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DEFORMATION RULE OF BORED PILE & STEEL SUPPORT FOR DEEP FOUNDATION PIT IN SANDY PEBBLE GEOLOGY

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ABSTRACT

Regarding the whole excavation process of the support system of the Southwest Jiaotong University Station of Chengdu Metro Line 6 (the deep foundation pit bored pile & steel support and support system) as the engineering background, this paper studies the deformation rule of the deep foundation pit bored pile & steel support of the sandy pebble foundation. The deformation rule of this support system, the settlement rule of the ground surface outside the pit, and the rule of the uplift of the loose at the bottom of the pit are studied. A key analysis of the positive corner of the foundation pit is conducted, and the rationality of the optimization of the support scheme is evaluated. This paper provides effective guidance for the subsequent deep foundation pit construction and provides a reference for deep foundation pit construction.

KEY WORDS

Sand pebble geology, Deep foundation pit, Bored pile, Steel support, Deformation rule

INTRODUCTION

With the development of cities, the frequency of deep foundation pits is increasing, and the requirements on the type of foundation pit support are also increasing. A single type of foundation pit support has been unable to satisfy people's support needs for the excavation process. Many foundation pits now use combined structures for support. Many scholars have conducted detailed scientific studies on foundation pit support in various areas.

In the 1930s, researchers abroad specialized in the study of deep foundation pit engineering. Terzaghi and Peck [1] began to study the ultimate bearing capacity of the loose under shear failure and instability. The foundation pit support design calculation method has been widely recognized by scholars and professionals. Based on this method, the theory has been improved and revised so that it can be better applied in engineering practice, and it is still used today [2]. In the 1950s, Italian engineers developed the support technology of piles + underground diaphragm walls, which became a major construction method for foundation pit engineering. In the 1960s, specifications, technologies and methods for the design and construction of deep foundation pit support were gradually established. In the 1970s, Japanese scholars proposed the SWM method (SWM is the abbreviation of Soil mixing wall). After several improvements, this method became mature and has been widely used in practical engineering. The earliest successful application of loose nail wall support technology to a project occurred in France [3], and the widespread application of loose nail wall support technology has promoted the development of related theoretical and experimental research. In the late 1980s, Zhou et al. [4] were used to simulate the pit dewatering through the inversion of permeability parameters based on the field pumping tests. Satty [5] proposed the analytic hierarchy process. Based on the summary of Qingdao coastal deep foundation pit engineering. Zhu et al. [6] discussed the deep deformation of the deep foundation pit supporting structure in more depth by considering the excavation process. Wei [7] considered the combination of deterministic factors and uncertain factors, an optimization method for foundation pit support schemes that was based on reliability analysis was proposed. Liu and Lei [8] regarded the majorization of the deep foundation pit support of the Guangzhou Metro as the research background, constructed evaluation model for supporting schemes of subway deep foundation pits. Dai et al. [9] studied the mechanical characteristics of deep foundation pit excavation and support in detail. Yu [10] proposed a complex horizontal support form and a supporting structure system for ground walls. Li et al. [11] calculated and analyzed the horizontal displacement of the pile at various excavation depths with the background of the deep foundation pit project of Guiyang West Road Station of Guiyang Metro Line 2. Li et al. [12] focused on the numerical simulation of the foundation pit supporting structure and on the application of analytical theory to improve the results. Zhang et al. [13] used the elastoplastic numerical simulation method to fully consider the coordination relationship of pile-loose deformation. Xiao and Peng [14] analyzed the selection of a deep and large foundation pit support in combination with on-site monitoring data and changes in surrounding environmental conditions. Yu et al. [15] aimed at overcoming the main limitation of the available method in the analysis of the stability of narrow and long foundation pits.

In recent years, the amount of research that has been conducted on deep foundation pit support has gradually increased, but the research on drilling deep foundation pit hole cast-in-place pile + steel support is less and immature. Therefore, this article studies the deformation rule of deep foundation pit bored piles + steel support.

BASIC ASSUMPTIONS AND ENGINEERING OVERVIEW

Basic assumptions

It is highly difficult for a numerical simulation to fully match the established model with the actual project, and it is necessary to impose basic assumptions on the model. The basic assumptions of this model are as follows:

(1) Rock and loose are regarded as homogeneous and isotropic elastoplastic materials, and the influence of precipitation on the loose characteristic and on the rheological effects of the loose is not considered;
(2) The supporting structure is regarded as an ideal elastomer;
(3) The initial crustal stress field is assumed to be the self-gravity stress field.
(4) It is assumed that groundwater is ignored throughout the excavation process. However, in engineering cases, necessary curtain water-stopping measures are often taken for foundation pits; hence, the forecast deviation value is often small.

Project overview

Project scale

The standard section of deep foundation pit of Southwest Jiaotong University Station of Chengdu Metro Line 6, which width is 22.5 m, overall length is 222.1 m, and the excavation depth is 26.64 m. The excavation depth of the foundation pit is an approximately rectangular parallelepiped structure. Figure 1 is a simplified geometric plan of foundation pit. Figure 2 is a picture of the construction pictures.

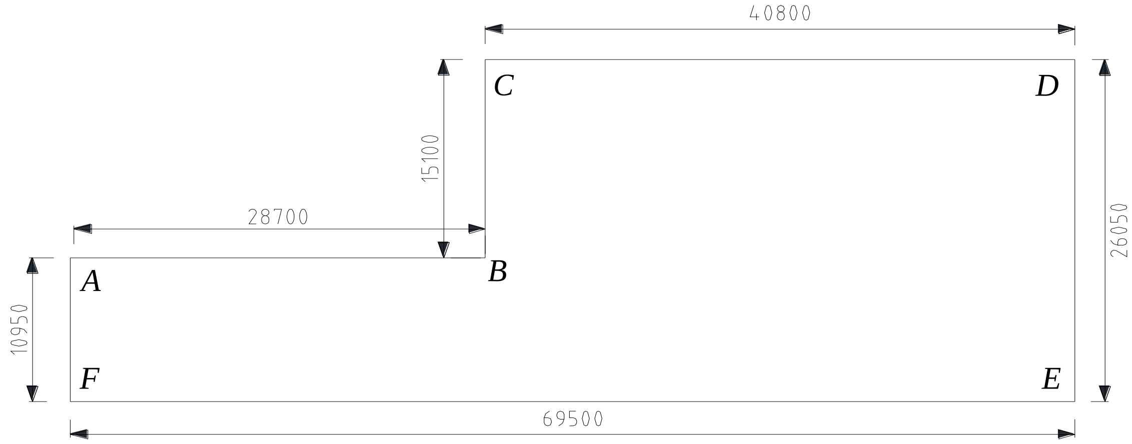


Fig. 1 – Foundation pit plane simplified diagram

Fig. 2 – Construction pictures

Material properties

The material properties of the loose and the supporting system are presented in Tables 1~4.

Tab. 1 - loose parameters

Stratum	Thickness /m	Underlying structural integrity	Natural density ρ / g/cm³			Cohesion c /kPa	Internal friction angle ϕ /o	Poisson's ratio v	Deformation modulus E_0 / MPa	Severity kN/m³
Artificial filling	3	Moist and loose	1.8×10^3			15	5	0.30	10.00	18
Silty filling	1	Soft structure	1.9×10^3			20	15	0.30	12.00	19
Fine sand	2	Loose structure	1.9×10^3			/	30	0.28	20.00	19
Slightly dense pebbles	3	Loose structure	2.0×10^3			/	32	0.20	30.64	20
Moderately dense pebbles	20	Loose structure	2.1×10^3			/	36	0.20	38.80	21
Compact pebbles	/	Loose structure	2.2×10^3			/	40	0.20	56.17	22

Tab. 2 - Physical parameters of the envelope structure

Name	Diameter /m	Severity /(kN/m³)	Elastic modulus /GPa	Poisson's ratio	Pile length /m
Steel support	Φ0.609	78.5	200	0.3	/
A6-type pile	Φ1.2	25	31.5	0.2	31.64 (Pile depth 5)
D6-type pile	Φ1.0	25	31.5	0.2	31.64
E6-type pile	Φ1.0	25	31.5	0.2	31.64
L6-type pile	Φ1.0	25	31.5	0.2	8.7 (Pile depth 3)
LZ-type pile	Φ1.2	25	31.5	0.2	29.74 (Pile depth 8)

Tab. 3 - Design values of the pre-loaded axial force for steel supports

Support position	AB section /kN		BC section /kN		CD section /kN		EF section /kN	
	f	f1	f	f1	f	f1	f	f1
First support (Construction permanent cover)	720	350	220	110	220	110	220	110
First support	/	/	860	400	860	400	860	400
Second support	1370	400	1360	500	1450	500	1430	500
Third support	2420	450	2450	500	2530	500	2430	500
Fourth support	2130	450	2130	500	2140	500	2130	500

Note: f is the design value of the axial force and f1 is the pre-added axial force value. These sections represent the range of design values of the pre-loaded axial force for steel supports.

Tab. 4 - Model parameters of the cover plate and the retaining wall

Name	Thickness /mm	Severity /(kN/m^3)	Elastic modulus /GPa	Poisson's ratio
Cover plate	800	25	31.5	0.2
Retaining wall	300	25	31.5	0.2

Process of foundation pit excavation

The deep foundation pit excavation adopts half cover excavation method. It is designed as two phases and divided into ten working conditions. The excavation process is shown in Table 5.

Tab. 5 - The excavation process

Working condition		Construction process
First phase	I	Establish the initial ground stress balance under the weight of soil.
	II	Setting of bored piles and temporary piles.
	III	Excavate -1.5 m, and install the first support at -0.5 m.
	IV	Excavate to -5.5 m, install permanent cover and concrete retaining wall at -4.5 m.
	V	Remove the first support, and L6 temporary pile and backfill the cover plate.
Second phase	VI	Excavate -4.185 m, and install the first support at -3.185 m.
	VII	Excavation -7.685 m, installation of a second support at -8.685 m.
	VIII	Excavate -17.185 m, and install the third support at -16.185 m.
	IX	Excavate -22.685 m, and install the fourth support at -21.685 m.
	X	Excavation -26.64 m, foundation pit excavation support is completed.

STRESS AND DEFORMATION OF THE FOUNDATION PIT

The foundation pit model is simulated and analyzed by abaqus finite element software, the total number of divided foundation pit grid units is 117012. The loose unit is C3D8R; the retaining pile is simplified as a continuous wall unit; the cover unit is C3D8R; the temporary pile unit is C3D8R; and the diagonal brace and cover pile are T3D2 pole units.

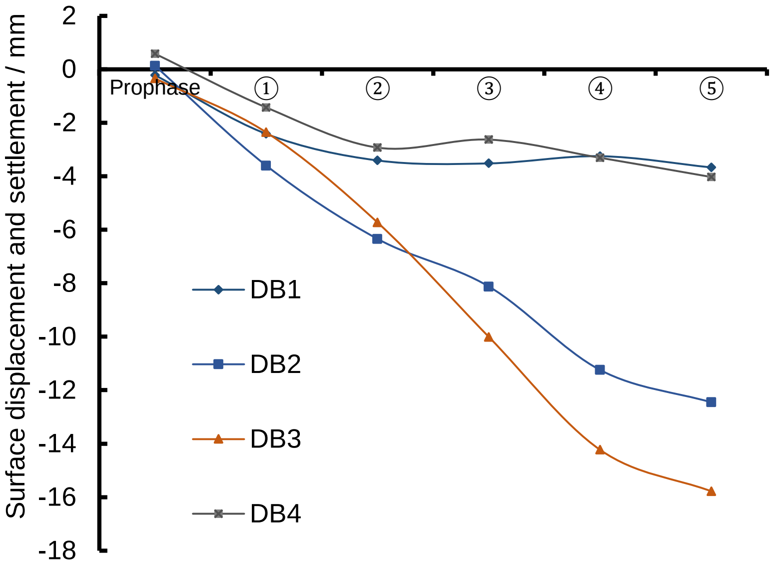
The C3D8R element is an 8-node hexahedral linear reduced integral element, it has the following three advantages: (1) Shear self-locking phenomenon is not easy to occur under bending load; (2) The solution of displacement is more accurate; (3) When the mesh is distorted, the accuracy of the analysis will not be greatly affected. The continuous wall unit is simulated by the solid unit, the spring stiffness element is used to simulate the mutual rubbing between the continuous wall and the soil. The T3D2 pole unit is a three-dimensional beam element defined by two nodes, and it is a lightweight element type that can simulate large deformation.

The contacts relationship of the components are as follows: the support structure and the loose body interact with each other by establishing surface-to-surface contact; the cover plate and the support structure realize a rigid connection between them via common nodes; and the components of the support structure also pass through the common nodes and release the rotational degree of freedom to realize articulation between them.

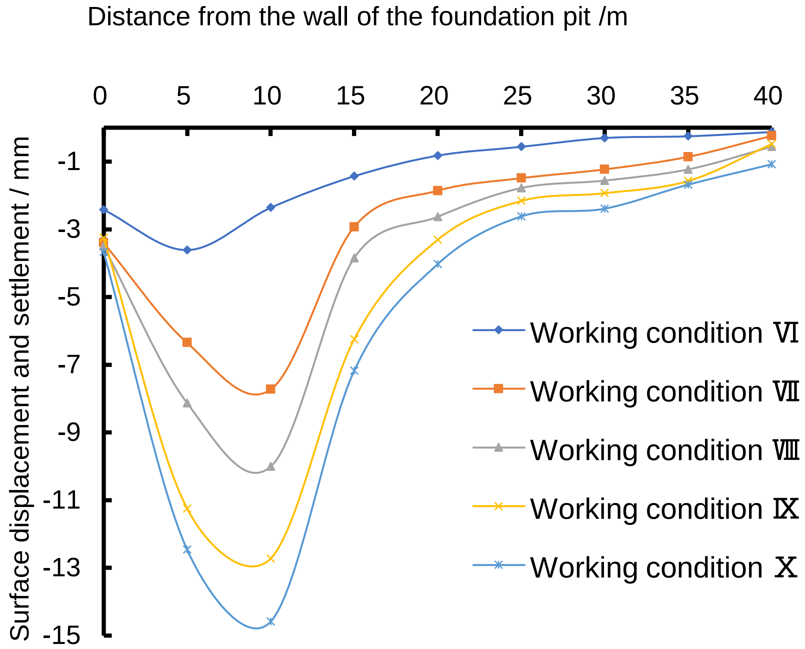
Change rules of the ground settlement and the pit bottom uplift

(1) Ground settlement outside the pit

Select the points on the section that correspond to the maximum settlement for extraction of the data for analysis, and organize the data into a curve form to better visualize the change trend of loose settlement. The curves are plotted in Figure 3 (a)-(b).



(a) Surface subsidence time-history curves



(b) Surface settlement curves from the foundation pit wall

Fig. 3 – Surface subsidence curves

According to Figure 3(a)~(b), the surface settlement curve increases almost linearly. In the later stage of excavation, the settlement curve of the foundation pit tends to be gentle, and the entire settlement curve shows a "parabolic" change. The main settlement occurs approximately 5 ~ 10 m from the foundation pit wall, and the maximum value is approximately 15 mm. After the steel support is erected, the deformation curve of the foundation pit gradually changed from a "triangle" to a "groove shape". The settlement trend of the ground surface outside the pit changed as the ground surface settlement increased rapidly with the distance from the pit wall. When the sedimentation of the foundation pit reaches the maximum settlement value, the ground sedimentation decreases with the increase of the distance from the pit wall, finally, stabilizes and approaches zero. According to the ground settlement map, the width of the impact of the construction of the foundation pit exceeds twice the depth of the construction of the foundation pit.

(2) Loose uplift at the bottom of the pit

The change curve of the pit bottom uplift can well reflect the change of the loose pressure at the bottom of the pit during excavation. A change that is too large demonstrates that the earth pressure on the bottom of the deep foundation pit is too large and, hence, the deformation of the envelope structure is too large, thus, it can easily cause instability of the structure, and it is necessary to study the loose at the bottom of the pit. Select the loose in the middle as the research object, and plot the deformation curve of this loose under each working condition, as shown in Figure 4.

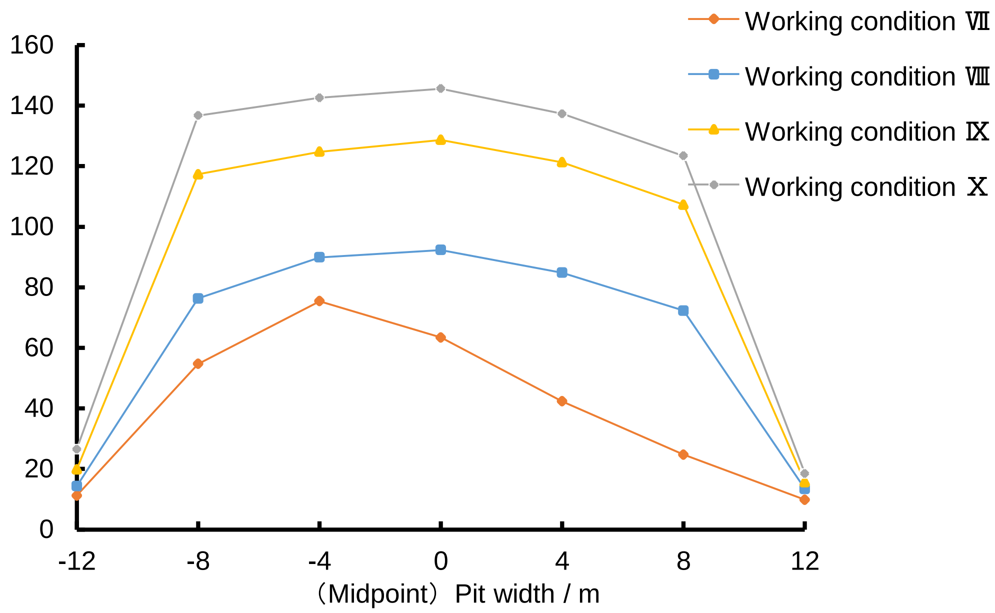


Fig. 4 – Variation of the loose uplift displacement at the bottom of the pit

According to Figure 4, the change in the settlement of the loose bulge is substantially influenced by the excavation of the first phase. The maximum displacement of the uplift of the foundation pit loose occurs at the midpoint of the foundation pit. However, when the deep foundation pit is constructed in the first stage, the loose body has already undergone the uplift phenomenon. Therefore, during the second phase of the excavation process, the maximum displacement of the loose uplift under working condition six occurred at the midpoint of the cover plate. With the continuous excavation of deep foundation pits, this effect is gradually eliminated. The uplift of the loose occurs in the middle of the bottom of the pit. The maximum rise of the foundation pit is approximately 140 mm. In addition, according to the figure, the uplift amount of the foundation pit is constantly increasing over time. Since the deep excavation of the second phase is deeper, the uplift amount of the foundation pit is relatively large. During the third construction process, the uplift amount changed the most. This is because the deep foundation pit has a deeper support interval here, and the pressure on the retaining structure is also the largest, thereby resulting in a sudden increase in the loose uplift.

DISPLACEMENT CHANGES OF THE SUPPORTING STRUCTURE

Variation of the vertical displacement of the envelope structure

In this numerical simulation, the bored cast in situ pile is simplified as an underground continuous wall, therefore, this article will study the change rules of the vertical displacement of the underground continuous wall. Several points at the positive corner are used to analyze the vertical settlement of the wall top. The curves of the displacement and deformation are plotted in Figure 5.

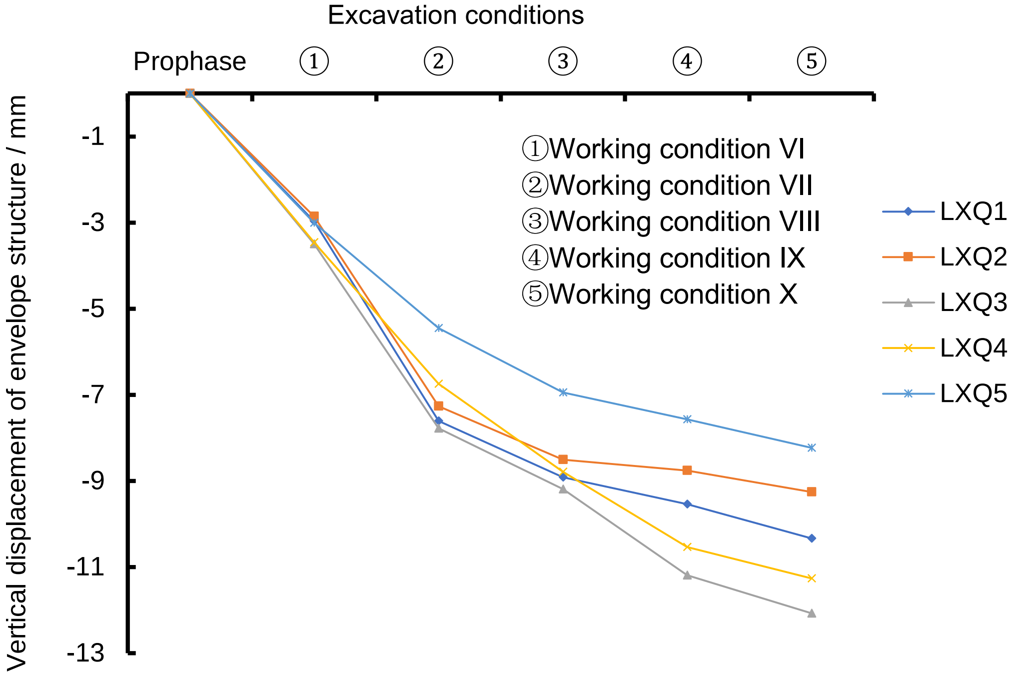
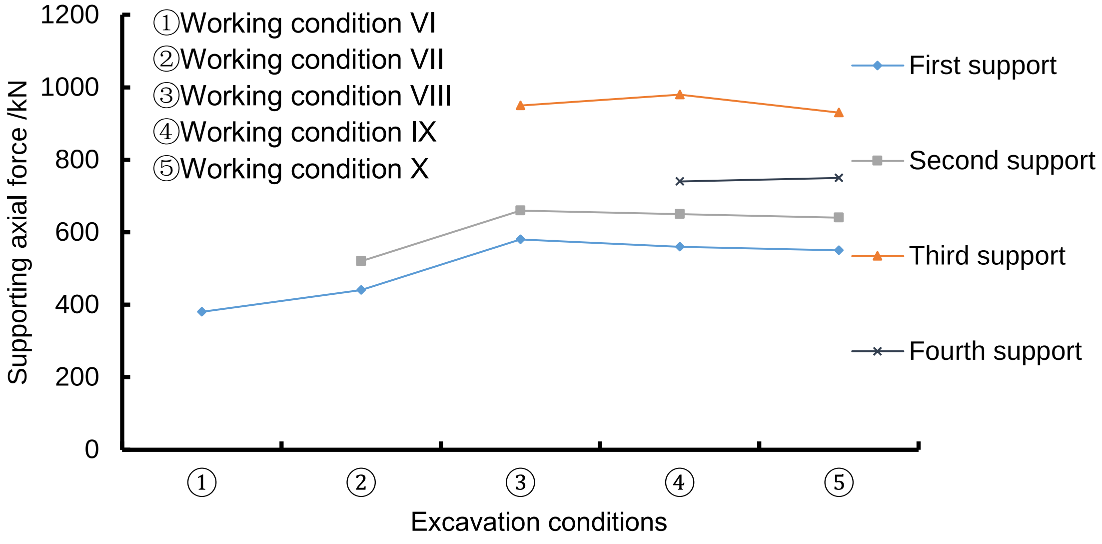


Fig. 5 – Curves of the vertical settlement of the envelope structure

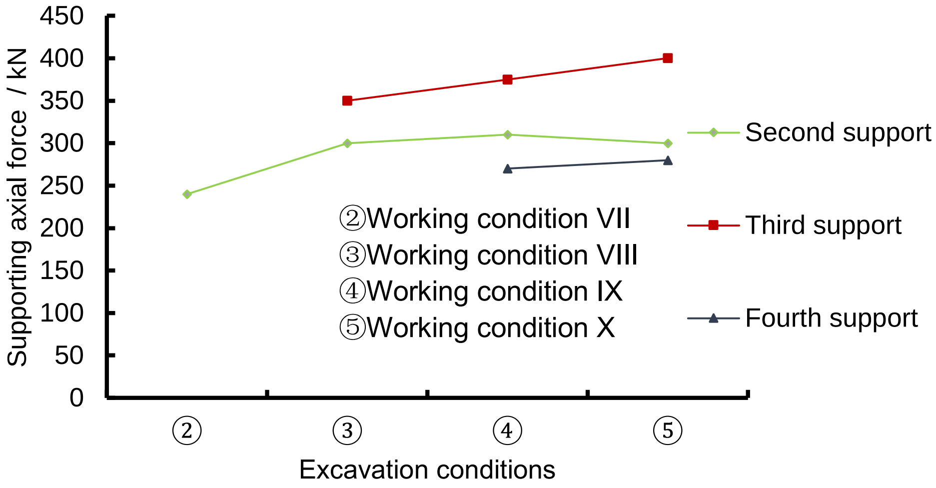
According to the settlement curves in Figure 5, the retaining structure moves downward. Especially prior to the installation of the second steel support, the envelope structure shows a significant downward trend. This is because the first support only supported one side and the other side of the envelope structure is connected to the cover plate. Exerting its supporting role has led to a significant decline in the envelope structure. When the second steel support is installed, the supporting structure and the steel support form a single unit, which fully utilizes its maximum support advantages. Hence, the subsequent settlement trend is slow, and, eventually, the settlement level stabilizes when the loose supports have been finished. The maximum settlement of the retaining structure is approximately 12 mm, which accords with the value that is specified by the foundation pit code.

Axial force of the steel support

The prophase excavation support involves only one steel support, and the support depth is relatively shallow. In addition, it must be removed in the subsequent phase, there is no continuity, and the change rule cannot be studied. Therefore, this article only extracts the four steel supports of the second phase of the deep foundation pit and studies the rule of their axial force change. The oblique rods with relatively high stress and the first crossbar of the standard section are extracted as research objects, and the stress variation rules are analyzed. The variety of the axial force is plotted in Figure 6 (a)~(b).



(a) Steel support of the standard section



(b) Inclined steel support of the pit angle

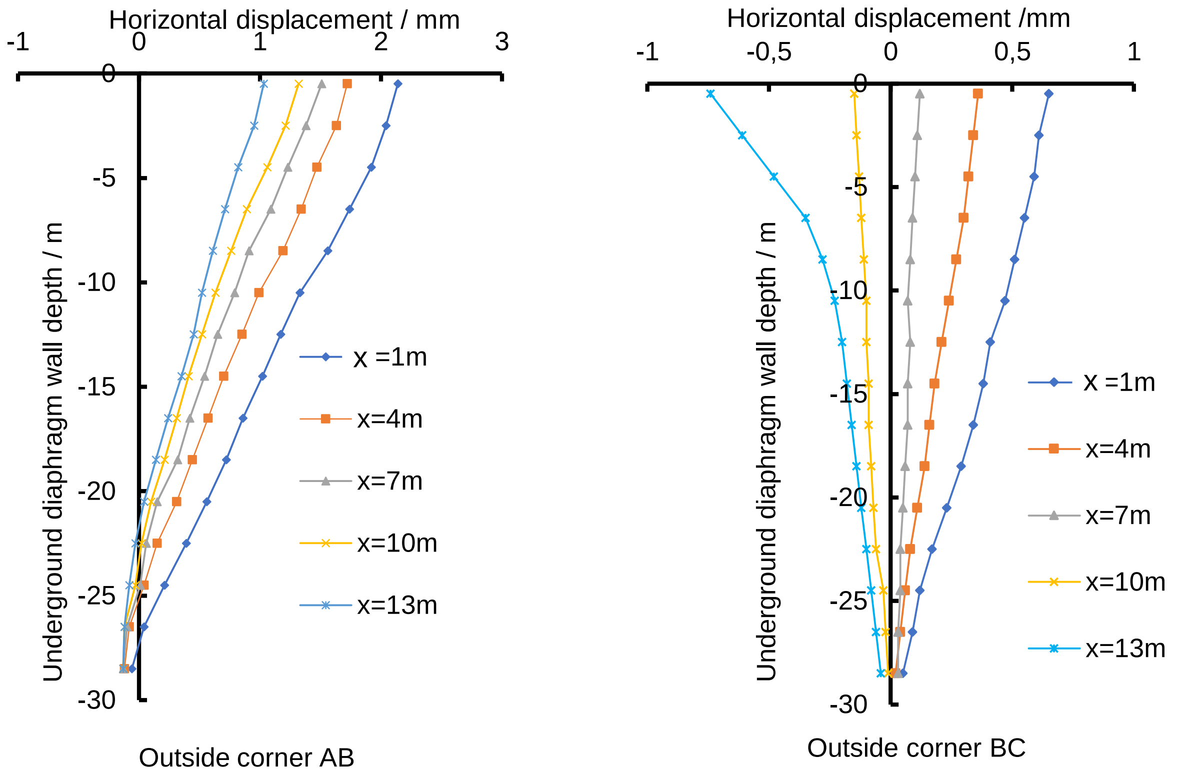
Fig. 6 - Axial force changes of the steel support

In Figure 6, the force change rule of the steel support in the standard section is plotted. With the installation of the steel support and the excavation of the loose, the axial forces of the first and second steel supports slowly increase, and they attained their largest values when the third steel support is installed. The third steel support axial force initially increase and subsequently decrease, and the fourth steel support axial force is approximately stable. The axial force of the third steel support is much larger than those of the other three steel supports. This is because the role of the steel support in the support system is resisting the horizontal deformation of the envelope structure. According to the change curve of the deep horizontal displacement of the envelope structure, the maximum point of its horizontal displacement is at the third steel support setting. Hence, the axial force of this support exceeds those of the other supports. In the later stage of deep foundation pit excavation, the axial force of the steel support tends to be stable. Hence, the support system that is composed of the steel support and the surrounding structure is in a safe and reliable state. The support axial force of the pit angle consists of the axial forces of only three steel supports; this is because the upper surface of the second support is a cover plate and the first steel support does not have an inclined support at the pit angle. The axial force deformation of the second steel support increased initially and subsequently decreased steadily. The variety of the axial force of the three supports is approximately consistent with the change of the supporting axial force of the standard section of the foundation pit. The axial force of the inclined support is lower than that of the standard section. The horizontal deformation of the pit angle retaining structure is smaller than the horizontal deformation of the standard envelope section. The place where the maximum horizontal displacement is attained by the pit angle retaining structure is the same as that of the standard envelope structure, namely, near the setting of the third support.

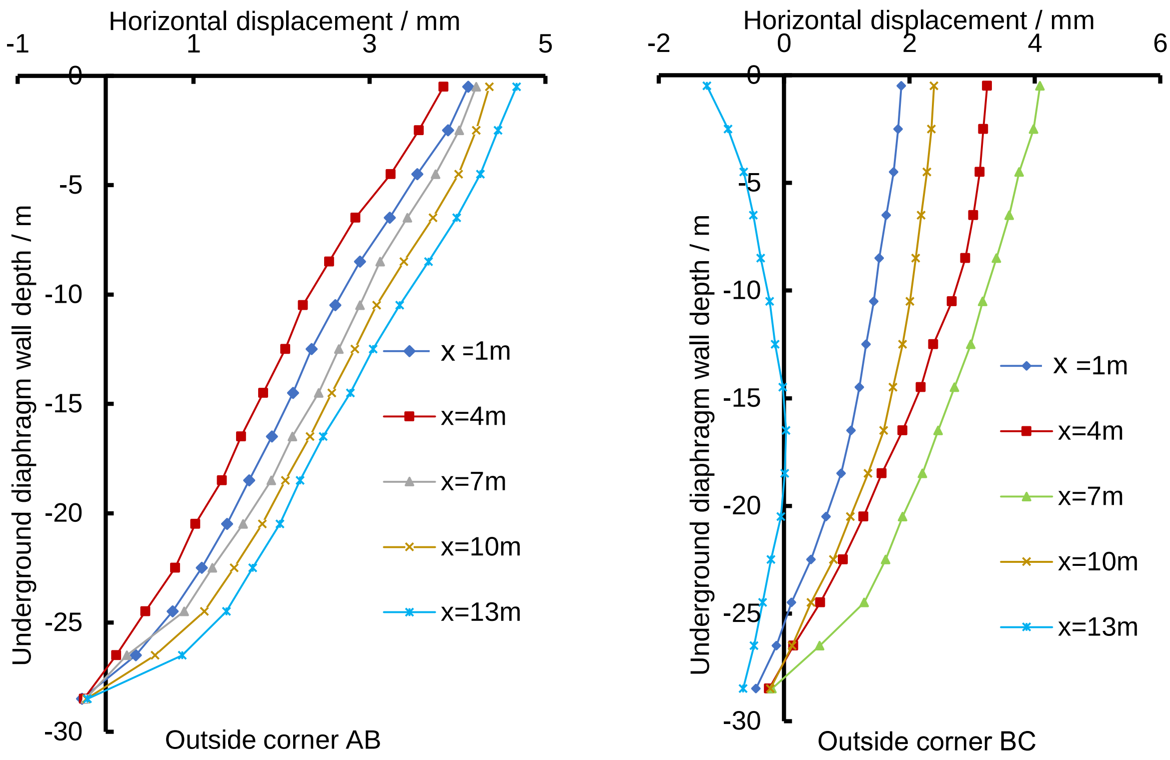
Analysis of the Pit Angle Effect of the Retaining Structure

The pit angles in the foundation pit are divided into two types: the internal corner and the positive corner. The pit angle has a strong spatial effect, and the positive corner is the most unstable place in the deep foundation pit retaining structure. Therefore, the pit angle should be researched extensively.

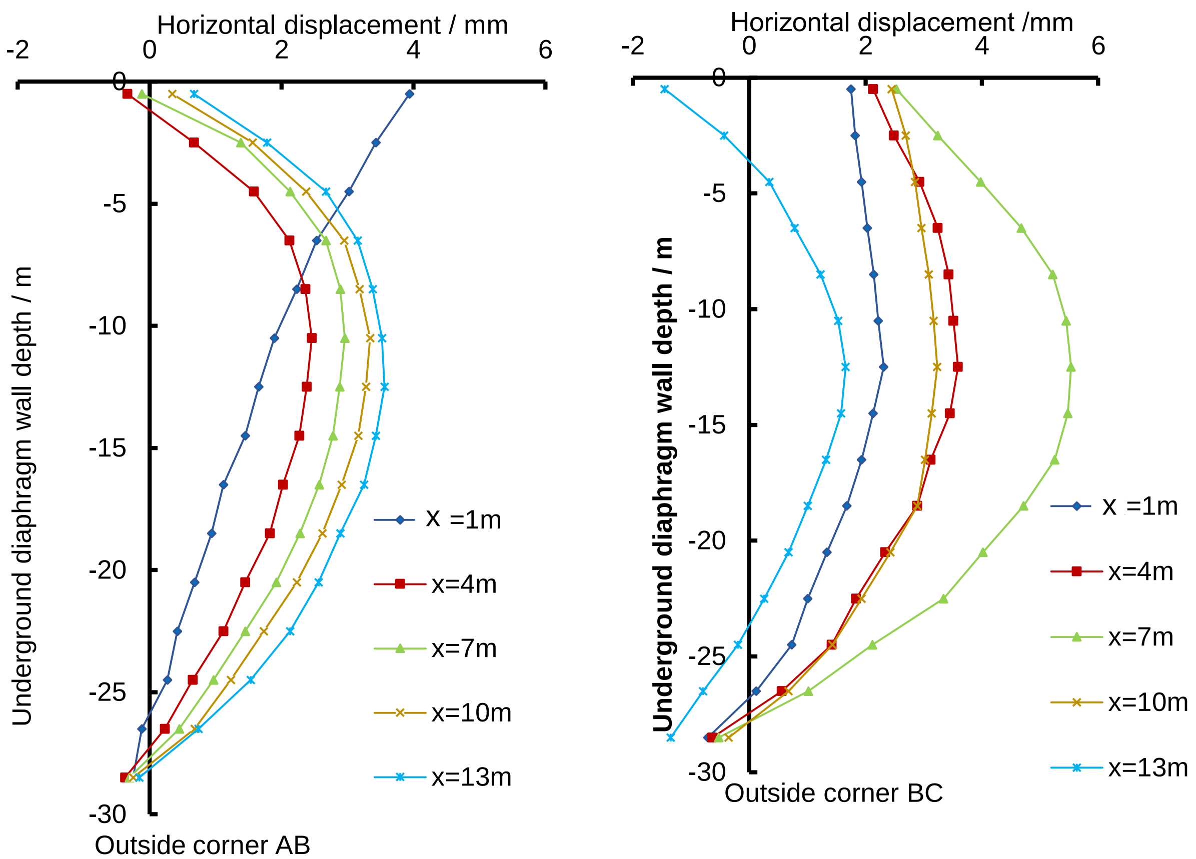
According to Figure 1, the maintenance structure has one positive corner B (the positive corner is the angle greater than 180 degrees, point B in this paper is 270 degrees) and multiple internal corners, such as A and C (the internal corners is the angle less than 180 degrees, point A and C in this paper are 90 degrees). Due to the soil pressure of the positive corner in deep foundation pit is relatively large, it is the most unstable force area in the deep foundation pit retaining structure. Therefore, the positive corner should be avoided as much as possible. If the positive corner cannot be avoided, it should be studied via numerical simulations to analyze the reasons for its instability and to provide corresponding guidance for subsequent construction. During the excavation of the first phase, the excavation of the foundation pit is shallow, and the horizontal displacement of the supporting structure is relatively small; hence, the change rule of its horizontal displacement is investigated. The data of the deep horizontal displacement of the underground diaphragm wall with positive corners of 1 m, 4 m, 7 m, 10 m, and 13 m on the AB and BC sections under each working condition are analyzed, and the deformation rules are summarized, as shown in Figure 7(a)~(e).



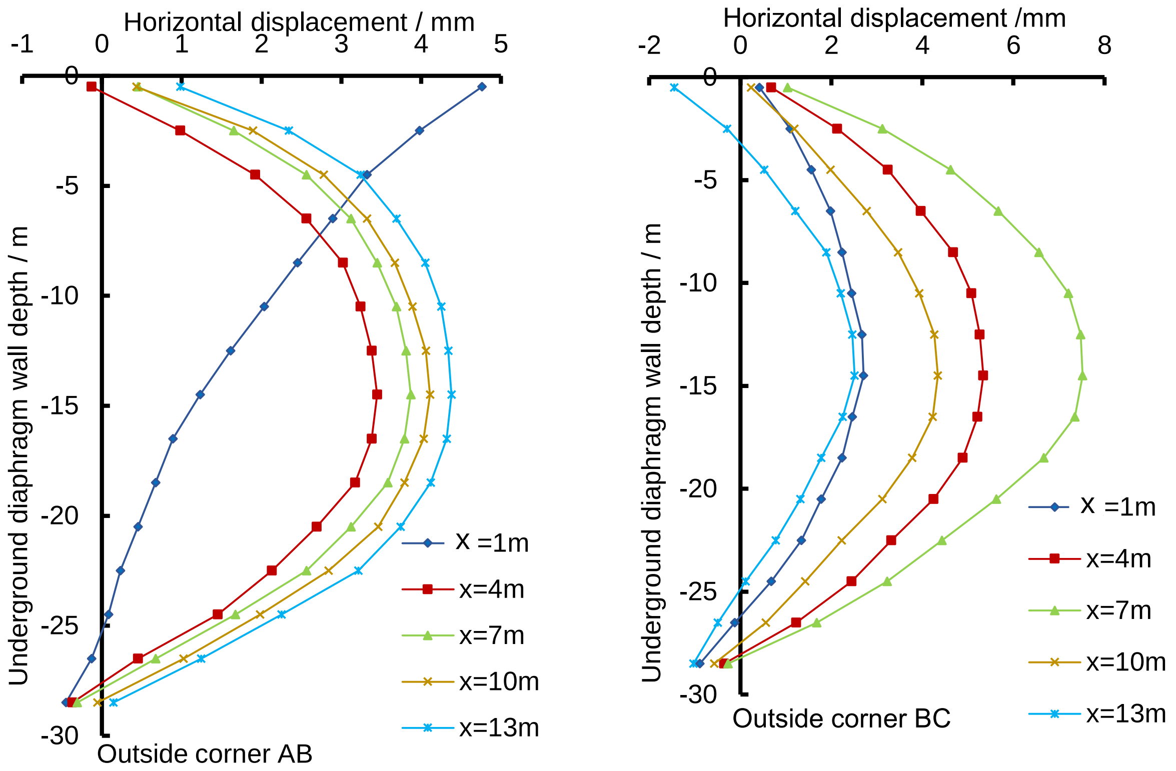
(a) Working condition VI



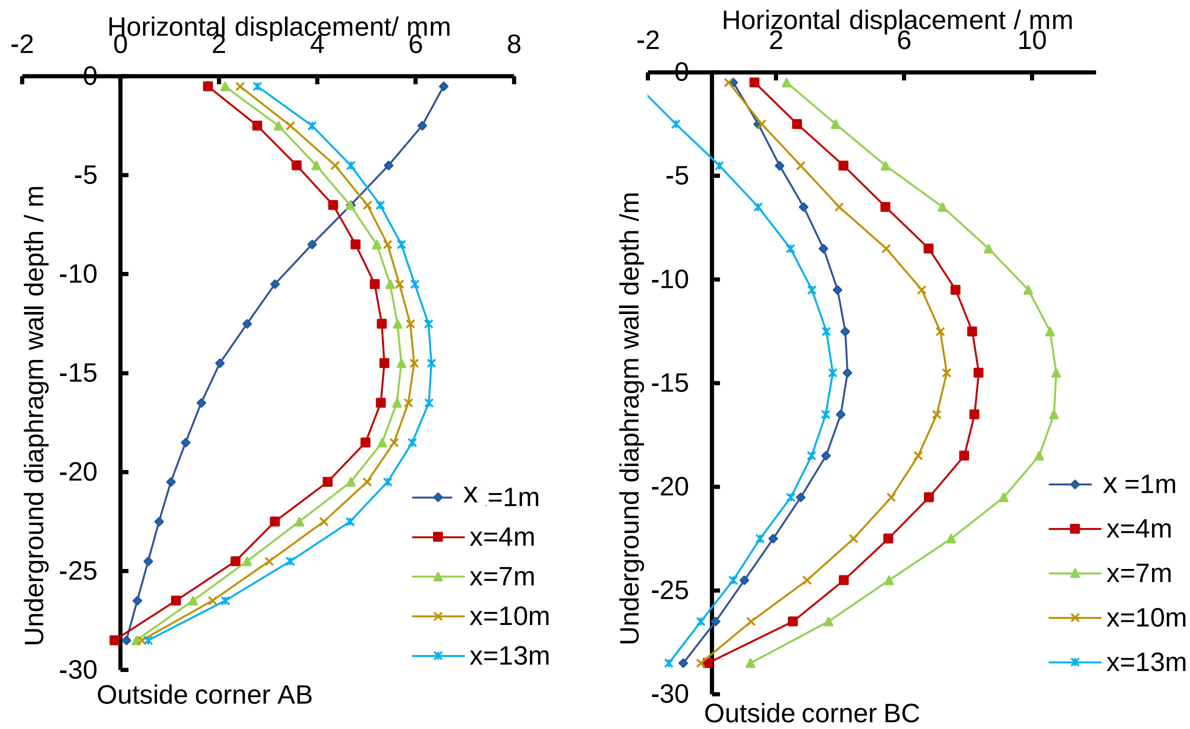
(b) Working condition VII



(c) Working condition VIII



(d) Working condition IX



(e) Working condition X

Fig. 7 – Curves of the horizontal displacements of the retaining structure at both ends of the positive corner under various working conditions

According to Figure 7, under working condition VI, the retaining structures of the positive corner AB section are in a cantilever state and almost all move horizontally into the foundation pit. The point with the largest horizontal displacement is not at the positive corner but at approximately 4 m from the positive corner. This is because a horizontal support and multiple inclined supports are set near the positive corner, which effectively prevent the destruction of the positive corner of the foundation pit. The enclosure structure of the positive corner BC section is also in a cantilever state, but the rule of movement to the outside of the pit is farther away from the positive corner of the pit. This is because this place is near the internal corner C. Due to the inclined support and the effect of the CD segment on the internal corner, the retaining structure is subjected to internal forces that exceed the earth pressure outside the deep foundation pit. Therefore, the displacement of the envelope structure corresponds to negative values.

Under working condition VII, the change rule of the envelope structure in section AB is similar to the deformation rule under working condition VI. With the continuous construction of the deep foundation pit, the retaining structure moves horizontally into the pit, and the retaining structure of section BC undergoes a "bending" change. This is because section BC is an inclined support with a large axial force, which can bear most of the lateral pressure of the loose outside the pit. The support structure is no longer in a cantilever state, and the axial force slowly becomes a fixed force at both ends.

Under working condition VIII, the horizontal displacement change rule of the envelope structure in section AB is approximately the same as that of the overall envelope structure, and the envelope structure exhibits a "bulge" phenomenon. However, a different trend is observed near the positive corner. Here, the envelope structure does not follow the rule “a small change in the middle and a large change in the middle”. This is because the positive corner of the deep foundation pit is squeezed by not only the earth pressure but also the pressure that is induced by the horizontal movement of the support structure of the BC section into the pit after being subjected to the axial force of the inclined support. Thus, the supporting axial force is much smaller than the pit pressure on the envelope structure, and the envelope structure is in a cantilever state. With the continuous construction of the deep foundation pit, the variety rule of the BC section's retaining structure shows an increasingly strong "bow step" shape; hence, the BC section exhibits a satisfactory embedding effect. The more complicated force occurs at the place that is connected with the inside corner, and the envelope structure moves outside the pit.

During the excavation under working condition IX, the envelope structures of the positive corner AB and positive corner BC sections continued to increase with the excavation of the deep foundation pit, and the "bulge" phenomenon became increasingly apparent. Hence, the sand pebble geology has a satisfactory embedding effect on the bottom of the envelope structure. The change rule of the horizontal displacement under working condition X is almost the same as those under working conditions VIII and IX. The displacement deformation of the envelope structure attains its maximum value. The displacement of the envelope structure at the positive corner of segment AB reaches 6 mm, which satisfies the maximum deformation displacement that is specified by the code. The maximum point of the envelope structure of the BC section occurs at the third support, and the maximum displacement is approximately 10 mm, which satisfies the maximum deformation displacement that is specified by the code.

In summary, the change rule of the retaining structure at the positive corner pit is similar to the change rule of the overall structure. However, various differences are readily observed: The horizontal displacement change along the short side at the positive corner B differs substantially from that of the ordinary support structure, and according to the preliminary analysis, the pre-loaded axial force of the steel support is too small. However, the negative change in the displacement near the internal corner C indicates that the envelope structure is moving horizontally outside the pit, which may be caused by the excessive axial force of the second inclined support. Thus, the forces at the positive corner and the internal corner of the retaining structure are highly complicated, and this corner is the most unstable place.

CONCLUSIONS

1) The curves of the surface settlement results of the 3D numerical simulation are analyzed, and the ground settlement of the loose body is found to increase continuously with the excavation of the foundation pit. The maximum point of loose surface settlement is not near the pit wall but at a distance of approximately 6-10 m from the pit wall. After erection of steel support, the variation law of the surface settlement curve outside the foundation pit is that the surface settlement increases rapidly with the increase of the distance from the pit wall. When the settlement of foundation pit reaches the maximum settlement value, the surface subsidence decreases with the increase of distance from the pit wall. From Figure 3 (b) we can clearly see this trend.
2) According to the analysis of the envelope structure, the settlement of the envelope structure increases and eventually becomes flat. With the continuous excavation of the deep foundation pit, the retaining structure exhibits a "bulge " phenomenon, which also demonstrates that the two ends of the retaining structure are better restrained and the sand pebble geological retaining structure exhibits a satisfactory embedding effect.
3) Focusing on the pit angles of the supporting structure, the results demonstrate that the positive corner of the supporting structure is the most complicated place, (the positive corner is the angle greater than 180 degrees, point B in this paper is the positive corner). With instability changes, in the support of the foundation pit, the positive corner of the foundation pit should be avoided as much as possible. If it is unavoidable, in-depth study of the positive corner should be conducted to identify the cause of the instability of the positive corner, and the axial force should be adjusted reasonably to transform the envelope structure of the positive corner into a stable state under stress to ensure the safety of foundation pit construction.

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