Study on Influencing Factors of Deep Foundation Pit Deformation under Surcharge

Cheng Cao[1,*], Xinyu Du[2]
[1]*China Construction Fourth Engineering Division Corp. Ltd, Xi'an 710065, Shaanxi, China*
[2]*Xi'an University of Technology, Xi'an 710048, Shaanxi, China*
**Corresponding Author*

Abstract: The surrounding piles of deep foundation pit(FP) construction site will have an adverse impact on the stability of the FP. Therefore, this paper uses COMSOL finite element software to build the foundation pit model as an example. By changing the size of the piles, the position of the support layout and the embedment depth of the supporting piles, it analyzes the influence of the factors influencing the loading and deformation control on the excavation deformation rule of the FP. The conclusion is as follows: when the pile position is fixed, the horizontal displacement of FP supporting pile and the surrounding surface settlement increase with the increase of the pile load. When the size of the pile remains constant, the horizontal displacement of the foundation pit supporting pile decreases as the pile is far away from the FP, and the position where the maximum surface settlement appears corresponds to the position of the pile.

Keywords: Surcharge; Foundation Pit Excavation; Horizontal Displacement; Ground Settlement

1. Introduction

In the realm of geotechnical engineering, support has emerged as a key technological tool for ensuring the stability of nearby structures and the safety of deep excavation [1-3]. Deep and sizable foundation pits located in urban areas have frequently suffered instability and damage as a result of external loading in recent years[4–7], which has resulted in safety incidents and fatalities. For instance, excessive soil buildup in the short term contributed to Building 7's general collapse in Shanghai's "Lianhua River Jingyuan" neighborhood; the foundation pit of Guangzhou Haizhu City Plaza fell as a result of the presence of several high-rise structures close by. Thus, it is crucial to research the influencing elements of the excavation deformation of the cantilever support pile for the internally supported loess foundation pit in order to effectively regulate and prevent the occurrence of such engineering incidents.

The impact of site loading on excavation deformation of foundation pits has been the subject of substantial research in recent years, and the rich research findings have successfully aided in the development of related research fields. Through an indoor model test, Atkinson et al. investigated the effect of surcharge on the mechanical change of the tunnel; Xie Huanhuan [8] utilized PLAXIS 3D to model the excavation process of a FP in Tongren; Based on the modified Cambridge model, Sun Yongchao et al.[9] developed the construction model of a deep FP in soft soil and investigated the effects of surcharge on the deformation of retaining walls and surface settlement; Yu Xiaogang [10] employed FLAC 3D software; he then examined the change of the FP support and the law of surface settlement under the pile load situation; Yu Chengshu[11] investigated how pile loads produced by pipe gallery sections affected foundation pit support displacement and surface settling. He discovered that the displacement and surface settling of the foundation pit support steadily grew as the pile weight rose; Wei Gang et al.[12] studied changes in tunnel confining pressure under ground surcharge and investigated the effects of factors like surcharge size, tunnel burial depth, and surcharge location on the tunnel; Wang Min et al.[13] studied the negative effects of temporary ground loading on existing tunnels in urban underground spaces using theoretical analysis; Huang[14] studied the influence of ground surcharge on tunnel deformation and collapse; Niu Cong et al.[15] used equivalent beam theory and finite element technology to study the effects of temporary ground loading on existing tunnels in urban underground spaces; Wang Na [16] studied the impact of temporary stacking during the construction process on the stability of the FP using the construction of a specific subway section as an example; Huang et al.[17] verified the influence of surcharge on the collapse of shallow tunnel by FLAC-PFC numerical software. There is minimal research on the variables influencing the deformation of FP excavation under pile loading, despite the fact that the research mentioned above mostly uses numerical approaches to assess the various effects of pile loading on foundation pits.

In order to comprehend the mechanical strength parameters of loess soil and ultimately choose the parameter values that satisfy the study goals, this article summarizes prior research and experimental findings. It decides to take into account creating a loess excavation model utilizing an elastic-plastic constitutive model. The control variates are used to explore the key determinants of deformation of foundation pit excavation support pile under surcharge, and then the deformation law and internal mechanism of loess foundation pit support under surcharge are studied and analyzed. In this model, the Drucker Plague yield criterion combined with the Mohr Coulomb yield criterion equation is used to determine the limit state of soil from elastic deformation to plastic deformation.

2. Constitutive Model of Soil

A loose material formed up of numerous particles of various sizes, soil. The elastoplastic constitutive model is thought to be employed in this paper's nonlinear finite element calculations of soil mass during foundation pit excavation and support. The elastoplastic constitutive model assumes that the elastic and plastic components of soil's overall strain are given by the following equations:

$$d\varepsilon = d\varepsilon^e + d\varepsilon^p \tag{1}$$

In the equation $d\varepsilon$ represents the total strain; $d\varepsilon^e$ represents elastic strain; $d\varepsilon^p$ represents plastic strain;

Among them, the elastic strain component $\{d\varepsilon^e\}$ calculate using the generalized Hooke's law of elasticity, as follows:

$$\{d\varepsilon^e\} = [C]\{d\sigma\} \tag{2}$$

In the equation $[C]$ is the tangent flexibility matrix related to the stress or strain path;

The plastic constitutive model includes three major theories: ① yield surface or yield condition theory; ② Theory of Flow Law; ③ Work hardening theory. Among them, the plastic strain component $\{d\varepsilon^p\}$ the calculation is based on the theory of elastic-plastic increment, and the commonly used calculation of plastic increment $\{d\varepsilon^p\}$ as shown in equation (3)

$$\{d\varepsilon^p\} = \Delta\lambda\{n\} \tag{3}$$

In the equation $\Delta\lambda$ the modulus of plastic increment is obtained from the hardening law; $\{n\}$ the direction of plastic flow increment is determined by the flow law;

Appropriate soil yield strength criteria are helpful for the convergence of model calculations as well as the validity and reliability of calculation results in the process of numerical modeling in geotechnical engineering. To fulfill the demands of convex yield surfaces and the standards of less-material, more-measureable features, we first examine meeting or reflecting the yield and failure characteristics of geotechnical materials as much as feasible. As a result, the limit state of soil between elastic and plastic deformation is determined by this article using the Mohr Coulomb yield criterion equation in conjunction with the Drucker Plague yield criterion. The yield criterion condition can be expressed by the following equation:

$$f(I_1, J_2) = \sqrt{J_2} - \alpha I_1 - k = 0 \tag{4}$$

They are, respectively, the stress Rhode angle, the second invariant of the stress tensor, and the first invariant of the stress tensor in the equation I_1、J_2、α.

among I_1 and J_2 the expression is as follows:

$$\begin{cases} I_1 = \sigma^{xx} + \sigma^{yy} + \sigma^{zz} \\ J_2 = \frac{1}{2} s^{\alpha\beta} s^{\alpha\beta} \end{cases} \tag{5}$$

In the equation σ^{xx} is the stress component in the x-direction; σ^{yy} is the stress component in the y-direction; σ^{zz} is the stress component in the z-direction; $s^{\alpha\beta}$ is the shear stress tensor;

among α and k it is a constant of the Drucker Plague yield criterion, which can be φobtained by mutual conversion with the Mohr Coulomb material parameter cohesion c and internal friction angle. In the plane strain state, the constant of the Drucker Plague yield criterion is defined as:

$$\begin{cases} \alpha = \frac{\tan\varphi}{(9+12\tan^2\varphi)^{1/2}} \\ k = \frac{3c}{(9+12\tan^2\varphi)^{1/2}} \end{cases} \tag{6}$$

3. Model Establishment

The site's center serves as the axis of the axisymmetric rectangle that serves as the loess foundation pit. As a result, a numerical model (Figure 1) is created utilizing 1:1 modeling and half of the right side of the foundation hole. The foundation hole has a horizontal width of 80 meters and a height of 50 meters. The soil is separated into two strata. First layer of soil is Q3 with 20 meters of loess thickness, and second layer is Q4 with 30 meters of loess thickness; The foundation pit is 30 meters deep, and a pile support system is used, consisting of a cast-in-place (CIP) pile plus three prestressed internal supports. Table 1 displays the physical characteristics of the support structure, with the CIP pile's diameter being 800 mm and its embedded depth being 6 m; The CIP pile's bottom corner is 30 meters from the left boundary, and its top corner, excluding the diameter of the pile, is 90 meters from the right boundary. The first internal support is positioned 4.8 meters below the surface, the second internal support is 9.3 meters below the surface, and the final internal support is 14.35 meters below the surface. As the excavation depth rises from 20 kPa to 100 kPa, the prestressing force is applied. The table (1) below provides specifics regarding the foundation pit's construction procedure.

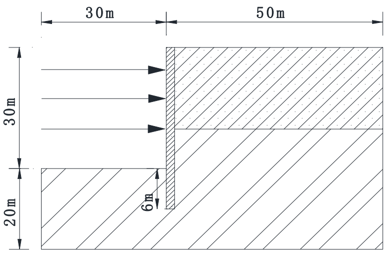


Figure 1. Calculation Model Section

Table 1. Supporting Scheme

Process steps	**Construction progress**
1#	Excavate the foundation pit soil to 6m and arrange the first internal support at 5m
2#	Excavate the foundation pit soil to 10m and arrange the second internal support at 9m
3#	Excavate the foundation pit soil to 16m and arrange the third internal support at 15m
4#	Excavate the soil of the foundation pit to the bottom, and all excavation is completed

The horizontal displacements on the left and right sides of the model are confined, but their vertical displacements are not, in order to simplify the model and make calculations easier. The vertical and horizontal displacements at the bottom of the model are also forcibly constrained. To avoid grid re division of excavation volume and achieve the goal of saving memory, the initial displacement at the bottom of the excavation surface of the FP should be set to zero. The CIP pile adopts a linear elastic model, and a compression operator is set at the contact boundary between the CIP pile and the soil to achieve a coordinated vertical displacement between the pile and the soil, while the horizontal displacement of the pile is not affected. Finally, to improve the computational convergence of the model at the contact boundary, the mesh division of the CIP pile and its surrounding soil is relatively dense. The mesh division diagram is shown in Figure 2.

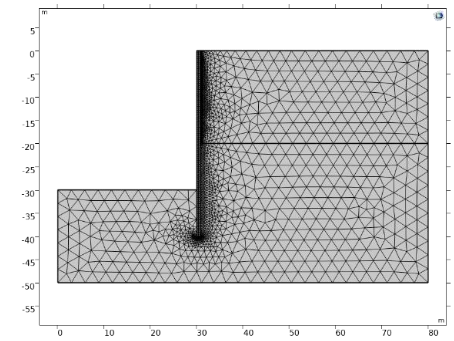


Figure 2. Computing Model Grid Diagram

The soil parameters involved in the construction of the FP model include compression modulus, Poisson's ratio, density, cohesion, and internal friction angle. The compression modulus, Poisson's ratio, and density values of the model are derived from the "Properties of Northwest Loess", and the cohesion and internal friction angle values are derived from relevant articles in "Loess Science". The parameters of the CIP pile in the foundation pit model include Young's modulus, density, and Poisson's ratio, all of which are based on the previous experience of

FP support engineering in the loess region and taken according to the "Design Specification for Concrete Structures" .The specific parameters are shown in Table 2 and Table 3.

Table 2. Physical and Mechanical Parameters of Soil

Soil layer name	Density/(kg/m3)	Compression modulus/MPa	Poisson's ratio	Cohesion force/kPa	Internal friction angle/(°)
Q3 loess	1850	6	0.3	40	25
Q4 Loess	1800	8	0.3	50	25

Table 3. Physical and Mechanical Parameters of Support Structure

name	Material Science	Diameter/mm	Length/mm	density /(kg/m3)	Elastic modulus/MPa
Concrete support pile	C25	φ 800	36000	2400	25×103
Steel pipe support	Q235B	φ 609	30000	7800	20×104

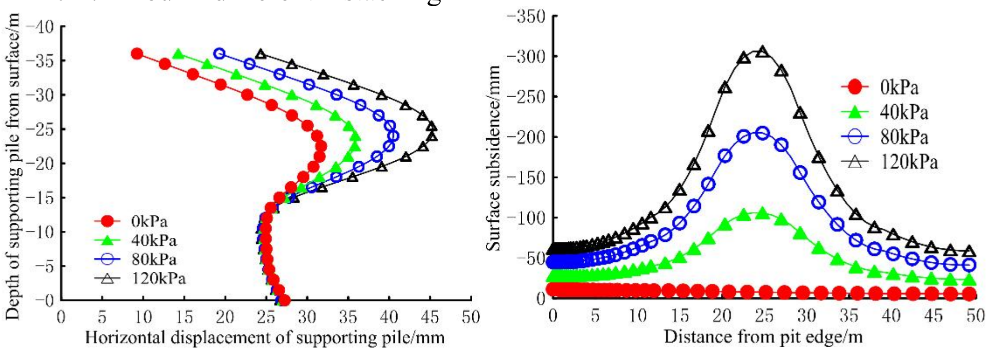
4. Result Analysis

The transportation vehicles parked around the foundation pit and the accumulated steel bars all belong to the pile load around the foundation pit. If the surrounding pile load is not handled in a timely manner, it may cause damage or even failure of the FP support system, ultimately leading to the collapse of the FP. Therefore, it is necessary to study the impact of surrounding surcharge on excavation of foundation pits.

4.1 Changing the Size of the Heap Load

Exploring the influence of surrounding stacking load on the deformation of the FP support structure for the internally supported cantilever CIP pile foundation pit in the loess region, three inner supports are first arranged at the left side of the CIP pile -4.8m, -9.3m, and -14.35m. The activation conditions are set as follows: when the excavation depth of the soil layer exceeds the depth of the inner support arrangement, the insertion depth of the CIP pile is taken as 6m, and the surface stacking load is set at a distance of 20m from the edge of the foundation pit, with a stacking width of 10m. Four different stacking conditions are set, The stacking values are 0kPa, 40kPa, 80kPa, and 120kPa in sequence. By comparing and analyzing the horizontal deviation of support piles, surface settlement, and pit bottom uplift, the impact of pile load on the deformation of loess FP excavation is analyzed.

As shown in Figure 3 (a), under four different loading conditions of 0kPa, 40kPa, 80kPa, and 120kPa, the range of 15m inserted into the soil by the support pile remains almost unchanged. The deformation of the support pile under all four types of stacking loads presents a "convex" shape, and the maximum deformation value increases from 30.742mm at 0kPa to 45.331mm at 120kPa with the increase of stacking load, with an increase of about 47%. As shown in Figure 3 (b), there is a simple linear relationship between the surface deformation and the distance from the edge of the FP under the condition of no stacking load, which is manifested as decreasing with the increase of the distance from the FP; As the surcharge increases, the surface deformation also increases from 11.336mm at 0kPa to 306.089mm at 120kPa.



(a) (b)

Figure 3. Influence of Heap Load on Displacement and Deformation of FP

Comparing the four working conditions in Figure 3, it can be seen that the accumulation of load around the FP has a significant impact on the deformation of the FP during construction, which can easily lead to engineering safety accidents. Therefore, it is particularly important to optimize the support plan for the surrounding accumulation of load during the construction process of the FP.

4.2 Analysis of Factors Affecting the Stability of FPs under the Action of Surrounding Surcharge

In conclusion, taking the 80kPa surcharge around a FP in Xi'an during construction as the research object, the influence of the location of the research reactor load, the layout of the internal support and the embedded depth of the support pile on the excavation deformation of the FP with surcharge around was analyzed in detail.

4.2.1 The influence of internal support arrangement on the deformation stability of foundation pits

This group studies the influence of internal support arrangement on the deformation of FP support structure, considering the condition that the embedded depth of the support pile and the surrounding pile load remain unchanged, the insertion depth of the support pile is taken as 6m, and a vertical pile load with a width of 10m is set on the surface 20 meters away from the edge of the FP, with a pile load value of 80kPa. Simulate the arrangement of four types of internal supports in the foundation pit, each with three internal supports. The positions of the three supports under each working condition are:

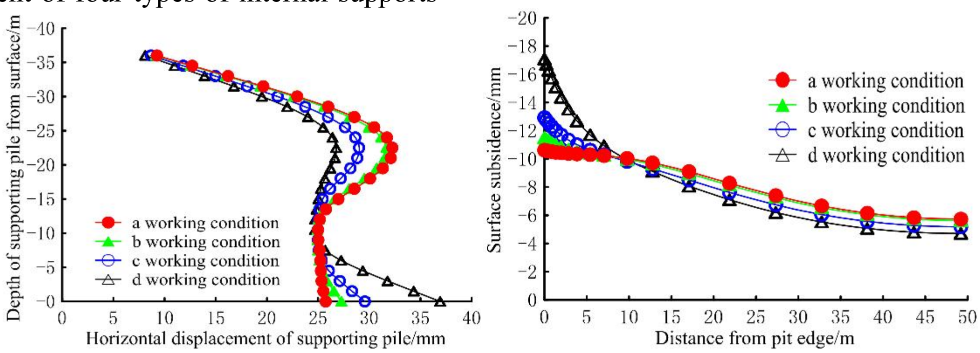
Working condition a: -3.50m, -9.00m, -14.00m;

Working conditions b: -4.80m, -9.50m, -14.35m;

Working conditions c: -6.00m, -11.00m, -16.00m;

Working conditions d: -8.00m, -13.00m, -18.00m.

From Figure 4 (a), it can be seen that changing the arrangement of the internal support has a significant effect on suppressing the deformation of the supporting pile body. It is found that the horizontal deviation of the supporting pile within the scope of the internal support under all four working conditions is about 25mm, which is significantly reduced compared to the deformation outside the scope of the internal support. At the same time, it was found that as the position of the internal support arrangement moved downwards, the position where the maximum deformation of the support pile occurred gradually moved upwards from the middle of the support pile, and the maximum deformation value also increased accordingly. Therefore, early support of the FP is beneficial for limiting the deformation of the support piles and effectively preventing the occurrence of safety accidents during the construction process of the FP.



(a) (b)

Figure 4. Displacement and Deformation of Foundation Pit under Different Supporting Conditions

The curve in Figure 4 (b) can be divided into two parts. Part 1: When the internal support arrangement is in working condition a, the surface settlement value around the FP gradually decreases as it moves away from the FP; Part 2: When the internal support arrangement is in working conditions b, c, and d, the change in surface settlement value around the FP can be divided into two stages. Firstly, there is a sudden change stage, during which the surface settlement value decreases significantly and the phenomenon occurs within 7.5m from the foundation pit; Next is the stable stage, during which the decrease in surface subsidence gradually tends to be gradual. It has also been indirectly verified that timely support during the early construction process of foundation pits can effectively suppress the deformation of support piles, thereby preventing the occurrence of safety accidents in foundation pit engineering.

4.2.2 Impact of embedded depth of support piles on deformation stability of foundation pits

This group studies the effect of the embedded depth of support piles on the deformation of foundation pit excavation. There are three models, including standardized models. Except for changing the length of support piles, all other set conditions remain unchanged. The lengths of support piles for each foundation pit model are 33m, 36m, and 40m, respectively, and the corresponding embedded depths of support piles are 3m, 6m, and 10m.

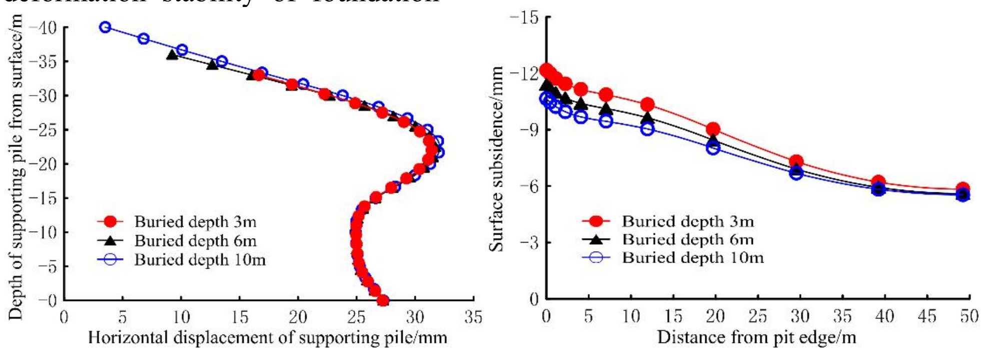


Figure 5. Influence of Embedded Depth on Displacement and Deformation of Foundation Pit

Figure 5(a) shows that the maximum displacement value and the location at which the maximum displacement value occurs are not significantly affected by adjusting the depth of the support pile into the earth. As the buried depth of the support pile increases, the surface settlement value in Figure 5(b) steadily lowers, and all of these events take place near the border of the FP. Under the three working circumstances, the maximum surface settlement values are 10.648mm, 11.399mm, and 12.169mm, respectively. From this, it can be shown that decreasing the support pile's buried depth has a little overall influence on the FP's deformation while having a certain effect on managing the deformation of the excavation.

5. Conclusion

This chapter solved and calculated the established numerical model, and analyzed the obtained results. The method of controlling variables was adopted, and the numerical model was calculated and solved by changing the size and position of the surrounding pile, the arrangement of internal supports, and the embedding depth of support piles. The development of support pile offset, surface deformation, and pit bottom displacement under different working conditions was analyzed, and the results were analyzed to obtain the following rules:

(1) When the FP is excavated to the same depth, the presence of surrounding surcharge significantly increases the horizontal displacement of the support pile body, and as the surcharge increases, the horizontal displacement of the pile body also increases more and more. The surcharge has a greater impact on the horizontal displacement of the middle part of the pile body, but a smaller impact on both ends.

(2) Internal support can successfully prevent the supporting pile body from deforming. As the position of the internal support moves downwards, the maximum horizontal displacement of the supporting pile body gradually moves upwards, and the maximum deformation also gradually increases; The surface subsidence value also undergoes a sudden change stage, and the maximum value of surface subsidence gradually increases. From this, it can be seen that timely support of the FP can effectively prevent the occurrence of engineering safety accidents

(3) The horizontal displacement and surrounding surface settling of the support pile decrease as the embedding depth increases, however the change amplitude is rather

moderate.

(4)The ultimate purpose of studying the influence of overloading on the stable state of FP is to serve the engineering construction. Through the analysis and research on the stability of FP in loess area, the influence of overloading on the deformation rule of FP is obtained, which has important significance for the construction and management of FP engineering in loess area.

Acknowledgments

This work was partly supported by the National Natural Science Foundation of China (Nos. 42272319, 42101132 and 42172314)

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