 and 2, the ring beam deformation of the inner support system is ignored, and the obtained horizontal stiffness coefficient is constant within the calculated width (between adjacent bracings). In the calculation of bracing stiffness with ideal symmetry shape and excavation procedure of foundation pit, formula (2) can be simplified into the form of formula (1).

$$K_T = \frac{2\alpha EAS_a}{LS} \quad (1)$$

$$K_R = \frac{\alpha_R EAb_a}{\lambda l_0 s} \quad (2)$$

Wherein, K_T and K_R are the stiffness coefficients of the elastic fulcrum in the calculated width;

α and α_R are the relaxation coefficient;

L and l_0 are the length of bracing member;

A is the section area of the bracing member;

E is the elastic modulus of the bracing member;

S and s are the horizontal spacing of support;

b_a and S_a are calculated widths;

λ is adjustment coefficient of the fixed point on bracing.

In fact, the stiffness of the elastic fulcrum is large different between the bracing fulcrum and the ring beam span. When the horizontal stiffness coefficient of bracing system obtained by

Equations 1 and 2 are used to analyze the deformation of foundation pit, the theoretical calculation result is smaller than the measured deformation value in excavation engineering [14]. Whether varying horizontal stiffness coefficients are used for different parts of ring beams has an impact on the calculation results of foundation pit deformation, and the impact is beyond the allowable error range [15]. Therefore, it is an unsafe model simplification method to calculate the horizontal stiffness coefficient of bracing system as a constant in the plane analysis of supporting structure. The influence of non-uniformity of ring beam deformation on the calculation of horizontal stiffness coefficient should not be ignored.

Chen Shukun [15] questioned that the horizontal stiffness coefficient of the internal support system was simplified as a constant in the specification. For the pile-brace support system, different support stiffness formulas should be adopted for the support point and the middle span of the ring beam. Considering the influence of supporting rigid body displacement and enclosing purlin deformation, the model of fixed supported beam at both ends is established. The formulas for calculating the support stiffness at the support point and mid-span position are derived and given. Yang Min [16] et al. simplified the ring beam and bracing of pile-brace support system into a continuous beam model. Then, the two adjacent bracings and the ring beam between them are taken as the calculation unit, which is simplified as the fixedly supported beam model at both ends. The simplified formula for calculating the support stiffness at any length away from the support point (Equation 3) is derived in detail, which is adopted by the software "Qimingxing" for foundation pit design. Xu Yang [17] analyzed the differences, advantages, disadvantages and application ranges of the two methods being from design criteria and software "Qimingxing" respectively for calculating the horizontal stiffness coefficient of the bracing system. When the calculated length of the inner support is large, the bending stiffness of the ring beam is much larger than the supporting compressive stiffness, or the inner truss bracing system is used, the idea of average equivalence of design standards is recommended. Liu Hankai [18] further discussed the influence of adjustment coefficient of bracing fixed point and the angle between bracing and ring beam on elastic fulcrum stiffness.

$$K_T = \frac{2\alpha EA}{LS} \left[\frac{1}{1 + \frac{\alpha EA x^4}{12LSE_j I_j}} \right] \sin \theta \quad (3)$$

Wherein, K_T is the horizontal stiffness coefficients of bracing;

α is the relaxation coefficient;

A is the cross section area of the bracing member;

E is the elastic modulus of the bracing member;

L is the length of bracing member;

S is the horizontal spacing of support;

x is the distance between the point on the ring beam and bracing;

E_j is the elastic modulus of the ring beam;

I_j is the section moment of inertia of ring beam;

θ is the Angle between the support and the ring beam.

Other scholars solved the problem of supporting stiffness of bracing system by establishing numerical calculation model. Yang Xuelin [19] and Gu Hanliang [20] et al., proposed the plane frame method to analyze the horizontal stiffness of the internal support system at different positions. The support system composed of the one layer of bracing and enclosing purlin is

analyzed in plane. An appropriate support stiffness is chosen to obtain support force per meter, and then the support force is then taken as the external load of the support system. A more accurate stiffness matrix is obtained by plane frame analysis of the support system. Aiming at the problem that it is difficult to coordinate the force and deformation on the retaining structure and the bracing node in the plane frame method [21], Lu Peiyi [22] proposed a correction method to simplify the three-dimensional calculation. In the calculation method of bracing stiffness based on plane frame method, the mechanical model of frame structure should be established first according to the form of bracing system. The process of forming the overall stiffness matrix from the element stiffness matrix is complicated. The preliminary selection of equivalent bracing stiffness per meter is difficult. In addition, many more accurate numerical methods such as comprehensive stiffness method [23,24], equivalent conversion method [25] and finite element method [26] have been explored by domestic scholars to solve the stiffness calculation problem of bracing system.

4. Conclusion

Compared with the numerical method, the method by horizontal stiffness coefficient of bracing system has the advantages of simple calculation model and easy parameter determination. The existing analytical calculation methods for the horizontal stiffness coefficient of the support system in the foundation pit do not consider the difference of the bracing stiffness in the calculation unit. Besides, the influence of unequal spacing of adjacent bracing on the horizontal stiffness coefficient was not considered. These two parameters can be further introduced to establish a more accurate analytical calculation method for the correction of the horizontal stiffness coefficient of the inner support system. A new analytical formula for calculating the horizontal stiffness coefficient of the bracing system should be proposed for the design or the analysis of internal force and deformation of excavation engineering.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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