

Design method of redundancy of brace-anchor sharing supporting based on cooperative deformation

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Abstract. Because of the complicated environment requirement, the support form of foundation pit is diversified, and the brace-anchor sharing support is widely used. However, the research on the force deformation characteristics and the related aspects of the cooperative response of the brace-anchor sharing support is insufficient. The application of redundancy theory in structural engineering has been more mature, but there is little theoretical research on redundancy theory in underground engineering. Based on the idea of collaborative deformation, the paper calculates the ratio of the redundancy degree of the cooperative deformation by using the local reinforcement design method and the structural component redundancy parameter calculation formula based on Frangopol. Combined with the engineering case, through the calculation of the ratio of cooperative deformation redundancy in the joint of brace-anchor sharing support. This paper explores the optimal anchor distribution form under the condition of cooperative deformation, and through the analysis and research of displacement field and stress field, the results of the collaborative deformation are validated by comparing the field monitoring data. It provides theoretical basis for the design of this kind of foundation pit in the future.

1. Introduction

In recent years, brace-anchor sharing foundation pit support, a new type of supporting structure, not only can ensure the safety of foundation pit surrounding environment, but also can shorten the construction period and save project cost. Brace-anchor sharing foundation pit support has excellent superiority and will play an important role in the development of foundation engineering in the future, but the engineering projects are extremely limited, and the relevant theory is not mature. In civil engineering, redundancy can be considered as progressive collapse resisting capacity. Some scholars carried out theoretical research on the degree of redundancy, making redundancy design concept widely used in structural engineering, which offers us corresponding guidance. However, there are fewer researches on the theory of redundancy in underground engineering^[1] at home and abroad.

The research of some domestic scholars mostly embodies a single form of support, such as brace and other single support forms, and there is no research on the redundancy of common support. Moreover, most of the researches are based on the redundancy research of the bearing capacity and the continuous failure, and the research on the redundancy design method based on cooperative deformation has not been found. There is no systematic research at home and abroad direct at the



redundancy of the foundation pit supporting system. Zheng G. , Cheng X. S. and so on in the document literature^[2] initially proposed the foundation pit engineering redundancy definition and its design method framework. Subsequently, Wang Haixu and Cheng Xuesong analyzed redundancy of soil nailing support Yang Angle location, and put forward the method to improve the redundancy^[3]; Zheng Gang and Cheng Xuesong used discrete element to simulate the collapse of the foundation pit, the continuous failure phenomenon was analyzed, and the influence of the support end connection on the redundancy of the foundation pit was discussed emphatically^[4]. In order to improve the redundancy of the support system, Luo Yangyang^[5] proposed to improve the transverse continuity of the foundation supporting structure with the plane shape as the outer convex shape. Zheng Gang^[6] put forward the concept of foundation pit engineering redundancy based on theoretical research and engineering practice and the redundancy of support system was studied: (1) the vertical deformation redundancy of the foundation pit supporting structure; (2) vertical supporting structure stability redundancy of the foundation pit; (3) the level deformation redundancy of the foundation pit supporting structure; (4) horizontal supporting structure stability redundancy of the foundation pit; (5) the redundancy of the vertical supporting structure in the horizontal support.

In this paper, through theoretical analysis to find the redundant redundancy ratio coordination deformation factor, strengthen the program through the example selection, selection of engineering cases are verified for the supporting system of redundant design and provide the basis and reference.

2. Design method of redundancy based on cooperative deformation

When the foundation pit supporting adopts only one form, the formula of strength redundancy degree SRF is put forward based on Frangopol, and the formula for calculating stiffness and redundancy is given as follows^[7]:

$$SRF_s = \frac{S_u}{S_r - S_u} \quad (1)$$

Among them, S_u is the maximum deformation value of the original structure, and S_r is the maximum deformation value of the structure after the failure of the component.

It can be seen from above that when the foundation pit uses only the form of pile-anchor support, the formula for calculating the redundant stiffness of anchor cable and the expression of redundant function are:

$$S_m = \frac{S_{mu}}{S_{mr} - S_{mu}} \quad (2)$$

$$S_m = f_1(x, y, m) \quad (3)$$

Type: S_m —Stiffness and redundancy parameter of anchor cable;

S_{mu} —Maximum deformation of original structure of anchor cable;

S_{mr} —Maximum deformation of structure after failure of anchor cable component;

m —Anchor cable stiffness;

x, y —Other affecting factors in addition to anchor stiffness;

The expression of redundant function is mainly related to the stiffness of anchor rope, but also with the spacing of support pile, the diameter of support pile, the stiffness of waist beam and so on. That is called x, y . When the foundation pit adopts only the form of pile-brace support, the formula for calculating the stiffness and redundancy of the bracing and the redundant function are expressed as follows:

$$S_z = \frac{S_{zu}}{S_{zr} - S_{zu}} \quad (4)$$

$$S_z = f_2(x, y, z) \quad (5)$$

Type: S_z —Stiffness redundancy parameter of brace;

S_{zu} —The maximum deformation of the original structure of brace;

S_{zr} —The maximum deformation of the structure after failure of brace component;

z —Bracing stiffness;

x, y —Other affecting factors in addition to brace stiffness;

The expression of redundant function is mainly related to the stiffness of brace, but also with the spacing of supporting pile, pile diameter, waist support stiffness and other factors, namely x, y .

The ideal synergy effect of brace-anchor sharing support at the junction is that pile-brace and pile-anchor deformation tends to be equal, so we need to strengthen the junction cable stiffness, reaching $S'_{mr}=S'_{zr}$, S'_{mr} , indicates that the maximum deformation value of the anchor cable with the support of the anchor cable after strengthening the anchor rope stiffness. S'_{zr} , indicates that the maximum deformation value of the brace with the support of the anchor cable after strengthening the anchor rope stiffness.

$$\frac{S'_z}{S'_m} = \frac{\frac{S'_u}{S'_{zr}-S'_u}}{\frac{S'_u}{S'_{mr}-S'_u}} = \frac{S'_{mr}-S'_u}{S'_{zr}-S'_u} = \alpha \quad (6)$$

$$\alpha = f(x, y, m, z) \quad (7)$$

Type: S'_z —The stiffness and redundancy parameters of the boundary support at the time of cooperative deformation are considered;

S'_m —Considering the cooperative deformation, the stiffness and redundancy parameters of the anchor cables at the junctions are considered;

S'_u —Considering the cooperative deformation, the maximum deformation value of the original structure is considered;

S'_{zr} —The maximum deformation of the bracing at the boundary after strengthening the anchor cable stiffness;

S'_{mr} —After strengthening the anchor cable rigidity, the maximum deformation value of the anchor at the junction;

α —Cooperative deformation redundancy ratio.

As can be seen above, the effect of deformation and synergy between the brace-anchor sharing supporting is equal to that of the pile-anchor, we need to strengthen the junction of anchor cable the stiffness to reach $S'_{mr}=S'_{zr}$ effect, so the α approaches 1, the best synergistic response effect.

3. Finite element simulation based on redundancy of cooperative response

3.1. General situation of engineering

The foundation pit excavation is 12M deep, and the foundation pit support is pile support + pile anchor. The vertical direction set up two brace and three anchor. The anchor cable prestress 250KN, the number of the first and third prestressed anchor cables is encrypted at the junction of brace-anchor sharing foundation pit support. Prestressed anchor angle was 20°, supporting pile length 21m, diameter 800mm, ground additional load 20kPa.

The constitutive model adopts M-C model, and the constitutive model chooses the elastic model prestressed anchor cable to select the implanted truss element in the Midas, and the linear beam element is selected in support pile and inner brace.

A total of seven ways of encryption cable combination can be set up, which are respectively as follow. (a) encryption the first cable (b) encryption second cable (c) encryption the third cable (d) encryption of the first channel and the second channel cable (e) encryption of the first channel and the third channel cable (f) encryption of the second channel and the third channel cable (g) encryption of the first and the second and the third channel cable.

Table 1.Parameters of different soil layers

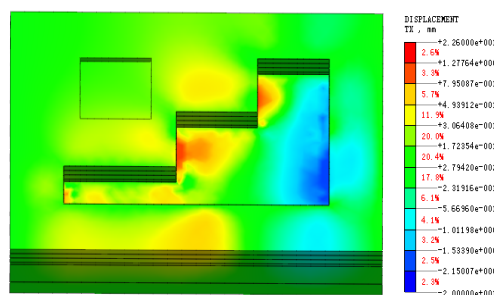
	Name	Bulk density $\gamma(\text{kN/m}^3)$	Cohesion $c(\text{kPa})$	Internal friction angle $\phi(\text{k}^\circ)$
1	Miscellaneous fill	18.0	7.0	15.0
2	Plain fill	18.0	8.5	18.5
3	Silt	19.1	10.2	25.6
3-1	Silty clay	19.3	25.0	8.6
4	Silty clay	18.7	25.0	7.9
5	Silt	19.4	9.7	26.7
6	Silty clay	19.3	29.0	10.0
6-1	Silt	19.5	6.8	27.9
7	Silt	19.5	9.5	27.2
8	Silty sand	20.0	2.0	30.0

Table 2. List of anchor parameters

Number	Aperture (mm)	Free end length (mm)	Anchorage length (mm)	Horizontal spacing (mm)	Tension lock value (kN)
MS1	400	9000	14500	2250	250
MS2	400	7000	14500	2250	250
MS3	400	5500	14500	2250	250

**Fig. 2-1** 3D model of finite element

3.2. Simulation result analysis

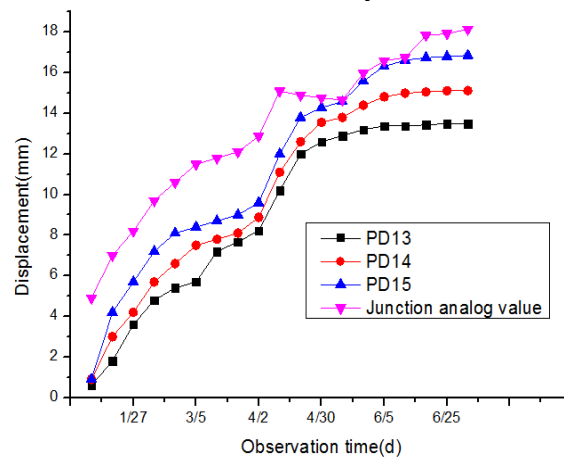
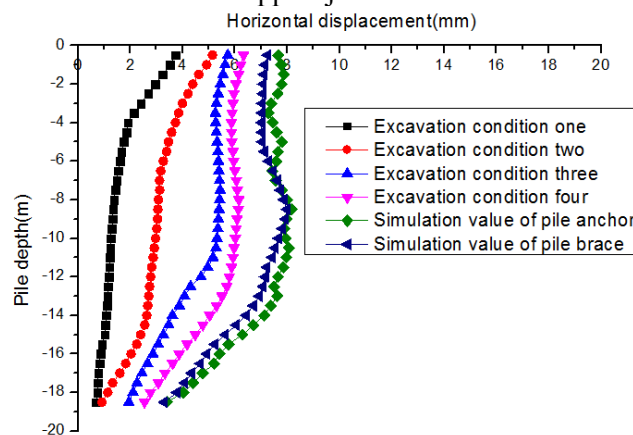
**Fig. 2-2** Horizontal displacement nephogram of foundation pit after excavation

After the encryption measures are taken, the finite element simulation is carried out respectively, and the results are extracted. According to formula (6), the ratio of cooperative deformation redundancy under the encryption measures is shown in table 3:

Table 3. Coordinated response redundancy ratio

Nam e	$S'_{mr}(mm)$	$S'_{\pi}(mm)$	$S'_u(mm)$	Redundancy ratio α
a	9.97	7.67	16.82	0.75
b	10.53	7.05	16.82	0.64
c	9.76	6.60	16.82	0.69
d	9.34	6.21	16.82	0.70
e	8.07	7.91	16.82	0.98
f	7.33	5.91	16.82	0.87
g	7.93	6.38	16.82	0.85

From table 3 can be found, encryption scheme (e) collaborative deformation redundancy ratio was 0.98, compared with other encryption schemes most close to 1, indicating the first encryption and the third anchor cable to improve the stiffness of the redundancy of the best.

**Fig. 2-3** The measured and simulated curves of horizontal displacement at the top of the anchor support joint**Fig. 2-4** Horizontal displacement curve of pile anchor, Pile Bracing simulation value and CX8 measured value at variable stiffness

As you can see in figures 2-3 and 2-4:

The horizontal displacement of pit top and the horizontal displacement of pile body increase with the excavation of foundation pit, and the simulation results coincide with the actual monitoring value, which shows that the finite element model is reasonable. With the increase of excavation depth, horizontal displacement of pit top and the horizontal displacement of pile body increases, brace axial force and anchor pullout force will successfully limit the displacement of supporting pile in the horizontal direction, in the late period of excavation pile displacement curve has obvious "bulge"

phenomenon, both pit top horizontal displacement curve of CX8 horizontal displacement curve, variation curve of each construction stage is basically the same.

PD13 is located in the pile-brace, PD14 is located in the brace-anchor sharing supporting junction, PD15 is located in the pile-anchor. Because the pile-brace stiffness is greater than the pile-anchor stiffness, it can be seen from the graph curve PD15 is located in PD13 above, in support of the junction due to the increase of the first and the third prestressed anchor number, improve the pile-anchor redundancy, enhance its ability to resist progressive collapse, can be seen from Fig. 2-3 curve PD14, curve PD13 and PD15 located between PD13, PD14 and PD15, the maximum horizontal displacement are respectively 6.48mm, 7.26mm, 8.09mm, the three data increased, little difference, that the deformation coordination is very good.

4. Conclusion

(1) The redundancy ratio α of cooperative deformation is calculated, and the ratio α of the degree of redundancy of the cooperative deformation to the joint of brace-anchor sharing foundation pit support is in connection with the stiffness of the cable and brace and other factors. The most effect of deformation and synergy between the brace-anchor sharing supporting is nearly equal in pile-brace and pile-anchor and achieves the effect of $S'_{mr}=S'_{zr}$.

(2) In order to improve the resistance to progressive collapse of the joint of brace-anchor sharing support joint, the distribution of the side wall stiffness of the retaining wall of the foundation pit should be uniform. In engineering, it is possible to increase the redundancy of anchor rope by increasing the number of prestressed anchor cables and sharing the supporting anchor at the junction, and the effect of cooperative deformation is best when the duty α approaches to 1. This paper sets up seven cable encryption combination, from the simulation data showed that the increase in the number of the first and the third prestressed anchor can most effective control the lateral displacement of supporting piles, brace-anchor sharing foundation pit support junction deformation coordination is good, and the monitoring data can be verified.

Acknowledgments

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